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Final Report of the Center of Excellence in Rotary Wing Technology at Rensselaer Polytechnic Institute

Contract Number DAAL03-88-C-0004

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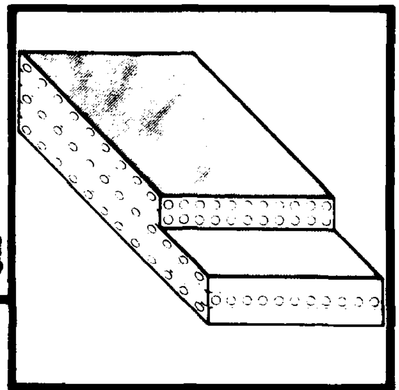
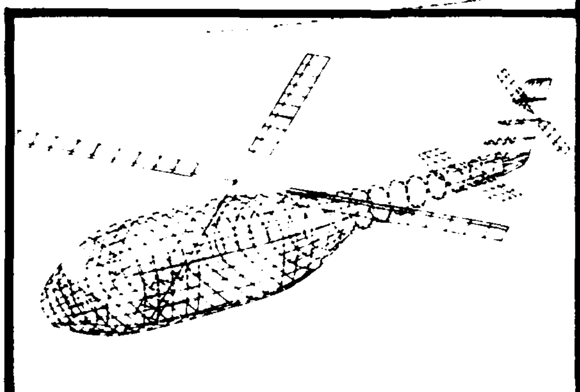
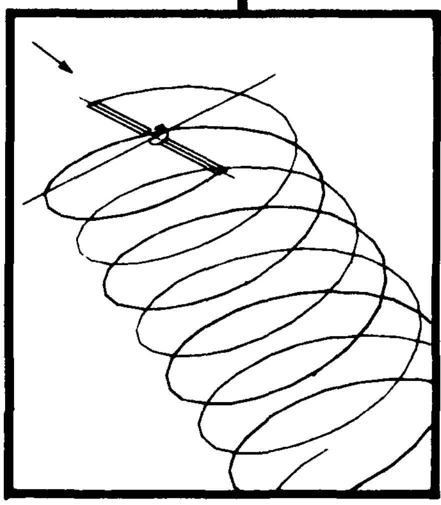
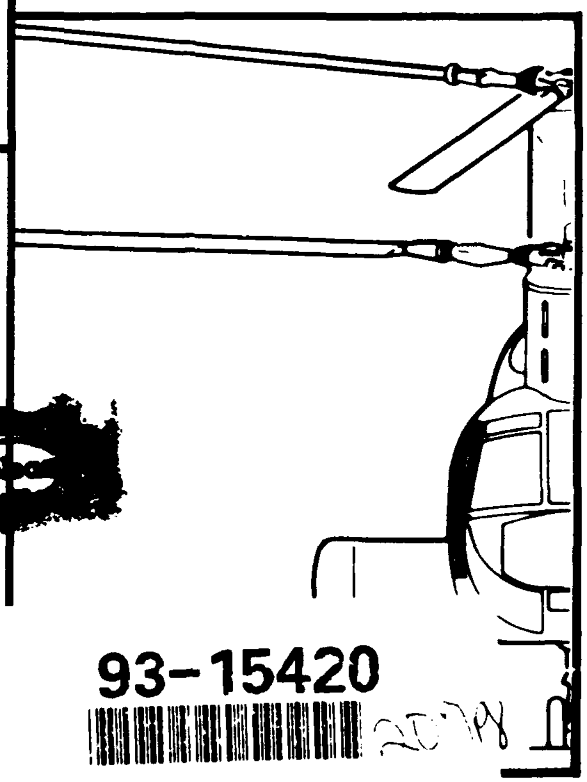
April 1, 1993









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13. ABSTRACT *(Maximum 200 words)*

The activities of a Center of Excellence in Rotary Wing Technology at Rensselaer Polytechnic Institute under a second, continuation five year contract with the U.S. Army Research Office are reported here. These include measures taken to revise and update comprehensive and in-depth curricula at advanced levels in rotorcraft technology; attract and retain outstanding young people in these programs; perform basic research at the leading edge of technology in structures, structural dynamics, unsteady aerodynamics and aeroelasticity disciplines as applied to rotorcraft; and accomplishing technology transfer to the rotorcraft community beyond the Rensselaer campus. Descriptions, references and statistics are provided to allow assessment of the extent to which these goals have been realized.

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FINAL REPORT OF THE
CENTER OF EXCELLENCE IN ROTARY WING TECHNOLOGY

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RENSSELAER POLYTECHNIC INSTITUTE

Preface

This report attempts to be a rather complete summary of all that transpired under a contract covering five years of effort, from 1/1/88 to 12/31/92. The text includes summaries of pertinent information; the appendices contain fairly detailed records of activities.

Because of the length of the totality of research summaries, figures and tables are placed immediately following the associated text. This has the effect of putting figures and tables in positions that are more easily referred to. The figures are grouped first, the tables second. All references are contained in one place, however, Section VII.

Where research results have been substantially reported in the open literature, the research summaries have been limited by referring to those publications. Thus, the degree of detail provided in research summaries is purposefully uneven, with greater numbers of figures and tables provided for those projects which were not, as of this writing, fully reported in the literature.

Executive Summary

The Rensselaer Rotorcraft Technology Center (RRTC) was supported in the second five years following its establishment by a contract from the Army Research Office which provided a total of $2,426,000 for the period from 1 Jan. 1988 to 31 Dec. 1992.

During that five-year period a number of fundamental research advances were brought about, which were reported in the literature, presented at national and international meetings, and - in a number of cases - transferred to the U.S. industry through one-to-one technical interchanges, consulting arrangements, or by additional contracts from an individual company to the RRTC. Among the cases of successful transfers of new technology were the following: coding a forced dynamic response analysis for rotor blades using generalized coordinates, accounting for geometric nonlinearities and suitable for incorporation in a particular company's comprehensive analysis method (V-F-1)*; interfacing a finite element based modal analysis with another company's comprehensive analysis code to advance rotor blade dynamics representations (V-E-3); incorporating finite element formulations for composite rotor blades into the 2GCHAS effort of the U.S. Army (V-E-3); developing "genetic search" techniques for rotor blade optimization codes for minimum vibration as used by a particular rotorcraft company (V-F-2); identifying limitations in standard computer code representation of elastomer behavior in lag dampers, together with approaches for correcting them (V-F-3b); and transmitting certain aspects of advanced computational fluid dynamics (CFD) analysis applications for elastic rotor blade analysis to the U.S. Army (V-E-5).

In the course of 90 RRTC visits to industry, other universities and government agencies over the contract period, there were 30 visits made by RRTC faculty and students to rotorcraft airframe industry companies, including Bell, Boeing, MDHC, Sikorsky (and UTRC, Hamilton- Standard), Schweizer and Robinson. Another 12 visits were made to engine and other rotorcraft equipment manufacturers, including G.E., Grumman, Lord, and IBM Defense Systems. A total of 29 more visits were made to government laboratories and offices, including the Army, Air Force, NASA and NRL. Conversely, a total of 60 visits were made by rotorcraft industry, government agency and other university personnel to the RRTC, during the contract period. In the course of all these visits, 59 formal lectures or seminars were delivered, for the benefit of those not involved in face-to-face interchanges.

The research described in this report resulted in 79 papers being published and 4 more being accepted for publication in rotorcraft related journals. Another 77 conference presentations were made during the contract period.

A total of 32 advanced degrees were granted to students studying rotorcraft technology in the Center, of which 18 were MS and 14 were Ph.D. degrees. Of these, 23 were earned by U.S. citizens and 9 were won by students not yet citizens or those intending to return to their native country. A total of 22 graduates found positions in the U.S. rotary wing industry, 12 with government agencies, and another 8 with the associated engine/equipment manufacturers during the contract period, if bachelor degree holders are included, as of this writing.

As a part of the activities of the RRTC, 6 short-courses were given, designed to up-date practicing engineers in the rotorcraft airframe, engine or associated equipment industries. A total of 95 were enrolled, representing a wide variety of U.S. and foreign companies, government agencies and universities. In addition, the 2nd International Workshop in Composite Materials and Structures for Rotorcraft was held at the RRTC in October '89, under ARO and AHS auspices. A total of 61 participants attended, representing 10 U.S. and 2 European companies, 6 agencies of our federal government, and faculty/staff of 8 U.S. and 1 European universities.

* Items in parentheses in the Executive Summary refer to sections in the report proper.

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I Introduction

In the five years following the establishment of Centers of Excellence in rotorcraft technology by the Army Research Office in 1982, many of the fundamental problems which were "at the cutting edge" of research at that time moved into the second echelon of applications research. These problems were not, of course, completely solved in the years from 1982 to 1987, but the underlying phenomena became well enough understood that when aircraft developments required it, the aircraft developers were able to solve them rather expeditiously. Such advances included composite materials applications to rotor blades, hubs and hinges, drive system components, and the fixed airframe (Bell and Sikorsky ACAP aircraft and Boeing Helicopter Company's Model 360); experimental flight tests of higher harmonic control, as an active means to reduce vibration; bearingless main rotors; the NOTAR™ (no tail rotor, circulation control tail boom for main rotor torque reaction and yaw control); five degree of freedom rotor isolation systems; and advanced rotor blade airfoil sections and planforms --- to name a few. Other research problems, however, well recognized five years ago, continued to elude satisfactory solution and remained worthy challengers of those who would advance basic knowledge in rotorcraft technology. Still other phenomena became recognized as important for the first time or emerged as more significant than was originally thought. These fundamental problems of the 1987 era constituted the area of technological challenge from which Rensselaer's Rotorcraft Technology Center selected research topics to include in its second five year program proposal to the Army Research Office [1].

It is indicative of the success of ARO's Centers of Excellence in Rotorcraft Technology programs that the nature of the proposal for the years 88 to 92 years vastly different than that written five years earlier. Curricular offerings in rotorcraft technology, experimental facilities, specialized computational methods, faculties with experience in and dedication to this field had all been substantially strengthened. As planned by their sponsors, the rotorcraft centers in that half decade passed from the start-up mode to one of consolidation, solidification and permanent rooting. It became far less important to identify the differences between the disciplines that are the foundations of rotary wing aircraft and those underlying fixed wing aircraft; that had largely been done. The 1987 RRTC proposal to ARO attempted to recognize which requirements for fundamental advances have been thrust into the regions of high research priority by rotary wing aircraft systemic and operational developments, experimental concept verifications and demonstrations, and by disciplinary advances. This report summarizes the research conducted under the resulting ARO contract to Rensselaer [2] and the closely related activities which supported that research and enhanced transfer of the results obtained to the industry and appropriate government agencies.

II Funding and Contractual History

A five year contract [2] was received at Rensselaer effective 1/1/88 for the purpose of continuing the development of a Center of Excellence in Rotorcraft Technology with the total funding of $2.426 million. The first support increment covered a period ending on 9/30/88. Subsequent increments were made available on October 1st of each of four successive years, and a final increment in the fall of 1992 to cover the remaining three months ending 12/31/92. The time history of the sum of this contract funding is shown on the financial forecast and expenditure chart of Fig. 1. Emphasis in planning for research tasks and other performance matters were established for each up-coming year on the basis of site visits to the RPI campus by the Army Research Office project monitors and evaluative panels and subsequent discussions. Emphasis on research projects, described in Section 5 of this report, were carried out, fundamentally, in accordance with ARO guidance formulated in this way. A list of the ARO evaluative panel members is shown in Table 1, and their years of activity on the panel indicated in Fig. 2. The dates of periodic site visits is shown in Table 2, attendees and their agenda in Appendix A. Note that the initial evaluation on May 10, 1988, rather than being "on site", was held at Durham, N.C. and involved all three Centers of Excellence.

A request for a no-cost extension resulted in the contract end date of Feb. 1, 1993; for a total performance period of five years and one month. The time history of actual expenditures is also shown in Fig. 1. A comparison of budget and expenditures by major categories is shown in Table 3.

Fig. 1

FORECAST vs ACTUAL EXPENDITURES

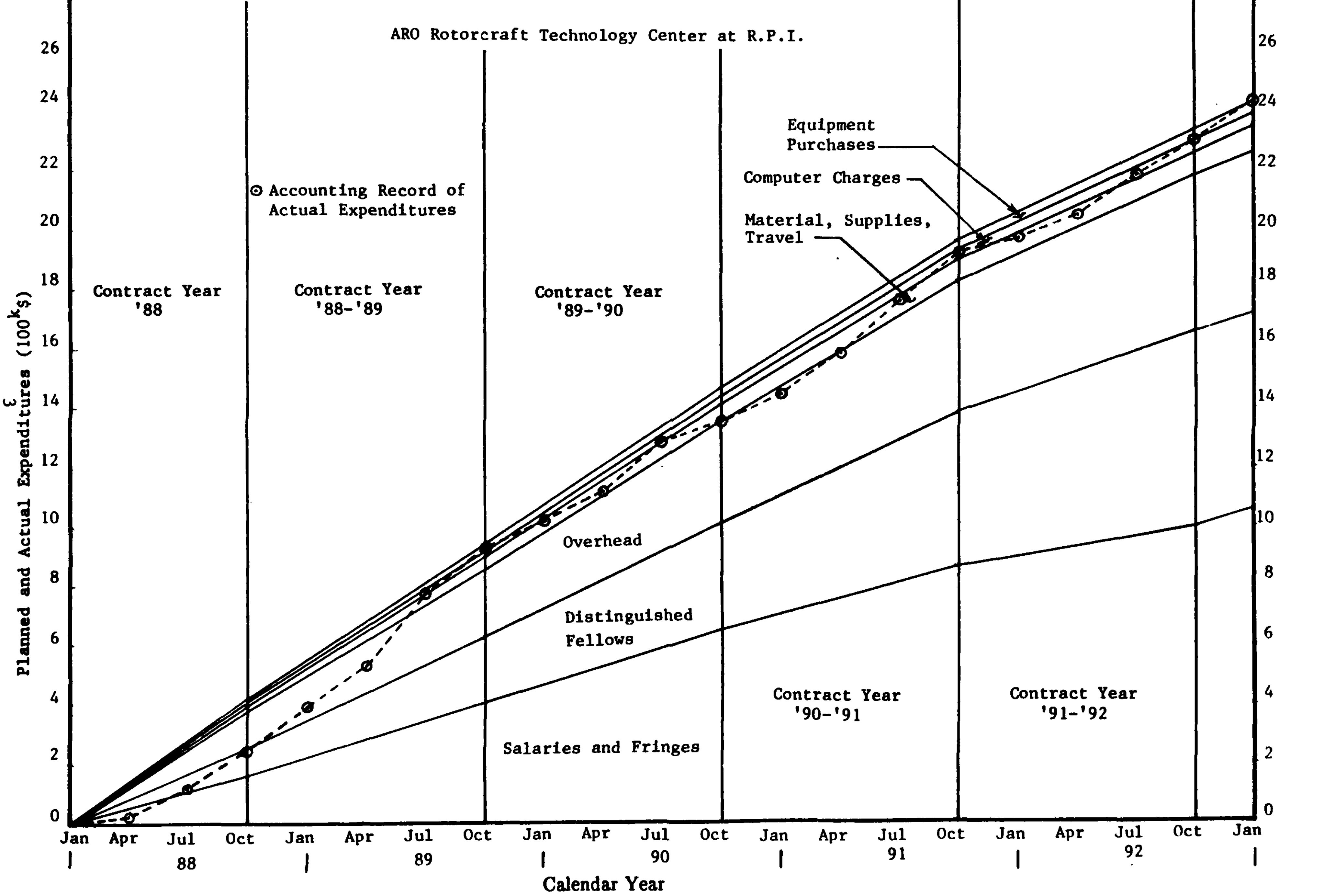


Fig. 2

Evaluative Panel Membership

Rensselaer RTC

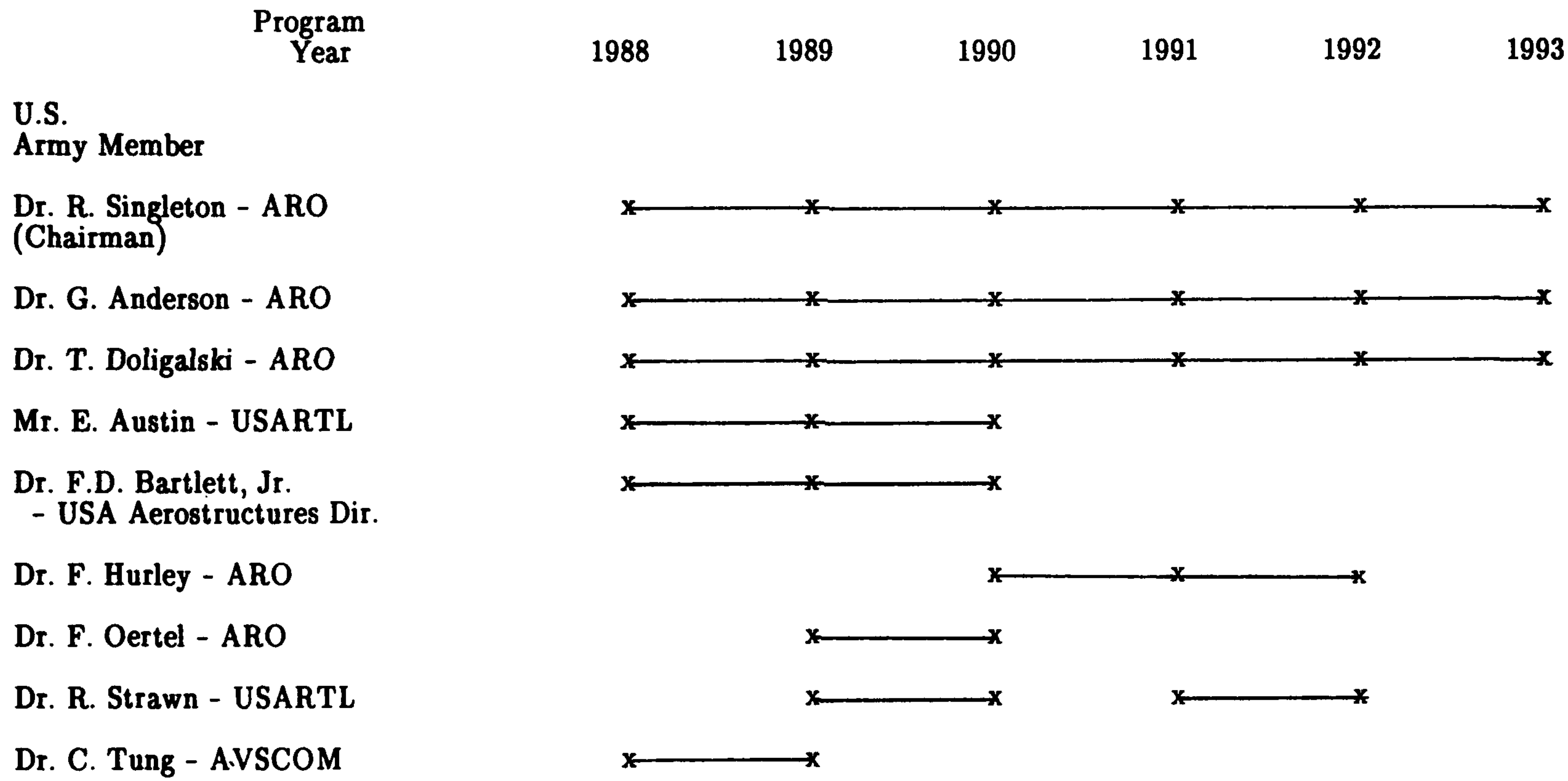


Table 1

Evaluative Panel Membership

Rensselaer RTC

Member	Member
Dr. Robert Singleton (Chairman) Director, Engineering Sciences Division U.S. Army Research Office	Dr. Frank X. Hurley Chief, Mobility Technology U.S. Army Research Office
Dr. Gary Anderson Chief, Structures and Dynamics Branch U.S. Army Research Office	Dr. Fritz Oertel, Jr. Chief, Multi Disc. Mechanic U.S. Army Research Office
Mr. Ed Austin Chief, Structures Lab AVSCOM, Ft. Eustis	Dr. Roger Strawn Research Scientist AVSCOM - Ames R.C.
Dr. Felton Bartlett, Jr. Chief, Structures Div. U.S. Army, Langley R.C.	Dr. Chee Tung U.S. Army Aeroflightdynamics Dir. Ames R.C.
Dr. Thomas Doligalski Chief, Aerodynamics Branch U.S.Army Research Office	

Table 2

Dates of Yearly ARO Evaluations

Dates	Sites
May 10, 1988	ARO - Durham
April 18-19, 1989	Rensselaer
June 29, 1990	Rensselaer
May 15, 1991	Rensselaer
October 6, 1992	Rensselaer

Table 3

Comparison of Accumulative Budget* and Expenditures by Category

Rensselaer Rotorcraft Technology Center

Category	Budget	Expenditures
Salary & Benefits(1)	70.9%	62.0%
Travel	1.5%	2.7%
Supplies & Services(2)	2.9%	2.5%
Equipment	0.7%	1.8%
Computer	1.8%	3.8%
Overhead	22.2%	27.2%
	100.0%	100.0%

* This breakdown reflects year-by-year reallocations; eg as influenced by fringe benefit and overhead changes.

(1) Includes graduate student and fellowship stipend and tuition.

(2) Includes subcontracts and publication costs.

III Center Organization and Management

The Rensselaer Rotorcraft Technology Center (RRTC) is organized as shown in Fig. 3. Professors Robert G. Loewy and R. Judd Diefendorf, were named initially as Co-Principal Investigators under the contract and functioned as Director & Assistant Director of the Center, respectively. In March, 1992, Dr. Olivier A. Bauchau was named Co-Principal Investigator and Assistant Director, in place of Prof. Diefendorf, who had left Rensselaer earlier for another position. Fig. 4 shows the chronological involvement of faculty with support under the contract.

Members of the Industrial Technical Advisory Panel, shown in Fig. 3, are listed in Table 4. Members were chosen deliberately as first-line supervisors who had responsibility for across the board technology within each of the major helicopter development and production companies in the United States. At the suggestion of Deputy Assistant Secretary of the Army for Research, Development and Acquisition, Mr. George Singley (DASARDA) and ARO Director, Dr. Gerald Iafrate, during a visit to the RRTC on Jan. 16, 1991, this advisory group was expanded to include representatives of U.S. Army agency offices. This is also shown in Table 4, and the modifier "Industrial" dropped, henceforth, from the committee title.

The faculty group shown in Fig. 3 as the Budget Advisory Committee, periodically reviews progress and accomplishments in all program performance areas: namely course/curricula development and revision; distinguished fellowship candidate attraction, selection & retention; continuing education; and research projects. The specific "next year" planned program of research presented for consideration at ARO site visits (see Appendix A), was selected by the Director from faculty proposals on the basis of advice from the committee, and allocations from each year's contract funding were made by the Director on the basis of their advice for the next years' research project budgets to accomplish what had been outlined in ARO guidance. Members of the Budget Advisory Committee are listed in Table 5.

Day to day supervision of the tasks established as described above, was carried out by each of the faculty members listed under research project headings in Section V as "Senior investigators". A complete list of the faculty contributing to the goals of the center are listed in Table 6. They are identified there as to chronology of involvement, research specialty, center role and whether directly funded by the ARO contract or not. For convenience, their years of funding under the contract are shown in Fig. 4. The faculty of the Center was ably assisted by staff during the contract period, in positions and for the terms shown:

Mr. Volker Paedelt	Manager, Composite Materials & Structures Laboratory	1/1/88-12/31/92
Dr. Donald Radford	Post Doctoral Fellow	6/1/88-6/30/88
Dr. M. Bobby Mathew	Post Doctoral Fellow	7/1/88-12/31/89
Dr. C.Y. Lin	Visiting Scholar Assoc. Prof., National Taiwan Inst. of Tech., Taipei, R.O.C.	1/1/92-12/31/92
Mr. R. Y. Li	Visiting Scholar Chinese Helicopter R&D Institute, Jingdezhen, Jiangxi Province, P.R.C.	7/1/92-12/31/92

Fig. 3

U.S. ARMY RESEARCH OFFICE
CENTER OF EXCELLENCE IN ROTARY WING AIRCRAFT TECHNOLOGY
AT RENSSELAER POLYTECHNIC INSTITUTE

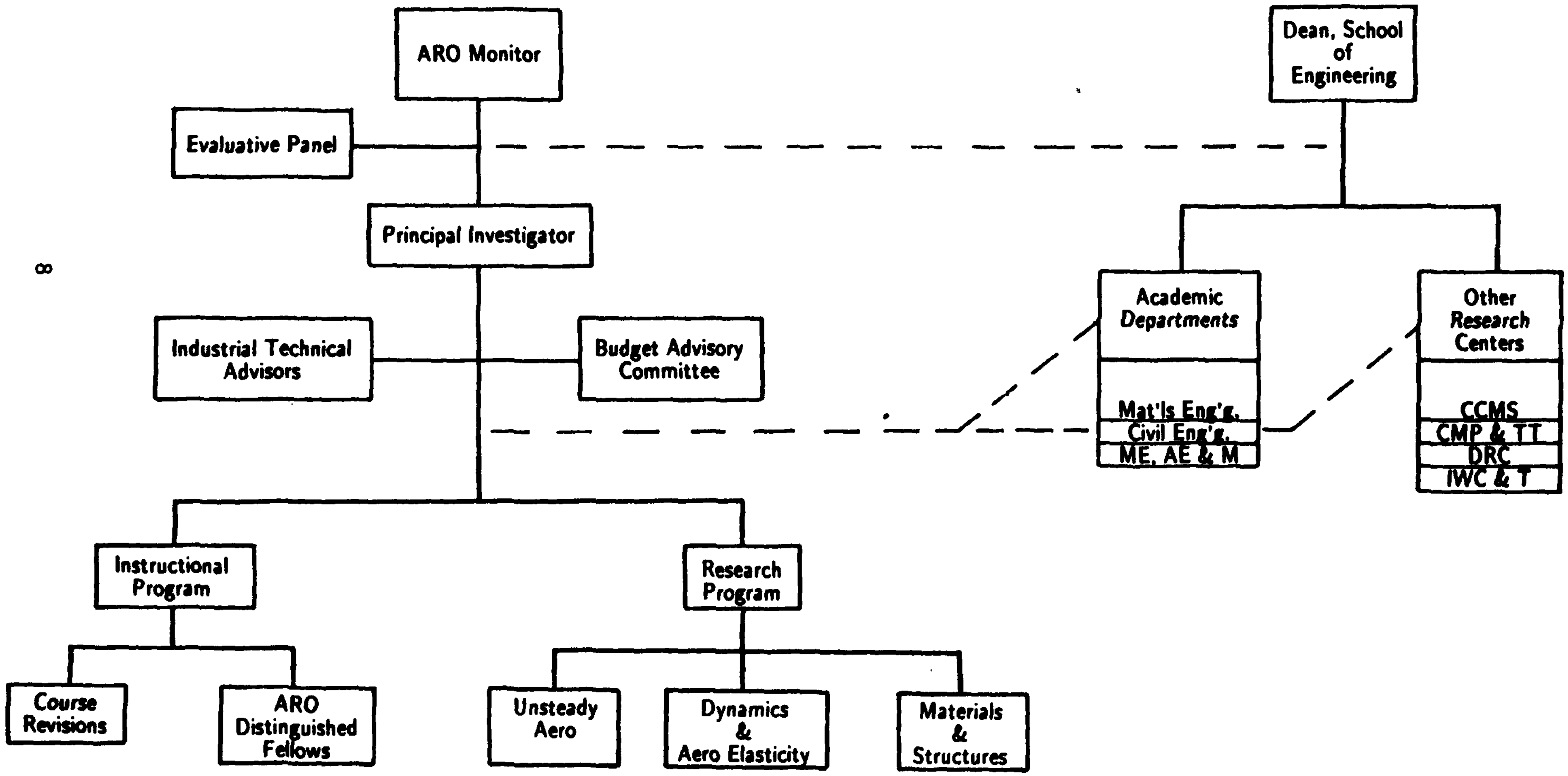


Fig. 4 - Faculty with Support under the Rensselaer RTC Contract

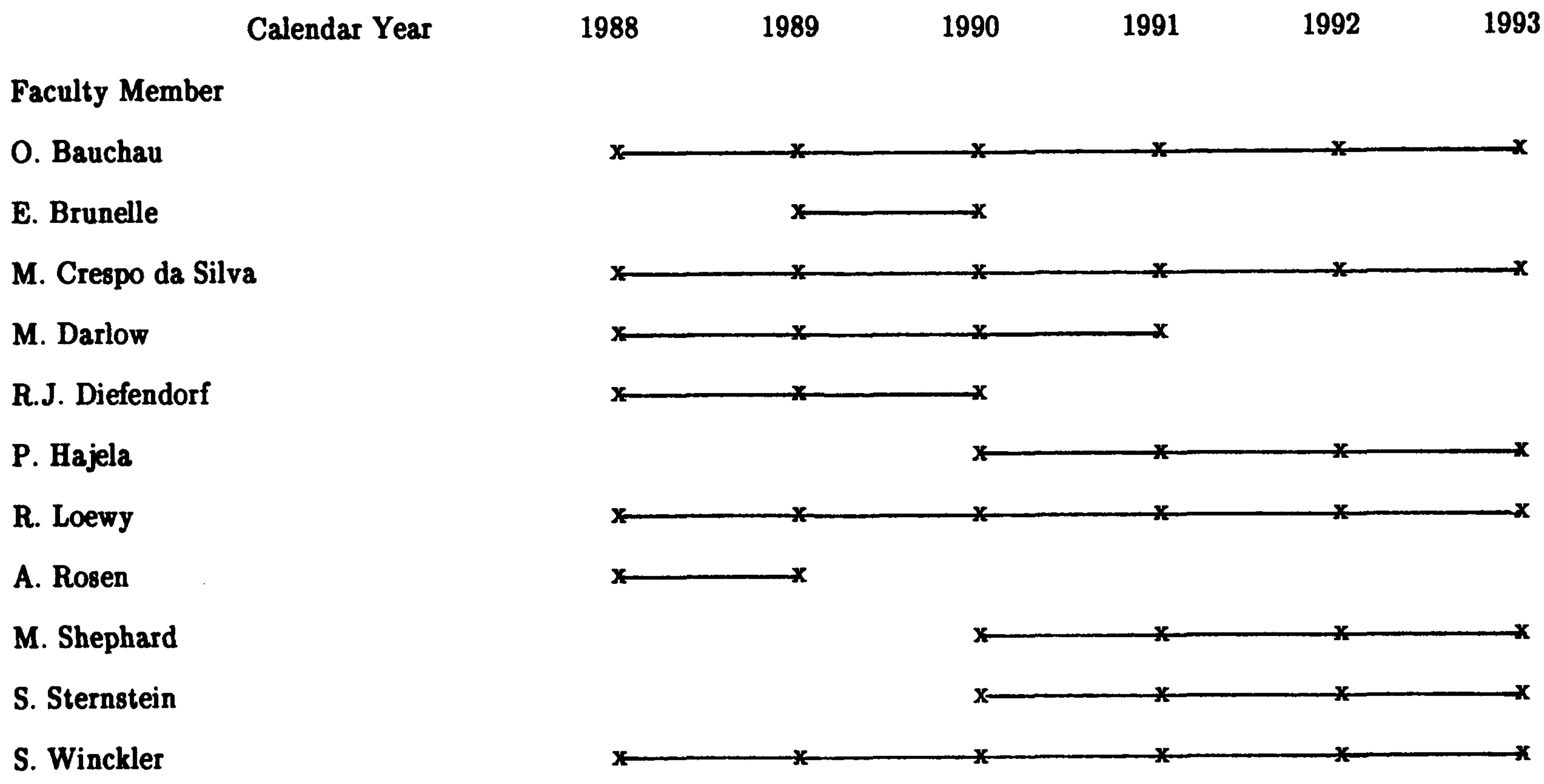


Table 4

Technical Advisory Panel Membership

Rensselaer RTC

Member	(Years Active)	Member	(Years Active)
Mr. Troy Gaffey Manager, JVX Technology Bell Helicopter Textron	(88 thru 91)	Dr. Wolf Elber Director, Aerostructures Directorate U.S. Army	(91 thru 93)
Dr. Jing G. Yen Director, Flight Technology Bell Helicopter Textron	(91 thru 93)	Dr. John Shaw Deputy Director, Research & Technology Boeing Helicopter	(91 thru 93)
Dr. David Jenney Chief of Technical Engineering Sikorsky Aircraft Division, UTRC	(88 thru 91)	Dr. Robert Ormiston Chief, Rotorcraft Dynamics Div. Aeroflightdynamics Directorate U.S. Army	(91 thru 93)
Dr. Raymond Carlson Chief, Advanced R&D Sikorsky Aircraft Division, UTRC	(91 thru 93)	Mr. Leslie Schweizer Vice President, Engrg & Quality Schweizer Aircraft Co.	(91 thru 93)
Dr. Andrew Lemnios Director, Research & Technology Kaman Aerospace Corporation	(88 thru 92)	Dr. Sam Crews Branch Chief, Dynamics & Analysis, U.S. Army, AVSCOM	(91 thru 93)
Mr. Andrew H. Logan Director, Research and Technology McDonnell-Douglas Helicopter Co.	(88 thru 91)	Dr. Fred Schmitz Chief, Full Scale Aero Research NASA, Ames R.C.	(91 thru 93)
Dr. Debashis Banerjee Director, Research and Technology McDonnell-Douglas Helicopter Co.	(91 thru 93)		

Table 5

Faculty Budget Advisory Committee

Rensselaer RTC

Dr. Robert G. Loewy, Director RRTC (88-94)
Institute Professor
Department of Mechanical Engineering,
Aeronautical Engineering and Mechanics

Dr. R. Judd Diefendorf, Assist. Director RRTC (88-90)
Professor
Department of Materials Engineering

Dr. Olivier A. Bauchau, Assist. Director RRTC (90-93)
Associate Professor
Department of Mechanical Engineering,
Aeronautical Engineering and Mechanics

Dr. Prabhat Hajela (91-93)
Associate Professor
Department Of Mechanical Engineering,
Aeronautical Engineering and Mechanics

Dr. Erhard Krempl (88-91)
Chairman
Department of Mechanical Engineering,
Aeronautical Engineering and Mechanics

Dr. Robert Mayle (88-91)
Professor
Department Of Mechanical Engineering,
Aeronautical Engineering and Mechanics

Dr. Mark Shephard (91-93)
Professor
Departments of Civil Engineering and of
Mechanical Engineering, Aeronautical
Engineering and Mechanics

Dr. Sanford S. Sternstein (90-93)
Professor
Department of Materials Engineering

Professor Richard Bielawa (88-90)
Associate Professor
Department Of Mechanical Engineering,
Aeronautical Engineering and Mechanics

TABLE 6

Faculty Members Contributing to Rensselaer RTC Program

Name	Title	Academic Department	Research Specialty	Program Role	Years of Involvement
Bauchau, O.	Associate Professor	ME, AE & M	Aeroelasticity	Senior Investigator	1/1/88 - 1/31/93 (1) 10/1/90 - 1/31/93 (2) 3/1/91 - 1/31/93 (3)
Bielawa, R.	Associate, then Adjunct Professor	ME, AE & M	Aeroelasticity	Supporting Investigator	1/1/88 - 1/31/93 1/1/88 - 9/30/90 (2)
Brunelle, E.	Associate Professor	ME, AE & M	Mechanics of Composites	Supporting Investigator	10/1/88 - 9/30/89 (1)
Crespo da Silva, M.	Professor	ME, AE & M	Structural Dynamics	Supporting Investigator	1/1/88 - 1/31/93 (1)
Darlow, M.	Associate Professor	ME, AE & M	Structural Dynamics	Senior Investigator	1/1/88 - 9/30/90 (1)
Diefendorf, R.J.	Professor	Materials Engineering	Composite Materials	Senior Investigator	1/1/88 - 9/30/90 (1)(2)(3)
Gabriele, G.	Associate Professor	ME, AE & M	Manufacturing Methods	Supporting Investigator	1/1/88 - 1/31/93
Hajela, P.	Associate then Professor	ME, AE & M	Optimization Theory	Leading Investigator	10/1/91 - 1/31/93 (1)(2)
Hirsa, A.	Assistant Professor	ME, AE & M	Fluid Mechanics	Supporting Investigator	10/1/90 - 1/31/93
Krempl, E.	Professor	ME, AE & M	Fatigue of Composites	Supporting Investigator	1/1/88 - 9/30/91 (2) 10/1/91 - 1/31/93
Loewy, R.	Institute Professor	ME, AE & M	Aeroelasticity	Senior Investigator	1/1/88 - 1/31/93 (1)(2)(3)
Mayle, R.	Professor	ME, AE & M	Aerodynamics	Supporting Investigator	1/1/88 - 9/30/91 (2)
Nagamatsu, H.	Professor Emeritus	ME, AE & M	Aerodynamics	Supporting Investigator	1/1/88 - 12/21/92
Rosen, A.	Visiting Faculty	ME, AE & M	Aeroelasticity	Supporting Investigator	1/1/88 - 9/30/88 (1)
Rusak, Z.	Assistant Professor	ME, AE & M	Aerodynamics	Supporting Investigator	10/1/91 - 1/31/93
Scarton, H.	Associate Professor	ME, AE & M	Structural Dynamics	Supporting Investigator	1/1/88 - 1/31/93
Shephard, M.	Professor	Civil Engineering	Finite Element Methods	Senior Investigator	10/1/91 - 1/31/93 (1)(2)
Sternstein, S.	Professor	Materials Engineering	Composite Materials	Leading Investigator	10/1/90 - 1/31/93 (1)(2)
Winckler, S.	Assistant, then Adjunct Professor	ME, AE & M	Mechanics of Composites	Leading Investigator	1/1/88 - 9/30/88 10/1/89 - 1/31/93

(1) With funding from the ARO contract (2) Member of Budget Advisory Committee (3) Co-Principal Investigator

IV Educational Components

A. Distinguished Fellow[illegible] Program

(Responsible Facult[illegible] [illegible].J. Diefendorf, 88-90; R.G. Loewy, 90-93.)

As part of the Center's efforts to attract promising young people to the study of rotorcraft technology at the graduate level, posters with self-addressed, postage-paid, tear-off return cards were designed, printed and mailed to 179 colleges and universities in the United States and Canada during the first 5 year contract, from '82 to '87. New posters were sent in each of the years 83, 84, 85 and 86. As a result of the program's growing visibility, the need to specifically advertise this program was seen as sufficiently reduced that no posters were used during the period of the subject contract.

The benefits of being chosen an ARO Distinguished Fellow included a stipend for eleven months keyed to the Consumer Price Index (C.P.I.) as published in the Economic Report of the President. Stipends actually disbursed under this program are shown in Table 7. In addition, all academic year tuition was paid by the fellowship. A $1,000.00 travel allowance was also provided, usually as necessary to provide one trip to a national meeting per year. This was customarily the American Helicopter Society Annual Forum, but could have been another or additional meeting, as mutually agreeable to the particular ARO Fellow and Program Director. A computer allowance of $1500/year, in addition to those which Rensselaer made available to all students for specific courses was also provided. And finally, office space contiguous or shared with other ARO Distinguished Fellows was offered, at the student's option.

Selection among candidates for ARO distinguished fellowships was based on the following criteria: (1) U.S. citizenship (a stated ARO requirement); (2) outstanding academic record, including the eminence of the institution at which it was attained; (3) a credible statement, in writing, of strong interest in rotorcraft technology; (4) some industrial experience (eg summer employment) was seen as highly desirable if not mandatory; (5) a commitment to participate as fully as possible in the program of the RRTC. Dossiers of candidates were considered by the Budget Advisory Committee (See Section 3 of this report). Those candidates this committee recommended for ARO Distinguished Fellowships were then reviewed by the Institute-wide "Topper" Committee. The "Topper" Committee consists of faculty chosen from among the Institute's five schools (i.e. colleges) and is charged by the Dean of the Graduate School with deciding which graduate students are so outstanding as to merit additional (i.e. "Topper") monetary support from the Institute. Their function in the case of the ARO Distinguished Fellowships was to insure that these highly desirable fellowships were to be awarded to students whose credentials were consistent with the highest standards being met in Rensselaer's graduate program.

That these difficult criteria were, in fact, met is best evidenced by the credentials and status of those students who were awarded RRTC ARO Distinguished Fellowships in the period covered by the subject contract. This is summarized in Table 8.

B. New Course Offerings and Revisions

(Responsible Faculty: R. Loewy)

During the second five years of the Center's development, new course and curricular changes of two kinds took place. At the graduate level, the importance of finite element analyses, nonlinear mechanics and computational fluid mechanics to rotorcraft technology added to the impetus to offer additional courses in these areas. The following courses, therefore, were either offered for the first time or significantly strengthened: 37.631, Nonlinear Vibrations; 37. 640 Analytical Dynamics; 37.666 Finite Element Methods II; 37.667 Nonlinear Finite Element Methods; 37.670 Finite Element Methods in Structural Dynamics and 37.672 Computational Fluid Mechanics. At the same time, a review of the undergraduate aeronautical engineering curriculum was conducted leading to a three-track option puttir a rotary wing concentration on an equal level with fixed wing and space technology, for the first time at RPI, and very likely, within U.S. colleges and universities. These new options are shown in Table 9 (from Ref. 3). Adoption of this new curriculum is evolutionary. Beginning in AY 92-93 the Helicopter Design Project is accepted as an option for satisfying the requirement for a senior-level "capstone design" course. The importance of such undergraduate aspects to a graduate level program of rotorcraft technology research, of course, is as a direct "feeder" of well prepared, entering students. As a result of these offerings and the ARO Distinguished Fellowship program, graduate enrollments with rotorcraft technology grew as shown in Fig. 5. Note that the number of graduate students in this program is approximately doubled by those involved who are not supported by the ARO contract. This must be considered an important measure of success in the program.

C. Graduate Level Thesis Research

Although Rensselaer has a Master's Degree option which does not require a dissertation, a large majority of all masters recipients, and - course - all doctoral level candidates, submit a thesis reporting the results of original research, as a part of their degree requirements. A list of graduate students involved in RRTC program research, their faculty advisor, research topic(s), and whether they received ARO contract funding support is given in Table 10. Results produced by such thesis research, of course, is incorporated in dissertations, titles for which are given in Appendix B, listed by degree year.

D. Intramural Exchange

Any multifaceted program which hopes to enhance synergism among its varied projects will set up as many avenues of interchange among its faculty, staff and students as possible. Such will, of course, enhance research performance, as is reported in Section 5, of this report. In many ways, however, the process is an important element of the students' education, all too often under-emphasized. One such activity of the RRTC, instituted at the program's inception, has been highly successful from both research interchange aspects and as an educational tool. It is reported briefly here for the latter reason. The mechanism is known as the "BBL", short for "Brown Bag Lunch".

Once a week during the academic year, all faculty and graduate students are invited to join in (bringing and) having lunch in a conference room at which informal presentations and discussions are held over the lunch hour. Subjects for these meetings are fourfold, of which two or three kinds are generally present in a single meeting: (1) brief "administrative" announcements (i.e. untechnical subjects of general RRTC interest); (2) reports of plans, problems, approaches to solutions, and progress on individual research projects; (3) general discussion of a single, relatively broad RRTC technical issue, the subject of which has been previously announced; and (4) a summary of matters of interest which arose in the course of a national or international level professional conference, off campus, which the presenter was able to attend.

A summary of BBL agenda's over the period covered by this report are given in Appendix C. It is important to note that the technical progress reports are listed by faculty name only to indicate who is responsible. The vast majority of these reports are given by the student(s) involved in that research. Students also join in the general discussions, of course, and make some of the "administrative reports" and professional meeting reviews.

The instructional aspects of these BBL's have been found to be substantial and significant. They include experience in making presentations; becoming accustomed to revealing difficulties and plans as well as results; "thinking on your feet" and responding "off the cuff" to questions and suggestions which can be challenging; receiving critique and suggestions on style and preparation from your mentor (in private and often reflecting the reactions of other faculty and, occasionally, other students), engaging in technical discussions "from the floor"; and generally learning the benefits and pitfalls of interchange meetings and discussions. The reaction of visitors (who attend when appropriate), of faculty participants and of the students themselves, all indicate that this is an activity well worth the time and effort.

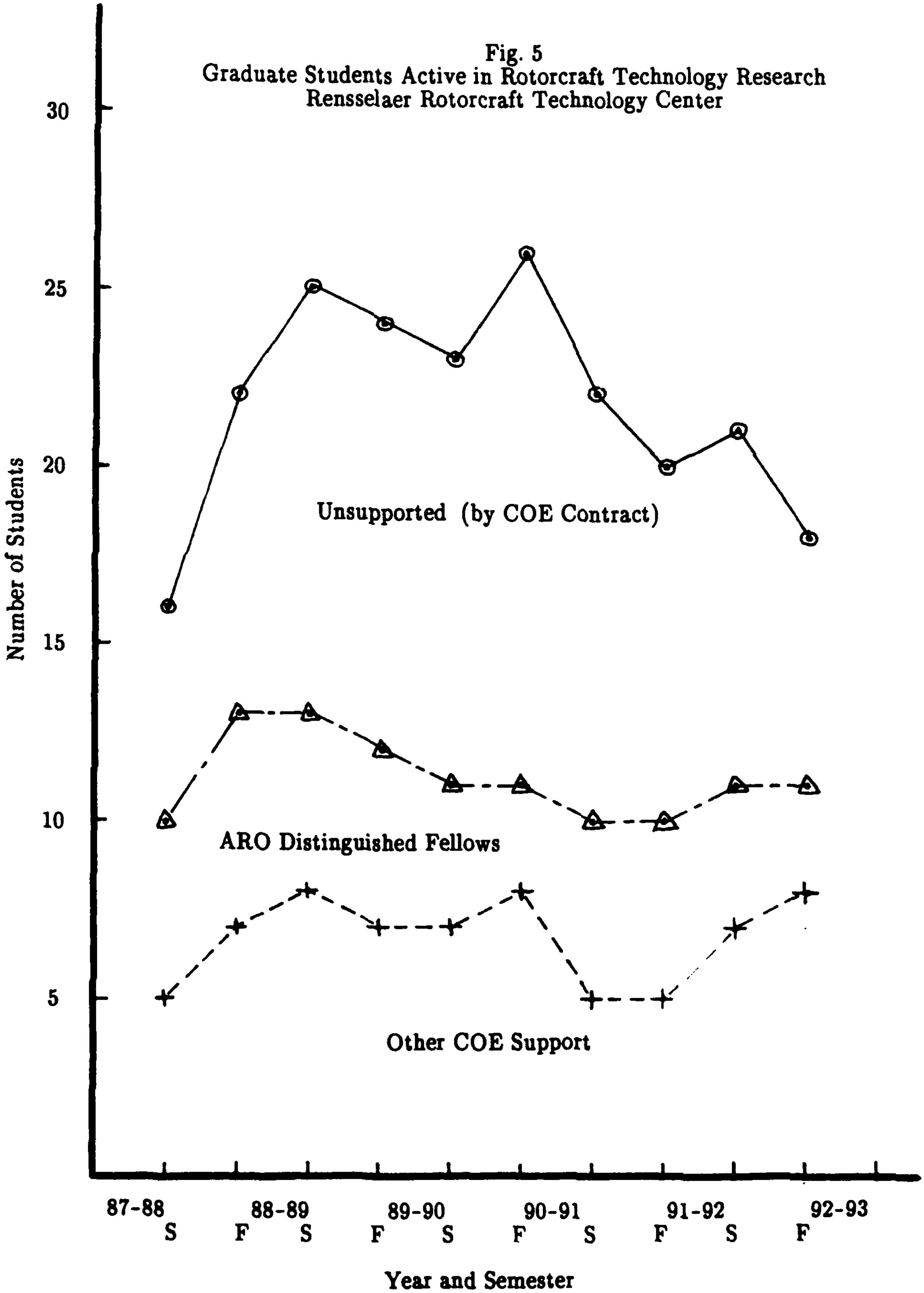


Fig. 5
Graduate Students Active in Rotorcraft Technology Research
Rensselaer Rotorcraft Technology Center
Number of Students
30
25
20
15
10
5
Unsupported (by COE Contract)
ARO Distinguished Fellows
Other COE Support
87-88
88-89
89-90
90-91
91-92
92-93
S
F
S
F
S
F
S
F
S
F
Year and Semester

Table 7

Rensselaer RTC ARO Distinguished Fellowship Stipends by Year

Year	87 - 88	88 - 89	89 - 90	90 - 91	91 - 92
Change in CPI* (%)	Base Year	4.5	5.0	7.0	4.0
Stipend (11 Months)	14,060	14,700	15,435	16,515	17,175

* Between 2 previous years (from Economic Report of the President)

TABLE 8

Summary of Credentials and Status of
Rensselaer's RTC ARO Distinguished Research Fellows Active during the Contract Period

Name	Undergraduate or Graduate University	Entering Grade Point Average (out of 4.0)	Prior Employment Experience	Date Entered Program	Status
Kraus, R.	Gannon Univ. Rensselaer	B.S. Magna Cum Laude 3.6 (Graduate)	G.E. (Large Steam Turbine)	June 1985	Engineer, Materials Processing Lab. Ph.D. Received December 1988
Straus, J.	Ill. Inst of Tech Rensselaer	3.7 (Undergraduate) 3.4 (Graduate)	Wright-Patterson AFB	September 1985	H. Power Battery Co. Ph.D. Received June 1991
Milliken, R.	U of Maine JIAFS Geo Wash U	3.87 (Undergrad) B S (B.S. with highest distinction) 4.0 (Graduate)	NASA Langley RC Mt. Washington Cog Railway	September 1986	Engineer, Bell Helicopter Ph.D. Received August 1988
Zotto, M.	Rensselaer Rensselaer	3.5 (Undergraduate) 3.8 (Graduate)	Manager, Big V Corp.	July 1987	Ph.D. Thesis in Progress
Trilling, T.	Rensselaer	3.6 (Undergrad) 3.7 (Graduate)	RPI Transonic Wind Tunnels	January 1988*	M.S. Received, May 1988 Engineer General Dynamics
Gordis, J.	Univ of Vermont Rensselaer	2.9 (Undergraduate) 4.0 (Graduate)	Stone & Webster	July 1988	Faculty Member, Naval Postgraduate School Ph.D. Received September 1990
Trainer, A.	Wichita State U Rensselaer	3.4 (Graduate) 3.4 (Graduate)	Mid-America Aviation Cessna Aircraft	July 1988	Engineer, Boeing Helicopter Ph.D. Completed, Degree Held Pending Thesis Submittal
Webster, B.	Worcester Poly M.I.T.	3.86 (Undergraduate) 3.6 (Graduate)	Kaman Aerospace	July 1988	Centric Engineering Systems Ph.D. Received December 1992
Butler, T.	Worcester Poly. Worcester Poly.	3.2* (Undergraduate) 3.9 (Graduate)	Equipment Maintenance, Billerica C.C., Massachusetts	January 1991	Ph.D. Thesis in Progress
Peck, A.	Lehigh Univ Rensselaer	3.3 (Undergraduate) 3.8 (Graduate)	Boeing Helicopter	June 1991	Engineer, Boeing Helicopter August 1992

* Appointments delayed due to funding uncertainties

Table 9

Undergraduate Aerospace Curriculum Objectives Accepted Sept. 1991

INTRO

Intro to Eng'g & Eng'g Processes A & B

Fund'ls of Flt' or Intro. to Space Eng'g or E-MAD

4 courses
9 credits
6.6% tot. cr.

//

CORE

Electives → 4 courses, 12 credits, 8.8% tot. cr.

- Math I,II, & DE, Prob & Stats
  Software Eng'g, Numerical Computing
- Phys I,II,III, Lumps
- Chem & Mat'ls I,II
- Mech's, Str of Matl's, Theory of Struct's I & II
- Intro to Fluid Mechs. I, Applied Fluids
- Compos. Lab or E-Lab*, Exp. Fluids I, and Exp. II or Mech Vibs Lab,
- Eng'g Thermo, B.L. & H.T.
- Theory of Propuls
- Intro to Auto. Control

H&SS Electives ← 8 courses, 24 credits, 17.6% tot. cr.

25 courses
81 credits
59.6% tot. cr.

//

DESIGN

SPACE VEHICLES	FIXED WING	ROTARY WING
Spacecraft Dynamics	Vehicular Perf.	Helic. Perf, S & C
Vehical Dyn & Cont'l	Vehic. Dyn & Cont'l	Vehicular Dyn & Control
Space Sys. Desgn Proj. (Capstone)	Fixed Wing Desgn Proj. (Capstone)	Helicopter Desgn Proj. (Capstone)

3 courses
10 credits
7.4% tot. cr.

Total Courses = 44 Total Credit Hrs = 136

NB: Sum of H&SS electives + free electives = 12 courses, 36 credits, 26.4% total cr.

Table 10

Student Involvement in Rensselaer RTC Research

Student	Faculty Advisor	For Program Year Beginning in 88	89	90	91	92	Research Area
N. Alura	M. Shephard				x		Automatic Mesh Generators
M. Beall	M. Shephard				x	x	F. E. Idealization for Composites
T. Bienvenue	M. Darlow			x	x		Optimization and Dynamic Testing of Composite Drive Shafts
C. Bonner	R. Loewy	x*					Extension of Generalized Coordinate Analysis to Composite Rotor Blades
B. Brosokas	O. Bauchau	x*	x*				Maneuver Loads
J. Brown	S. Sternstein					x*	Materials for Crashworthy Elements
A. Budhiraja	M. Shephard		x	x			Design Systems Supporting Analysis Idealizations
T. Butler	R. Loewy			x*	x**	x**	Modal Approach to Blade Maneuver Airloads
A. Castagne	R. Bielawa			x			Tail Cone Vibrations
S.L. Chang	P. Hajela				x		Optimization Theory Applications to Rotorcraft
H.S. Chen	R. Loewy		x	x	x	x	Integrity of Preloaded Joints in Composites
W.Y. Chiang	O. Bauchau	x	x				Damping Characteristics of Helicopter Rotors
	O. Bauchau		x	x	x	x	Finite Element Developments for Flexstraps
Y. Cho	M. Crespo da Silva		x*	x*	x	x	Nonlinear Blade Dynamics
J. Creonte	M. Darlow			x*	x*	x	Optimization and Dynamic Testing of Composite Drive Shafts
G. Damilano	O. Bauchau			x	x	x*	Maneuver Loads and Finite Element Based Modal Methods
G. DeLeonardo	O. Bauchau		x*				Maneuver Loads

	O. Bauchau			x*			Optimization Methodology for Rotor Design
J. Frederick	M. Darlow	x*	x*	x*			Optimization and Dynamic Testing of Composite Drive Shafts
R. Fricke	R.J. Diefendorf	x*	x*				Advanced Composite Configurations for Rotorcraft
	R.J. Diefendorf			x*			Innovative Fabrication of Composites for Rotorcraft
K. Frischknecht	R.J. Diefendorf	x					Advanced Composite Configurations for Rotorcraft
P. Gendron	R. Loewy			x*	x*		Modal Approach to Blade Maneuver Airloads
						x*	Application of Existing Aerodynamic Models to Maneuver Loads
J. Gordis	R. Bielawa	x**	x**	x			Fuselage Shake Testing and Structural Identification Research
D. Guernsey	O. Bauchau		x*	x*	x*		Finite Element Based Modal Methods and Maneuver Loads
W. Hassenpflug	M. Crespo da Silva	x	x	x	x*		Nonlinear Blade Dynamics
						x	Nonlinear Blade Stability in Maneuvers
R. Heffner	R. Bielawa	x	x	x			Fuselage Shake Testing Research
S. Hill	S. Winckler	x*	x*	x*	x*	x*	Hygrothermal and Microcracking Effects on Tailored Composite Rotor Blades
	E. Brunelle		x*	x*			
L. Imas	H. Nagamatsu		x				Passive Wave Drag Reduction of Helicopter Airfoils
P. Jones	M. Darlow	x	x*				Optimization & Dynamic Testing of Composite Drive Shafts
N.K. Kang	O. Bauchau		x	x	x	x	Finite Element Based Modal Methods and Maneuver Loads
A. Katz	R. Bielawa	x					Radio/Controlled Helicopter
B.Y. Kim	W. Brower		x				Theoretical Analysis of Passive Wave Drag Reduction
H.D. Kim	M. Crespo da Silva		x*				Nonlinear Blade Dynamics
R. Kraus	M. Darlow	x**					Optimization & Dynamic Testing of Composite Drive Shafts
E. Lee	P. Hajela					x*	Optimal Topological Design for Crash Requirements
M.R. Lee	O. Bauchau		x	x	x	x*	Optimization Methodology for Rotor Design

Dr. C.Y. Lim	Post-doctoral Research Associate					x*	Multidisciplinary Optimal Design of a Helicopter Rotor Blade
S. Lui	O. Bauchau	x					Finite Element Models of Rotor Blades
R. Milliken	R. Duffy	x**					Unsteady Airfoil Coefficients for *Rotors in Forward Flight*
A. Peck	O. Bauchau	x*	x*	x*	x**	x**	Composite Frame Optimization & Design
V. Questiaux	O. Bauchau			x	x		Optimization Methodology for Rotor Design
M. Reed	R. Hajela				x*		Optimization Theory Applications to Rotorcraft
						x*	Multidisciplinary Optimal Design of a Helicopter Rotor Blade
C. Rekow	S. Winckler					x	Thermally Induced Deformation in Composites
R. Smith	H. Nagamatsu		x	x			Unsteady Aspects of Passive Drag Reduction
J. Straus	R. Mayle	x**	x**	x**	x		Blade Vortex Parallel Interactions
N. Theron	O. Bauchau	x***	x***	x***	x***		Warping of Solid Cross-Sectional Helicopter Blades
						x	Maneuver Load & Finite Element Multibody Methods
A. Trainer	G. Gabriele	x**	x**				Optimization Methodology for Rotorcraft Preliminary Design
	G. Gabriele			x**	x**		Computer Aided Rotorcraft Conceptual Design
T. Trilling	H. Nagamatsu	x**					Passive Wave Drag Reduction *on Advancing Blade Tips*
N. Tutuncu	S. Winckler	x	x		x		Exploiting Thermal Deformations in Composite Structures
B. Webster	O. Bauchau	x**	x**				Prescribed Wake Model for Helicopter Rotors
	O. Bauchau		x**				Acceleration Potential Aerodynamics for Helicopter Rotors
	O. Bauchau			x**	x**	x**	Maneuver Load Aerodynamics for Helicopter Rotors
	M. Shephard			x**	x**	x**	
R. Wentworth	M. Shephard				x	x	Analysis Idealization Control Techniques
M. Weston	H. Nagamatsu		x				Unsteady Aspects of Passive Drag Reduction
R. Yatto	S. Winckler	x					Exploiting Thermal Deformations in Composite Structures
	S. Winckler		x				Composite Replacement Structure for Helicopters
C. Zaretzky	M. Crespo da Silva	x	x	x			Nonlinear Blade Dynamics
T. Zientek	R. Loewy		x	x			Aerodynamics of Rotors in Unsteady Maneuvers
M. Zotto	R. Loewy	x**	x**	x**	x**	x**	Air-Ground Resonance of Helicopters with Flexible Rotor Masts

* Supported under subject contract
** ARO Distinguished Fellow
*** In Absentia

V Research

Research accomplishments, the status of research still in progress and the dissemination of results obtained under the contract during its duration are summarized in the following paragraphs. It should be noted that the faculty researchers leading each of the projects that follow are designated "Senior Investigators". The other faculty/staff members shown were "supporting investigators" for the projects. In the case of ARO Distinguished Fellows, the projects shown were formulated with more latitude given to these outstanding students than is usual. Faculty involved in these projects, therefore, are designated "Faculty Supervisors".

A. Advanced Composite Laminates for Rotorcraft

(Sr. Invest'r. R.J. Diefendorf; O.A. Bauchau and S.J. Winckler)

Analytical modeling, fabrication and testing research intended to develop new two- and three-dimensional composite concepts were the subject of this project. Advantages sought were advanced elastic tailoring, improved load transfer and/or reduced fabrication costs.

Improving the tolerance of major load redistribution gradients such as occur at so-called "field splice" joints in helicopter fuselages and, typically, in composite rotor hub components was a motivating problem in this subject area. In particular, new analysis methodologies were sought which would be capable of predicting the elastic characteristics of laminates with "bend" and "splay" intralaminate fiber concepts. (These concepts are portrayed in Fig. 6.) Note that "theta" in these figures is defined as the angle of intersection between fibers and lines emanating radially from the center of the hole.

Therefore, means of both defining efficient bolt hole reinforcements in composites and manufacturing them were first investigated. Because traditional fiber orientations in composites had been limited primarily to X-Y orientations, efforts were concentrated on using cylindrically oriented fibers around pinned connections or bolt holes to improve strength, reduce stress concentrations, and allow material usage to more confidently approach property limits.

Samples were made using hand lay-up techniques and special tooling to orient "bend" and "hoop" fibers around holes as desired. Such reinforced specimens were mechanically tested by applying in-plane tension loads through pins inserted through the laminates. In some tests, nonlinear fiber samples exhibited improved strength after initial failure, while the control maintained a steady post-failure load. Generally, however, the presence of "hoop" fibers was associated with increased delamination, attributed partially to the increased thickness of these plys.

A braiding machine was modified to adapt it to the purposes of this project, ie using high performance fibers such as graphite. The braider fiber-carriers were re-designed and rebuilt to minimize damage to high modulus fibers, by increasing the radius of curvature on several fiber-contact surfaces and causing some of these surfaces, formerly stationary, to move. The intention of these modifications was to allow automated manufacture of bend and splay fiber arrangements which would have improved quality and decreased sample variability, through the elimination of hand construction.

Fabrication experiments were performed making use pre-impregnated, braided graphite-epoxy, hole-sleeving samples formed by the deformation method. These experiments made it clear that the size of the area containing non-linear fiber reinforcements in the hole-sleeve is determined by the initial preform diameter.

Furthermore, it was observed that the resin pre-impregnated on the graphite tow used in the pre-form restricted the fiber movement necessary to the deformation process. The question, "How can we make useful laminates with curved fiber paths?", therefore, emerged as at least as troublesome as "What fiber paths should be used?", in improving composite applications to load redistribution structures for mechanical joints.

Tests using dry tow to fabricate preforms were conducted to ascertain how eliminating resin pre-impregnation would alleviate the fiber movement problem in the precure deformation steps. Such would require that the preform be impregnated following deformation to final precure shape, a step involving uniformity and other quality considerations. The intent, in this case, was to achieve near net-shape preform manufacture, to alleviate the size-limiting problem. The approach taken was to braid the preform on a conical section and then deform it to the final shape.

The fabrication experiments performed with various approaches to the near net shape forming of dry fibers over a conical mandrel showed fiber slippage to be the overriding problem. Means to prevent fibers slipping down the sloping surface of the mandrel and accumulating at the bottom emerged as the primary need. A few degrees misalinement in the preform resulted in still larger misalinements in the final part, and all efforts to prevent fibers slipping down the sloping surface of the mandrel and tending to accumulate at the bottom, could not alleviate this situation.

Efforts were turned, therefore, to evaluating the comparative bearing strengths of laminates with discontinuous straight fibers, as result from drilling bolt holes in a conventional lay-up, versus laminates with continuous, curved fibers into which holes have been molded during the during process. The cure/hole molding fixture is sketched in Fig. 7. The pin diameter used was 1/4". Measured bearing stresses at failure for three types of specimens; ie drilled, braided/molded and woven cloth/molded, are shown in Fig. 8. Nine tests were run for each type of specimen. While scatter is greatest for the drilled specimens, their average failure stress is substantially higher than either of the molded hole types. In fact, the lowest data point for the drilled laminates is higher than all but one data point obtained with the other two types.

Attempts to account for this, using the theories of Refs. 4 and 5, produced the results shown in Table 11. Note that the ultimate failure strength reduction from the base case is 31%, when wavy outer zero plies are removed, and that for the two molded-hole specimens, these reductions are 35% and 36%. This work lead to the following conclusions:

- fiber waviness, especially in outer plies, which arises in braided and woven designs, lowers bearing strength more than does discontinuous fibers

- fiber misalinement theories used with classical laminate theory (CLT) predict the measured reduction in bearing failure stress with reasonable accuracy.

At that point, the research conducted under this project was concluded.

Fig. 6

CURVILINEAR FIBERS

Fiber arranged axisymmetrically
Polar coordinate system

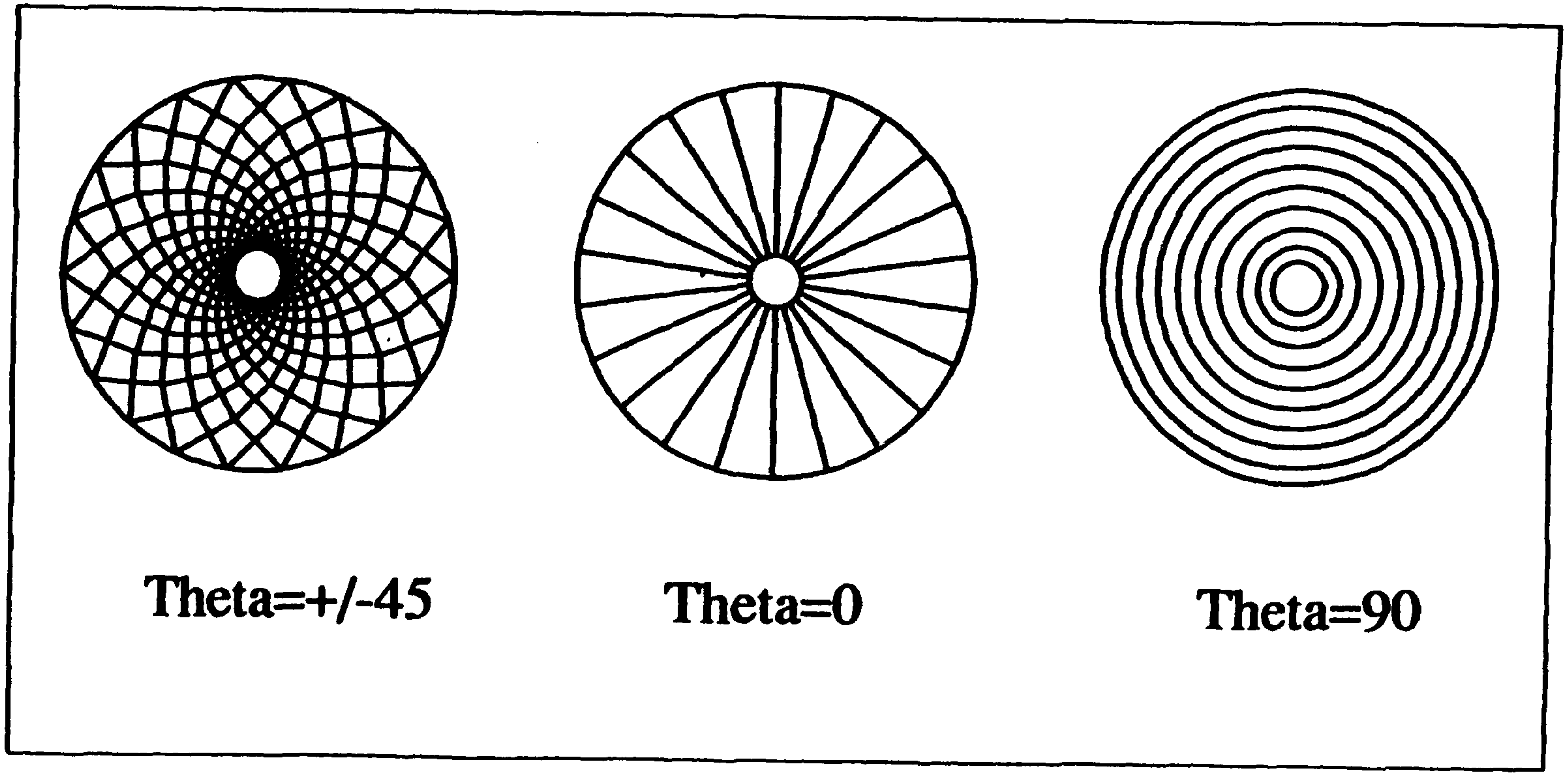


Fig. 7

Tooling and Molded Hole Lay-up

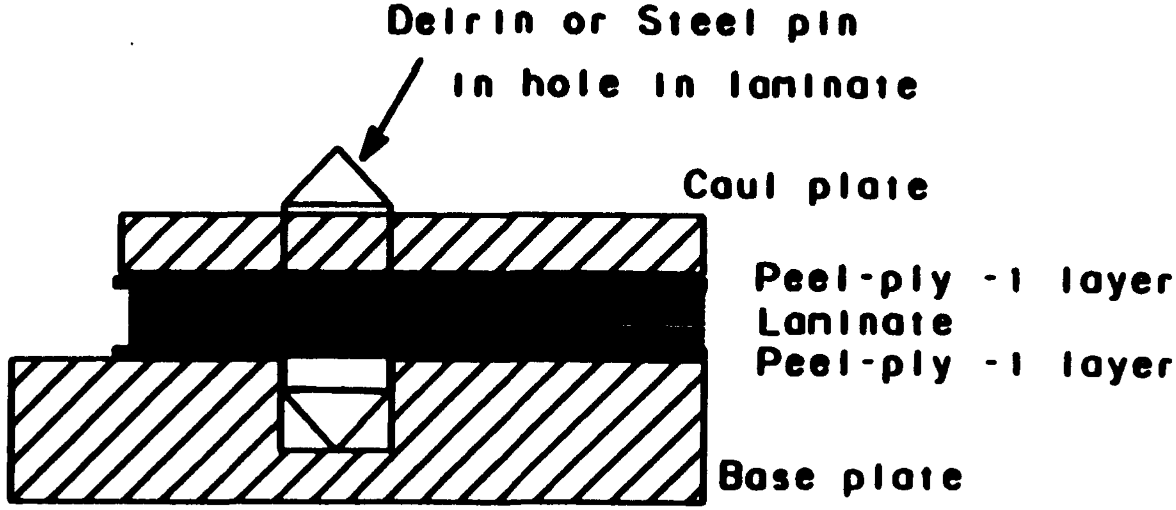


Fig. 8

Test Data

Bearing Stress by Sample Type

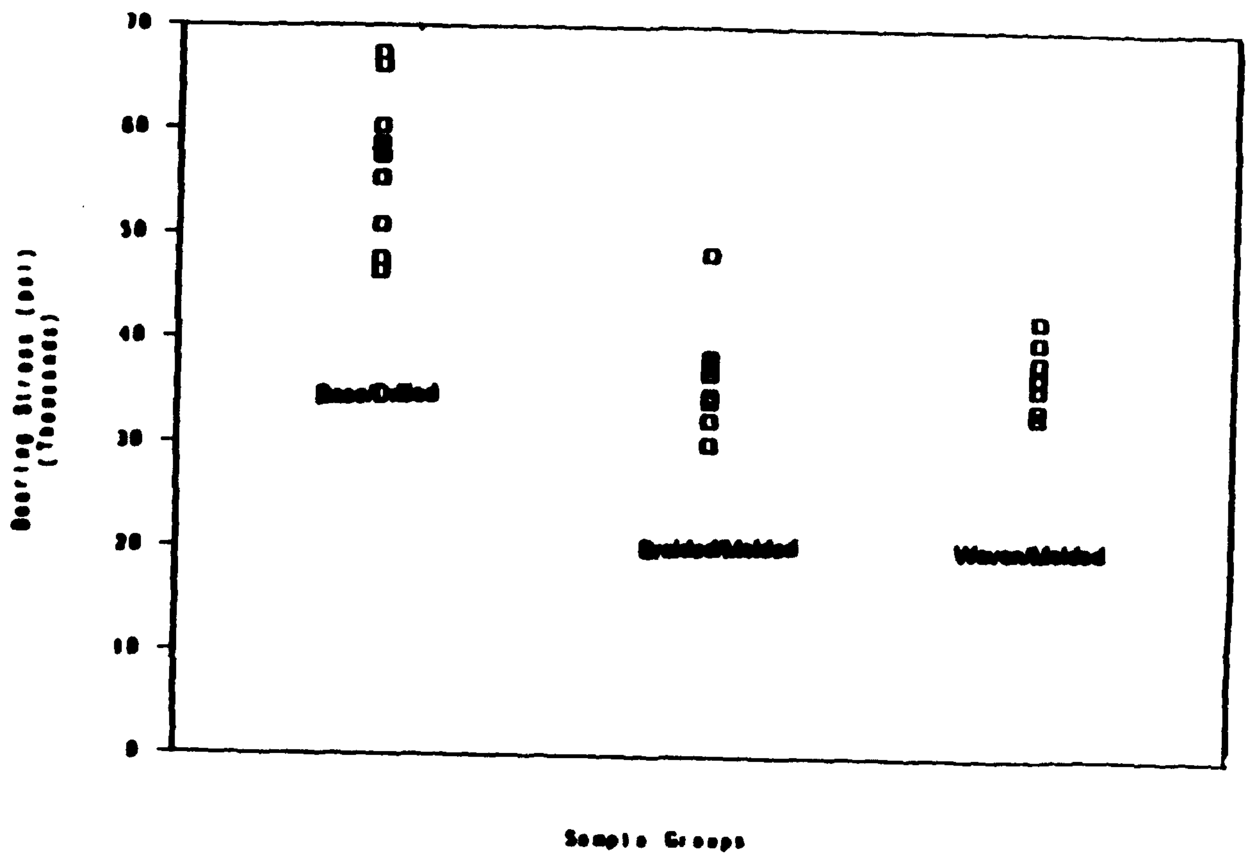


Table 11

Strength Loss Comparison:
Pin Joint Tests vs. Laminate Theory *with uniform compression*

Laminate Theory, uni-axial compression $[+45/-45/0/90]_{2s}$ AS4/3501	Compression failure (ksi)	% change from base
Baseline (first ply failure and ultimate)	84.9	0
Wavy outer zero: first ply failure *(reduced zero strength and stiffness)*	9.8	-88%
ultimate failure *(removed failed wavy zero plies)*	58.3	-31%
Pin joint bearing test results	Bearing stress (ksi)	% change from base
Baseline (First ply and ultimate failure)	57.2	0
Braided (first ply and ultimate failure)	36.3	-36%
Woven (first ply and ultimate failure)	37.1	-35%

B. <u>Hygrothermal and Microcracking Effects on Tailored Composites</u>
(Sr. Invest'r. S.J. Winckler; E. Brunelle)

Elastic couplings are usually the objective of tailored composite designs, and tension-torsion coupling is a frequently encountered example. These couplings rely heavily on matrix properties, and these properties are most susceptible to hygrothermal changes. Current designs use laminates in which extension and torsion modes are fiber-dominated. Hygrothermal changes do not have a strong effect on such laminates, but neither do blades making use of them possess tension-torsion coupling.The purpose of this research project was to examine means by which elastic coupling can be maximized and the hygrothermal sensitivity of all elastic properties reduced. This involved developing analytical models for predicting changes in stiffness and coupling during hygrothermal conditioning, which satisfactorily match test results.

As a first step, experiments were performed to quantify such effects. Samples were made and tested to measure elastic coupling on laminates which typically exhibit the kind of behavior desired for tailored composites. The experimental set-up provided for controlled temperature environments and was capable of measuring both the changes in shear modulus and changes in coupling with changes in temperature from room temperature to 200°f. The upper temperature limit was seen as an extreme condition likely to be encountered by, say, a rotor blade on start-up, after having been exposed to tropical sun on an airfield for several hours. Humidity variations dealt with two extremes: "dry" and submerged in water. The indicator used for moisture was percent weight gain.

Measurements of tension-torsion coupling were made under "room air" conditions (moisture content $\simeq$ 0.25%), with temperatures ranging from 30° to 90° C. Data was also obtained for dry specimens (moisture content $\simeq$ 0.02%) using a desiccator to store test specimens in a low-moisture-content condition. Such measurements, determining the effects of temperature and moisture content on the material shear modulus, were made over the same range of temperatures and moisture contents as was done for elastic coupling, and used as input to a model for predicting hygrothermal effects on elastic coupling. The results show the decrease expected in coupling and modulus for increased moisture content. The results for varying temperature, however, showed an unexpected effect in the lower ranges of (room) temperature. The stiffness appeared to increase slightly with the first temperature increase, before dropping off in the expected manner.

The theoretical studies discovered that certain laminates incorporating two materials instead of just one, referred to as hybrids, exhibit coupling with negligible variations due to hygrothermal (HT) effects. The laminate mixes in hybrids were chosen so as to trade-off independence from HT effects with degree of coupling. Thus, reductions in HT dependence were sought which provided acceptable levels and still provided useful amounts of coupling, by varying the ratios of the two materials used.

The theoretical modeling of the effects humidity and temperature (HT) have on elastic coupling took only shear modulus variations into account. This seemed a valid assumption, since shear modulus dominates the coupling. However, correlation between the theoretical results and experimental data showed the same form for the variations, but not the same magnitudes. Required data for some of the material properties was either suspect or unavailable, hence work was conducted to develop improved data. It is important to note that the desired properties cannot be determined by direct measurements on unidirectional samples. Hybrid test specimens were made using "dry" fiberglas layers for which the resin "run-off" of prepreg carbon layers provided the matrix material. Thus, data had to be "backed-out" of test results performed using hybrid samples. This technique required both accurate knowledge of the relative amounts of each material - graphite and glass - and accurate modulus measurements. Accordingly, ±45° single material (graphite) specimens were tested for modulus to determine the accuracy of these properties. The results, compiled in multiple tests of six different specimens, showed wide variation in moduli, as shown in Fig. 8. At this point, further attempts at correlation were terminated in favor of investigating the effects of microcracking.

Following review of existing microcracking theories, the microcracking model of Dvorak, Law and Hejazi [6] for a unidirectional laminate was chosen for (a.) arbitrary orientation and loading, (b.) self-consistent micromechanical formulation and (c.) independent crack-spacing parameter, expressed as a uniform crack density. This was adapted for a plane stress model used in Classical Laminated Plate Theory (CLT) to predict variations in transverse and in-plane shear compliances, all modulus terms (longitudinal, transverse and shear) and Poisson's ratios.

The single-ply stiffness microcracking model which was developed, allowed integrating plies with known crack densities into classical laminated plate theory, thus enabling laminate stiffnesses to be calculated, and crack density distributions to be represented through the laminate thickness. Relative crack densities due to applied loads could thus be determined for plies of arbitrary orientation within a laminate.

Such distributions for two different laminates under axial loading are shown in Fig. 9. The [0/45/-45/90] laminate represents a typical conventional uncoupled laminate. The [20/-70] laminate possesses tension-twist coupling. Fig. 10 shows the variation in compliance for these laminates as crack density increases. The increased sensitivity of the coupled laminate to microcracking as compared to the conventional laminate, is clearly shown in this figure.

Comparisons of these predictions with published data showed that the model accurately predicts laminate behavior. However, the published data is severely limited in range and none was available for coupled laminates. Experiments were seen as needed to create the unavailable data.

Experimental work was therefore conducted to demonstrate the effects of microcracking on ±45° samples, in which an applied longitudinal (ie 0°) force produced a shearing response. Since shear properties dominate coupling response, data on this mode could be used to predict coupling variations with microcracking. The expected cracking behavior was observed in specimens tested to failure. Fatigue-type tests were performed by subjecting specimens to tension-tension cycling to about 50% of ultimate strain, and crack density was seen to increase with the number of cycles. At various times during these tests, cycling was stopped and the axial modulus of the specimen was measured.

Two additional types of specimens were also tested: $[0/90_3]_s$ laminates, which often appear in the literature and were chosen because cracks were most likely to form in 90° plies; and $[20_2/-70_2]_s$ laminates, which possess tension-twist coupling. Fig. 11 shows the measured changes in axial modulus resulting from stress cycling for two specimens based on these laminates. Cycling of the $[0/90_3]_s$ specimens was conducted at peak stress levels corresponding to 45.6% of ultimate; that for the $[20_2/-70_2]_s$ specimens at 45.7%. On the log cycle scale (Fig. 12), it appears that there is no significant modulus change at low cycle numbers. As the number of cycles increases, the modulus drop-off becomes more severe. The same data plotted on the linear cycle scale of (Fig. 11) presents a different picture. The $[0/90_3]_s$ laminate's modulus drops rapidly at first, but then appears to approach a limit, indicating what appears to be a "shakedown"-type behavior. The modulus of the $[20_2/-70_2]_s$ laminate, however, appears to be dropping linearly and continuously, not approaching a limiting value. This indicates the need to develop laminates whose gross elastic behavior is unaffected by microcrack formation.

A basic assumption when dealing with microcracks is that cracks in compression have no effect on laminate behavior; a ply with closed cracks is assumed to be uncracked in evaluating compressive behavior. Thus, applied moments which create a stress distribution through a laminate in which the laminate may be partially in tension and partially in compression, make for a situation more complicated than when limited to loads uniform through the thickness. As loads change, and with them the overall moduli of the laminate, laminate behavior becomes load dependent.

The change in the location of the point where stresses change from tension to compression, denoted ζ_m, is shown in Fig. 13 for a $[0/90/0/90]_T$, graphite/epoxy laminate. The transition is plotted against the ratio of the applied axial load and moment, R_{NM}. The illustrated laminate has cracks only in the 90° plies. As the transition point moves through the laminate, cracks which initially were closed are opened and laminate properties change. The variation of one such property, the axial compliance of the laminate, is shown in Fig. 14 for a variety of crack densities. Other moduli show larger variations, up to about 20% for this laminate and range of crack density. On this basis, it appeared that properties that were previously considered constant throughout a particular structure and for a variety of loadings, may, in fact, vary over the structure and change with applied load, due to microcracking.

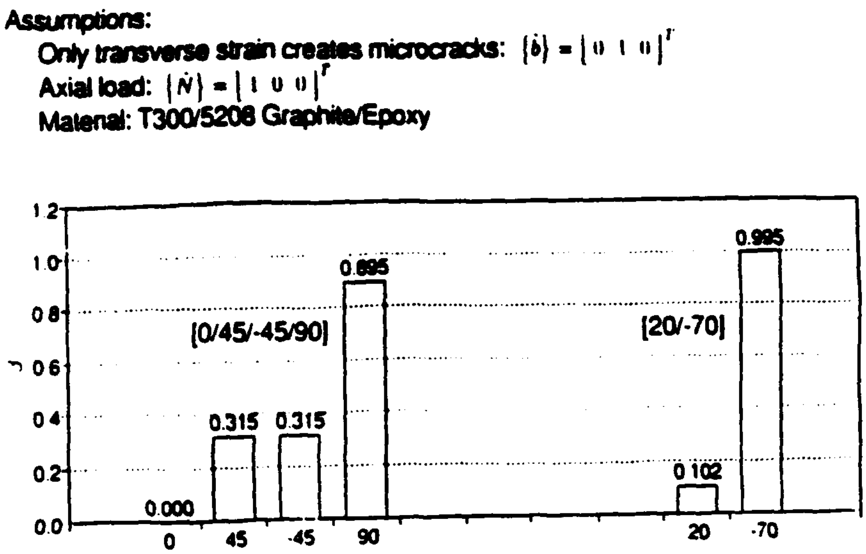


Fig. 9 Example Crack Distribution Mode Shapes

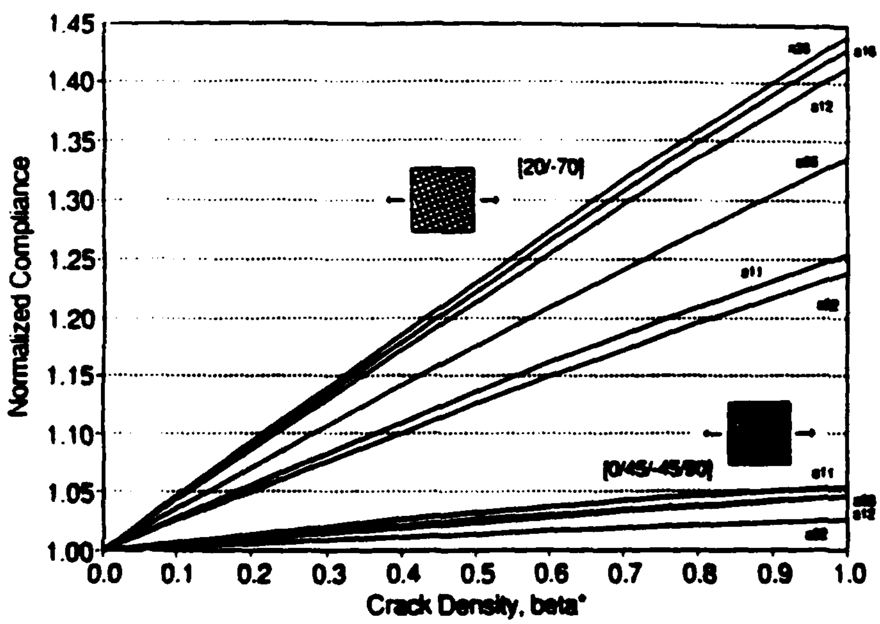


Fig. 10 Coupled vs. Conventional Laminates

Fig. 11 Typical Experimental Modulus Variations

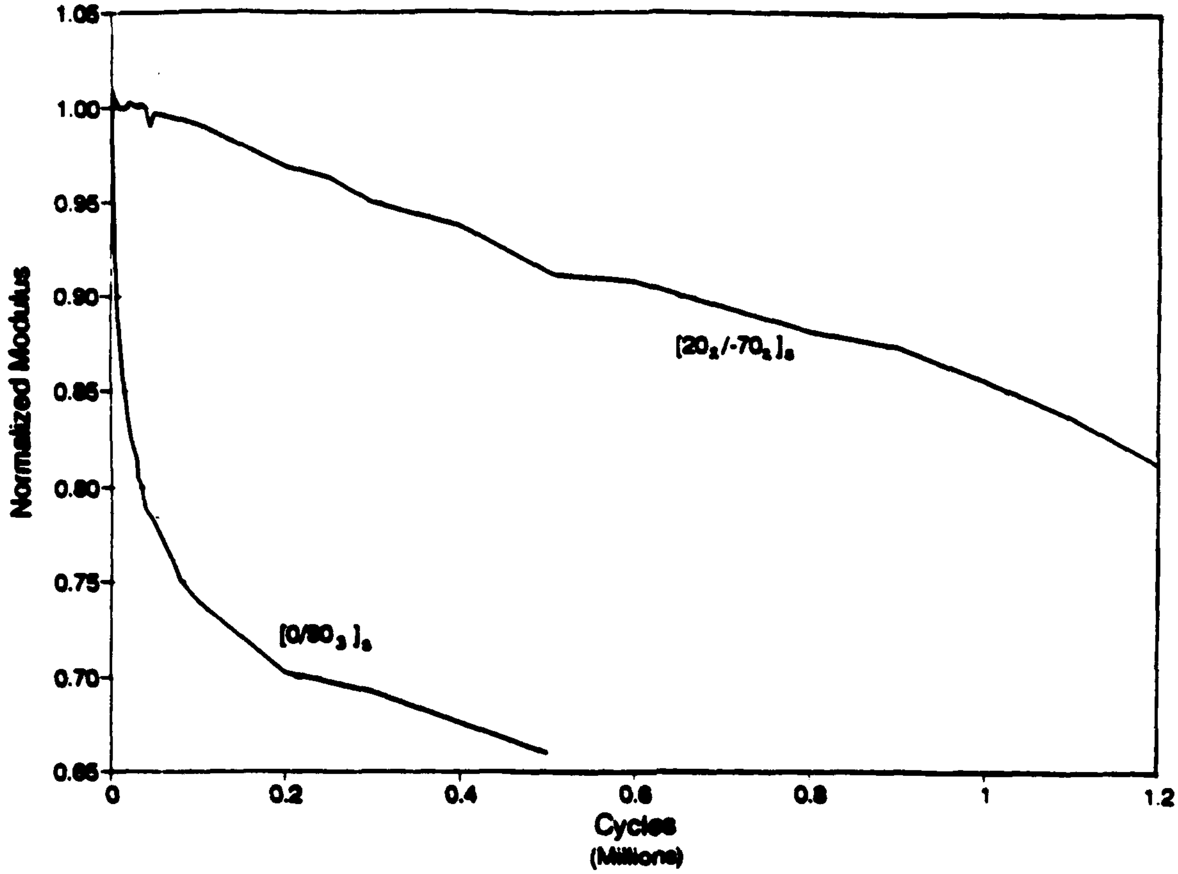
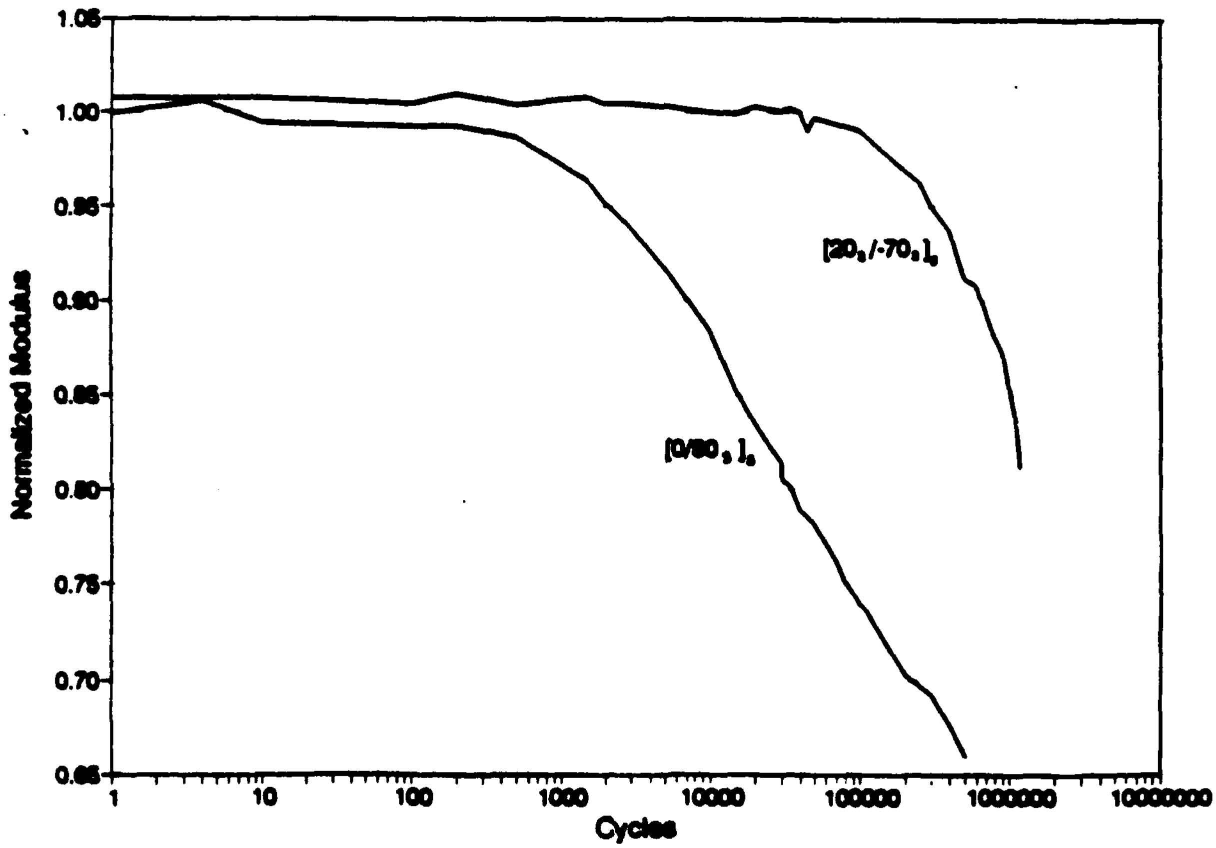


Fig. 12 Typical Experimental Modulus Variations



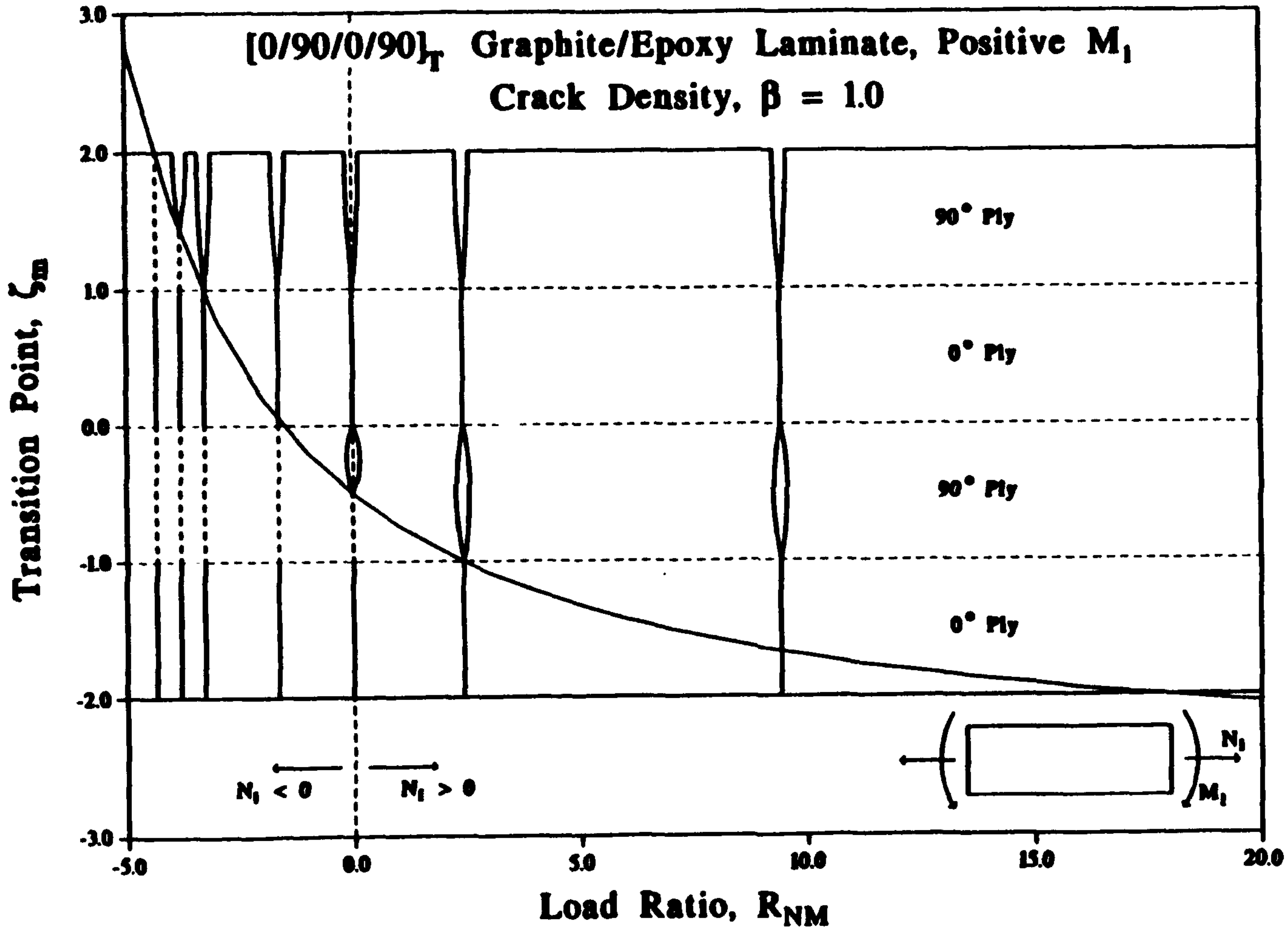


Fig. 13 Position of Tension/Compression Transition Point Due to Variation of Loading

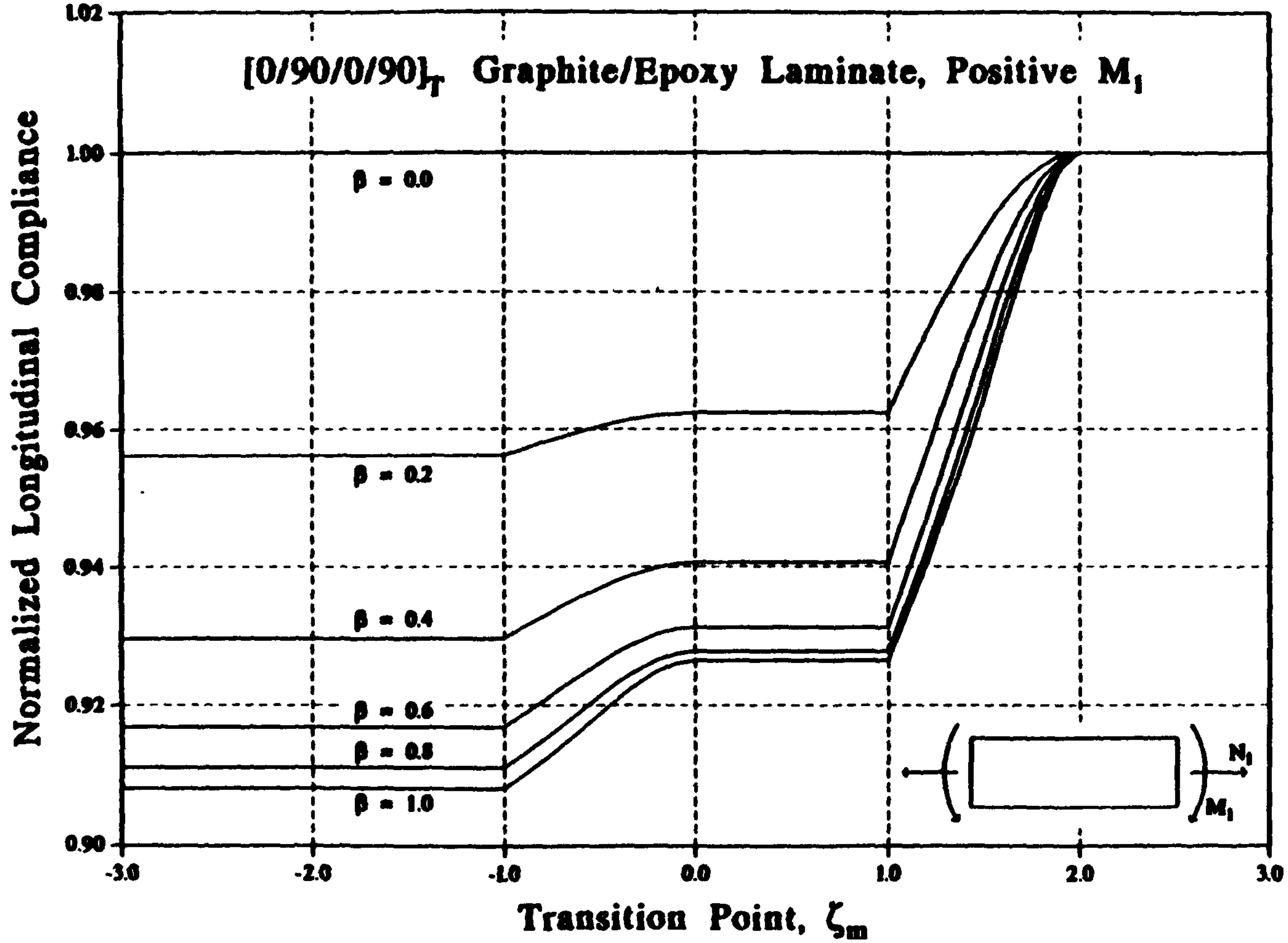


Fig. 14 **Effect of Transition Point Variation on Laminate Modulus**

C. Analysis and Design of Composite Fuselage Frames
(Sr. Invest'r. O. A. Bauchau)

The intent of this research was to develop a model, validated by appropriate tests, which would allow the accurate analysis and design of helicopter fuselage frame components using composite materials. The features to be included were strong curvature (height to radius of curvature ratio of the order of 1 to 3), major secondary stresses (crushing and curling) due to this curvature, sharp changes in gage thicknesses, and material anisotropy effects, including continuously varying directions of principal axes of orthotropy. These structural features had not been handled very well by existing analyses. Load concentrations typical of attachment points and damage tolerance and delamination sensitivity were also to be investigated.

Preliminary work initiated an experimental program aimed at manufacturing representative curved fuselage frame components. A straightforward, hand lay-up technique with wooden molds was used. Two specimens were fabricated by this means, intended for static testing. Attempts to test these curved I-beam specimens showed them to be very prone to lateral buckling. Since such frames are stabilized against lateral buckling by the fuselage skins they support when installed in the completed airframe, a test rig with features to eliminate this instability was required.

A finite element model of thin, curved frame components was also developed, to identify and quantify the major structural problems, such as web crushing and flange curling, which occur in curved I-beams. These preliminary studies were intended to improve understanding of the structural response of curved composite fuselage components to the extent that designs with improved performance and more efficient manufacturing techniques could be devised.

The behavior under load of a curved composite beam used in the ACAP program was studied, using an existing finite element code (ABACUS) and also applying a "strength of materials" type of analysis developed especially for this research. The curved I-beam configuration in question had flanges with the following lay-up: $[(0/90, 0, 0/90, 0, 0/90, \pm 45)_S, 0_2, (0/90)_3]$ and was subjected to a bending moment. It was shown that flange curling relieved the flange's axial load to such an extent that the load drops to zero at its edge.

The second example analyzed was an extreme case, in which the flange consisted of a unidirectional lay-up. Here the effect of curling is so pronounced that the axial stress in the flange changes sign. Although the same bending moment was carried in both cases, the maximum loads in the upper flange were 1,000 lb/in for the former and 2,000 lb/in for the latter. Similarly in the lower flange, the maximum loads were 2,000 to 4,000 lb/in for these respective cases. These comparative examples showed the importance of choosing proper lay-ups for composite beams with strong curvature.

Good correlation was found between the predictions of the 3-D FEM model of laminated composite I-beams, on the one hand, and those of the analytical model, on the other hand, for various flange lay-ups. Further, the stress distribution in the flanges was found to be characterized by a single parameter for the anisotropic case, α, incorporating material stiffness and geometric effects; namely,

$$\alpha^4 = \left[3 \frac{E_{11_f}}{D_{22_f}} \frac{1}{\left[\frac{R_f}{L_f}\right]^2} \frac{1}{\left[\frac{t_f}{L_f}\right]^2} \right]$$

Subsequently, material stiffness effects and their impact on stress redistribution in the flange were emphasized. Flange efficiency was defined in terms of P/Po, the ratio of the total load in the flange with curling to the total load in the flange without curling. It was found that flange efficiency decreases as α increases. For a particular material system, α is bounded by its transverse and longitudinal moduli, as follows:

$$\left[\frac{E_T}{E_L} \leq \left[\frac{\alpha}{\alpha_{ISO}} \right]^4 \leq \frac{E_L}{E_T} \right]$$

Where: α_{ISO} is the corresponding parameter for isotropic material.

Comparisons among various material systems showed that stiff material can provide maximum flange efficiency with the proper lay-up; however, improper choice of lay-up can result in a very inefficient flange. As α increases, greater stress nonuniformity over the flange width results in larger axial loads at the root, whereas the more uniform stress distributions over the flange, corresponding to smaller α values, result in larger bending moments at the flange root.

To assess the overall load-carrying capability of this kind of structure, analyses were performed for cases in which bending moments were applied to a beam with the given geometric configuration. A family of laminates was postulated and the maximum bending moment capacity was predicted using classical lamination theory and the Tsai-Wu failure criterion. The results raised some interesting points. Intuition might first lead a designer wishing to take maximum advantage of fiber strength and stiffness to chose a unidirectional fiber lay-up with 0° orientation. In fact, for the curved beam case, this lay-up would provide less strength than one with all the fibers running in the 90° direction, and a nearly quasi-isotropic lay-up provides maximum strength. Examination of another family of laminates illustrated that the lay-up and stacking sequence of the flanges drastically affect the overall load carrying capability. Difference factors up to five were observed. Again, a nearly "quasi-isotropic" lay-up seemed best, but might not guarantee the highest strength.

Accordingly, the research turned to the ultimate objective of producing a set of guidelines for use in the analysis and design of curved composite beams. A systematic procedure was sought to assess the structural performance of several alternate configurations, accounting for curling and crushing phenomena, including an optimization code to efficiently compare various design possibilities and choose, for a given loading and external geometry, the material system, web/flange lay-up and cross section combination which has the minimum weight.

Two cross-sectional configurations, "I" and box, were studied for curved frame applications. The stress distribution in the flanges were found to be characterized by two parameters, incorporating flange and web material stiffness and geometric effects. For a particular geometry and material system, these parameters were also found to be bounded by the ratios of the transverse and longitudinal moduli, and the particular lay-up and stacking sequence of the flanges to drastically affect their overall load carrying capability. In the "I" cross-section, curling moments in the two flanges are equal and opposite where they join the web, so that the web plays no role in the way these moments are carried. In the box configuration, however, the web provides "end fixity" for the flanges as they carry curling moments. Web design in box cross-sections is, therefore, important in determining flange efficiency and overall load carrying capability. A web with high bending stiffness in the box configuration will increase the curling moment which the flange can carry by providing high "end fixity", through the web torsional spring constant, which is reflected in a large value of a parameter $K^* \cong \left(\frac{\overline{D}_{22w}}{\overline{D}_{22f}}\right)\left(\frac{t_w}{t_f}\right)^3\left(\frac{2L_f}{D}\right)$. The curling moment at the point where flange joins web is then carried uniformly over the web. In the process of improving flange efficiency by increasing box cross-section web bending stiffness, there is a point at which improving flange efficiency further may decrease overall load carrying capability as the web becomes the critical design point. Thus, overall box beam strength was found to be determined by an appropriate combination of flange and web laminates and cross-sectional configuration.

An overall optimization was performed for a frame with an I-cross-section. Initial comparisons between optimized straight and curved I-beams with isotropic material properties under bending was examined. The optimizer distributes the structural weight so as to minimize web thickness and increase overall bending stiffness. While no preferred way to distribute the flange material emerges in a straight beam, for the case of a curved beam the material is distributed to minimize curling stresses; ie the web thickness is minimized, the overall bending stiffness maximized, the flange thickness maximized and flange width minimized. The optimizer distributes structural weight in a curved box beam similarly; ie to maximize overall bending capability and minimize flange curling.

Predicting the critical design point location is more difficult for a composite beam than for one of isotropic material because of the variety of ply orientations available and corresponding strengths through the laminate thickness. Initial curvature of a beam further complicates the optimization problem. While it was not possible to find the optimum flange and web lay-up combination for a given cross-section, because of these factors, certain trends were obtained. These studies confirmed intuition, in that placing flange fibers orthogonal to the web minimized flange curling. Further, the minimum allowable web thickness was established as that required to resist the web axial and crushing loads for both I- and box cross sections. For the box beam, low web bending stiffness seemed beneficial in reducing flange curling moments.

Good correlation was found between the analytical solution and the FEM model results for the web axial, radial (crushing), and shear load distributions in isotropic beams. Web stress distributions differ with location along a curved beam. The maximum cross-sectional axial load and bending moment, which cause maximum axial and radial stresses, occur at the mid-section of the beam; maximum shear stresses coincide with position of the maximum shear load at the ends of the beam. Comparison of the analytical model predictions with FEM results for a composite beam, shows good correlation of the axial stresses, as well as the maximum shear and crushing stresses, although at some stations significant inaccuracies were encountered. The maximum crushing and shear stresses in the web were smaller than web axial stresses, but not insignificant. Thus, it was found that, if manufacturing considerations in some applications dictate that one lay-up be held constant at all sections of the web of a curved beam, despite the fact that individual cross-sectional loads vary, a conservative approach would be to design for the maximum crushing load and the maximum shear load.

Finally, analyses of a C-sectional beam were conducted, and compared with test results obtained from the Boeing Helicopter Co. The results of this project were summarized in a doctoral thesis [7] and the graduate student who conducted this research began employment continuing the studies in the industry work-place.

D. Optimization of Composite Drive Shafts
(Sr. Invest'r. M. Darlow; O.A. Bauchau)

This effort was undertaken to advance the state-of-the art in helicopter drive shaft systems technology. More specifically, the rotordynamic behavior of supercritical, composite driveshaft systems for helicopter applications was investigated. The benefits of this research were seen as including lighter weight systems, lower maintenance costs, and higher reliability relative to current production aluminum driveshaft systems.

The project consisted of both analytical studies and experimental verification. The analytical portion used optimization techniques to find the least weight shaft system design consistent with specific power transmission requirements. Transfer matrix methods were used to model shaft dynamics, and shaft torsional buckling loads were determined using an analysis developed at RPI, under ARO sponsorship, by O. Bauchau [8]. The analytical portion using algorithms developed for optimizing shaft systems based on geometric envelope, torsional strength and elastic stability (buckling), torsional and lateral vibrations, and weight, had been completed and documented in previous published papers, and theses [eg. 9,10]. These studies considered, as examples, synchronizing shafts on the Boeing CH-47 and tail drive shafts on the Sikorsky UH-60 and the McDonnell Douglas AH-64 helicopters.

The experimental study had the purpose of demonstrating that supercritical composite shafting, designed using the optimization analysis, could be operated safely and reliably. A test rig capable of running subscale shaft models at speeds up to 11,000 RPM was constructed and checked-out. Vibration displacement measurements were taken, using non-contacting eddy current proximeters. These measurements were monitored in a test control space which contained state-of-the-art oscilloscopes, a computer with data acquisition system, a data recorder, and a digital vector filter. A spectrum analyzer with modal software was used to provide frequency response displays and perform modal analysis of the shafts.

In initial testing, a subscale aluminum shaft was balanced and run through its first and second critical speeds. This showed that external damping was necessary. A braided graphite/epoxy shaft was also designed, built and tested. This shaft was a subscale model of one designed optimally for the AH-64 helicopter. Natural frequencies were found during stationary tests and rotating tests followed. Successful balancing through the first and second criticals was accomplished. Based on a search of published literature, this was, apparently, the first successful operation of a graphite/epoxy driveshaft above several critical speeds. Although damper failures occurred, there was no indication from the tests that higher speeds could not be reached.

Critical speeds were measured for the aluminum shaft in the test rig within 2% of the predicted values, and for the composite shaft within 6%, but one extra experimental mode was discovered with the composite shaft which was not predicted analytically. Investigations as to the nature of this "extra" mode, and the reasons for it being "missed" in the numerical analyses were conducted. The test shaft was subsequently found to be bowed, and a microscopic study was performed on a small section of it, to assess manufacturing quality and ascertain why it was bowed.

Several forms of external damping were investigated and passive magnetic damping combined with Coulomb friction chosen, because it reduces susceptability to wear and is relatively easy to incorporate. Purely mechanical dampers deteriorated quickly. The amount of damping available for a given magnetic field was determined and a damper designed.

Tests of aluminum shafts in which the shafts carry properly scaled torques (about 10 NM) showed dynamic behavior unaffected by the application of steady torque. The composite shaft, on the other hand, appeared to be very sensitive to torque at low speeds (1st critical), but less sensitive at higher speeds (2nd critical).

A series of tests was completed which simulated the supercritical half-length of the AH-64 design using a braided composite shaft. The scaled operating speed of the shaft was 3552 rpm, which lies just below the second critical speed of 4050 rpm, and the scaled torque was 5.2 N-m. An electromagnetic eddy current damper was found to be effective at low speeds, but less effective at high speeds (above the first critical speed); the coulomb damper seemed necessary for sustained supercritical operation. The shaft was balanced in stages, using the Unified Balancing Approach [11], through the second critical speed and to a point approaching the third critical speed.

Work was also begun on modifying the composite shaft design optimization analysis to allow variations of fiber layup along the shaft's axial length. The additional design flexibility of incorporating fiber geometries which vary over the length of the shaft should provide further reduction in system weight. It is expected that this approach could also lead to designs which eliminate separate flexible couplings between shaft segments, by permitting sufficiently low local bending stiffness at the ends of the shaft to accommodate the levels of misalinement for which separate flexible couplings are intended. It was at this point that the research was terminated after four years of effort.

E. Helicopter Maneuver Rotor Loads
(Sr. Invest'rs, O. Bauchau, M. Crespo da Silva, R. Loewy)

This research was an exploratory evaluation of the effect rotor design characteristics have on violent maneuver capabilities and the structural dynamic rotor loads encountered thereby. The task was subdivided into several parts involving methodology advances to be completed before the investigation envisaged could be successfully conducted. First a rotor blade dynamic response prediction method, given the applied loads, was to be developed which uses a modal superposition approach. Second, a finite element based, multibody method would be established both as a means of evaluating modal approaches, and as a useful methodology in its own right. Third, perturbation methods, with exact mathematical treatment of more approximate physical models were to be used to insure that no basic instability associated with maneuver conditions would be overlooked. All of these methods were to account for geometric nonlinearities and composite blade design characteristics, including elastic coupling and large shear deflections. In the first two approaches, non-periodic rotor hub motions were to be accounted for and step by step time integrations implemented.

1. Application of Generalized Coordinate Analyses
(Sr. Invest'r, R. Loewy; A. Rosen and B. Mathew)

The maneuver research of this project intended to contribute to the methodology of designing rotors for which agility is a major consideration. Including blade loads during maneuvers in optimization studies requires high computational efficiency, if only to provide a proper starting point for such studies in nonconvex design spaces. The computational efficiency of modal methods, ie use of generalized coordinates, therefore, provided the motivation for this project. New rotors will certainly use composites, the elastic tailoring possible with composites, and root retention system kinematic couplings which enhance aeroelastic stability. Accordingly, the first tasks undertaken in adapting generalized coordinate analyses to maneuver blade load prediction were to include the effects of transverse shear deflections and cross section warping as well as the effects of elastic coupling. The generalized coordinate methods presented in Refs. 12-16 are analyses with capabilities for predicting blade response, both static and dynamic, with geometric nonlinearities, so long as strains are small. In the extended cases, cross-sectional warpings were also taken to be small relative to cross-section depth. This was tantamount to a small strain restriction for shear strain.

Two alternative means of dealing with transverse shear deflections were considered. In the first, normal modes which account for transverse shear deflections were to be used as generalized coordinates and the strain energy associated with transverse shear strains included by quantifying the shear strains in those modes. In the second, normal modes which do not account for transverse shear displacements would be used and their strain energies limited (as is the usual Euler-Bernoulli beam method) to those generated by normal (ie bending) strains. In addition, however, modes of pure transverse shear deflection would be defined and used as additional degrees of freedom.

Natural mode and frequency calculations were first made for a rotor blade with the same mass and geometry characteristics as that of the BO-105 helicopter to assess the importance of transverse shear deformations. Its structure, however, was taken as the composite box beam of Ref. 17. Calculations for the non-rotating modes were made using a transfer matrix analysis, for the range of shear web fiber angles in that reference. Errors in natural frequencies entailed in neglecting transverse shear deflections were shown to range from 2% to 67% between 1st and 5th modes, respectively, when the fiber angle in the web is 15°, and from 0.5% to 24%, respectively, when the ply angle is 30°.

With the effect of transverse shear deformations shown to be significant, and earlier influence of cross-sectional warping known to be strong on torsion for composite blades [18], the generalized coordinate analysis method was extended to include both effects. As a means of addressing the accuracy of the extended method, two cases for which solutions exist were analyzed. The first predicted the coupled extensile-torsional motion of a pretwisted rod under tensile load and compared the results obtained using the new method with those of an exact solution, assuming first that both ends of the rod were free to warp (F/F) and then assuming that one rod was clamped with respect to warpage (C/F). Differences due to these end-conditions were found to be confined to regions within approximately one rod depth of the end in question, as would be expected from St. Venant's principle, for members with rather typical structural characteristics. Results comparing non-dimensionalized extensile and torsion deformations versus non-dimensionalized length X/L, for the present theory and the exact solution [19] showed very good agreement, considering, particularly, that the analysis used, as degrees of freedom, five quarter sine-wave modes each, for twist and extension and for length-wise variation a single, St. Venant torsion warping shape [20].

The second case examined with the new theory was classical planar bending of a sandwich rod, for which both theoretical and test results exist [21,22]. Agreement as to predicted tip deflection under a load in the depth direction was very good, considering that the referenced theory ignored both the skin depth compared to core depth and shear effects in the skins and both were accounted for in the new theory. All these developments were subsequently reported in [23].

Further development of the methods of Refs. 12-16 for the purposes of rapid, design-oriented dynamic analysis of maneuvering rotors included a Lagrangian Multiplier approach to allow hub retention system parameter variations to be investigated efficiently. Two idealized rotor hub-hinge system models were postulated to assess the new method's capabilities. Trends of natural frequencies, damping ratios, and the amount of blade pitch induced by root flapping or lagging motions for variations of root retention system parameters were examined. These theoretical extensions and their application to practical helicopter cases were reported in Ref. 24.

The final theoretical developments extending the basic generalized coordinate method included the effects of sweepback, as currently used at blade tips. As a means of addressing the accuracy of the method extended so as to include sweepback, comparisons were made with the results of curved beam theory and with those of a transfer matrix method. The latter comparison examined sweptback blades in both a "cranked" configuration (ie where sweepback appears as a local discontinuity in the elastic axis direction) and as a locally curved elastic axis. The intent in this research was to establish accuracy limits on using natural modes and frequencies, obtained for one swept-back rotor blade configuration, as generalized coordinates in an analysis of a blade, identical in all other respects, but with different sweepback.

The transfer matrix analysis was used to calculate up to 9 coupled transverse bending-torsion, nonrotating natural modes and frequenceis for the following beams with uniform properties: straight, circular quadrant, and two "cranked" cases - one with 45° bend, one with 90° bend. Modal analyses showed that quite reasonably agreement can be expected for up to 5 modes, if enough modes, say 9, from calculations for a beam with different sweepback, are used as generalized coordinates. The agreement is significantly better for blades with continuously varying sweep, if local curvature expressions are used in the analysis, rather than a series of discreet changes in sweepback. Some of these results are tabulated in Figs. 15 & 16.

Extending the equations of motion for a rotor blade, using the methodology of Refs. 12-16, to include hub linear and angular accelerations and velocities, as are encountered during maneuvers, was accomplished in terms of a "velocity component transformation". The axial displacement of the blade along its elastic axis, relative to the hub, was assumed to be determined by the inextensibility condition, as in the earlier analyses. Without the "rigid body" hub rotations associated with maneuvers, the velocity coordinate shape functions had been selected simply as "reasonable" shapes. Since the displacement shape functions had been selected as the uncoupled, nonrotating (flat-blade) modes, the mass and stiffness matrices in the equations of motion which result - when the displacement and velocity coordinates are properly related, for that case - should have been diagonal matrices (by the orthogonality condition). They were, to wit about 1%. When constant and linear (with radius) shape functions were added to the velocity component coordinates, however, as required for a maneuver case, the off-diagonal term errors grew to 10%. This experience lead to definition of velocity component shapes, in addition to those required by "rigid body" hub motions, as dictated by the definitions used in the derivation of the method. That is, the axial extension, bending and twisting shapes and their derivatives which appear in the velocity component expressions were calculated as exactly those resulting from the displacement coordinate definitions and their derivatives and by the inextensibility assumption. Only these consistent shapes were included as velocity component shape functions. When this was done, off-diagonal terms in the mass and stiffness matrices were calculated as zero, to within at least six significant figures.

Two more aspects of nonlinear blade response prediction using generalized coordinates demanded refinement and extension of a fundamental nature, over the course of these studies. The first refinement was to correct for the lack of adequate cyclic blade control pitch representation in the mathematical models of Refs. 16. This inadequacy was brought to the forefront by continuing efforts to match Boeing forced response results. The second aspect involved torsional stiffness modeling and arose from attempts to correlate with the simple, nonlinear forced response cases reported by O. Bauchau in Ref. 25.

Cyclic pitch has the effect of changing what can be considered as the "initial configuration", in a non-linear analysis, at every azimuthal station. Pitch angle changes the coupling between motions in the plane of rotation with those out of that plane. Since the generalized coordinate formulation involves kinetic energy integrals of the blade physical properties, the mode shapes used in the modal basis, and the blade pitch angle - cyclic pitch, if expressed as part of a total pitch angle, can require recalculation of these integrals at every azimuthal step. A major advantage of the method had been that these integrals need only be calculated once for any given case, greatly reducing the computational time required. It was thus important to redefine and separate these integrals in a way which extracted and segregated the cyclic pitch angle.

To be explicit as to properly accounting for cyclic pitch, it is necessary to review the basic formulation. First, recall that the strain energy of the blade expressed in terms of generalized coordinates, using the natural free vibration mode shapes of a blade with zero twist and zero mass coupling between bending and torsion is written:

$$U_E = \frac{1}{2}\{q_e\}^T[K_e]\{q_e\}$$

where $[K_e]$ is given by:

$$[K_e] = \begin{bmatrix} m_1\omega_1^2 & 0 & \cdots & 0 \\ 0 & m_2\omega_2^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & m_n\omega_n^2 \end{bmatrix}$$

and the generalized coordinates, q_e, result from the definition of what was called the "principal curvature transformation". Each of the terms in $[K_e]$ is the effective mass, m_i, in a given mode, times the natural frequency squared in that free vibration mode. To express the strain energy in terms of the displacement generalized coordinates, q, that are ultimately to be used, their relation to the "principal curvature" coordinates, q_e, must be described. The details of this nonlinear transformation are reported in Ref. 13. It is sufficient here to note that the "principal displacement" coordinates are related to the physical displacement coordinates by a nonlinear relation which reflects the total motion, as it enters the kinetic energy; ie

$$[D_1]\{q_e\} = [[D_2] + [D_3]]\{q\}$$

The resulting strain energy relation in cartesian displacement coordinates is, then, expressed as follows:

$$U_E = \frac{1}{2}\{q\}^T[K]\{q\}$$

where [K] is:

$$[K] = [K_1] + [K_2]$$
$$[K_1] = [D_2]^T[D_4][D_2]$$
$$[K_2] = [D_3]^T[D_4][D_2] + [D_2]^T[D_4][D_3] + [D_3]^T[D_4][D_3]$$
$$[D_4] = [D_1]^{-1^T}[K_e][D_1]^{-1}$$

To both include cyclic pitch and segregate terms associated with it, the matrices on the right hand side of the above equations have to be partitioned so that the local pitch angle, θ, appears in blade integral elements in the forms:

$$D_{2ij} = \int_O^L f_{ij}(x) \begin{Bmatrix} \sin\theta, \text{ or} \\ \cos\theta, \text{ or} \\ 1 \end{Bmatrix}$$

$$D_{3ij} = \int_O^L f_{ij}(x) \begin{Bmatrix} \sin\theta, \text{ or} \\ \cos\theta, \text{ or} \\ 1 \end{Bmatrix}$$

Since blade pitch can be defined as:

$$\theta = \theta_o + \theta_c$$

where θ_o is the steady blade pitch, and θ_c is the cyclic pitch, the matrices $[D_2]$ and $[D_3]$ can be partitioned using the relations:

$$\sin(\theta_o + \theta_c) = \sin\theta_o\cos\theta_c + \cos\theta_o\sin\theta_c$$
$$\cos(\theta_o + \theta_c) = \cos\theta_o\cos\theta_c - \sin\theta_o\sin\theta_c$$

The cyclic pitch terms in the integrals in $[D_2]$ and $[D_3]$ are as follows:

$$[D_2] = \cos\theta_c \left[[D^a_{2s}] + [D^a_{2c}]\right] + \sin\theta_c \left[[D^b_{2s}] - [D^b_{2c}]\right] + [D_{2o}]$$

$$[D_3] = \cos\theta_c \left[[D^a_{3s}] + [D^a_{3c}]\right] + \sin\theta_c \left[[D^b_{3s}] - [D^b_{3c}]\right] + [D_{3o}]$$

Collecting terms and defining:

$$[D^a_2] = \left[[D^a_{2s}] + [D^a_{2c}]\right]$$

$$[D^b_2] = \left[[D^b_{2s}] - [D^b_{2c}]\right]$$

$$[D^a_3] = \left[[D^a_{3s}] + [D^a_{3c}]\right]$$

$$[D^b_3] = \left[[D^b_{3s}] - [D^b_{3c}]\right]$$

The resulting relation between the "principal curvature" and physical coordinate systems is then given by:

$$[D_1]\{q_e\} = \Big[\cos\theta_c[D^a_2] + \sin\theta_c[D^b_2] + [D_{2o}] + \cos\theta_c[D^a_3] + \sin\theta_c[D^b_3] + [D_{3o}]\Big]\ \{q\}$$

Adopting the abbreviations $s_t = \sin\theta_c$ and $c_t = \cos\theta_c$,

the stiffness matrices are expressible as

$$[K] = [K_1] + [K_2]$$

$$[K_1] = c^2_t[D^a_2]^T[D_4][D^a_2] + s^2_t[D^b_2]^T[D_4][D^b_2] + c_t s_t\Big[[D^a_2]^T[D_4][D^b_2] + [D^b_2]^T[D_4][D^a_2]\Big] +$$

$$s_t\Big[[D^b_2]^T[D_4][D_{2o}]^T[D_4][D^b_2]\Big] + c_t\Big[[D^a_2]^T[D_4][D_{2o}] + [D_{2o}]^T[D_4][D^a_2]\Big] +$$

$$[D_{2o}]^T[D_4][D_{2o}]$$

$$[K_2] = c^2_t\Big[[D^a_3]^T[D_4][D^a_3] + [D^a_2]^T[D_4][D^a_3] + [D^a_3]^T[D_4][D^a_2]\Big] +$$

$$s^2_t\Big[[D^b_3]^T[D_4][D^b_2] + [D^b_3]^T[D_4][D^b_3] + [D^b_2]^T[D_4][D^b_3]\Big] +$$

$$c_t s_t\Big[[D^a_3]^T[D_4][D^b_2] + [D^a_2]^T[D_4][D^b_3] + [D^b_3]^T[D_4][D^a_2] +$$

$$[D^b_3]^T[D_4][D^a_3] + [D^a_3]^T[D_4][D^b_3] + [D^b_2]^T[D_4][D^a_3]\Big] +$$

$$s_t\Big[[D_{3o}]^T[D_4][D^b_2] + [D_{3o}]^T[D_4][D^b_3] + [D^b_2]^T[D_4][D_{3o}] +$$

$$[D^b_3]^T[D_4][D_{2o}] + [D^b_3]^T[D_4][D_{3o}] + [D_{2o}]^T[D_4][D^b_3]\Big] +$$

$$c_t\Big[[D^a_2]^T[D_4][D_{3o}] + [D^a_3]^T[D_4][D_{2o}] + [D^a_3]^T[D_4][D_{3o}] +$$

$$[D_{2o}]^T[D_4][D^a_3] + [D_{3o}]^T[D_4][D^a_2] + [D_{3o}]^T[D_4][D^a_3]\Big] +$$

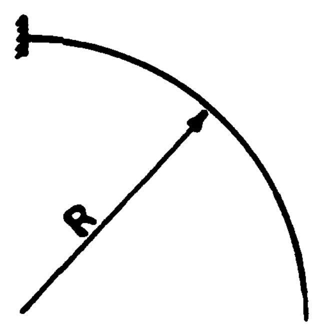
$$\Big[[D_{3o}]^T[D_4][D_{2o}] + [D_{2o}]^T[D_4][D_{3o}] + [D_{3o}]^T[D_4][D_{3o}]\Big]$$

where s_t and c_t are, in general, functions of the azimuthal angle ψ.

Turning to the torsion stiffness modelling, lack of correlation between the non-linear forced response results of the generalized coordinate analysis which are the subject of this project and those of Ref. , appeared to be influenced by the unusually high natural frequencies in torsion associated with the particular model chosen in that reference. This had the apparent benefit of isolating the source of discrepancies to a narrow area of the program, promising that they could be resolved rather quickly. Such activities were still underway at the completion of the contract.

Fig. 15
QUADRANT
NONROTATING NATURAL FREQUENCIES(RAD/Sec)

	MARBL2			
TRANSFER MATRIX	USING QUADRANT MODES (5)	USING St. BEAM MODES (5) (CURVATURE)	USING St. BEAM MODES (9) (CURVATURE)	USING St. BEAM MODES (9) (CRANKED)
5.007	5.007	5.676	5.005	5.203
23.90	23.90	25.05	24.06	24.83
75.07	75.07	80.28	75.61	76.71
138.5	138.5	143.2	139.9	145.4
171.6	171.6	175.9	173.3	175.8



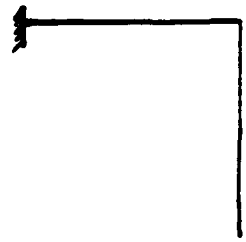
$\chi_y = \frac{1}{R}$

R = 187.2"

Fig. 16a

90 DEG. SWEEP

NONROTATING NATURAL FREQUENCIES(RAD/Sec)

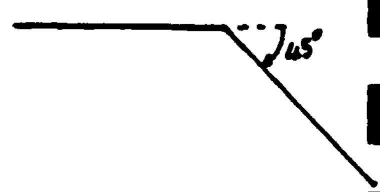


MARBL2			
TRANSFER MATRIX	USING 90 DEG. MODES (5)	USING 45 DEG. MODES (5)	USING 0 DEG. MODES (9)
6.250	6.269	6.550	6.487
16.98	17.03	17.71	17.58
84.61	85.99	86.33	85.38
118.2	119.4	120.3	119.6
196.2	191.2	241.3	227.3

Fig. 16b

45 DEG. SWEEP

NONROTATING NATURAL FREQUENCIES(RAD/Sec)



MARBL2		
TRANSFER MATRIX	USING 45 DEG. MODES (5)	USING 0 DEG MODES (9)
5.132	5.140	5.254
23.34	23.45	24.92
84.05	85.45	84.67
114.6	114.0	117.3
182.7	182.6	213.9

2. Adaptation of Existing Non-Linear Aerodynamics Modules
(Sr. Invest'r, R. Loewy; B. Mathew)

The aerodynamic module of the Boeing Helicopter Company, C-60 comprehensive rotor analysis program, was requested and provided to Rensselaer as a potential source of non-linear, quasi-static airloads for maneuver studies. Since the aerodynamic module of C-60 was never intended to be run except as part of the larger program, discovering how to input needed quantities and access desired results was not trivial. Its first application in obtaining the lift, drag and pitching moment distribution on a helicopter blade performing a rudimentary flight maneuver considered an idealized vertical pull-out, ie a symmetric flight-path along a circular arc.

The helicopter example chosen had characteristics very similar to that of the YUH-61A helicopter. (Gross weight = 17000 lbs; propulsive force = 1800 lbs; rotor speed = 286 rpm; flight velocity = 100 ft/sec., rotor radius = 24.5 ft., four blades; chord = 23.33 in.) A constant-g pull-up was postulated for the purposes of comparison, to gain a preliminary qualitative understanding of how maneuvers change blade air loads, using this idealized example. The major assumptions used initially were (1) rigid, hinged blades, (2) thrust perpendicular to the tip path plane and (3) uniform induced velocity. Collective and cyclic control inputs were estimated using appropriate expressions from a standard text in an open-loop procedure; i.e. no adjustments were made to the simple estimates for collective and cyclic, following calculation of the airloads. Lift force variations with azimuth at 95%, 85%, and 75% radius were calculated for the postulated flight condition, first using the linear option of C-60, in which the lift curve slope is constant and no compressibility effects are included.

Subsequent calculations employed the nonlinear option of C-60. This involves a "table look-up" procedure for airfoil section characteristics. In in this case, static airfoil tables for the NACA 23012 airfoil were used to obtain values of C_L, C_D and C_M. A reasonable steady lift component correlation with the linear case was obtained. Comparisons of the drag results from the two methods on the advancing side (azimuth angles between 36° and 144°) at 95% radius indicated that there are compressibility effects for this flight condition, playing a lesser role (as expected) at 85% and 75% radius. Neither lift nor pitching moment results showed that the rotor in question stalls on the retreating side (azimuth angles between 216° and 324°) in postulated pull-up maneuvers up to 2g's. Such effects were unmistakable, however, in the pitching moments when the normal accelerations were increased to 3g's. Furthermore, moment stall effects were experienced under this condition as far inboard as 75% radius. Further, a small mean lift change, even though control input intended a 3-to-2 increase, based on linear aerodynamics, confirmed the stall indicated by pitching moments.

These early results using the C-60 computer program in maneuvering blade loads research suggested that the next logical step was to incorporate radial variations of airfoil sections. This would allow investigating that means of minimizing the unfavorable effects of compressibility and stall encountered in the lift, drag and pitching moment distributions predicted for a typical helicopter blade performing an idealized vertical pull-out. To insure that "loading" new airfoil data into the C-60 table look-up portion of the program would be done properly, correlation efforts were conducted using a version of CAMRAD, made available to the RRTC by McDonnell-Douglas Helicopter Company. This contained different airfoil section data than our C-60 module (NACA 0012).

For correlative purposes, airloads were calculated using both CAMRAD and C-60 for the instant in the pull-up maneuver at which the normal loads are vertical. Rotor shaft angles were chosen arbitrarily with respect to the vertical, and CAMRAD was used to determine blade collective and cyclic pitch control inputs, such that vertical and longitudinal hub forces and pitch and roll hub moments were balanced. These trim calculations assumed that the required side force and rotor torque would be provided by other means - the "Wind Tunnel" option in CAMRAD. All of this, plus the associated blade coning, flapping and lagging responses, were also used as input to the C-60 aerodynamic module. After careful attention to making the inputs identical, excellent agreement was obtained, establishing the equivalence of these particular CAMRAD and C-60 aerodynamic modules.

The instantaneous, "snap-shot" nature of the maneuver comparisons conducted to this point embodied differences from straight, steady level flight at higher than normal gross weight only in two respects: the linearly varying inflow - fore and aft - due to the aircraft's instantaneous pitch rate, on the one hand, and the gyroscopic moments that must be applied to the rotor to make it generate those pitch rates, on the other hand. Fig. 17 shows four curves of aerodynamic loading at the 95% radial station for a 1.25g symmetric pull-up, for each of the out-of-plane and in-plane directions. These four curves are (1) with neither pitch rate inflow nor gyroscopic moment (labelled "baseline"); (2) and (3) with these two effects separately; and (4) with both effects. It is clear that the gyroscopic moment requirement has a large effect, whereas the pitch rate inflow does not.

Even with side-force and torque provided as required, in the CAMRAD "wind tunnel" trim option, unreasonable values of certain parameters, such as shaft angle, began to be required for trim when pull-up accelerations were specified as significantly greater than 1.5 g's. When a typically sized tail-rotor and fuselage were defined and incorporated into the program input and cases rerun for 0, 1.5 and 1.75 g's using CAMRAD's "free flight" trim option, reasonable results were also obtained up to 1.5 g's in the idealized pull-up maneuver, but at higher values, side-slip angles too large for practicality were predicted for trim. We concluded that use of CAMRAD in these maneuver studies should *be limited to establishing* "straight and level" trim conditions prior to instituting maneuver control inputs, and that in subsequent time steps, C-60 should be used to calculate rotor blade airloads.

In making these comparisons, several aerodynamic characteristics affecting the blade loads were noted. Radial and tangential components of induced velocity were not included in the calculations initially, as they seemed of negligible importance. Adding them into the RRTC program, however, produced a noticeable change in some airloads, although in most cases the changes were not significant. Induced velocity components parallel to the disc plane did account for as much as 5% change in the loads at some blade stations.

A much more significant change was noted with an accounting for dynamic stall. The model used for dynamic stall estimates a dynamic stall"delay angle" and subtracts it from the angle of attack of the blade element. This "reference angle" is then used to get the slope of the lift curve, based on the change in lift from zero degrees angle of attack to the reference angle. This leads to the estimate used for the lift coefficient. To estimate drag and pitching moment, the "reference angle" is used in a direct table look-up for drag and moment coefficients. The equation used to account for this dynamic stall delay and produce the reference angle of attack (for lift), α_{refL}, is as follows.

$$\alpha_{refL} = \alpha(r) - \Gamma_L \frac{A}{|A|} \left(\left|\frac{c}{2}\frac{\dot{\alpha}}{v}\right|\right)^{\frac{1}{2}}$$

where:

$\alpha(r)$ - blade element angle of attack
Γ_L - lift stall delay function, dependent on Mach number

A - ratio of $\dot{\alpha}/v$
c - blade element chord

$\dot{\alpha}$ - blade element rate of change of angle of attack
v - blade element resultant velocity

The equations for the reference angles for moment and drag are the same, except that a moment stall delay function, called Γ_M, is substituted for Γ_L.

Figs. 18 and 19 show the effect of including the stall delay angle on lift and drag. In these figures, the baseline case is that calculated using the RRTC C-60 airloads module to match the Boeing Helicopter case (called "RPI C-60"). These graphs demonstrate the importance of dynamic stall to airloads on the retreating side, even without maneuver loads.

Another dynamic effect shown to be significant in these comparisons is the effect of the slope of the induced velocity versus azimuth on dynamic stall. This term affects the rate of change of the blade section angle of attack and, therefore, helps determine the stall delay angle, defined above. The equation for the blade rate of change of angle of attack is as follows:

$$\dot{\alpha} = \dot{\theta} + \frac{\lambda_T}{\lambda_T^2+\lambda_P^2}\left[-\frac{\Delta\dot{v}}{\Omega R} - \frac{\ddot{\zeta}}{\Omega R} - \frac{V_x}{\Omega R}\dot{\beta}\cos\psi + \frac{V_x}{R}\beta\sin\psi\right] - \frac{\lambda_P}{\lambda_T^2+\lambda_P^2}\left[\frac{V_x}{R}\cos\psi\right]$$

where:

V_x = component of flight speed in disk plane
$\dot{\theta}$ = rate of change of the blade geometric pitch (rad./sec.)
$\Delta\dot{v}$ = rate of change of induced velocity normal to the disk (in/s^2)
$\ddot{\zeta}$ = blade flap displacement acceleration (in/s^2)
β = blade flap slope (radians)

Since the only place in the airloads module in which the rate of change of induced velocity is used is in the dynamic stall model, this $\Delta\dot{v} = \frac{\partial \Delta v}{\partial \psi}\Omega$ term was removed from the expression for $\dot{\alpha}$, to see how this affects loads obtained using the dynamic stall model. Fig. 20 compares section drag for the baseline case with a case which is identical except that $\Delta\dot{v}$ is dropped. In the region where stall is most evident, the retreating side, the loads are shown to be sensitive to this term, but in other areas no changes are evident.

CAMRAD was exercised further, at this point, to evaluate other phenomena likely to affect rotor blade maneuver loads. The validity of neglecting shaft accelerations in the rotor response was tested by evaluating the forcing function of the rotor equations with and without them. For most conditions, the terms due to the rigid body accelerations were small compared to the magnitude of the forcing function. The accuracy of the "quasi-static" assumption was tested by completing a comparison case using the CAMRAD "flutter" analysis which does not make the "quasi-static" assumption. Natural coupled modes of the aircraft are used, however, in calculating transient response in a totally linear analysis. Agreement between the two methods for similar conditions was satisfactory, considering the differences between the two models. As a result, the "quasi-static" assumption was considered acceptable for the maneuver considered.

The results of the transient method were then used to predict time histories of blade bending and aerodynamic loads for a maneuver of which CAMRAD is capable. These loads were subsequently analyzed for the causes of high bending and torsion moments by isolating effects such as dynamic stall, static stall, and compressibility. Dynamic stall was accounted for, using the Boeing stall model as described above. The maneuver selected was limited to a maximum 1.8g vertical load factor (30,350 lb thrust) to avoid program iteration complications and assure the accuracy of the assumptions.

The control selected was a combination of collective and lateral cyclic with the use of an attitude feedback provided by CAMRAD's stability augmentation system (SAS) option. The resulting maneuver did, in fact, provide a maximum normal load factor of 1.8g with minimal lateral acceleration. Inflow was represented by a three degree of freedom model, based on momentum theory, with a fully developed inflow at each time step, except for one case which used a dynamic inflow model (Ref. 26). Since the peak acceleration of 1.8 g's occurred in about 2.88 seconds, the analysis of the blade loads was centered around this time, and maximum moments were assumed to occur at the blade root, for this rotor with cantilevered blades. All three maximum moments showed significant increases during the maneuver. The steady chord bending and torsion moments changed slightly, while the steady flap moment changed significantly due to increased thrust.

The 1.8g maneuver aerodynamic loads were referred to the local blade chord plane and, at 120 knots flight speed, included dynamic stall and compressibility effects. They are referred to here as the baseline maneuver loads. These baseline aerodynamic loads, bending moments, and torsion moments were analyzed at trim and at the time of maximum thrust to determine the part of the loads due to dynamic stall, static stall, or compressibility effects. Static stall was found to have little effect on the blade moments in steady or maneuvering flight, although the effect was increased in the maneuver. Dynamic stall and compressibility caused significant changes in the bending moments in both steady and maneuvering flight. Dynamic stall had the most significant effect on the flap bending moment. Due to dynamic stall influences on lift, the amount of increase in the maximum oscillatory flap bending moment in the maneuver was 1681 ft-lb, of which only 118 ft-lb was due to dynamic stall in steady flight. The steady flap bending was reduced by 1023 ft-lb in the maneuver, due to a net decrease in lift due to dynamic stall. But in steady flight, dynamic stall lift increased the steady moment by 60 ft-lb. Of all the aerodynamic effects considered, compressibility had the largest effect on the bending moments and aerodynamic loads. In steady flight, compressibility causes the flap bending moments (steady, maximum oscillatory, and maximum) to decrease, however, in the maneuver, compressibility lead to increased moments. In steady flight, the loss of lift (– 220 lb) due to compressibility on the advancing tip caused the maximum oscillatory and steady flap moments to decrease. In the maneuver, this loss was small, leaving a net increase in lift due to compressibility and a resulting increased steady flap moment. Compressibility also caused large increases in the maximum chord bending moment due to the drag increase. Comparing the aerodynamic moment due only to compressibility to the total maneuver moment, showed that the large oscillatory load around the blade tip was due solely to compressibility effects. This tip oscillatory loading had a significant influence on the oscillatory torsion moment, but not as large as expected. Although torsion and bending moments due to non-linear aerodynamic effects were significant, the largest portion of the increase in moments in maneuvers was due to increasing loads in the linear aerodynamic region.

Other comparison cases that were completed in this study included the following changes: a symmetric NACA 0012 airfoil, a flight speed of 80 knots, and a hot day case. For similar maneuvers, it was found that the VR-12 airfoil, designed primarily to improve steady level flight performance over airfoils such as the NACA 0012, improved maneuver loads as well.

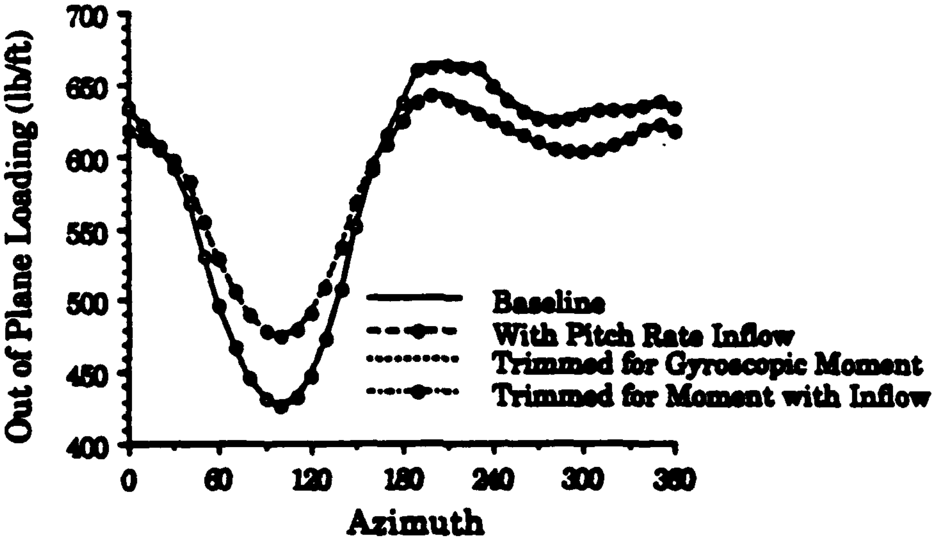
The case performed using hot day conditions (4000 ft altitude and 95° F) showed that at maximum thrust, all the moments, with the exceptions of the steady flap and chord moments, were higher than standard sea level conditions, but not due to non-linear aerodynamic effects.

A case was performed which included a lag in the inflow to account for rapid changes in the thrust and hub moments. This calculation used the Pitt-Peters dynamic inflow model [26]. Exact solutions of the three linear differential equations of the Pitt-Peters model were obtained for the perturbed inflow, and the perturbed inflow was calculated at each time step, based on the perturbed forces, and successively added to the trim inflow and to the perturbations from previous time steps. Comparisons made between results obtained using the different inflow models showed that, as might be expected, the lagged inflow lead to larger thrusts over the entire maneuver. The maximum thrust with lagged inflow also occurred sooner in the maneuver (2.17 vs. 2.24 seconds). Chord bending and torsion moments were larger, too, with the lagged inflow, as a result of the larger aerodynamic loads, due to higher angles of attack.

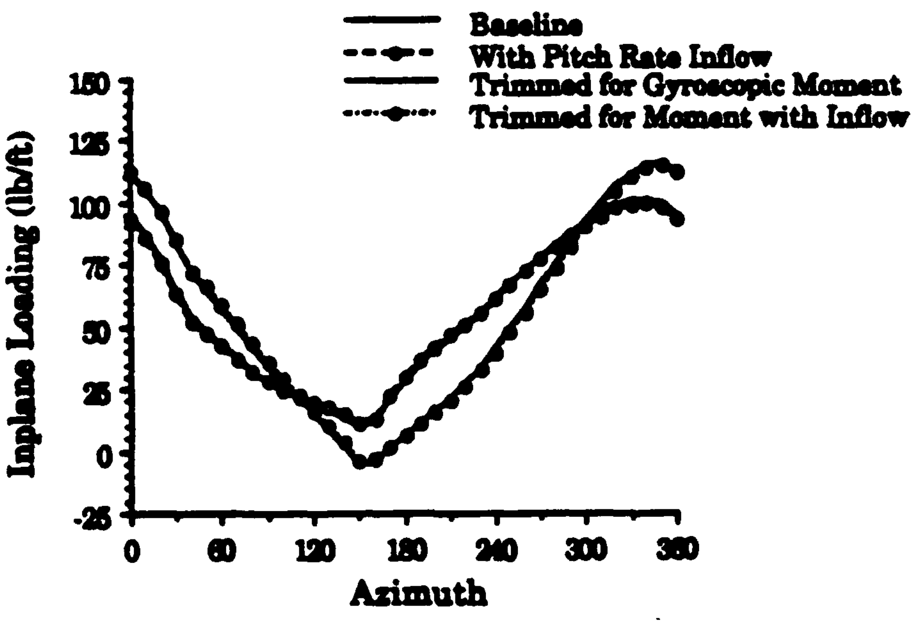
Fig. 17

Effect of Aircraft Pitch Rate and the Need to Trim Gyroscopic Moments on Rotor Airloads in a Symmetric Pull-Up

$\frac{r}{R} = 0.95 \qquad g = 1.25$



Effect of Inflow and Gyroscopic Trim on Out of Plane Loading



Effect of Inflow and Gyroscopic Trim on Inplane Loading

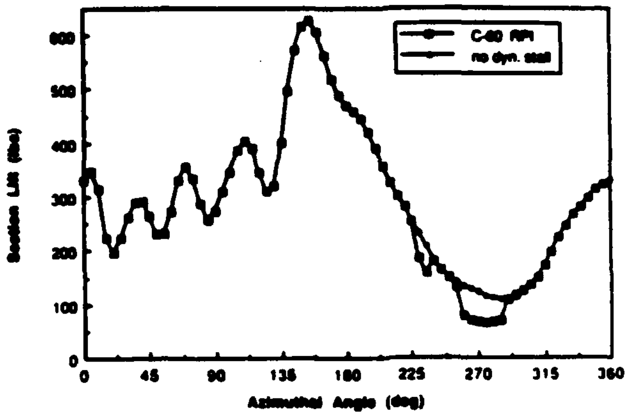


Fig. 18 C-60 Section Lift Comparison at r/R = 0.65
(with and without dynamic stall)

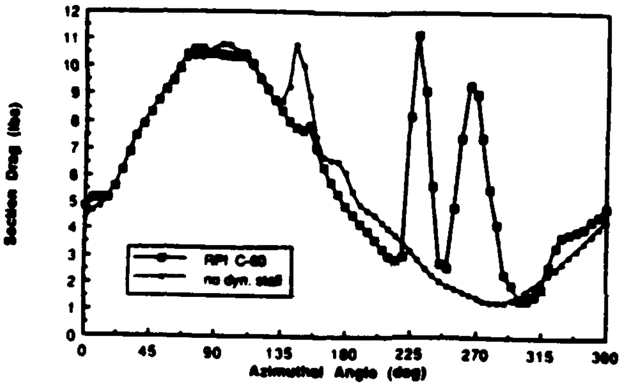


Fig. 19 C-60 Section Drag Comparison at r/R = 0.65
(with and without dynamic stall)

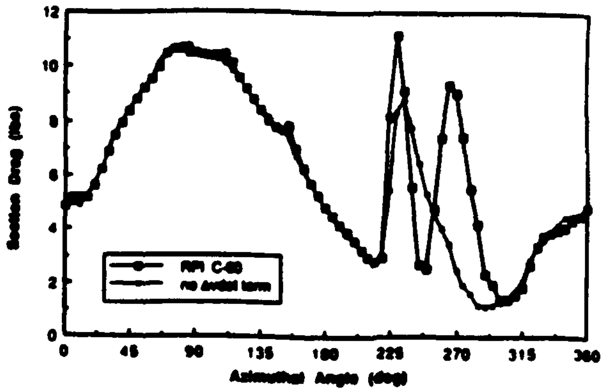


Fig. 20 C-60 Section Drag Comparison at r/R = 0.65
(neglecting Avdot Term)

3. Development of Finite Element, Modal and Multi-Body Analyses
(Sr. Invest'r, O. Bauchau)

As another approach to making available to maneuver load research an analysis method which properly accounts for full rotational dynamics and coupling among flap and lag bending and torsion; geometric nonlinearities; elastic couplings, transverse shearing deformations and warping of the cross-sections; and yet is computationally efficient, a finite element based modal method was developed.

The analysis reported in Ref. 27 was extended to include the case of a "free" hub, i.e. a rotor whose hub has 6 rigid degrees of freedom. The quasi-static aerodynamic portions of this code were improved to include a prescribed wake model using finite element in time techniques, and adapted to and coupled with DYMORE.

In the free hub approach taken, rigid body rotations and angular velocities were first expressed in terms of Euler Parameters, so that there would be no restriction on the magnitude of rigid body rotations that could be considered. Further, the full rotation dynamics were treated in a rational manner. Provisions were also made to couple the rotor with a vibrating fuselage, as this coupling seemed likely to be important in violent maneuver cases. This coupling of the rotating and non-rotating systems was accomplished by imposing a kinematic constraint at the hub, enforced using the Lagrangian Multiplier technique.

Developments using the finite element based modal method confirmed that it combines the versatility of the finite element analysis in accurately modeling complex structures, the simplicity of modal methods and their efficiency in reducing the required number of degrees of freedom, and the power of perturbation techniques in retaining representation of nonlinear interactions. Computations assessing the accuracy of the new method were performed for the beam model of Ref. 28 with its neutral bending planes at 45° to the vertical and for several tip gravity loads. The % errors relative to the results of a full finite element formulation were small and both correlated well with experimental results [29]. The 1-mode calculations were made using a single uncoupled static deflection shape in each direction in the coupled, non-linear equations; multi-mode calculation results showed improving accuracy when more and more perturbation modes were incorporated.

Studies to select the most advantageous finite element in time computational formulation were also conducted, using the classical problem of a rigid body with one axis of rotational symmetry tumbling freely in space, following release with two initial angular velocities, one about the axis of symmetry, one about an axis normal to it. This problem was selected since it has a closed form, exact time-history solution, against which finite element in time solutions could be compared. The "mixed" method results reported in Ref. 30 are in exact agreement with those obtained in the present effort. All of these comparisons show the superiority of the "mixed" formulation, not only with respect to the size of errors, but in their predictability. These advantages appear to outweigh the slightly higher computational complexity of using both Euler Parameters and Lagrange multipliers.

On the other hand, modal formulation for multibody dynamic problems was found to be cumbersome. There is a large computational "overhead", consisting of the management and manipulation of all the coefficients of the modal expansion. This burdens modal analysis with an increased computational cost. Furthermore, its accuracy is often difficult to guarantee.

Accordingly, an alternate formulation dealing directly with a full finite element model was derived, in which there is no need to distinguish between rigid body motion and elastic motion. The motion of each node is tracked by the finite element procedure. Large rigid body motions result in finite rotations, but finite rotations are also required to properly model the large elastic rotations. In this effort, the conformal rotation vector was used to model finite rotations. This representation of finite rotations was found preferable to Euler parameters as it involves only three parameters, as opposed to four, resulting in improved computational efficiency.

The full finite element formulation was also found to handle constraint equations ("hinges") between two elastic bodies much more easily. Indeed, such constraints only involve the degrees of freedom of two nodes, one on each body, which contrasts with the formulation of constraint equations between elastic bodies in a modal representation, which involves all the elastic and rigid degrees of freedom of both bodies. Mathematical details were presented in Ref. 31. Additional cases of flexible beams under steady and oscillatory loading which produce deflections large enough to involve geometric nonlinearities were also solved and compared with results in the literature to evaluate proper choices of modal bases. The results were presented in Ref. 25. Similar analyses and comparisons were done for the Blackhawk main rotor blade.

To evaluate the methods further, the classical case of a spinning top was investigated to assess the accuracy with which rigid body motions and the effect of constraint equations would be predicted. The base point of the spinning top was constrained in two ways: as regards (a) displacement and (b) velocity. Three sets of initial conditions were investigated, chosen to yield three different types of motions: precession always in the same direction; precession which changes sign during the motion; precession which does not reverse direction, but does stop momentarily (cuspidal motion).

The characteristics of a rigid link constraint was also assessed by studying single and double pendulum problems. A rigid link imposed the constraint of a fixed distance between two points. For instance, the pendulum problem can be seen as the motion of a point mass in a two dimensional space subjected to the constraint of a given distance between the origin and the mass point; this fixed distance was the constraint condition. The analytical solutions for the single and double pendulum were readily obtained and integrated. Three problems were analyzed and compared with classical results in the literature.

The results of comparisons of two approaches to analyzing the dynamic behavior of multibody systems became quite clear by the end of June 1991. They are best reviewed by reiterating the differences in the two methods. In the first approach, each elastic body was represented in a local, noninertial frame of reference with unknown rigid body motions with respect to a global inertial system, and a finite element-based modal analysis methodology was used to model the elastic behavior of the body. Constraint equations were used to model the interaction among the various elastic bodies. In the second approach, all elastic bodies were represented directly in a single inertial frame, and a full finite element methodology (without a modal reduction) was applied. Constraint equations were used again to model the interaction among the elastic bodies.

It was concluded that:

1. The accuracy of model methods strongly depends on the choice of the modal basis.

2. Nonlinear kinematic couplings are poorly represented by natural vibration mode shapes. This is easily understood since both phenomena are of a

different physical nature: one is a purely nonlinear kinematic phenomenon, the other a purely linear vibratory phenomenon. Even a large number of orthogonal vibration modes may not "synthesize" nonlinear kinematic behavior properly.

3. Adding perturbation modes to classical natural mode shapes considerably improves the accuracy of modal methods. Perturbation modes contain information about the nonlinear behavior of structures extracted from higher order derivation of the Lagrangian.

4. The nonlinearities associated with rotational dynamic effects are sometimes poorly represented by both natural vibration mode shapes and perturbation modes, resulting in a poor correlation for the angle attack.

5. When accurate predictions of rotor behavior are sought, modal analysis should be avoided, and full finite element methods preferred. In the case of violent maneuvers, rotational dynamic effects can be expected to be especially pronounced, hence application of modal analysis techniques should be considered, at best, suspect.

6. Large mathematical "overhead" is associated with nonlinear modal methods. This involves storing and manipulating the many coefficients appearing in the elastic modes. The number of coefficients grows as N^n where N is the number of modes, and n the highest power of the nonlinearities.

7. When rigid body motions are added to elastic behavior, this "overhead" increases roughly tenfold, and is responsible for the very rapid increase in computational effort required to deal with modal methods as the number of modes increases.

8. The computational effort involved in integrating the full finite element calculations presented in this work did not seem prohibitive when compared to that of modal analysis. This observation should not be generalized. It is clear that as the number of degrees of freedom in the finite element model increase, the cost of solution increases as well and will eventually become more expensive than that of the modal solution. It seemed, however, that for typical rotorcraft problems, the full finite element method could be directly competitive with modal solutions.

Two approaches developed for dealing with kinematic constraints were evaluated. In the first, constraints were enforced in terms of displacements; in the second, the time derivative of the constraints were enforced. In both cases a Lagrange multiplier technique was used to enforce them within the framework of a mixed formulation. The following conclusions emerged:

1. Enforcing the time derivative of the kinematic constraints yields numerical schemes which are far more accurate than those obtained enforcing the kinematic constraint itself.

2. When kinematic constraints are enforced, the problem becomes very "stiff" due to the presence of the large fictitious stiffness associated with the constraint. Integration schemes applied to these very stiff problems can easily become unstable. When the time derivative of the constraint was enforced,

this numerically unstable behavior disappeared.

3. Enforcing the time derivative of the kinematic constraints is only slightly more complex than enforcing the kinematic constraint itself.

To further evaluate the potential of the multibody formulation in rotorcraft dynamic analysis, the ground resonance problem was treated in this form. The configuration undertaken involved a four bladed, lag-hinged rotor mounted on an elastic body. Each blade was uniform and was attached to the hub with a revolute joint, and the massless elastic supporting body carried a concentrated mass at the hub. Motion was restricted to the plane of rotation, resulting in a system with 71 displacement degrees of freedom, considering the flexible blade representation. The response of this system was found by integrating the equations of motion in time using the HHT scheme. To excite possible instabilities, a short impulsive lateral load was applied at the hub. The time history of the loading pulse was triangular.

The multibody formulation's ability to deal with variable rotor speed was tested by applying torque at the hub revolute joint to increase rotor speed. Torque variations were applied which grow linearly from zero to T_0, then remain constant at T_0. Two torque levels were examined. For the higher torque level, the rotor speed increased rapidly enough to pass through an unstable region quickly, and no instability was observed. For the lower torque level, the rotor speed increased slowly, dwelling in the unstable zone long enough for an observable instability to be excited.

At this point we concluded that the multibody formulation for helicopter nonlinear dynamic analysis was implemented and validated. By using the components of the conformal rotation vector to represent finite rotations, enforcing constraint equations using the augmented Lagrangian method, and using the Hilber-Hughes-Taylor scheme to control the numerical instabilities associated with time integration of constrained dynamical systems, excellent correlation was found between results of the multibody formulation and existing analytical solutions for simple rigid body problems.

The ground resonance example involved direct time integration of rather "stiff" equations, with kinematic constraints enforced in a time derivative fashion. The Hilber-Hughes-Taylor integration scheme was used to provide high frequency numerical damping and to avoid numerical instabilities in the integration process. A critical re-examination of time integration solution techniques was, therefore, made. Several displacement based and mixed finite element formulations and several finite difference and finite element in time integration schemes were reviewed, focusing on stability, accuracy, and efficiency.

The following conclusions were drawn from a study conducted to evaluate three broad categories of time integration methodologies: Fourier decomposition techniques, finite difference techniques, and finite element in time techniques.

1. Direct integration of nonlinear finite element dynamic equations is practical for rotor problems. A complete helicopter blade system (including flex-beam and torque tube) was modeled with a displacement-based finite element model involving 17 cubic beam elements, corresponding to 314 displacement degrees of freedom. The response of the blade under specified loading was computed for one revolution using the HHT time integration scheme with 180 equal time steps. CPU time of 1400 seconds was required on a Sun 68020 Workstation; high power engineering workstations would cut this by a factor of 10 to 50.

2. Integration schemes should provide: unconditional stability, second order accuracy, and high frequency numerical damping. The Hilber-Hughes-Taylor scheme seems ideally suited for time integration of rotor problems.

3. Mixed finite element formulations do not seem to provide better computational efficiency than displacement based models. While mixed formulations may approximate internal forces better for a given mesh size, the computational cost of increasing the degrees of freedom to include both displacements and internal forces overpowers the gain in accuracy. For a given accuracy level, the displacement based formulation seems more computationally efficient. This conclusion only holds for direct integration of rotor equations; indeed, for modal reductions, mixed methods are superior to displacement based approaches.

4. For linear problems, several finite element in time schemes were shown to be equivalent to members of the Newmark family. In fact, among the FET schemes reviewed, all unconditionally stable schemes were found equivalent to "average accelerations" or "trapezoidal rule" schemes. This does not imply, by any means, that other FET schemes must also present the same equivalence. Mixed FET formulations (i.e., with both displacements and momenta as independent field variables) reviewed in this work have the same characteristics as their displacement based counterparts, and hence, present no computational advantage.

5. When FET methodologies are applied either to higher order polynomial approximations, or to periodic problems, the bandedness of the system's equations is destroyed, resulting in a drastic increase in computational effort. This conclusion, once again, holds only for the direct integration of finite element equations. When dealing with fully coupled modal equations, the system's matrices are fully populated, so that the computational efficiency of the FET approach is not hindered by use of higher order approximations or periodic conditions.

6. The various FET formulations reviewed do not introduce the high frequency numerical damping needed to stabilize the integration process. Alternative FET formulations, such as the time-discontinuous Galerkin formulation proposed in the literature, promise the desired numerical damping. Use of such formulations for rotor problems remains to be investigated.

4. Development of a New Finite Element for Flex Straps
(Sr. Invest'r, O. Bauchau)

Finite element analysis components appropriate to rotor flexstrap structures were also developed, since predictions of the rotating dynamic behavior of such structures in a nonlinear regime are suspect if existing finite element packages, such as NASTRAN, are used. Further, standard beam elements seemed unlikely to be suitable for the analysis of flexstrap structures because chordwise bending deformations are not negligible, length to width ratios can be below 5, highly anisotropic materials may be used, transitional zones between different cross-sectional sizes probably are important, and compressive stresses caused by flap and lead-lag bending are large enough to put parts of the flexstrap structure into compression, despite the action of centrifugal force.

A rational, static two-dimensional model of flexstrap structures was sought, based on nonlinear composite shell theory, which models the effects of high anisotropy for both in-plane and out-of-plane bending behavior; accounts for the presence of elastic coupling and transverse shearing deformations; and models geometric nonlinearities appropriate for small strains. This shell model was to be an effective design tool, compatible with the various beam models used to represent the helicopter blade and with the finite element-based modal solution scheme to be used in the aeroelastic analysis. Its formulation was completed before the end of 1989 and was reported in Ref. 32. Validation calculations were completed subsequently, using results contained in Ref. [33] as a basis for comparison. This work was not directly supported from contract funds, but provided results useful to rotor blade dynamics analysis in maneuvers and is reported here for the sake of completeness.

Validation calculations for the new two-dimensional structural elements to be used in the analysis of flexstrap components were compared with several benchmark problems. One was concerned with the so-called "shear locking" phenomenon, which resulted in overestimating plate/shell stiffness as a result of inability to have strain energy in shear approach zero as plate/shell thickness approaches zero. Use of the Hellinger-Reissner formulation in this effort gave a formulation that is good at predicting the overall stiffness of the plate but not local stresses. Natural vibration frequencies of plate structures were compared to the results of analytical solutions for plates with several kinds of boundary conditions, using both biquadratic and bicubic elements in the current methodology. Good correlation was observed for the various frequencies, and the bicubic element gave a much more accurate prediction.

Further applications, using the new element in configurations typical of modern helicopter rotor hub retention arrangements showed that the new element will be useful for predicting overall deflections and local stresses except for local stresses when plates become thick. This should not be a serious limitation for predicting the dynamic behavior of flex-strap retained rotors. It also appeared from these studies that the dynamic behavior of flex-structures will be affected by shell-like deformation modes. This seems particularly significant for lead-lag and torsion modes when the flex-structure is made of highly anisotropic composites. Thus, use of shell models appeared to be indicated in designing composite flex-structures for rotor blade retention systems.

A practical application of the above methodology dealt with the MBB BK-117 helicopter bearingless tailrotor [34]. The cruciform flex-strap is depicted in Fig. 21a. The predictions for two models were compared with experimental measurements. In the first model the entire tail rotor blade (ie both flexstrap and blade) was modeled with beam elements, whereas in the second model the flexstrap is modeled with shell elements, and the blade is modeled with beam elements. Fig. 21b shows the predictions for the torsional stiffness of the blade versus tail rotor speed. The shell model shows a much higher stiffening than the beam model, and the experimental measurement is in closer agreement with the shell model.

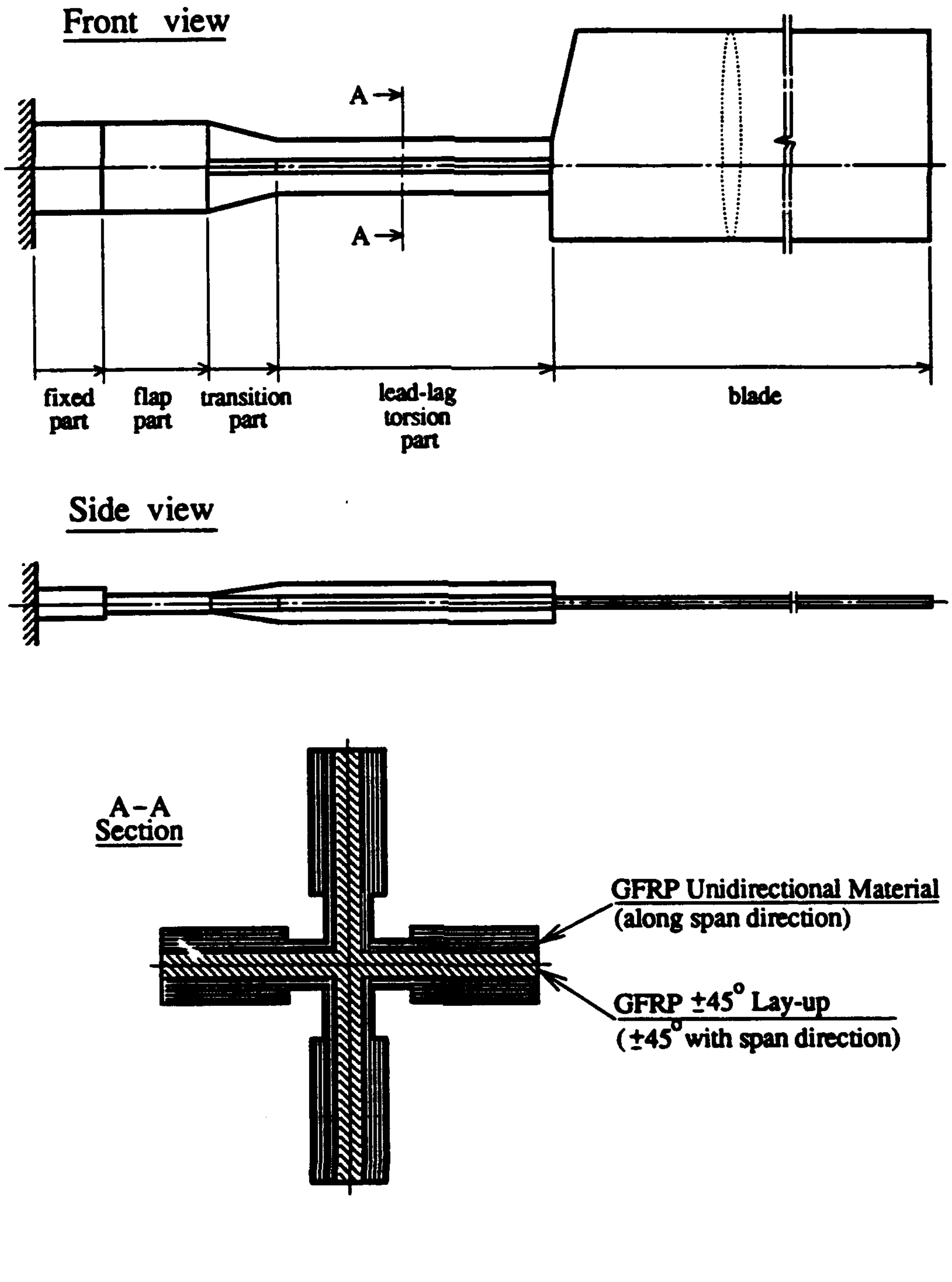


Fig. 21a A sketch of the MBB bearingless tail rotor blade

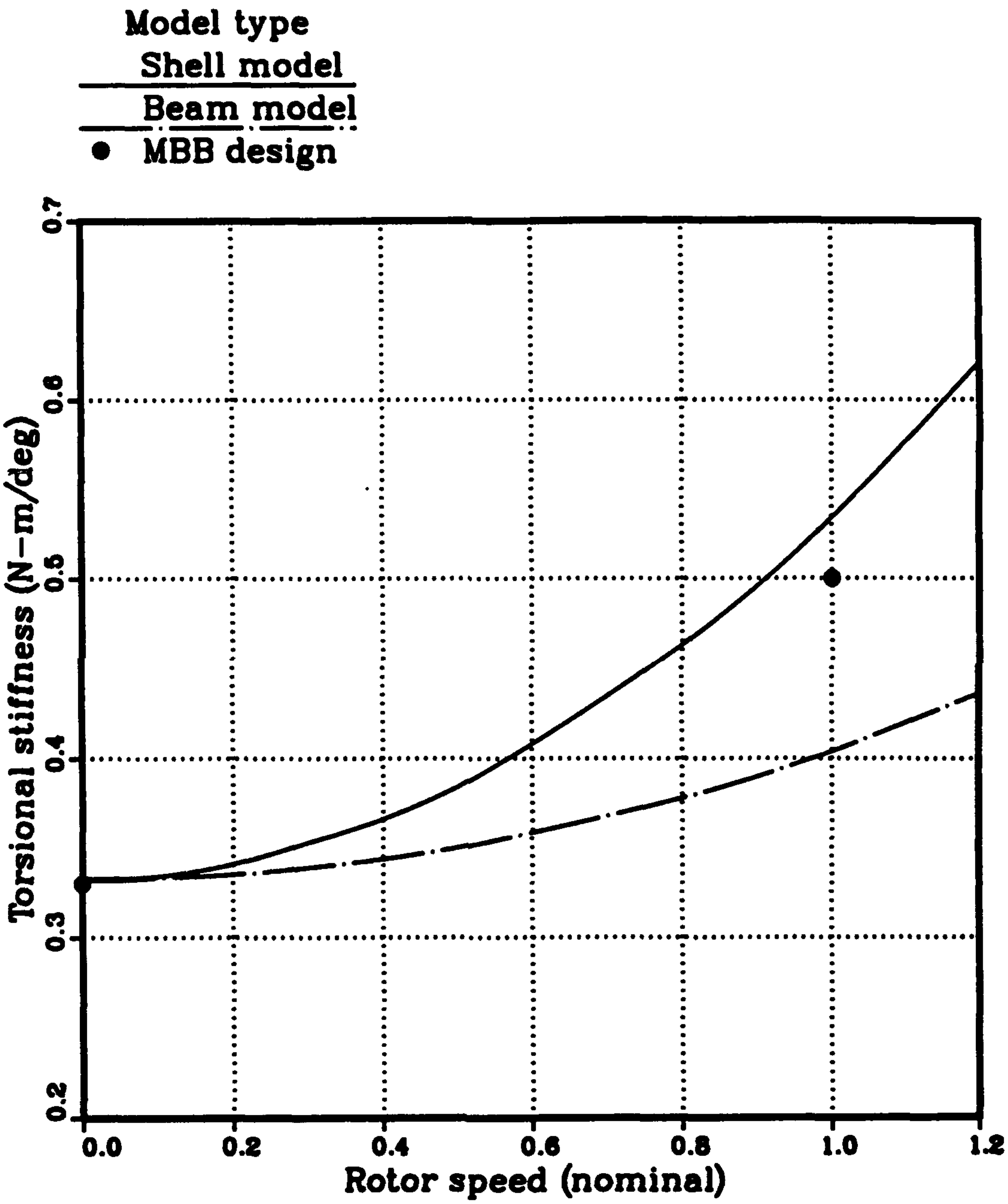


Fig. 21b Comparison of torsional stiffnesses of the MBB rotor blade by shell and beam models

5. <u>Formulation of Advanced Transient Aerodynamic Models for Rotors</u>
(ARO Fellow B. Webster, Faculty Supervisors O. Bauchau, M. Shephard, Z. Rusak)

Existing methods applicable to the aerodynamics ultimately to be included in maneuver analyses were reviewed and categorized early in the contract period, as to being:

(a) linear, 2-D, sinusoidal, velocity potential methods (Theodorsen, Greenberg, Loewy);
(b) linear, 2-D, finite state, velocity potential methods (Edwards, Freidmann);
(c) linear, 2-D, indicial response, velocity potential methods (Wagner, Küssner, Sears, Lomax et al, Beddoes and Leishman);
(d) linear, 3-D, steady, acceleration potential methods (Kinner, Mangler, Joglekar and Loewy);
(e) nonlinear, 3-D, sinusoidal, acceleration potential methods (Van Holten, Pierce);
(f) nonlinear, 3-D, sinusoidal, velocity potential methods (Rosen & Rand); and
(g) linear, 3-D, finite state, empirical methods (Peters).

The following conclusions were drawn, based on this review:

(1) all existing analytical aerodynamic operators neglected effects important in maneuvers (Leischman's method, being incorporated into 2GCHAS, would be available and Van Holten's acceleration potential, lifting line method could be extended. These two seemed most suitable.)

(2) a space/time finite element approach promised to overcome difficulties encountered in applying finite difference techniques in which computational meshes had to be unstructured and geometries were complex, and should allow all important effects to be accounted for.

Two approaches to advancing aerodynamics methodologies for maneuver analyses were undertaken: (a) fundamental extension of CFD techniques and (b) formulating a wake-accountable model for direct incorporation into structural dynamic response modeling.

In the first, a worthwhile research goal in the CFD area appeared to be to capture rotor unsteady aerodynamic phenomenon more accurately, by using a model based on the compressible Euler/Navier Stokes equations and numerical approximation solution techniques. Further, adaptive finite element methods seemed a potentially superior numerical approximation solution technique for unsteady rotor aerodynamics, compared to conventional finite difference methods, since:

- they handle complex geometries more easily
- they accommodate unstructured meshes
- they are suitable for incorporation into an adaptive analysis framework
- they possess unique stability features

During this formative period, a detailed review of the formulation of the finite element method was conducted, and Drs. F. Caradonna, J. McCroskey, and R. Strawn of the U.S. Army Aviation Systems Command Aeroflightdynamics Directorate (Ames Research Center) were contacted. Drs. T.J.R. Hughes, of Stanford University; and J.T. Oden, of the University of Texas at Austin were also consulted, and as a result, the method of Ref. 35 selected to be the basis for future unsteady rotor aerodynamics calculations. In addition, the application of a mixed Galerkin/least-squares FEM formulation to these rotor CFD calculations, using entropy variables developed by Prof. T.J.R. Hughes was investigated. This formulation automatically satisfies the Clausius-Duhem inequality (entropy production property), is consistent with respect to the variational equations, and is stable (satisfied Babuska-Brezzi conditions) both for high and equal order interpolants.

A "university" version of the Ref. 35 program was obtained from Stanford University, with the help of RPI's Scientific Computation Research Center (SCOREC), near the end of CY 1990, and test cases successfully run. RPI mesh generation programs were also sent to Stanford for their use, as part of a developing collaboration.

An interface between the ENSA2C code from Stanford and the Finite Quadtree mesh generator developed at Rensselaer was constructed so as to allow the automatic generation of graded, unstructured meshes for arbitrary 2-D geometries. The initial adaptive analysis procedure employed an error indicator based on classic interpolation errors, with modifications proposed by Loehner. The initial results for the adaptive procedure demonstrated its effectiveness, so long as the initial mesh was fine enough in the region of the airfoil. If the initial mesh was too coarse at the airfoil, the simple error indicator could miss weak shocks.

As part of efforts to develop adaptive procedures, the work of C. Johnson in formulating a posteriori error estimator was carefully investigated. Consideration was also given to incorporating moving airfoils into the domain. Since multi-body problems could involve individual bodies not necessarily undergoing the same motion, Eulerian reference frames were not considered exclusively; rather use of a combination of Lagrangian and Eulerian reference frames was studied. This appeared to call for use of an ALE (Arbitrary Lagrangian Eulerian) method. Applying this approach to compressible flow problems was seen as difficult, due to the time dependency of time derivatives in domain integrals. Initial efforts concentrated on the formulation of a streamline diffusion finite element method, following the techniques of Johnson and Hughes.

By the end of CY 1991, an adaptive finite element methodology for 2-D steady compressible rotor aerodynamic calculations was finalized. This adaptive methodology consisted of three components coupled together; namely, the Finite Quadtree mesh generator, the ENSA finite element program, and an error indicator based on interpolation theory.

To validate this methodology, the flow around a NACA 0012 rotor blade cross section was calculated at $M = .8$ and $\alpha = 1.25°$ and compared to existing AGARD results [36]. This case was particularly difficult to predict accurately, due to the presence of a weak shock on the lower surface. Beyond showing excellent correlation of values of C_L, C_D, and C_M, as given in the AGARD results, the ENSA finite element results indicated that the adaptive process actually reduced the total number of computational mesh points. This example showed how computational mesh changes during the adaptive process helped capture the high gradient flow features near the leading edge, trailing edge, and shock regions accurately. Comparisons of predicted local Mach numbers along the upper and lower surfaces of the airfoil section and those obtained using the ENSA finite element method made it evident that the adaptive process predicted the shock regions on both the upper and lower surfaces, and the stagnation point near the leading edge more accurately. They illustrated, further, that this improvement in solution quality occurs not only along the surface of the blade cross section, but also in the entire near field flow region.

These studies, however, also showed that to obtain such high quality results from the adaptive process, issues relating to boundary conditions (eg far field imperturbability, non-penetration, and trailing edge flow continuity) and to error indication (eg what flow variables should be assessed, etc.) had to be addressed.

Efforts then directed to determining what must be done to modify the ENSA finite element program to allow a rotor blade cross section to move arbitrarily within the fixed computational domain, determined that, in using space-time finite elements, there is no need to modify the basic equations which govern flow. That is, the Euler Equations need not be modified, as they must be in ALE methods; all effects due to mesh motion are handled naturally by the coordinate transformations relating each space-time element's isoparametric coordinates and the fixed physical space-time coordinates. This ability to handle multiple relative motion between different elastically deforming bodies was seen as important to future efforts to simulate the flow field of a rotating flexible rotor and an elastic airframe in forward flight. To validate this effort, experimental results [37] for a NACA 0012 blade cross section oscillating in a flow at M = .6, reduced frequency k = 0.1616, and angle of attack = 2.89° + 2.41° sin (k τ), and also at M = .755, reduced frequency k = 0.1628 and angle of attack 0.016° + 2.51° sin (k τ) were compared to results produced with the space-time element. Here $k \triangleq \frac{c\omega}{U}$ and τ is non-dimensional time, ie $\tau = \frac{Ut}{c}$. Good agreement was achieved for these difficult unsteady transonic rotor flow cases [38, 39, 40]. Both the temporal appearance/disappearance of the shock and the position of the shock region on the upper surface during the first half of the oscillation were predicted. The strength of the shock was also well predicted.

Before the end of CY 1991 a link to the Cray YMP at NASA Ames was established and the larger analyses in this project were run on that machine. By this means a two order of magnitude reduction in CPU time required was achieved.

During the final six months of the contract, an adaptive mesh enrichment procedure was developed and incorporated into the ENSA finite element flow solver. This procedure allowed the computational mesh to refine/derefine throughout the cycle of motion of a rotor airfoil, to efficiently capture the widely varying flow field scales, as they evolve temporally. It is based on single level refinement procedures which are edge-based and independent of mesh enrichment history. The shapes of the elements are controlled by edge swapping and Laplacian mesh smoothing. The oscillating airfoil case described above was repeated using the adaptive mesh enrichment capability. Near field mesh changes with time were demonstrated, as well as the periodicity of the intensity of the shed wake, and good agreement with experimental data for coefficient of pressure was obtained.

At the close of the contract period, the promise of these CFD studies seemed sufficient to justify continuation of the research under other auspices.

As regards adapting wake-accountable aerodynamics to structural response analyses, numerical difficulties were encountered in early attempts to improve aerodynamic models in structural dynamic response formulations using classical lifting line theory. Lifting surface theories based on an acceleration rather than velocity potentials, therefore, emerged as particularly appropriate for application to the helicopter rotor aerodynamics representation, for two reasons. First, singularities exist only on the blade surface in this formulation i.e., there is no wake geometry (velocity potential singularity) to keep track of. Second, the three-dimensional integration required over the wake in the velocity potential approach to determine induced velocities is replaced by a single integration of the pressure gradient along a particle path. To verify these advantages and gain confidence in these theoretical aspects, a steady, fixed-wing program was developed, for comparison with existing methods.

A similar approach had been used for rotors by Joglekar and Loewy and extended to the unsteady case by Peters and his co-workers. The intent in this project was to extend this methodology to a maneuvering helicopter.

The relative position and orientation of the rotor at all times with respect to the present position and orientation of the rotor are known, since the maneuver path is computed step by step. The linearized path of a particle of air that reaches a point on a rotor blade at any time is also known in terms of the governing equations of the fluid; ie in terms of induced velocities. However, at each instant, the pressure field is computed in a different coordinate system based on the rotor position, orientation and lift distribution at that instant. As a result, the computation of the inflow requires the knowledge of the kinematics of the maneuver (i.e. position and orientation of the rotor disk), and pressure harmonics history.

Implementation of this procedure was begun in early 1992, within the nonlinear dynamic multibody finite element code. That is, DYMORE was expanded to incorporate a lift computation based on simple two dimensional airfoil theory, with a table look-up procedure to obtain nonlinear lift, drag, and moment coefficients. This would depend on a calculation of either a linear rotor induced flow distribution using momentum theory [41], or a generalized dynamic induced flow distribution, based on the theory developed by Peters and He [42,43]. This entailed the development of a structural-aerodynamics interface and the selection of a proper scheme to calculate the generalized dynamic inflow states.

It should be noted that both the linear and generalized dynamic induced flow calculations present a first order approach to the induced flow problem associated with the maneuvering helicopter. Both approaches have associated limitations; the linear inflow theory in that it is a very approximate, static theory with substantial inaccuracies by its very nature, and the generalized inflow theory in that it is based on some linearizing assumptions which require the free stream velocity to have a constant orientation with respect to the rotor disk.

Implementing of structural dynamic-aerodynamic interface schemes encounters the difficulty that the points along the span of the rotor blade where the airloads need to be calculated, from a structural analysis point of view, are not necessarily the ideal points to calculate these loads, from an aerodynamics point of view. For instance, airloads are needed at the Gauss-Legendre integration points of the beam elements with which the rotor blade is modeled, in the case of the DYMORE program. Typically one would have fewer elements and thus fewer integration points near the tip of the blade, where the strain and the spanwise derivative of stain are generally smaller. In this region, however, the airloads typically change most dramatically, which calls for a large number of points for airload calculation, in order to capture the true nature of the airloads. To solve this dilemma, the concept of the aerodynamic reference line was introduced.

An aerodynamic reference line, a straight, almost radial line, is associated with each rotor blade. Since DYMORE allows blades to be curved, this reference line is placed in such a position and orientation as to best represent the blade in an average sense. Along this reference line, a number of "airstations" are placed at the mid-chord points of all the blade cross-sections. Since these "airstations" do not necessarily lie on a straight line, it is clear that they do not necessarily lie on top of the aerodynamic reference line.

The motion of the airfoil at the airstations is calculated from the kinematics of the blade's structural reference line, taking into account the positions of the airstations relative to the structural reference line. Assuming the induced flow is known, the airloads at the airstations can then be calculated. These loads may then be transformed to points on the aerodynamic reference line coincident with projections of the respective airstations onto the aerodynamic reference line. Cubic splining can then be used to calculate the airloads at points on the aerodynamic reference line coincident with projections of the respective structural Gauss-Legendre points onto the aerodynamic reference line. Since these structural Gauss-Legendre points actually lie on the structural reference line, the airloads are then finally transformed from the projected points on the aerodynamic reference line to the actual Gauss-Legendre points on the structural reference line. The structural response calculation can then proceed, and, at the next time step, feeds back into the kinematics of the airstation, as mentioned above.

Whereas airloads can be calculated when the induced flow is known, the generalized dynamic induced flow calculation requires knowledge of the circulatory lift on the blade. It has been found that using the circulatory lift of the previous time step renders a stable calculation scheme, provided that the time steps are small enough. This, in essence, establishes a second feedback loop in the airload calculation, the first being the calculation of airstation kinematics based on the structural response mentioned above. In the case of the induced flow calculation based on momentum theory, airload calculations are possible "outside the loop", in the sense that only the blade kinematics need be used to calculate the induced flow at an airstation at any point in time.

To calculate forcing functions for the generalized inflow state equations, it was found necessary to integrate the product of the non-dimensionalized circulatory lift with modified Legendre functions over the rotor radius. Various numerical integration schemes were considered for calculating these integrals. Using the orthogonality characteristics of the Legendre functions and the fact that the induced flow can also be expressed in terms of these functions, it was also possible to approximate these integrals with a least squares formulation, without actually performing numerical integration. Both this least squares approximation and Gauss-Legendre quadrature were implemented, but in the end the Gauss-Legendre quadrature was the only method that was retained, because of problems with the least squares approach in satisfactorily treating the blade root cut-out and a non-radial aerodynamic reference line. Further, this scheme showed no superiority to Gauss-Legendre quadrature in other respects.

The time averaged induced flow distributions calculated using DYMORE are compared, in Figs. 22 through 25, with results presented in Ref. 43, for four radial lines on the rotor disk at 0°, 90°, 180° and 270° azimuthal positions, for the rotor model wind tunnel tested by NASA [44]. It should be noted that two sets of results were presented in Ref. [43] for this case. One set was corrected to account for the induced flow caused by the fuselage; a second was not. The DYMORE results were not corrected for fuselage interference and should, therefore, be compared to the "without fuselage" results from Ref. [43]. At 90° and 270° positions, however, the uncorrected and corrected data of Ref. [43] are indiscernible from one another, so that only the corrected data has been plotted in Figs. 23 and 25.

It is evident from these results that the generalized dynamic induced flow calculation was successfully implemented in the DYMORE code. Small differences between the DYMORE data and the data from Ref. 43 can be ascribed to the fact that an updated and slightly different correction for non-linear effects, supplied by the authors of Ref. 42 and 43, was implemented in DYMORE, compared to that which was actually used in obtaining the Ref. 43 results.

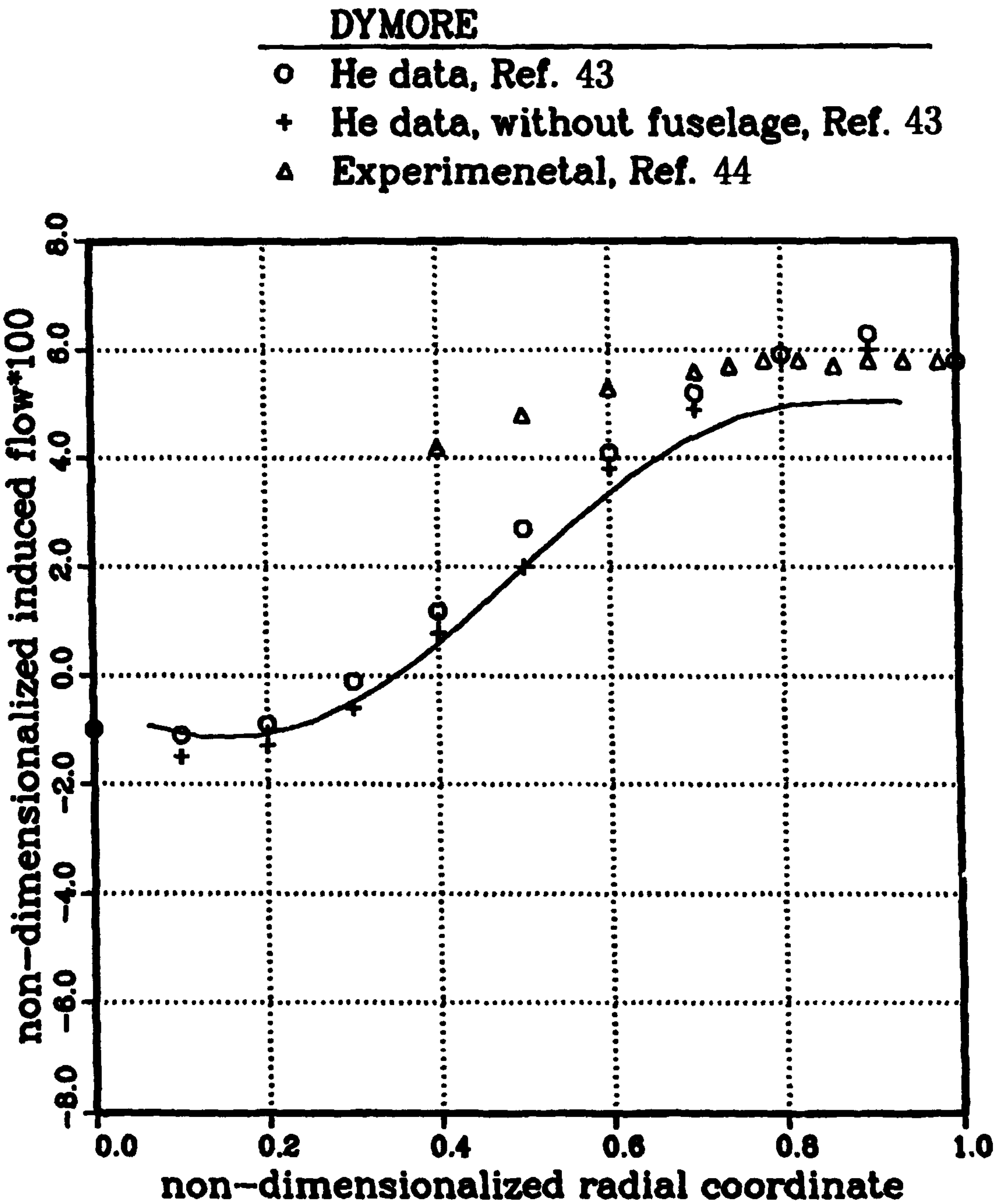


Fig. 22 **Time averaged induced flow distribution along radial line at 0 degrees azimuthal position**

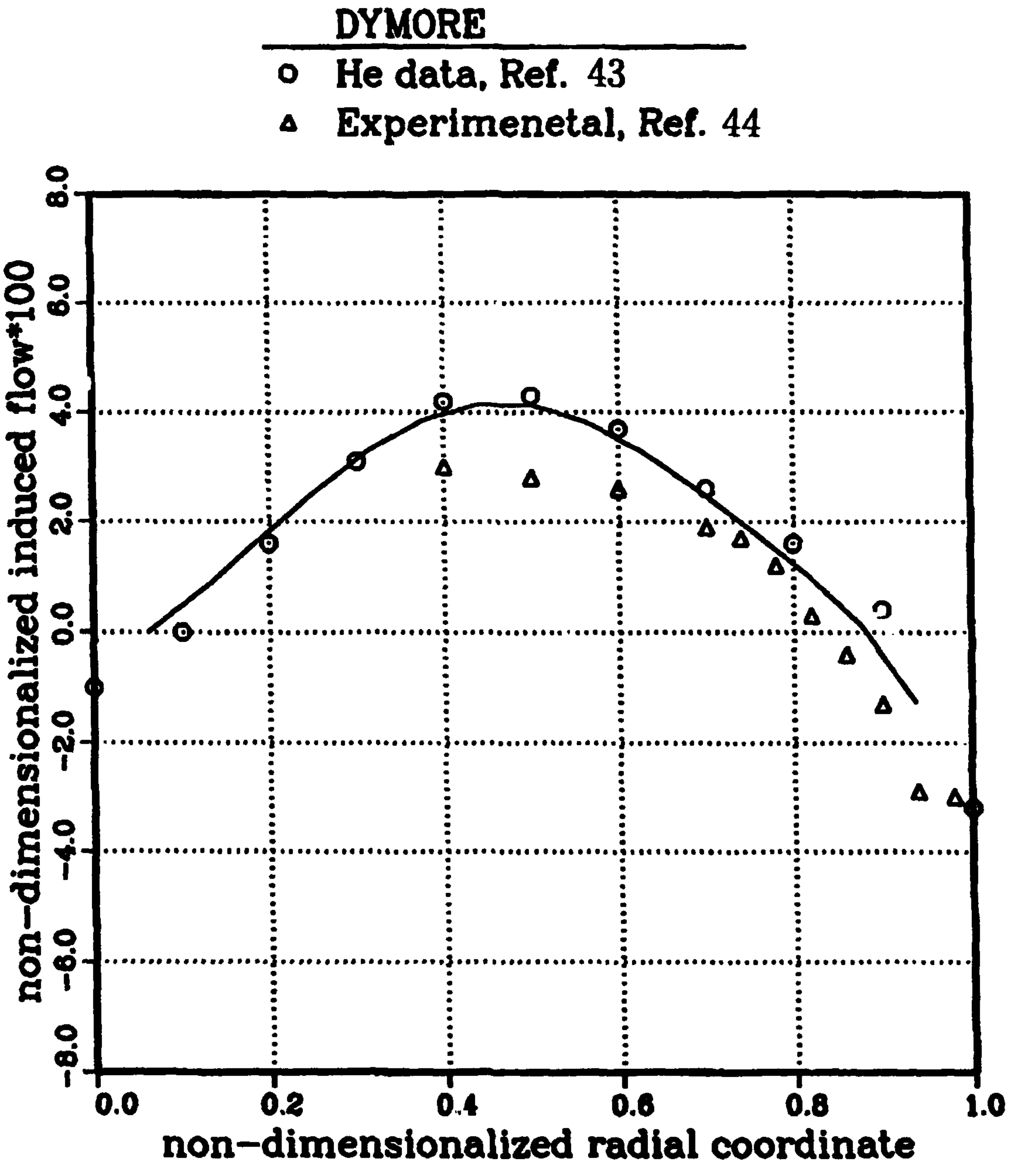


Fig. 23 Time averaged induced flow distribution along radial line at 90 degrees azimuthal position

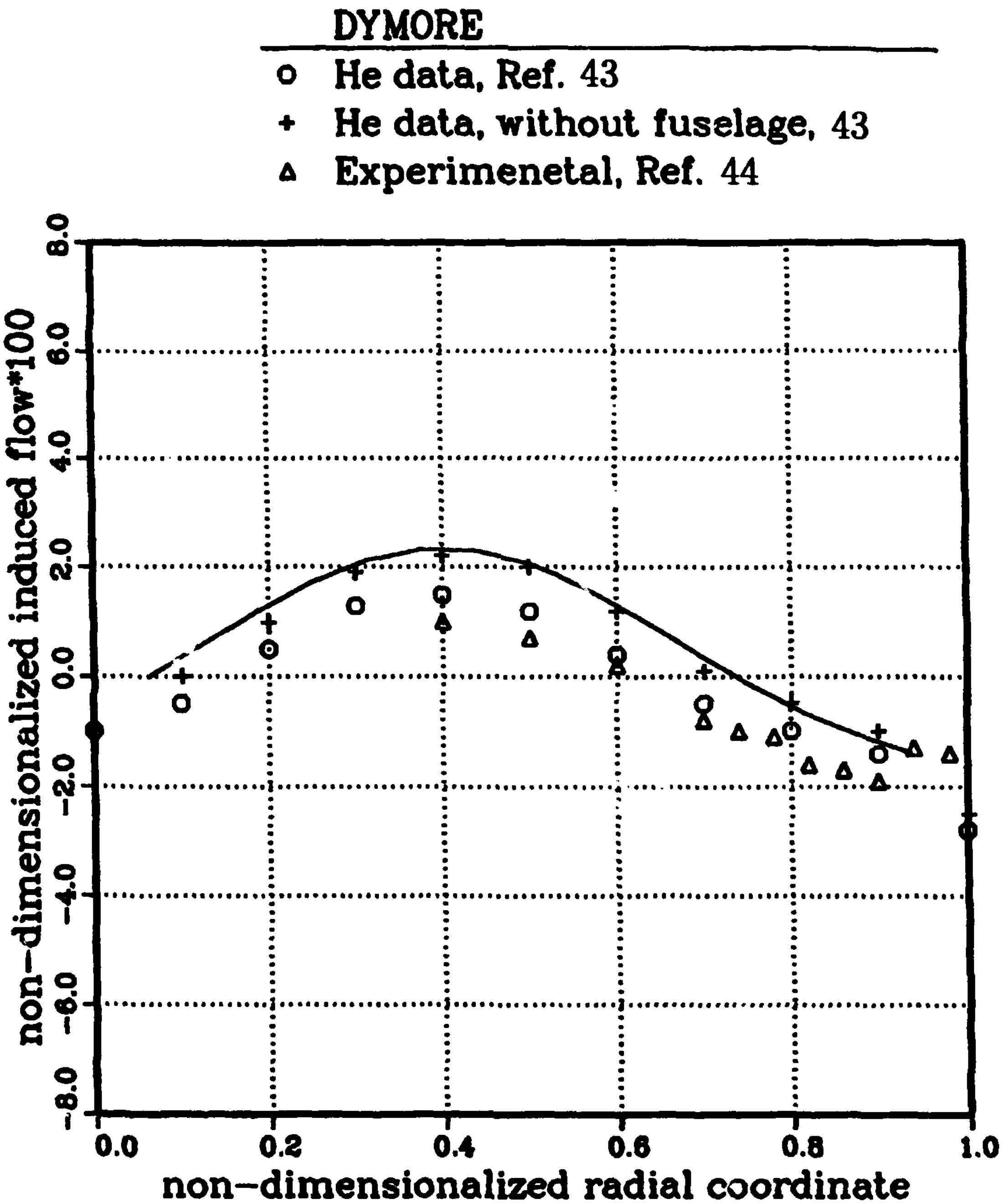


Fig. 24 **Time averaged induced flow distribution along radial line at 180 degrees azimuthal position**

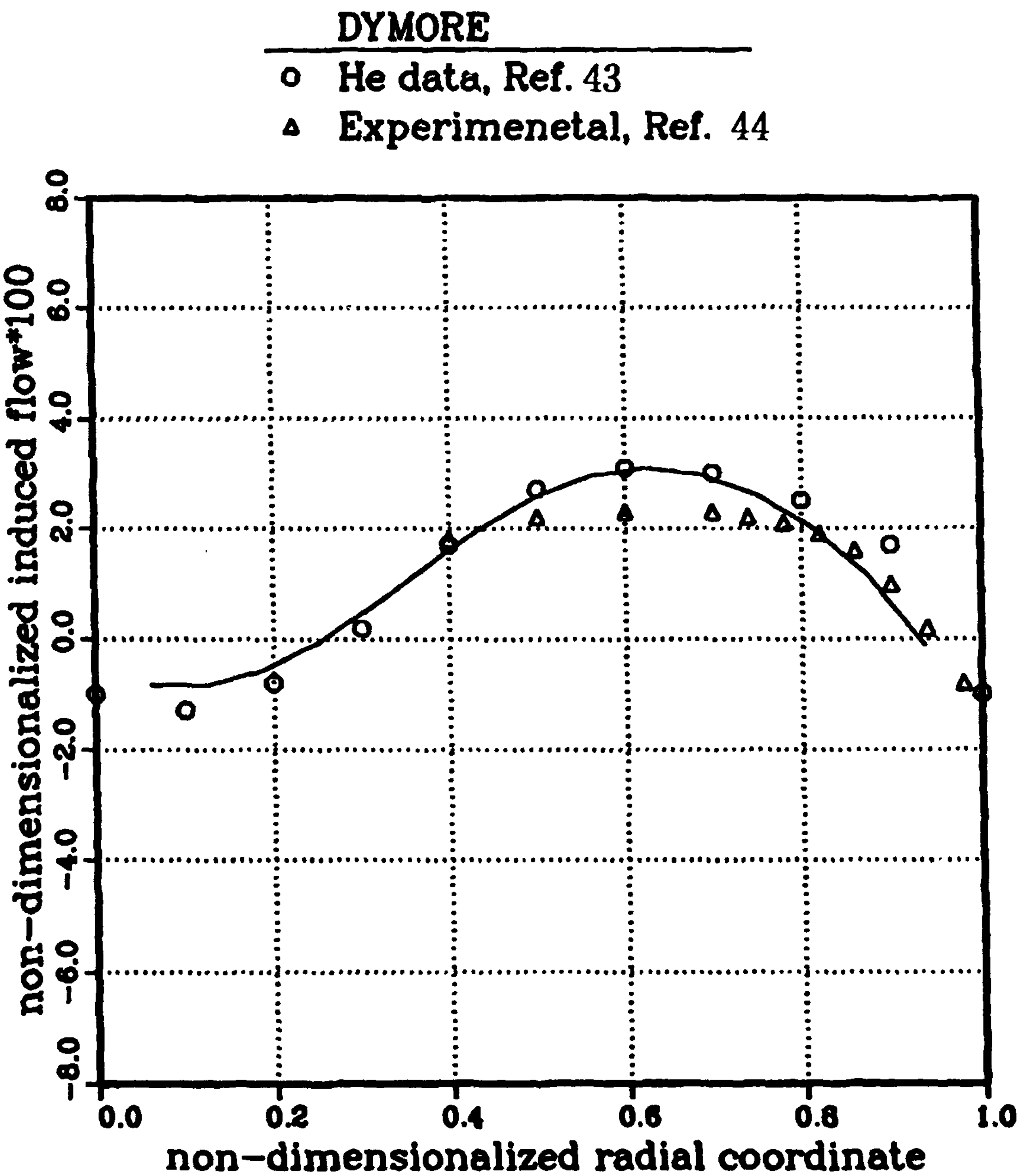


Fig. 25 **Time averaged induced flow distribution along radial line at 270 degrees azimuthal position**

6. Theoretical Studies of Blade Aeroelastic Response and Stability (Sr. Invest'r. M.R.M. Crespo da Silva)

The equations of motion of a rigid rotor blade connected to the hub of a helicopter that is in a maneuvering flight condition were formulated. Computerized symbolic manipulations, with MACSYMA, were used to assist in the formulation and to generate the associated Fortran code.

To test the computer programs developed, a steady state periodic solution for the case of forward flight was obtained by harmonic balancing, by numerical solution of a two-point boundary value problem, and by using a finite Fourier series technique. It was found that the last technique, where 8 harmonics were accounted for, was very accurate and numerically efficient. These comparisons also verified the fact that the method of harmonic balancing requires the use of a number of higher harmonics to obtain accurate values for even the first few harmonics in the response; a known drawback of the harmonic balancing method.

Trim conditions for a helicopter performing a steady turn were then examined, preliminary to subsequently analyzing the stability characteristics of the perturbed response. This investigation considered the effects of system parameters such as the g-number associated with steady turns and the radius of curvature of such turns, when the turn is in steady flight with constant speed tangent to the hub's trajectory, so as to result in a constant acceleration of the hub, and a set of linearized equations with periodic coefficients results.

The model consisted of a rigid blade with flap and lag hinge offset and a linear lead-lag spring of stiffness k_ζ and linear flap spring of stiffness k_β. The hub moved with constant speed along a horizontal circular trajectory of radius R_0, with bank angle ϕ and pitch angle θ. The position of the center of mass of the fuselage was eliminated as a parameter in this study, by disregarding the moment trim equations. The pitch angle θ was determined from tangential equilibrium, assuming a known fuselage drag coefficient, and the bank angle ϕ determined from radial equilibrium. The required thrust coefficient was then defined by the horizontal force components and aircraft weight.

This analysis assumed uniform induced flow as predicted by Glauert's hypothesis, quasi-steady strip theory aerodynamics and linearized motion velocities and angles. Viscous dampers were accounted for about both flap and lag hinges.

To isolate the effects of the postulated maneuver from other effects, stability boundaries were calculated for hover over a range of gross weights but assuming constant inflow; for two inflow ratios, maintaining gross weight in forward flight for a number of advance ratios and in high speed forward flight with two gross weights. The case of the uniform turn maneuver at 2 g's was compared with the forward flight case at the same advance ratio and gross weight and the effect on the stability boundary shown to be minor. The stability modes emerging from these analyses were coupled flap-lag; and the effect of isolated rotor loading (gross weight) was shown to be substantial; that due to isolated inflow less so and only as regards the lag natural frequency position of the stability boundary; and the effect of advance ratio, also, to be substantial.

Another case representing a deceleration maneuver was calculated, using a quasi-static approach, in which fuselage drag was the only decelerating force and rotor propulsive and side force were required to be zero. Stability boundaries for successively lower advance ratios were calculated and it appeared that, as the advance ratio was reduced, the unstable regions reduced.

It is noteworthy that most of the complex expressions in the fortran program developed to analyze the response of a helicopter blade in a maneuver were generated directly with MACSYMA. The MACSYMA programs developed the differential equations of motion from Lagrange's equations, and all the steps necessary for the numerical iterations and for the generation of the matrices that were used in the stability analysis. The fortran programs and subroutines computed the many steps that finally lead to an automatic plot of the stability boundaries for the blade when the flight conditions are specified. Stability charts in flap-lag frequency parameter space were generated and plotted using the DISSPLA numerical package. Details of the research described above appear in Ref. 45.

The approximations frequently used for analyzing the dynamic response and stability of flexible rotor blades include expanding the equations about the undeformed state of the blade, which is not an equilibrium state and - also - retaining only quadratic nonlinearities. Both assumptions can introduce serious errors in the results, especially those related to the blade's torsional motion. In this project, therefore, an in-depth investigation of the aeroelastic response and stability of rotor blades in forward flight was conducted. Special care was devoted to the determination of the trimmed periodic solution for the case of a blade in forward flight. Analyses were based on the full nonlinear differential equations of motion. Periodic solutions to the full nonlinear equations were obtained by a combination of numerical methods and the method of harmonic balance. The time dependency of the periodic solution was written in the form of a Fourier series which, when substituted into the original full nonlinear differential equations, transformed the partial differential into a set of ordinary differential equations. This set was then solved numerically with a 2-point boundary value problem solver. Hence, the coefficients of each harmonic of the periodic solution retained the influence of nonlinearities, without relying on the kind of approximations mentioned above. The trim condition, which requires that the average (per revolution) forces and moments of the rotor blade balance the forces and moments produced by other parts of the helicopter was imposed on the periodic solution throughout the iteration procedure.

The trimmed periodic solution for a soft-inplane case was obtained for several values of weight coefficients, Lock number and torsional frequency for the parametric study using linear and uniform inflow models by including two harmonics. It was found that the first harmonic component of lead-lag solution, as well as cyclic pitch, can be much different depending on the inflow model. It was also found that the weight coefficients significantly affect the trim solution and the first harmonic components of lead-lag. However, while the effect of Lock number on the trim solution is negligible, its effect on the lead-lag and torsional response is not. As the uncoupled rotating torsional frequency is increased, the magnitude of the torsional response decreases rapidly and the response resembles that of a rotor blade with high torsional frequency.

The stability of the motion about the trimmed solution which is the objective of this research was investigated by linearizing the full nonlinear partial differential equations about the trimmed periodic solution, obtained as indicated above. The stability of these infinitesimally small perturbed motions about the trimmed periodic solution of the full nonlinear partial differential equations of a rotating helicopter rotor blade in level, steady flight was studied using a modal reduction technique and Floquet theory, with substantial use of symbolic computation to manipulate the equations. In earlier published work on the dynamics of a hingeless rotor blade in hover or forward flight [46-49], Galerkin's method or the Rayleigh-Ritz method was applied to the nonlinear partial differential equation of motion obtained by expansion of the nonlinearities about the undeformed state of the blade, which is not an equilibrium state. In the present work, the modal reduction procedure was applied to the perturbation equations linearized about the actual particular solution of the nonlinear equations. These are either equilibrium, for the case of hover, or the steady state trim solution for the case of forward flight. For this, actual eigenfunctions for hover which were determined numerically, were used in the modal reduction procedure, instead of non-rotating beam modes.

The perturbed motions for the flap, lead-lag and torsional degrees of freedom about the periodic solution were represented by a modal expansion with the indicated modal basis. Then, the Taylor series expansions of the kinetic and strain energies about the periodic solution were obtained up to $0(\epsilon^2)$. Also, the generalized forces were linearized about the particular solution for the problem, which is a periodic solution for the forward flight regime. The expanded kinetic and strain energies, along with linearized generalized forces, yielded linearized ordinary differential equations for the perturbed motion, with periodic coefficients. Since the kinetic and strain energies, and the generalized forces were expanded in Taylor series, their expressions involved periodic terms which varied in time. Therefore, applying floquet theory for the stability analysis required an integration of the coefficients of the generalized coordinates in the energy expression as time varies. To avoid this numerical inefficiency, Fourier series representations of the coefficients of the generalized coordinates were used in the energy expression. A fourier series representation based on 11 values of the azimuth angle turned out to be very accurate for determining stability.

In a modal reduction technique, the choice of modal base is critical to obtaining accurate results. In the subject analysis, the eigenmodes for hover were used. These were obtained using a transition matrix method [Ref. 50]. Since the problem of a rotating blade subject to aerodynamic loads is non self-adjoint, the eigenmodes for the hover flight condition are complex and non-orthogonal. However, it was found that the phase difference of the complex eigenmodes along the beam was not significant, so that the use of real approximate eigenmodes turned out to be a good alternative. The approximate real modes were obtained by neglecting damping terms and off-diagonal terms of the matrix associated with the $\underline{\dot{x}}$ term in the matrix representation of the equation of motion. The approximate real modes were orthogonalized using a Gram-Schmidt orthogonalization scheme. The results for hover showed convergence using only two modes; additional modes resulted in only minor improvement. This rapid convergence is believed to be associated with use of the actual eigenfunctions for the hover flight condition. The eigenvalues obtained were also compared with those obtained by the transition matrix method. The eigenvalues, especially the real parts obtained from the two different approaches, were in close agreement for a wide range of values of collective pitch.

The stability analysis was conducted using two modes with the trimmed periodic solution mentioned above. The real parts of the flap, lead-lag and torsional characteristic exponents, which were obtained using linear and uniform inflow modes, are almost identical. The effects of the weight coefficient, Lock number and torsional flexibility on the stability of the rotor blade motion were examined. The results showed that the larger values of weight coefficient and Lock number, as well as the lower values of torsional frequency, stabilize the rotor blade motion. Details of this research are given in Ref. 51.

F. Rotorcraft Optimization Studies
(Sr. Invest'rs. O. Bauchau & P. Hajela)

Formal mathematical approaches for optimizing helicopter rotor designs are being increasingly used by the rotorcraft industry. The research reported here consists of several related efforts which are expected to advance the state of this particular aspect of rotorcraft design and, in the process, investigate innovative approaches to reducing helicopter vibrations.

1. Optimization of Helicopter Blade Vibrations Using Finite Elements in Time
(Sr. Invest'r. O. Bauchau)

Reducing the oscillatory hub forces and moments which are the primary cause of helicopter vibrations is a frequent objective. The aim of the present research is to investigate the effect of simultaneous application of suppressive force and structural optimizations in design studies of a helicopter blade, to determine whether some level of synergy could be achieved. In other words, to determine whether the improvements obtained with both approaches applied simultaneously are more significant than when used separately. To simplify the analysis, a two-dimensional, non-rotating blade, clamped at its root and subjected to a known, unchangeable periodic loading was used initially as a model. The response of the structure was calculated using finite elements in time.

The exploratory optimization process first attempted to minimize the vertical shear force, T(t), and flapping (ie out-of-plane) moment, M(t), at the root of and normal to the radial axis of the beam. The objective function was defined as the integral, over the period, of the sum of the squared moment and the square of the product of the shear force multiplied by blade length. This device kept the dimensional units of each component of the objective function the same. The objective function thus appeared as:

$$F = \int_0^T [L^2T^2(t) + M^2(t)]dt$$

The initial objective function was noted F_o and the optimal F_{opt}. The optimization process started from the same initial design, in all cases, to insure that the same local optimum was reached. This initial design was defined by the following uniform properties:

Length (L):	3.25m
Mass/unit span:	3.292 kg/m
Moment of inertia/unit span:	5.910^{-3} kg.m
Bending stiffness:	$1.595\ 10^5$ N.m^2
Axial stiffness:	$8.9\ 10^7$ N
Shear stiffness:	$2.623\ 10^7$ N

The improvement in the objective function was defined as

$$\text{improvement} = \frac{F_o - F_{opt}}{F_o} \times 100\%$$

"Optimal control", ie the most beneficial vibratory suppression force, was pictured as provided through a single oscillating vertical actuator, whose location on the beam and force time history were to be optimized. The optimization proceeded with the spanwise location of the actuator on the beam fixed initially, with the optimization variables being its force values at the eight time nodes which determined its vibratory force output. When the optimizer reached an optimal design, the corresponding improvement of the objective function was recorded. This process was repeated successively with the actuator placed at each one of the ten nodes of the beam. The resulting improvements were used to identify the spanwise location which was "optimal". Practicality demands that an actuator stay within a reasonable distance of the hub; thus only those optimal locations constrained to be at or "inside" the 40% spanwise station on the beam were considered. On this basis, it appeared that the best improvement occurred when the actuator was placed at the 30% span station.

As an indicator of nonlinear geometric effects in this optimization, free vibration frequencies were calculated for both the undeformed beam and again for the beam deformed at the maximum amplitude in response to the applied oscillatory load, for both the initial and optimized cases. Natural frequency variations between linear and nonlinear cases, for the optimized configuration, varied from over 50% error for the first mode to zero for the fourth mode, with rather uniform error variations for the intermediate modes. The improvement in objective function for the optimized case was 45.68%.

For cases studying variations in structural characteristics, the minimization of the objective function was driven by 24 design variables: the bending stiffness, I, and the mass, m, at the 12 Gauss points along the beam. Obviously, there were large numerical differences in the magnitudes of the two sets of variables, the stiffness being approximately 10^5 times larger, numerically, than the mass.

Four cases were run in which only upper and lower bounds differed as "side constraints" on the design variables. The four cases were:

Case 2.1	$I \in [10^1, 10^{10}]$	$m \in [10^{-5}, 10^1]$
Case 2.2	$I \in [10^5, 2\ 10^5]$	$m \in [2, 5]$
Case 2.3	$I \in [1.4\ 10^5, 1.8\ 10^5]$	$m \in [3, 4]$
Case 2.4	$I \in [1.5\ 10^5, 1.7\ 10^5]$	$m \in [3, 3.5]$

The first case represented a free optimization with virtually no side constraints. The last case was tightly constrained for both sets of design variables. The results showed that case 2.1 achieved virtually zero for the objective function - at least in part - by setting bending stiffness to zero at the root, and that the constrained optimal solutions all involved the minimum permissible stiffness. Improvements in the objective function were such that if case 2.1 was defined as producing 100%, the following cases were decreasingly successful, with case 2.4 having only a 50% improvement.

In the investigation of the potential of simultaneous optimization, all of the features used earlier were brought to bear, optimizing the position of the actuator the same way it was for the optimal force suppressor case. The bounds used in Cases 2.2, 2.3, and 2.4 were applied here, too. To assess the benefits of the optimization using both force suppressor actuator and structural characteristics simultaneously, involved comparing power required and improvement values for the same, practically constrained cases. The improvement of the objective function using simultaneous optimization, with the same side constraints on the mass and stiffness properties as case 2.4, provided an improvement of 61.93%, with only 13.9 Watts required from the actuator. Since this compared with 45.68% and 50.42% for the two individually optimized cases, and power as high as 25.2 watts for the actuator, we concluded that simultaneous optimization had significant advantages, based on the simple model used in this research.

Following vibration optimization using an active mass, ie a "force suppressor", it seemed prudent to continue by examining improvements possible using a "passive" mass which, however, might be moved from one spanwise position to another, depending on the flight condition. Lumped masses and composite lay-up properties could be varied in these optimization attempts. Initial studies selected target natural frequencies randomly; and, again so as to preserve all initial design frequencies, except for placing the second flapping frequency between 2.86 Ω and 3.1 Ω. Both cases showed that the frequencies could be placed very well.

A k^{th} harmonic vibratory hub force or moment index was also chosen for minimization as described in Ref. 44; namely,

$$V_i = \frac{(\phi_s \quad . \quad . \quad . \quad \phi_M)\{\phi_i\}^T\{f_o\}}{\omega_I^2 - (k\Omega)^2}$$

Where $\{\phi_i\}^T\{f_o\}$ is the generalized forcing function in the i^{th} mode and the denominator the inverse of the undamped amplification factor, depending on the i^{th} natural and the forcing frequencies, ω_i and $k\Omega$, respectively. The remaining bracketed term in the numerator represents the hub modal shear or moment and determines the type of index calculated; e.g., hub horizontal shear, vertical shear, or out-of-plane moment. All the quantities in this vibration index were computed using a finite element code, so that arbitrarily complex configurations could be handled.

Four cases were studied involving three of the blade's lowest flapping modes and applied sinusoidal loads at 3, 4, and 5Ω. Three vibration indices, one for each applied loading component were considered for each mode, for a total of 9 possible objective function components. The complexity of the integrated objective function clearly gives rise to the possibility of numerous local minima. The optimization problem in this process was formulated as follows:

Minimize

$$OBJ = \sum_i V_i^2$$

subject to

$$h(x) = \text{total mass} = \text{constant}$$

$$\underline{x}_i \leq x_i \leq \overline{x}_i$$

Where

$\underline{x}_i$ and $\overline{x}_i$ are the lower, upper bounds of design variables respectively.

In the first of the four cases, the optimization process was started from a configuration with uniform cross sectional properties. Reauctions in all vibration indices of over 90 percent were achieved except for the 4Ω shear in the first flapping mode. The reduction of vibration indices for each mode was shown to result from trade-offs among modal hub force or moment resultants, generalized force, and amplification factor. For example, the vibration index for the first flapping mode decreased due to the reduction of generalized force, even though the modal hub shear for 4P shear index increased. It appeared that large reductions cannot be achieved for the first flapping mode; indices for second and third flapping mode, however, significantly lower than those in the initial design did result.

The distributions along the span of zero degree ply thickness and lumped masses which resulted showed that the optimizer redistributed the stiffness and mass properties so as to place more stiffness and mass at the tip of the beam.

In the second case, the optimization process was started from an initial design with spanwise nonuniformities introduced by lumped masses. Here again, over 90 percent reduction in the objective function was achieved, with indices for each mode in the optimization process again reduced to almost zero, except for the first flapping mode 4Ω shear index. It is important to note that the second flap frequency crossed the 3Ω line during this optimization process, despite the fact that the process was gradient-based. The optimal design obtained in this case involved a smaller decrease in objective function.

In the fourth and final case examined, the importance of the first flapping mode was investigated by rerunning the first (initially uniform properties) case without including first flap in the objective function. This mode has often been ignored in optimization studies [52,53]. The vibration indices for the second and third flapping modes could not be minimized as efficiently as previously. It thus appeared that, even though the vibration indices for the first flapping mode could not themselves be greatly reduced, the presence of the first flapping mode in the model allows important reductions in the second and third flapping mode indices. The presence of the first flapping mode may be felt mostly by preventing the optimized second flap mode from crossing the 3Ω line.

These studies lead to the conclusion that the existence of multiple local optimum solutions for the blade design problem which place natural frequencies in specific manners with respect to the $n\Omega$ lines can be dealt with by the proper procedure. Since large response to excitation occurs if a frequency is resonant, it is unlikely (though possible) that gradient-based optimization processes will drive the design across $n\Omega$ lines. Accordingly, the following optimization procedure appeared advisable. First, a frequency placement step should be used to place the frequencies in specific positions with respect to $n\Omega$ lines. Second, a vibration index minimization step should be applied to obtain a minimum vibration design, subjected to frequency constraints to prevent $n\Omega$ line crossings. Various optimum solutions may then be obtained by placing the frequencies in various relations to the n per/rev lines, and the best, or "global" optimum found.

These studies were continued by considering the potential of a semi-active device consisting of two masses whose spanwise positions are adjustable as a means of reducing vibrations in different flight conditions. The optimization process was repeated for four different aerodynamic loadings. The results show that an optimum configuration can be found within the allowable travel of each mass.

An articulated rotor blade (Ref. 52) was modeled using beam-type finite elements. The blade chosen is 8.5344 meters long with a 3.57% offset hinge and was modeled by 7 finite elements. The model contained both structural mass and adjustable masses. The adjustable masses (each was 6% of total mass of the original blade) was modeled by sliding joints, prismatic joints, and universal joints. The locations of the two masses were the design variables.

The four different aerodynamic loadings corresponded to flight conditions for 88, 99, 110, and 122 knots steady level flight. Nodal values consistent with the finite element model were computed from in-flight measured airloads [54] representing 3, 4, and 5 per-rev lifting airloads typical of a four-bladed articulated rotor system. These harmonics were chosen because they are the prime contributors to the airframe vibration created by a four-bladed rotor system.

The design goal was to find the optimum locations of adjustable masses to minimize the 4P vertical shear and 3P and 5P roll and pitch hub moments in the rotating system. The method formulated and solved an optimization problem in which the adjustable masses location design variables attempt to minimize the objective function, which was a combination of the vertical shear, roll, and pitch moments. The objective function was formulated using the Global Criterion Approach [55], and combines the harmonics since they occur simultaneously in a given flight condition, but not those which occur in different flight conditions. The entire self-adaptive rotor concept envisioned mass position adjustments made in flight, from one flight condition to another, so each flight condition was examined separately. In this approach, only the first three flapping modes were included, and the optimization was subject to constraints on the spanwise position of masses; ie ± 25% of span on either side of the 75% radius point.

The results showed a significant reduction in all vibration indices, comparing initial and optimum configurations, with the exception of the 3p moment at 110 knots. This clearly demonstrated that two adjustable masses with total mass equal to 12% of the rotor blade mass can drastically alter the response of helicopter blades, and when optimally located, can result in significant vibration reductions.

These positive results were tempered by knowledge that the initial configuration was selected rather arbitrarily; two lumped masses were placed at outboard locations on the blade, and the mass of the baseline design cut down so as to keep the total mass constant. As a result, the initial configuration was a rather poor design to start with. Nevertheless, even with this very crude approach, vibration reduction was obtained in most flight conditions when comparing the baseline and optimum designs, and these results suggested a strategy to take full advantage of adjustable masses. First, optimization techniques should be used to find the optimum mass and stiffness distribution of a blade for minimum vibration at a specified "normal" flight and loading condition. Then, adjustable masses should be used to minimize vibration levels at all other flight and loading conditions. Although not investigated specifically, it appeared that the positions of adjustable masses could be varied differentially among blades in a particular rotor, as a fine "tracking and balance" adjustment to minimize 1p vibrations.

Because of the encouraging results obtained with two independently positionable concentrated masses, the potential of a semi-active vibration reduction device consisting of one adjustable mass was investigated. The aeroelastic evaluative analyses were performed using four different aerodynamic models: linear inflow with/without ONERA dynamic stall and dynamic inflow with/without dynamic stall, for three different flight conditions. The articulated rotor blade model used in these studies was the same variation on the Ref. 46 blade described above. One adjustable mass, representing 12% of total blade mass, was placed at various locations between 0.23R and 1R. The three flight conditions were steady, level forward flight at 23, 88, and 104 knots. The results showed that no single mass location provided vibratory load reduction throughout the whole flight envelope investigated, thereby establishing the importance of the semi-active radial positioning feature.

Figs. 26-28 show the peak-to-peak values of the sum of the blade root vertical shears occurring in 3p, 4p, and 5p harmonics for 23, 88 and 104 knots forward flight velocity, respectively. As can be seen, the locations of the mass which provide minimum vertical shear differ among the four different aerodynamic models and among the various flight conditions. Figs. 29-31 show the double amplitude values of only the 4p fixed hub vertical shear for these same three airspeeds. Again, minimum values of vertical shear are obtained with the semi-active mass at very different radial locations.

For comparison, these same results were plotted in Figs. 32-39 with the various flight conditions on one figure. Figs. 32 to 35 show the sum of the blade vertical shears in the 3p, 4p and 5p harmonics, with the various aerodynamic models separated among the figures. Figs. 36 to 39 show the 4p hub vertical shear alone for the various aerodynamic models. Figs. 40 & 41 show the 4p rolling and pitching moments in the non-rotating system for three flight conditions. It can be seem that, again, various radial locations of the adjustable mass are necessary to obtain the minimum loads.

In summary, these blade optimization studies show that proper placement of blade non-structural mass can reduce fixed-system vibratory loads, but that the position of the mass and the load reductions realized are dependent both on flight condition, and - in the absence of feed-back control of the mass position - on an accurate estimate of the aerodynamic forces. Based on this study, therefore, a semi-active control system for optimum placement of an adjustable mass seems to be a desirable flight vibration reduction option.

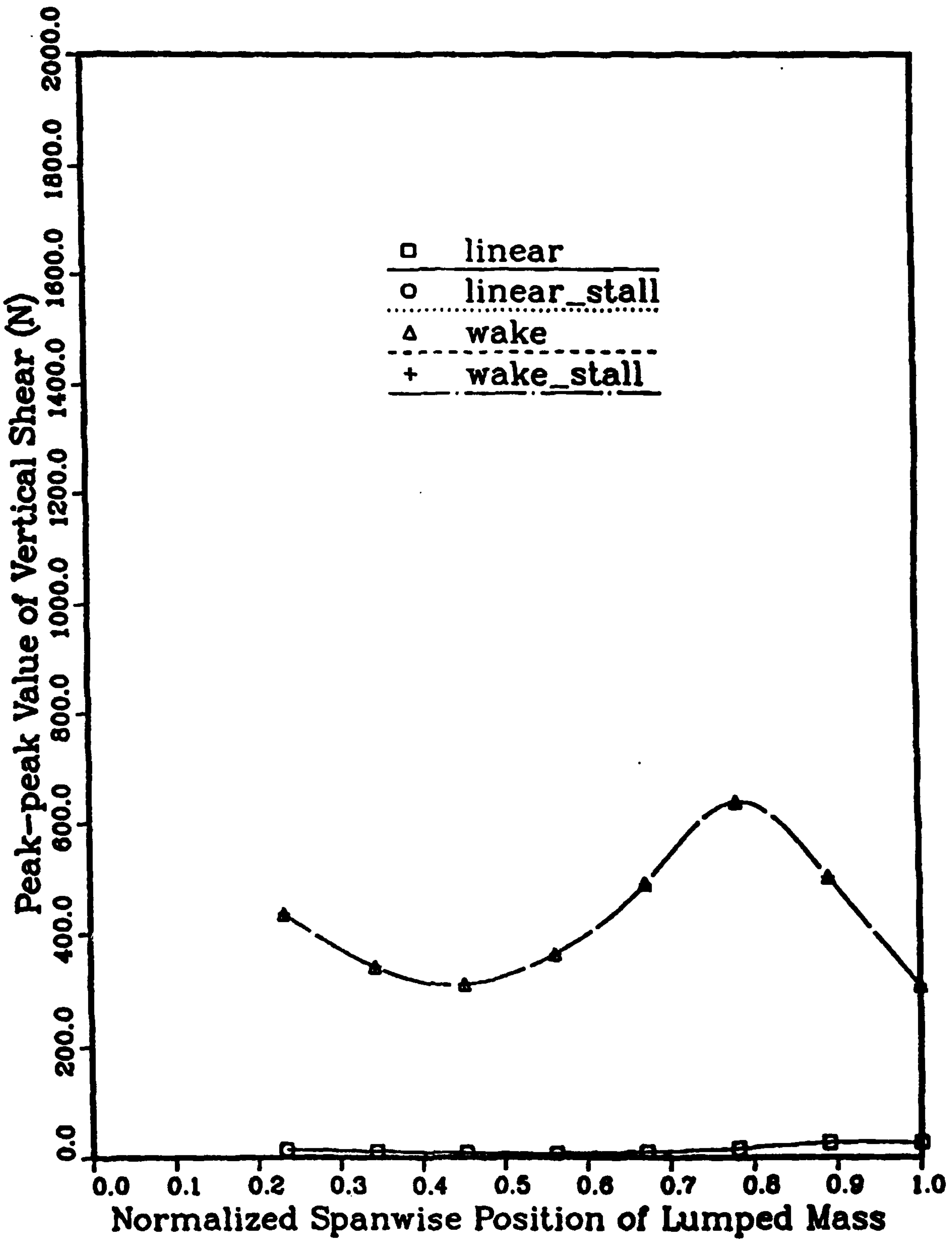


Fig. 26 Peak-peak Value of Vertical Shear (3,4, and 5p) with one 12 percent, adjustable lumped mass (at v = 23 knots)

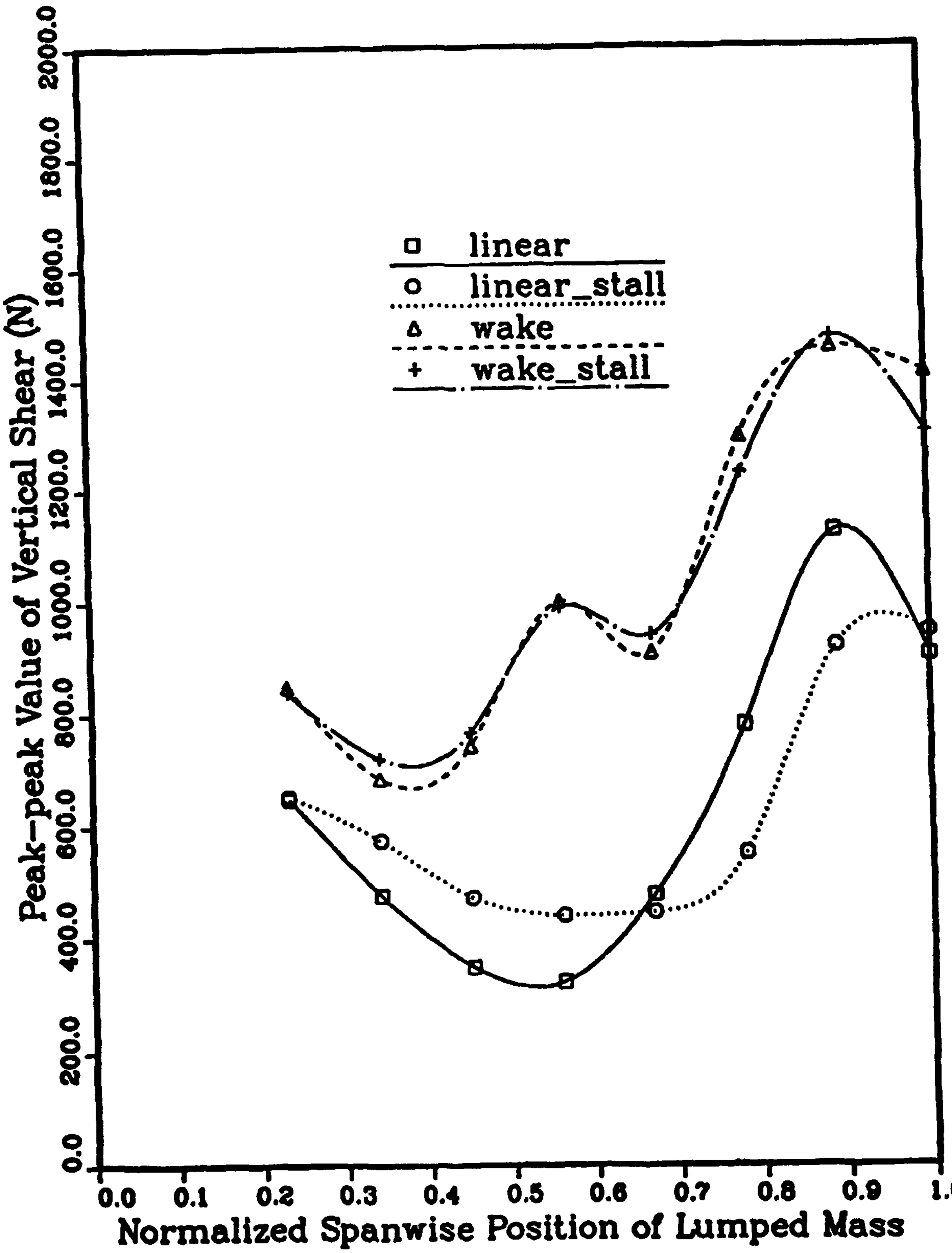


Fig. 27 Peak-peak Value of Vertical Shear (3,4, and 5p) with one 12 percent, adjustable lumped mass (airstations are chosen at Gauss points) (at v = 88 knots)

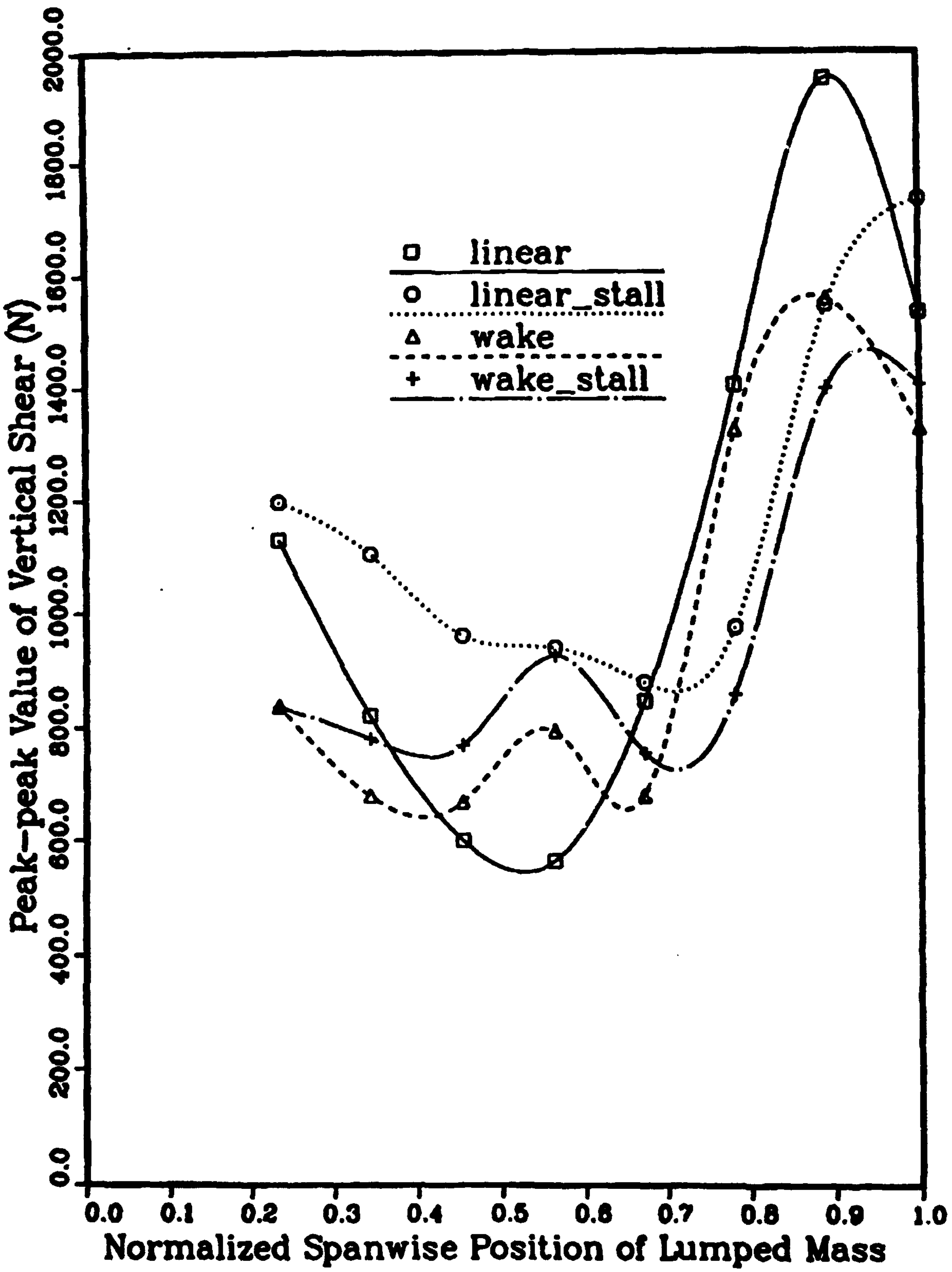


Fig. 28 Peak-peak Value of Vertical Shear (3,4, and 5p) with one 12 percent, adjustable lumped mass (Gauss points) (at v = 104 knots)

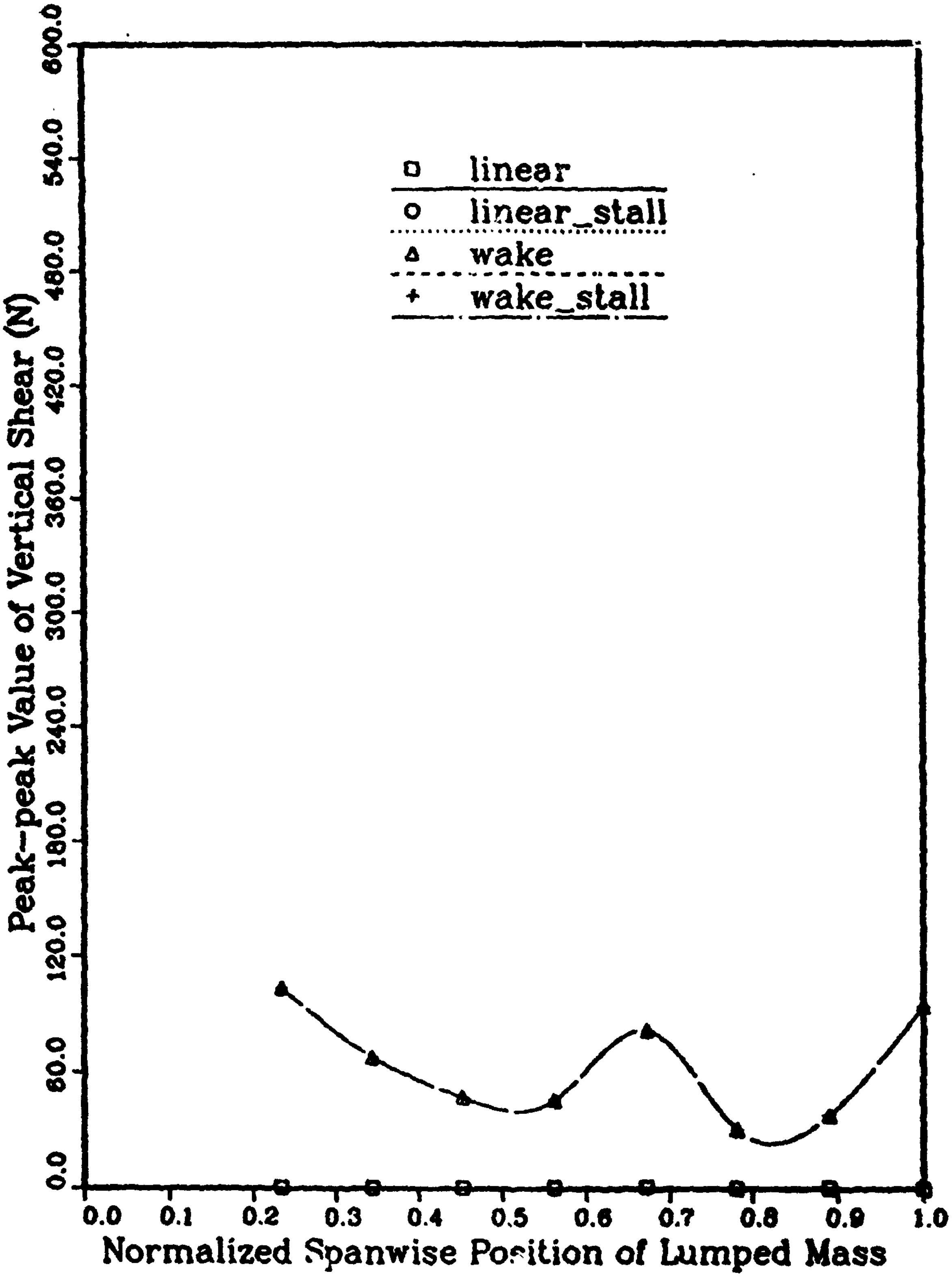


Fig. 29 Peak-peak Value of Vertical Shear (4p only) with one 12 percent, adjustable lumped mass (at v = 23 knots)

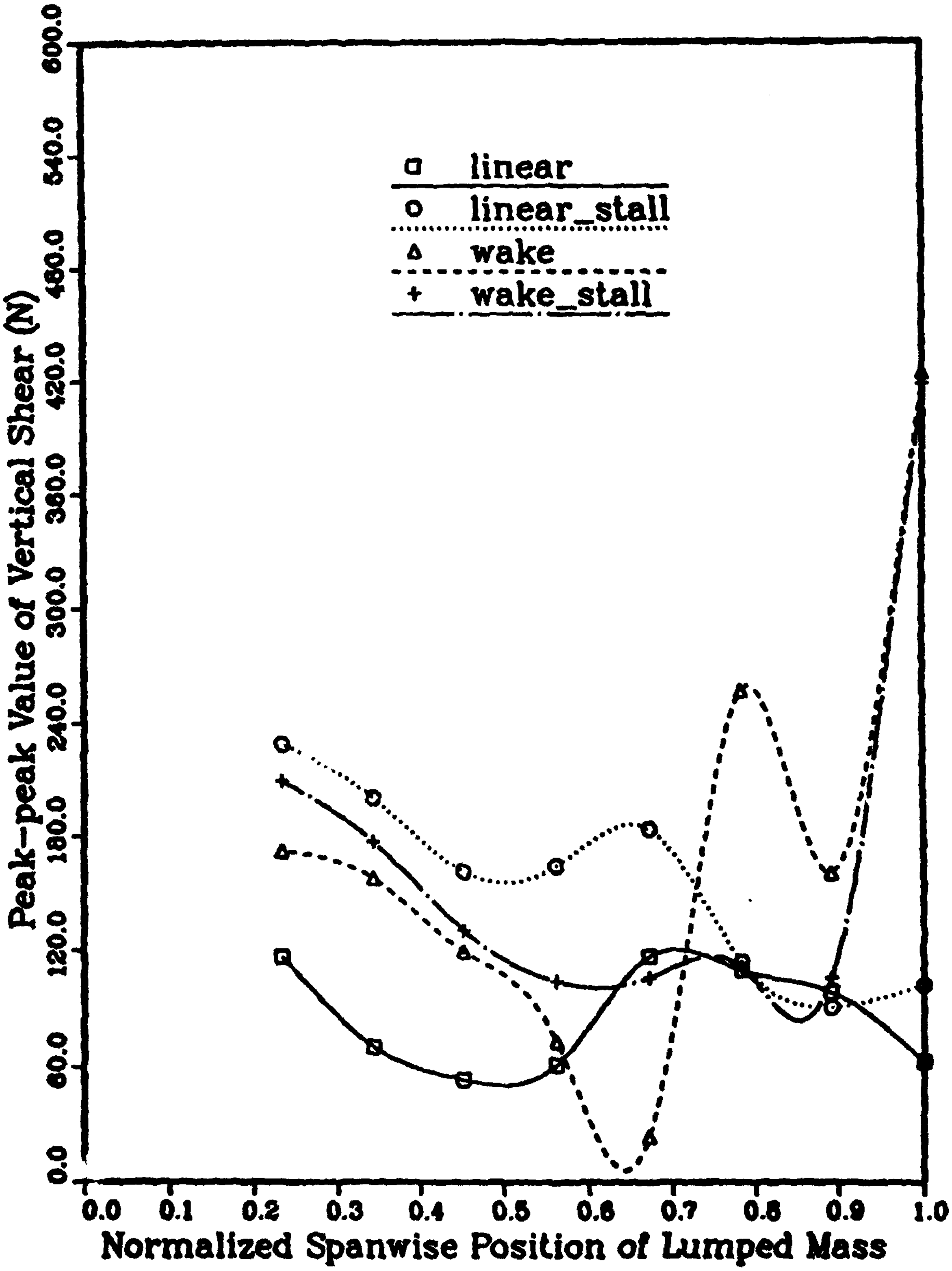


Fig. 30 Peak-peak Value of Vertical Shear (4p only) with one 12 percent, adjustable lumped mass (at v = 88 knots)

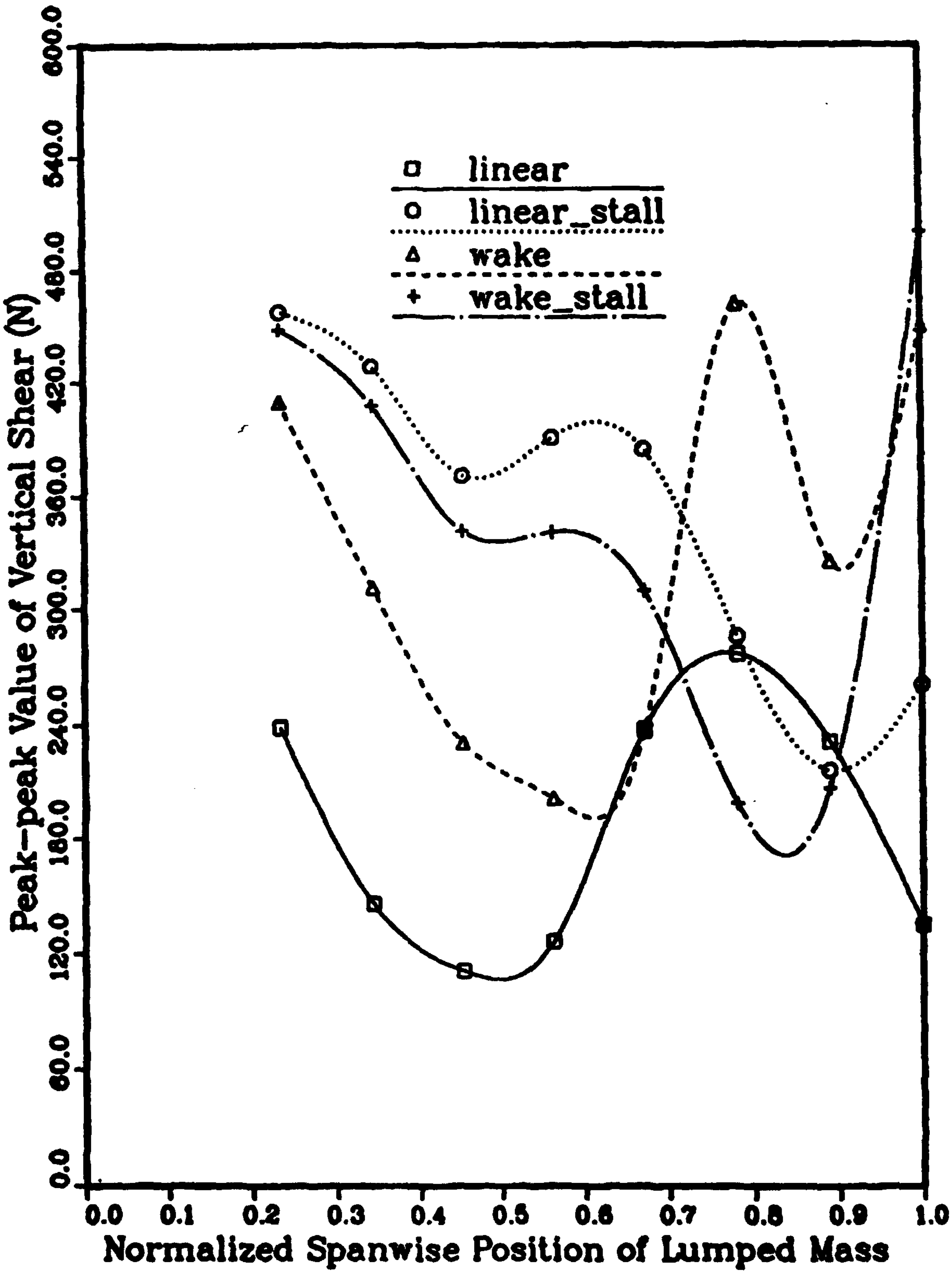


Fig. 31 Peak-peak Value of Vertical Shear (4p only) with one 12 percent, adjustable lumped mass (at v = 104 knots)

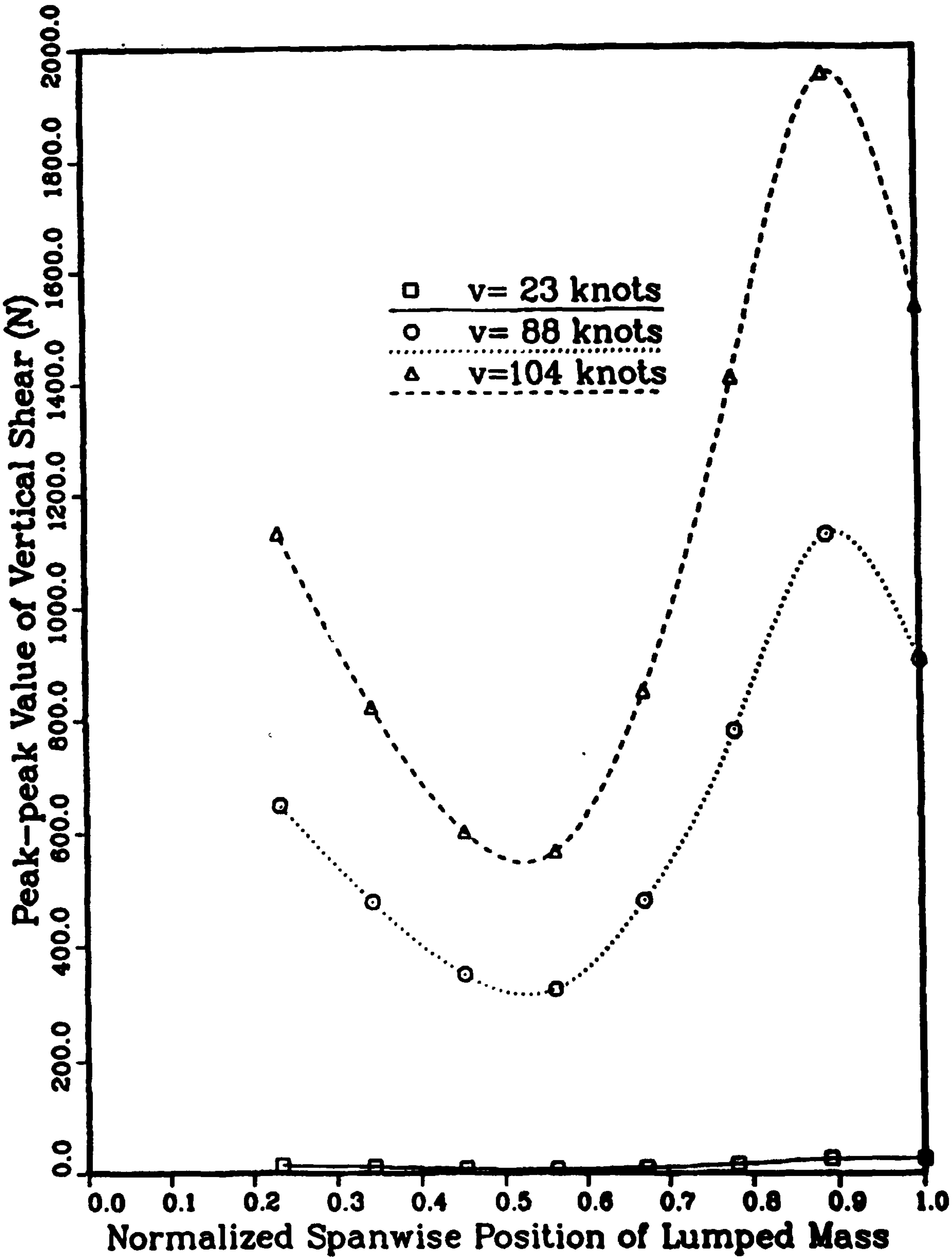


Fig. 32 Peak-peak Value of Vertical Shear (3,4, and 5p) linear baseline, with one 12 percent lumped mass

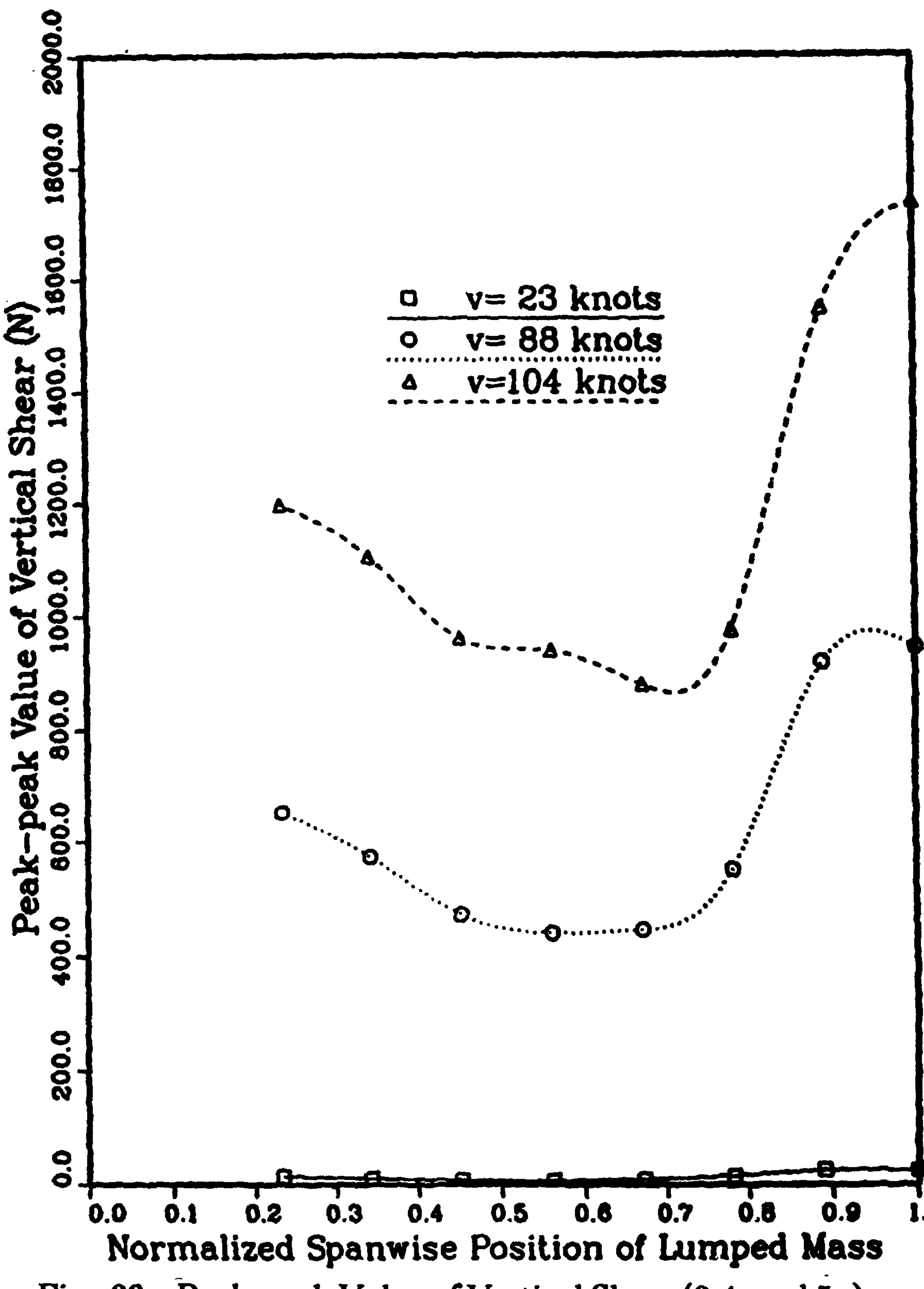


Fig. 33 Peak-peak Value of Vertical Shear (3,4, and 5p) linear & stall baseline, with one 12 percent lumped mass

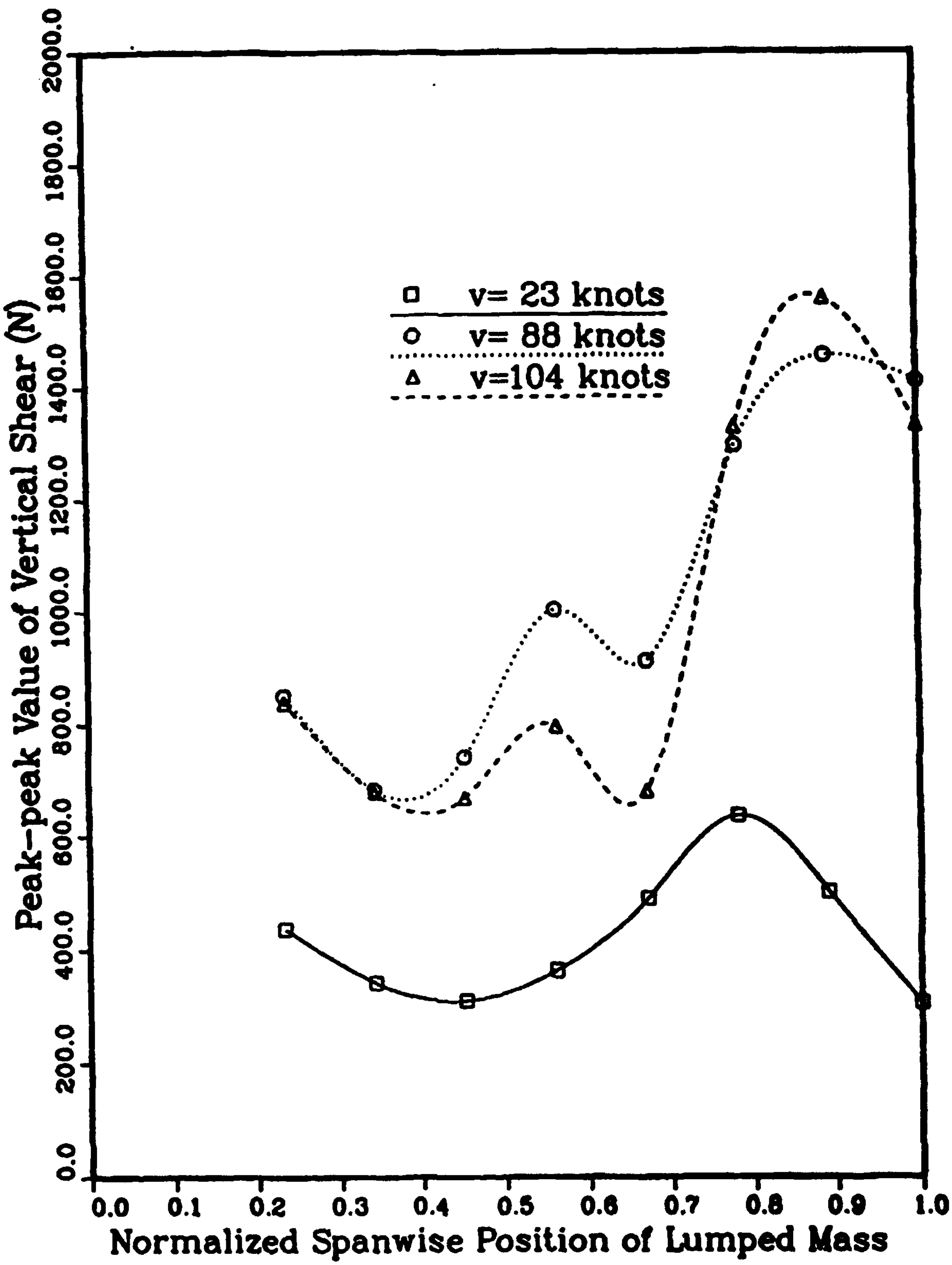


Fig. 34 Peak-peak Value of Vertical Shear (3,4, and 5p) wake baseline, with one 12 percent lumped mass

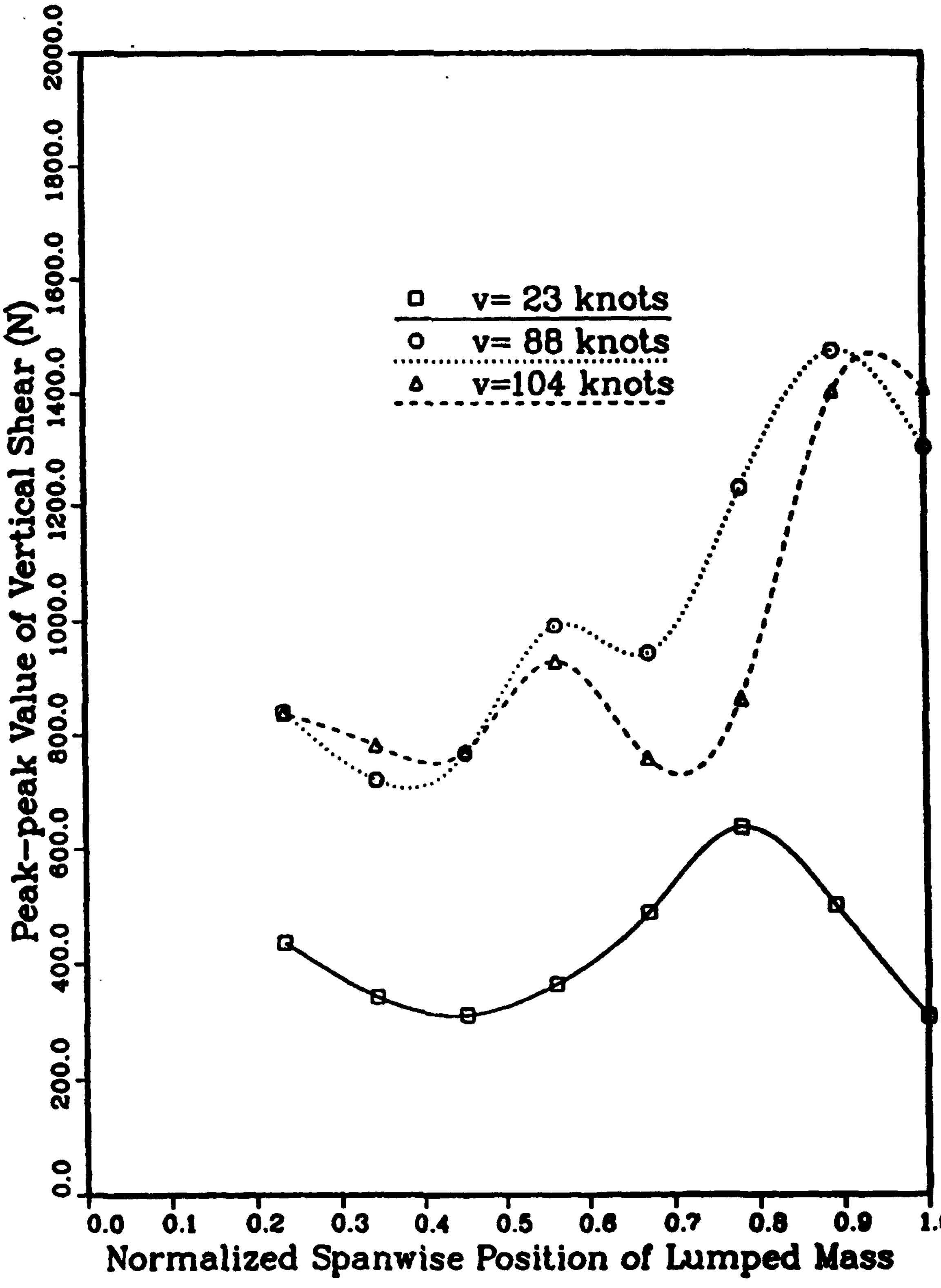


Fig. 35 Peak-peak Value of Vertical Shear (3,4, and 5p) wake & stall baseline, with one 12 percent lumped mass

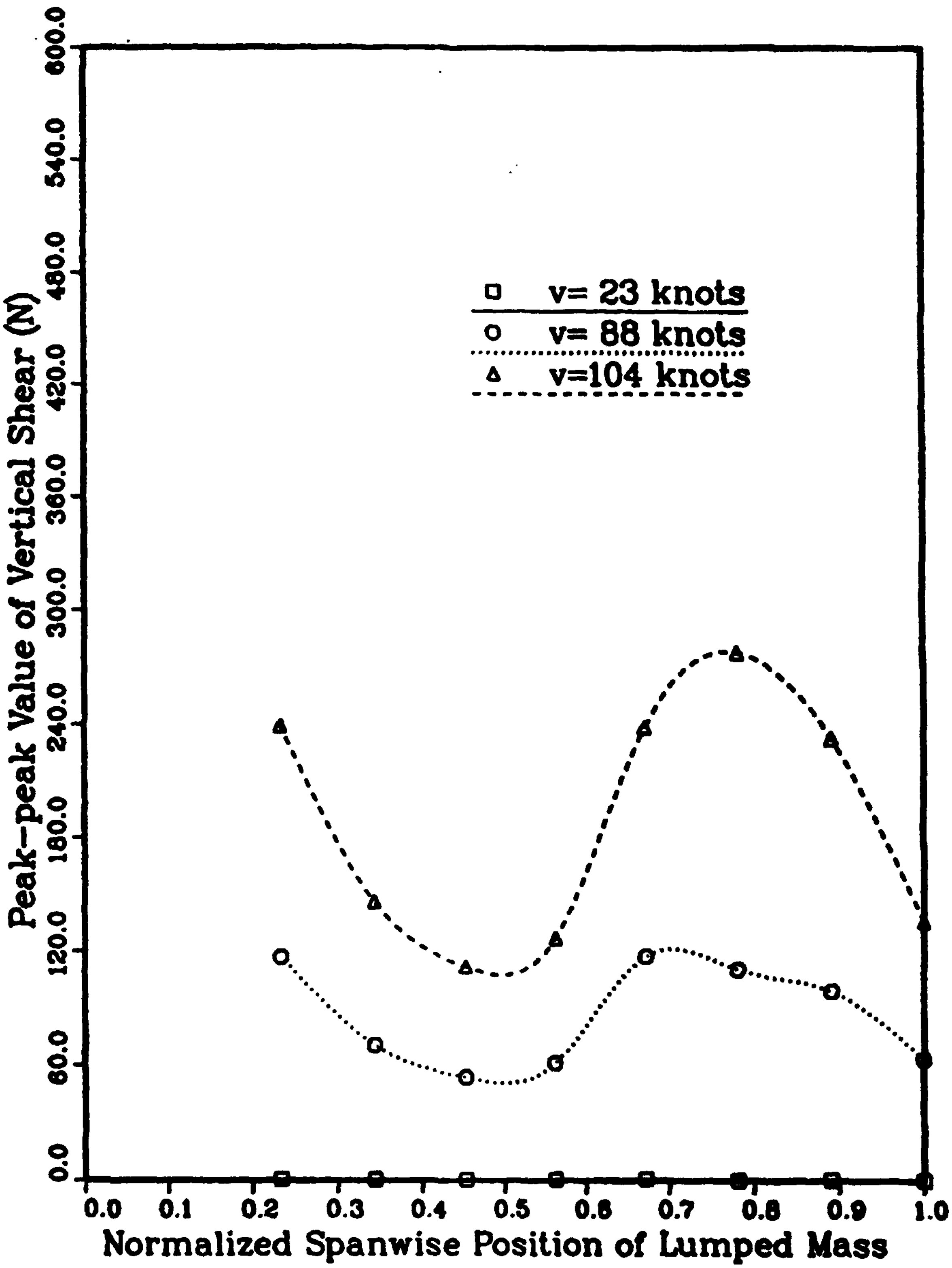


Fig. 36 Peak-peak Value of Vertical Shear (4p only) linear baseline, with one 12 percent lumped mass

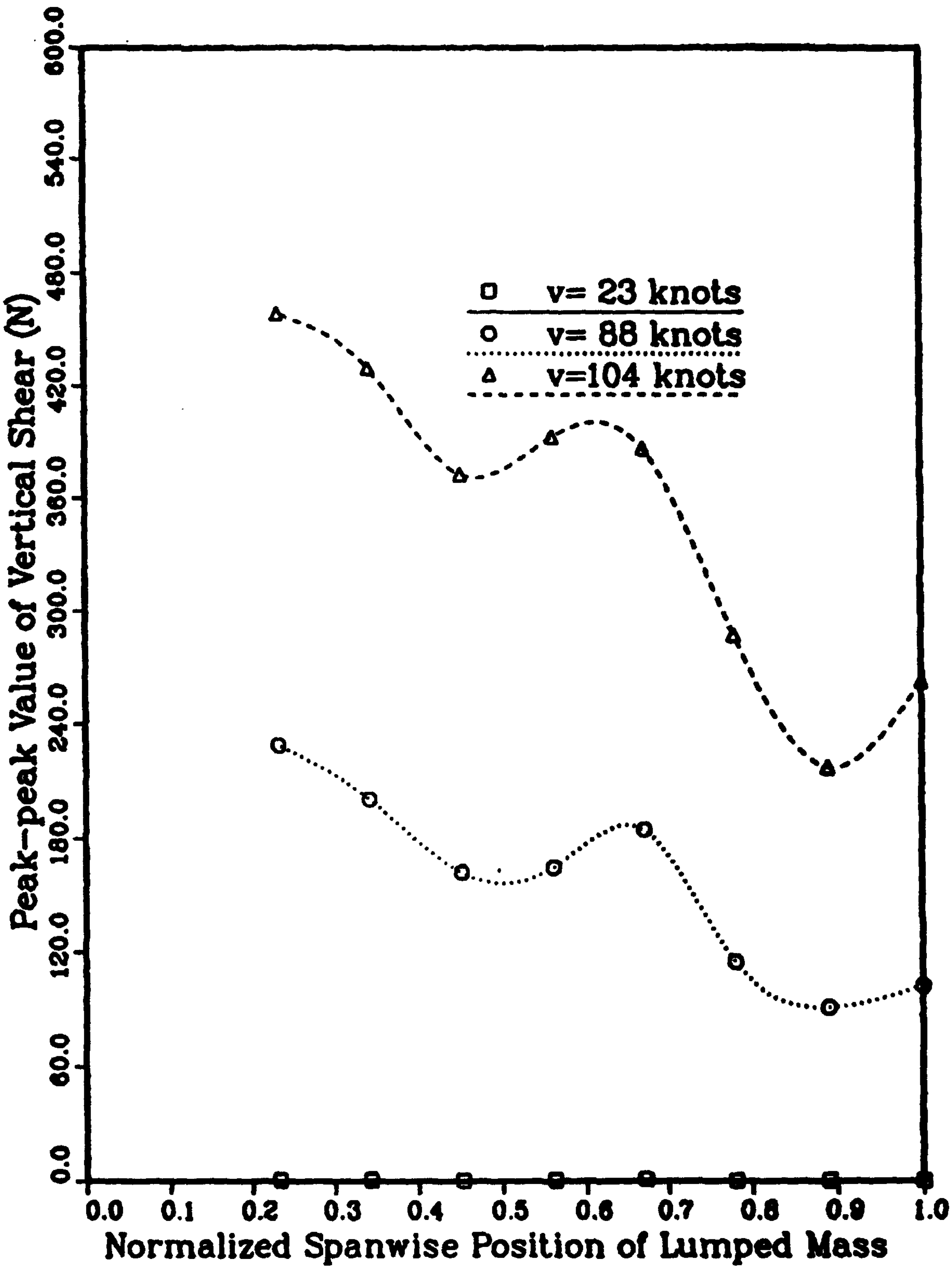


Fig. 37 Peak-peak Value of Vertical Shear (4p only) linear & stall baseline, with one 12 percent lumped mass

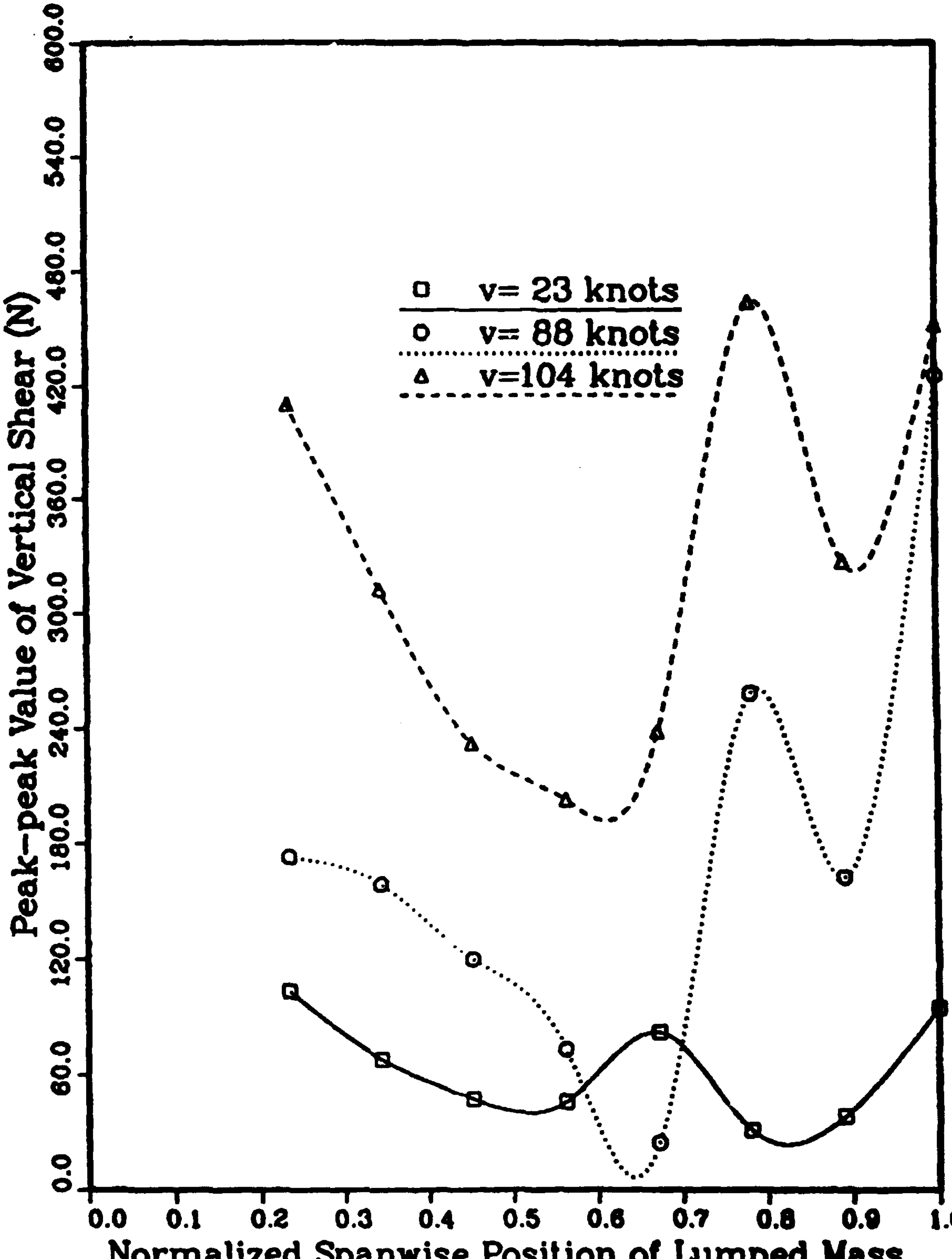


Fig. 38 Peak-peak Value of Vertical Shear (4p only) wake baseline, with one 12 percent lumped mass

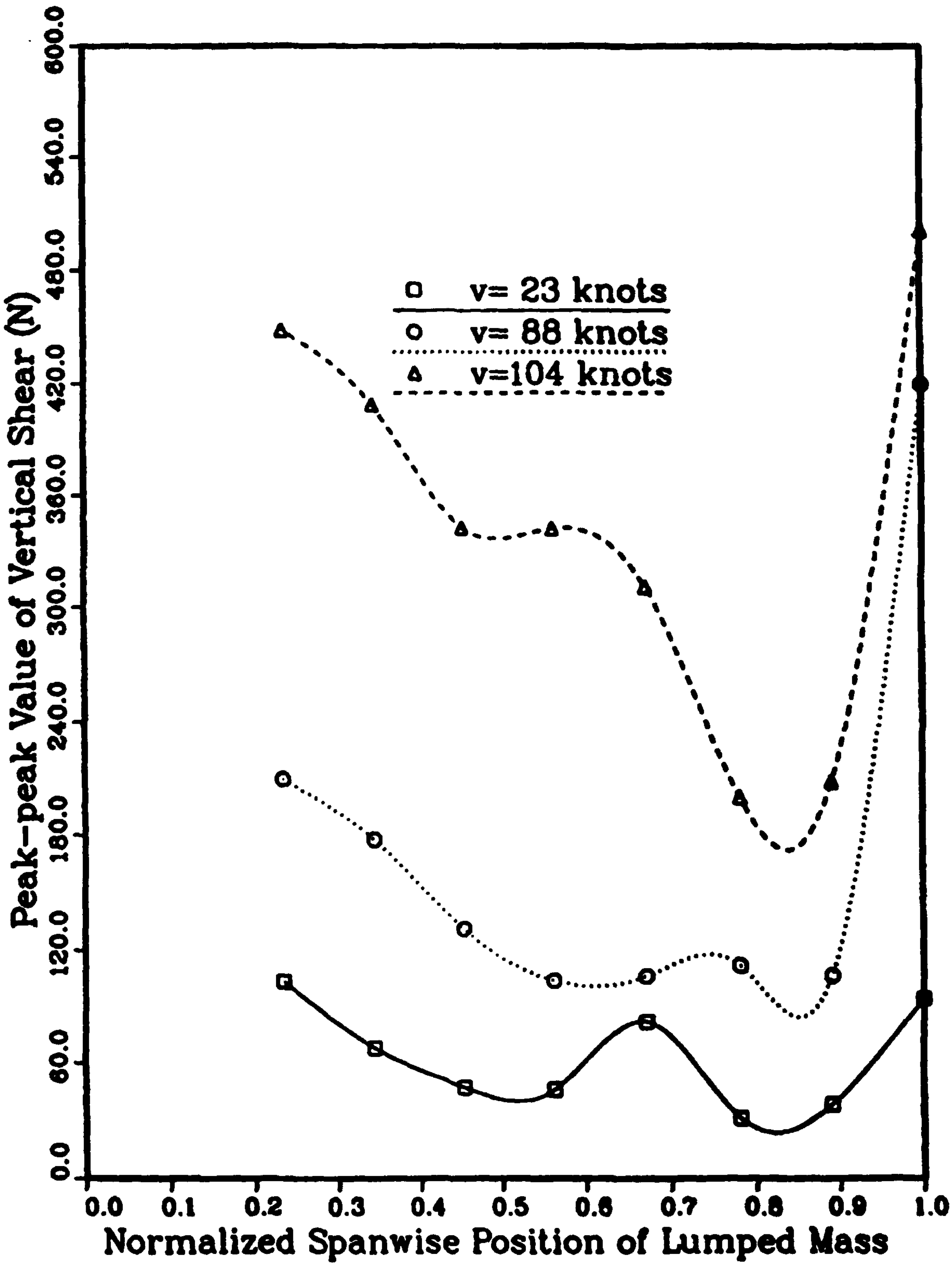


Fig. 39 Peak-peak Value of Vertical Shear (4p only) wake & stall baseline, with one 12 percent lumped mass

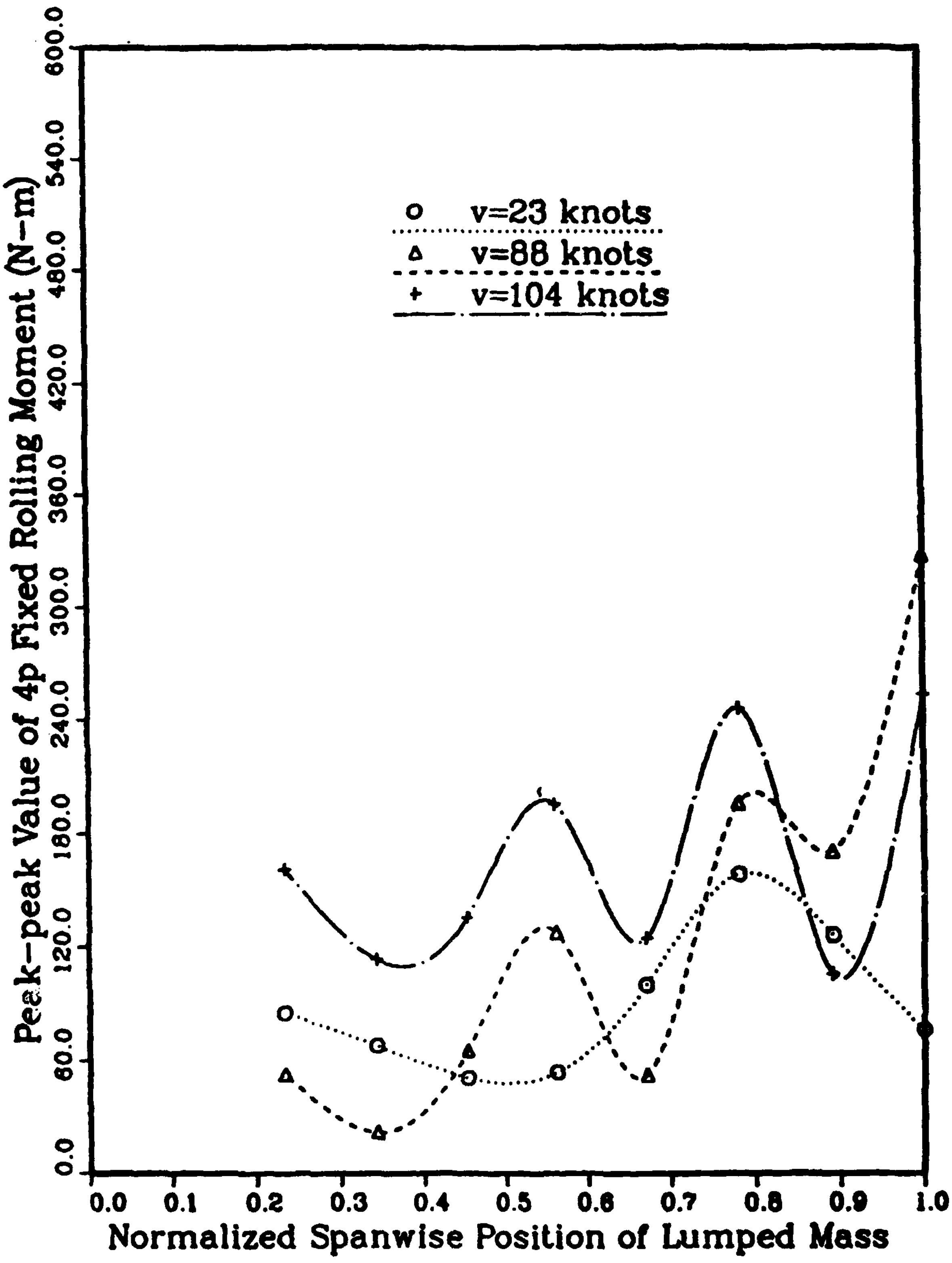


Fig. 40 Peak-peak Value of 4p Fixed Rolling Moment with one 12 percent lumped mass (at v = 104)

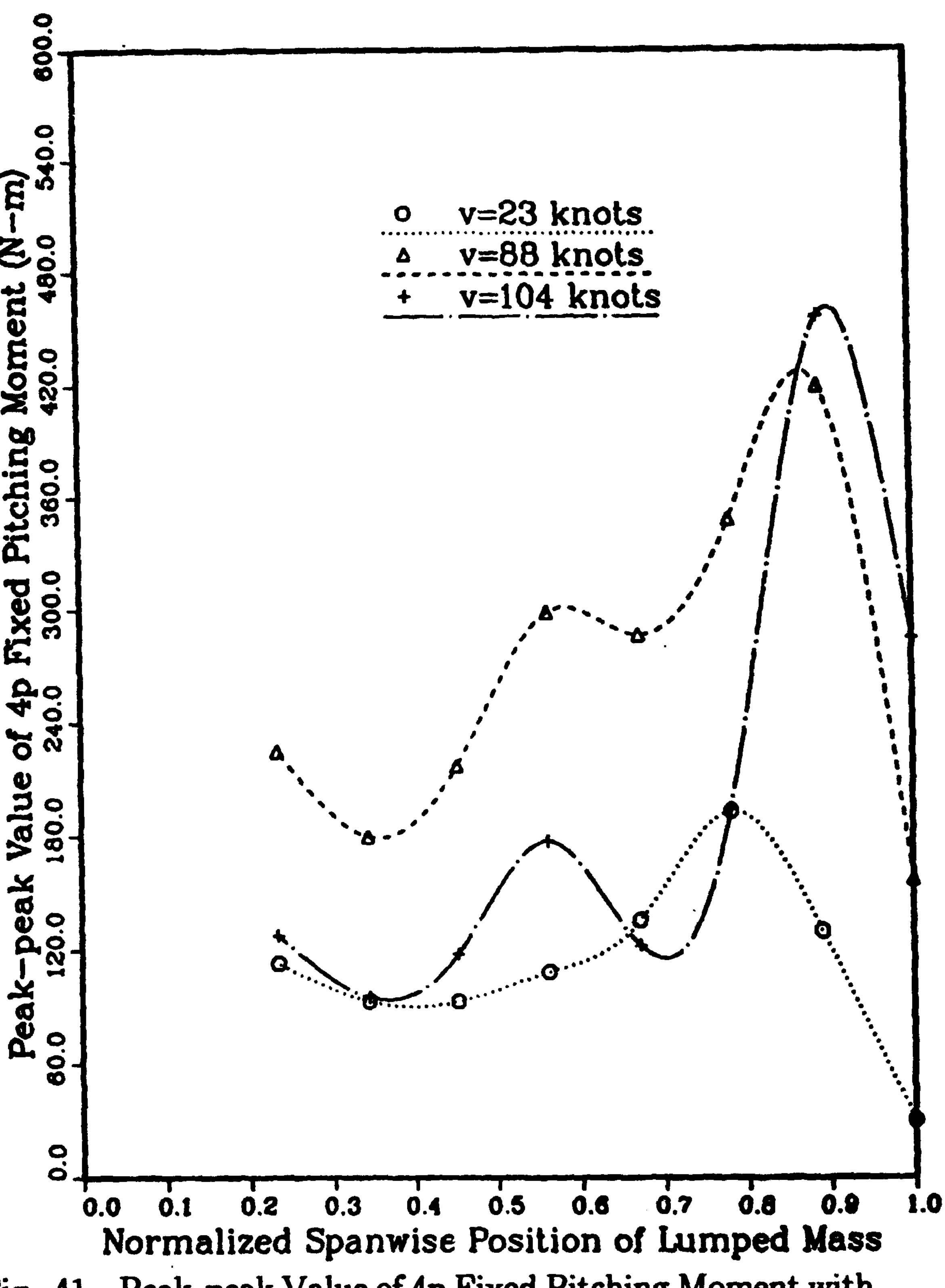


Fig. 41 Peak-peak Value of 4p Fixed Pitching Moment with one 12 percent adjustable lumped mass (at v = 104 knots)

2. <u>Advancing Rotor Blade Optimization Methodology</u>
(Sr. Invest'r. P. Hajela)

Two specific problems in the extension of formal optimization theory as applied to rotor blade design were considered under the subject contract. Namely:

a. efficient and robust optimization methods for problems where the analysis is known to be nonlinear. The candidate methods were first implemented on simpler structural models to assess their usefulness, intending that they would ultimately be used in the design of nonlinearly responding rotor blades. A literature search was conducted and preliminary implementations under taken in late 1990. Mechanisms by which an FET formulation of the rotor blade could be efficiently incorporated into an optimization process were first examined. This effort involved collaboration with Prof. Bauchau.

b. formulation of the rotor blade design problem as a coupled interdisciplinary problem. While the theoretical background necessary to account for coupled problem interactions had been known to some degree, its implementation in the rotor blade design problem offered new challenges. The version of CAMRAD available to Rensselaer was examined for adequacy to the purpose of providing representative analysis modules sufficient to proceed with this implementation.

Two methods were first examined for application to optimization problems where the system behavior is known to be nonlinear. They were implemented on a simple structural system with material nonlinearities. In the first approach, a complete nonlinear analysis for response was performed before the first pass through the optimizer. In addition. the sensitivity of the response to the design variables was obtained through a semi-analytical approach. The optimizer was then invoked, and all subsequent requests for analysis originating from within the optimization were obtained on the basis of a first order approximation of the response to correct the imbalance in the equilibrium equations.

The second approach implemented in this study was based on a simultaneous solution of the nonlinear equations of <u>equilibrium</u> and the optimization problem. In this approach, a few load-step iterations were performed to advance the nonlinear analysis. At this stage, the sensitivity of this partial response to the design variables was obtained. With this sensitivity, a piecewise linear approximation to the optimization problem was formulated, and an optimal solution to this subproblem was obtained. This solution was further enhanced by constructing both linear and secant approximations of the response to the load parameter. Once the solution to this approximate subproblem was available, the nonlinear analysis was advanced further. This process was considered converged when the load was at the applied level and the optimal solution did not change in successive iterations.

The computational effort expended in the two approaches was nearly the same. However, the second approach was expected to be more efficient in problems of larger dimensionality. A third approach put under consideration was to perform the <u>response</u> analysis and optimization solutions simultaneously. This required that the design space be extended to include the response variables as additional design variables. The positive aspect of this increased dimensionality problem was that no explicit solution of the nonlinear analysis problem appeared ever to be required. In the initial implementation of this approach, the importance of proper scaling of the design space was confirmed. In particular, the design space corresponding to the solution of analysis equations appeared to be very flat, and presented difficulties in the solution of the corresponding subproblem. These difficulties were not particular to the nonlinear analysis problem only, and had also been encountered in linear analysis problems. An alternate solution to the problem that is based on minimization of strain energy presented a design space that had more desirable characteristics, and had been shown to work well for linear analysis problems. The extension of this method to the nonlinear analysis problem was, therefore, planned.

The use of global sensitivity equations to generate coupled system sensitivities was implemented in the ıramework of CAMRAD-based rotor blade analysis. The results generated were not completely satisfactory, with significant differences in sensitivities generated through the global sensitivity approach and a system finite difference approach. This was attributed largely to a lack of control on the part of the user in generating sub-system partial derivatives, in the present setup of the CAMRAD program available at Rensselaer. The global sensitivity equation solver was checked on a number of test problems and appeared to be free of implementation errors. Reexamination of the merits of the global sensitivity approach in the background of another, more accessible, rotor blade analysis procedure seemed advisable, and the CAMRAD studies were suspended during the first half of 1992.

The research effort on the multidisciplinary problem of rotor blade design were, therefore, redirected so as to replace the nonlinear programming based procedures for optimization with a genetic algorithm based search process. The optimization problem based on genetic search considered selection of mass and flap-bending stiffness distributions at twenty spanwise stations along a typical helicopter blade. The blade was sized to minimize the 4/rev hub shear and hub pitching and rolling moments at two different airspeeds, and with an upper bound on structural weight. This represented one of the highest dimensionality optimization problems approached through the genetic search process to that time; ie, early 1992. The results of these preliminary numerical experiments were reported in Ref. 56 and established areas for further research in genetic search-based optimization for rotorcraft design proglems. They included key research issues that must be addressed for successful implementation; as follows:

a) Identifying robust strategies to handle an increased number of design variables without incurring an inordinate increase in computational costs.

b) Developing methods to handle design constraints that would be more effective than the penalty function approach used in then current implementation.

c) Establishing guidelines to select algorithm parameters on the basis of known problem dimensionality and characteristics of the design space.

d) Extending the genetic search process so as to be operational in a parallel processing mode. This would result in significant speed-up for large sized problems typical of rotorcraft design.

This work was performed largely by Dr. C.-Y. Lin, who spent the year at Rensselaer as a postdoctoral research associate. The analysis procedure used in this effort was a subset of the Boeing C60 code.

3. Fundamental Advances for Improving CrashWorthiness
(Sr. Invest'rs. P. Hajela, S. Sternstein)

This effort had two parts, both with the goal of improving helicopter crashworthiness. The first focused on the determination of optimal structural topology for carrying prescribed loads and simultaneously providing a desired level of energy absorption capacity. The second reëxamined the combination of material properties and simple structural arrangements from the viewpoint of nonlinear, viscoplastic dynamic behavior.

3a. Optimal Topological Design Theory Development
(Sr. Invest'r. P. Hajela)

The topology design problem attempted to determine an optimal geometry for transmitting applied loads to prescribed boundaries. This is one of the most difficult problems in structural design. The energy absorption capacity of a structure depends not only on the properties of the material, but also on the distribution of the material in the structure. The problem of discovering the material distribution for maximum energy absorption was chosen, to provide focus for this research.

The search for an optimal topology must be conducted in a design space that is both nonconvex and disjoint. Consequently, the genetic search approach (Ref. 57) provides a preferred optimization strategy with which to undertake it. The approach has been successfully adapted to the topological design of statically loaded truss structures subject to stress and displacement constraints. In all cases considered, topologies subsequently identified as globally optimal were discovered, using the genetic search approach. The results of this work were presented in an invited lecture at a NATO Advanced Research Workshop (Ref. 58). A significant feature of this work was that it represented the first effort in which kinematic stability of the structure was directly enforced. In all previous work, kinematic stability was added through the use of heuristics, applied only after stress sizing was completed. It should be noted, however, that in the absence of kinematic stability, dynamic (eg crash) response computations cannot rationally be included in the optimization process. The truss topology optimization problem was, therefore, extended to include local buckling constraints. This represented another important step in the direction of adapting topological optimization procedures to crashworthiness requirements.

The steps taken in this research were as follows:

a) A literature search of existing tools applicable to crash response optimization problems was completed. Efforts were begun to acquire the computer code KRASH, which has been used in the industry to model helicopter crash response. Plans were formulated with the specific intent of increasing understanding as to how the results of more fundamental research in component and topology optimization can be integrated into such design evaluation programs.

b) Efforts began to extend the topological optimization formulation to include the presence of flexural structural members. This seemed an obvious and necessary, but currently unavailable, component of the crashworthiness design optimization problem.

3b. Energy Dissipation in Crashworthy Designs
(Sr. Invest'r. S.S. Sternstein)

Among the most promising schemes to dissipate the energy associated with a crash, while limiting deceleration rates to values tolerable by personnel, is the use of carbon fiber composite columns, in which these structural components, loaded in compression, are designed to crush or granulate, thereby dissipating a large amount of energy in the form of work-of-fracture-surface-formation. Virtually all of the schemes being pursued seriously, however, suffer from a common difficulty; namely, the requirement for a substantial floor structure which is rigid enough to react the ground impact loads uniformly among the dissipative structural members. Clearly, the absence of uniform structural loading would result in substantially reduced efficiency for energy dissipation. Equally important, the interaction among the various structural elements in the highly nonlinear dynamic crash situation are so complex that attempts at structural-material optimization have been minimal. It has been difficult enough simply to evaluate postulated configurations.

The research in this project, undertaken in the latter part of 1990, focused on fundamental analysis of the efficiency of energy dissipation by various mechanisms. A highly simplified model was formulated which included nonlinear rate and load dependent behavior for the dissipative members. It incorporated a primary rotor-engine-transmission mass, primary airframe stiffness parameter, secondary cockpit-cabin-contents mass, secondary structural stiffness parameter, four kinematic position variables (with four associated velocities and four associated accelerations), and a generalized nonlinear constitutive equation representing the behavior of a crash energy dissipation member. The intent of this model was to provide a framework for the evaluation of crash member material constitutive parameters, in terms of the input initial conditions for velocity and kinetic energy at first ground contact. In concentrating on defining desirable dissipative material behavior, no attempts were made to represent the structural response of any rotorcraft in its entirety, during impact.

The resulting system of nonlinear first and second order differential equations were non-dimensionalized and programmed for solution on a PC. Parametric solutions were obtained for several sets of parameters. For example, modeling crash impact with this two-mass model showed typical non-dimensionalized pilot velocity responses as shown in Figs. 42-44. Slopes of these curves represent pilot acceleration as a result of impact, and it is clear that there is an optimum combination of energy dissipation/damping, not the maximum possible.

Based on predictions using this model, it appeared that use of structural polymeric foams, reinforced in preferred directions with carbon fibers to increase yield stress and stiffness, could have merit. While such materials may have lower energy dissipation efficiency per unit area than conventional structural members, they might be designed to be more effective per unit mass and to provide more consistent performance overall. For example, they may provide more uniform load distribution than discrete structural members, thereby reducing the strength/stiffness requirements imposed on the floor in order to redistribute loads with an efficient degree of uniformity. To investigate this further, development of a variational model for the path-dependent energy dissipation of generalized viscoelastic materials was initiated. Such a model was seen as serving to characterize the behavior of matrix materials in composite structures. The Euler-Lagrange equations were examined for several generalized viscoelastic models. Including more complex, nonlinear constitutive behavior was anticipated as requiring treatment using numerical optimization schemes.

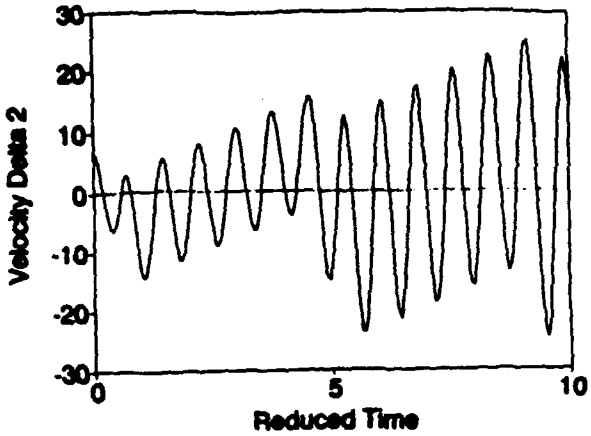


Fig. 42 No Dissipation - Worst Case

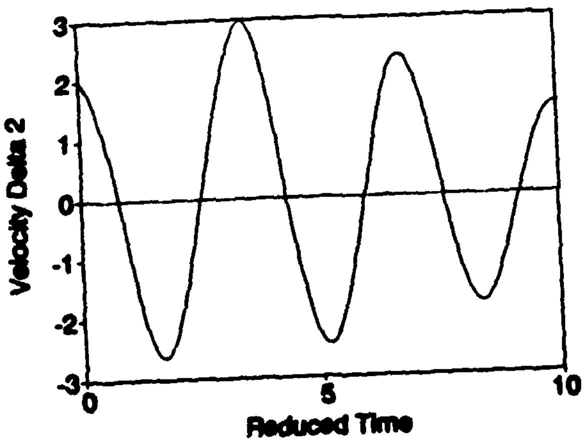


Fig. 43 High Dissipation With Damping

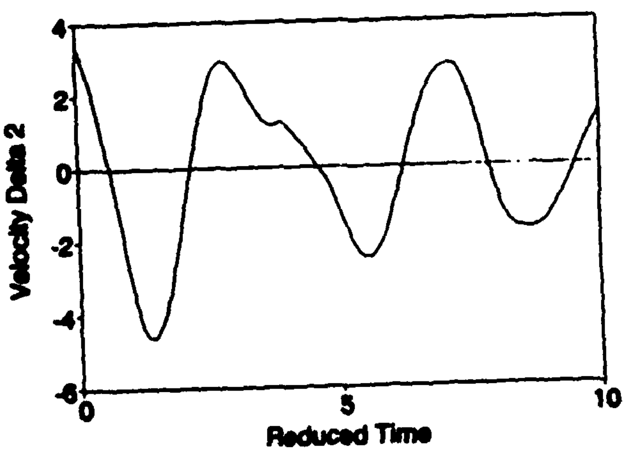


Fig. 44 Medium Dissipation with Damping

G. Blade-Vortex Interaction Studies
(ARO Fellow J. Straus, Faculty Supervisor M. Mayle)

Rotor blade impulsive airloads, of the type that contribute to higher harmonic vibrations, are thought to be influenced substantially by blade encounters with vortices trailed from other blades. Because some of these interactions occur with the blade leading edge close to parallel with the offending vortex, the two-dimensional case is of considerable interest.

RRTC research on two-dimensional blade-vortex interactions through December, 1988 included both theoretical and experimental models of the phenomenon. Potential theory was used to represent the interaction, using discrete vortices and a Joukowski airfoil. Vortex-induced velocities were accounted for in predicting both the impinging, concentrated vortex's trajectory and those of induced vortices shed continuously from the airfoil's trailing edge. In this sense, the theoretical calculation is a highly nonlinear one. Pressure measurements, integrated over time, resulted in preliminary experimental lift histories corresponding to those measured on an instrumented test airfoil. Details of these results were presented in the 26th Annual AIAA Aerospace Sciences meeting in January, 1988 (59).

Subsequent research efforts were directed towards a more complete understanding of the experimental lift histories, including the presence of 17Hz and 50Hz "noise" in the recorded signals. Removal of this "noise" was considered imperative for an accurate comparison with theory. The lower frequency noise was removed by providing additional structural support for the "following" test airfoil. In spite of efforts to design the vortex generating airfoil to have high natural frequencies, using advanced composite structural techniques, it vibrated appreciably at the higher frequency, as a result of the impulsive changes of incidence applied to produce a concentrated vortex. These vibrations were dramatically reduced by increasing the number of supports between the vortex generating airfoil and its actuator. Following these modifications, incremental lift coefficients were acquired for various interaction distances and the results compared with the predictions of potential theory. Additional experiments were then conducted with the "following" airfoil at various (fixed) angles of attack and measurements made of vortex circulation strengths, orientations, and interaction distances. Hot-wire measurements of the test airfoil boundary layer and surrounding flow were also made to reveal, in greater detail, the bases for other kinds of change in lift observed during interactions. Appropriate comparisons with theoretical results were made in continuing efforts to understand the basic two-dimensional blade vortex interaction phenomenon.

The effort to design and build a hot-wire anemometer traverse mechanism, that would allow velocity measurements to be made close enough to the test airfoil during vortex passage to enable meaningful inferences relative to vortex/airfoil boundary layer interactions, was not simple. Difficulties were again encountered with mechanical vibration of the test equipment during vortex passage. The data was again contaminated with the associated "noise". Appropriate isolation of the probe traverse apparatus was ultimately achieved and considerable data taken.

Velocity contours measured at chord-wise locations 0.1, 0.3 and 0.6 of chord behind the leading edge, showed that as a vortex passes 0.1 chordlengths above the airfoil, there is an induced velocity reversal associated with vortex positions at 0.3C and beyond. This was believed to be a result of the formation of a secondary vortex. It also appeared that vorticity in the boundary layer was "pulled" from the airfoil surface toward the free stream by the passage of the free vortex. Closer examination of the velocity profiles associated with the passage of a counter clock-wise vortex, revealed that the velocity profile at the

10% chord location remains laminar throughout the vortex interaction; at 30% chord, the boundary layer, initially laminar, underwent a short-lived transition to turbulence during the interaction. The boundary layer flow at 60% chord, however, was transitional even before it experienced the influence of vortex passage, yet there was no indication of it becoming fully turbulent during the interaction. The velocity profile there was seen to vary so as to be more like a turbulent profile, but never reached that state. With the passing of the vortex, the velocity profile at that chord station was actually seen to go laminar, prior to returning to its final steady state transitional profile.

RMS velocity distributions showed that a large amount of turbulent energy was being spewed into the inviscid portion of the flow at 30% and 60% chord, and at all chordwise locations a large amount of turbulent energy was generated. The vorticity was observed to enter the inviscid flow at a point underneath the vortex and not at the trailing edge, as is commonly assumed in potential flow CFD codes. The cause of this behavior could not be conclusively associated with the existence of a secondary vortex formation, since the hot-wire anemometer probe used for velocity measurements could not differentiate among the directional components of velocity.

Velocity profile measurements were also taken during passage of a positive (clockwise) vortex. The rapid variations in the magnitude of velocity measured as the negative vortex passed the 30% and 60% chord points were not observed for this case. However, almost periodic variations in velocity magnitudes at the surface were found and seemed possibly due to a secondary vortex. In either case, ie clockwise or counterclockwise vortex passage, the pressure distribution measurements showed lift changes equal in magnitude only different in sign, thus indicating no significant effect of these boundary layer changes on the overall aerodynamics of the lifting surface.

These results all appear in detail in Ref. 60.

H. <u>Shaft Flexibility Effects on Ground/Air Resonance</u>
(ARO Fellow M. Zotto: Faculty Supervisor, R. Loewy)

The effects of rotor shaft flexibility and the associated rotor control coupling on the so-called ground/air resonance instability of helicopters was studied in this research. Several types of advanced helicopters appeared to be designed with relatively flexible shafts. Since the literature reports no studies of their influence, a ground/air resonance study varying shaft flexibility and shaft-blade coupling, therefore, seemed pertinent.

Linearized equations of motion for a mathematical model with a rigid airframe, a rotor shaft flexible between the swash plate and hub, and a fully articulated rotor with rigid blades were derived and put in a form which emphasized the differences between hub motions resulting from fuselage motion and those due to shaft flexibility. Twelve degrees of freedom are included: two blade lag modes and two blade flap modes; fuselage pitch and roll about and translation along lateral and longitudinal axes; and shaft flexibility allowing hub translation and bending slope in each of these two directions. Since the study concentrated on the unique aspects of rotor shaft flexibility, only uncocked hinges and rather rudimentary aerodynamic forces were included. The nature of the shaft-pitch coupling was shown to be similar to a "virtual δ_3"; however, bending of the rotor shaft in a given plane affects the pitch of a blade both in that plane and perpendicular to it. Multiblade coordinates were employed to eliminate periodic coefficients and stability examined using an eigenvalue solution.

To ensure a reasonable range of parameters, helicopter dimensions published for the

OH-58D helicopter were used, as a guide. Ground and air instability (in hover) were examined with and without shaft flexibility. A range of values for control linkage parameters and δ_3 were also examined. In addition, because such can influence rotor shaft bending, all cases were studied both with and without a mast-mounted sight (MMS).

The numerical examples led to the following conclusions:

(1) Shaft flexibility/control coupling adds new modes of instability for "ground resonance" cases, but small amounts of shaft structural damping appears to provide stability in normal operating RPM ranges. These new modes of instability are clearly associated with aerodynamic effects, and since the aerodynamic representation in this study was limited to 2-D, static theory, no conclusions were drawn regarding the precise positions of these new stability boundaries.
(2) "Air resonance" instabilities appear to be more susceptible than "ground resonance" instabilities to shaft flexibility/control coupling effects, as might be expected. Sufficient shaft structural damping to stabilize the former cases will also stabilize the latter; but not necessarily vice versa.
(3) Incorporating a typical MMS will generally increase the amount of shaft structural damping required for stability.
(4) Parametric variations for the helicopter type examined suggest that decreasing shaft stiffness, increasing MMS mass and mass offset above the hub, increasing negative values of pitch-lag coupling θ_ζ, decreasing negative values of δ_3 and/or increasing values of a kinematic shaft-pitch coupling parameter, η, are all destabilizing as regards "air resonance" instability. Here η is defined as the radial distance from rotor shaft center to the point of pitch link attachment to the pitch arm divided by the tangential distance from pitch link to the blade pitch axis.

Although the aerodynamic structural damping and control linkage models used in this study were rudimentary, the results suggested that for certain combinations of shaft flexibility and shaft/pitch coupling, no reasonable amount of structural damping can insure stability. Thus, shaft flexibility beyond some limiting value requires that shaft/blade pitch coupling effects be considered to insure ground/air stability.

A paper on this subject was presented at the AHS Annual Forum, May 22-25, 1989 [61]. Opportunities for discussion after presentation at the Forum resulted in the following suggestions for extending this research: (1) leading edge versus trailing edge pitch horn attachment points should be considered, (2) pitch link "canting" should be accounted for and (3) these investigations should be carried into the forward flight regime.

Accordingly, a complete, nonlinear mathematical modeling of the kinematic couplings that are possible for an articulated hub were programmed. The mathematical models followed those presented in Ref. 62. Studies of the kinematic control couplings that are possible for an articulated hub with arbitrary pitch horn configuration and canted pitch links were completed by mid 1990. Exact cases were run and the magnitude of coupling determined for the kinds of hub motion consistent with small strains of the rotor shaft. No linear approximations were found accurate to within 10%, however, a simplified quadratic form which ignored "foreshortening" of the pitch arm as it rotates, did give an excellent approximation to the exact case. Pitch change variations versus azimuth were calculated for a helicopter similar to the OH-58, with lateral rotor shaft deflections of 1/2" and pitch link canted radially and tangentially to 5° and 10°, respectively. The hub displacement chosen was about twice the expected displacement for a typical case, yet the differences in the approximate and exact solutions were only about one tenth of a degree for either pitch link cant angle. Thus, the linearized canted pitch link solution was seen as adequate and was incorporated into the analysis reported in Ref. 61.

Numerical results were also run in an attempt to determine what values of pitch link cant are needed to counter the destabilizing effects of shaft bending slope-induced kinematic couplings, δ_3, or lag pitch couplings due to upper control linkage geometry. These results showed diminishing effects as EI increases, as would be expected. For certain values, however, there were regions in which the areas of instability grow larger, the stiffer the shaft. This implied that flexible rotor shaft motion is stabilizing under certain conditions.

The complexity of these interrelations prompted a more detailed examination of the nature of the instabilities. In particular, pitch-lag instabilities were investigated for a model with a rigid shaft, as δ_3 and lag-pitch coupling were varied. The results presented in Ref. 63 were duplicated with our equations. Attempts to similarly check the results reported in Ref. 64 showed that details of blade mass distribution and the way they affect mean coning and lagging angles as a function of collective pitch can be very important in such analyses. More important, these investigations found that negative lag-pitch couplings are stabilizing for the air resonance case but shift the stability boundaries adversely for ground resonance cases. Since decreased lag damping reduces main rotor blade forced in-plane moments in forward flight, some addition in landing gear damping may be a desirable trade, available through lag-pitch coupling. Such was reported in a national specialists' meeting, and published in the AHS Journal [65].

Subsequently, the case of a helicopter with significant shaft flexibility was extended from the hover case to the forward flight case. Equations of motion for the ten degree of freedom problem consisting of rigid blade flap and lag, rigid fuselage pitch, roll, and lateral and longitudinal translations, and the hub rotations and translations in two directions relative to the fuselage due to rotor shaft bending, were derived using MACSYMA. Peter's equations [66] for an isolated rotor in forward flight, with flap and lag degrees of freedom, were checked as a subcase. The sensitivity of stability boundaries to the trim condition, as evidenced in fuselage attitude, and values for collective and cyclic blade pitch, and the zero and first harmonics of blade flap and lag motions, had been encountered in earlier attempts to correlate ground and air resonance results with those in the literature. Care was taken, therefore, in solving the nonlinear trim problem. The eleven unknowns were solved including higher order terms, by setting the thrust equal to the resultant of gross weight and drag, and pitch and roll moments set equal to zero; by applying harmonic balance to the steady-state, blade flap and lag motion for zero and first harmonic components; and by pitch and roll equilibrium of the fuselage. Trim variables presented in Wayne Johnson's "Helicopter Theory" [41] were replicated for a range of rotor advance ratios from 0 to 0.4.

Floquet-Liapunov theory was also successfully implemented. Calculations run reproduced Peters' natural frequency and stability boundary results, when a hinge arrangement was assumed which has the lag hinge "closest" to the axis of rotation [66]. The more usual sequence which has the flap hinge "closest" to the rotational axis yielded somewhat different results, as a consequence of differences in the trim values of coning and steady lag angle. These differences appear to grow with increasing Lock number. The higher order coning terms appeared to be responsible for the differences in results and they appear only in the stiffness matrix; higher order flap trim terms found in the damping matrix had no effect on the results. Equilibrium trim values were retained up to third order and while flap terms in the stiffness matrix are apparently important, steady lag trim values are not.

At the close of the contract period, stability analyses for the forward flight case including dynamic inflow and a representation of reverse flow were being prepared. Interest in these analyses are sufficient that they will be completed to show the effect of advance ratio, shaft stiffness and blade pitch-mast bending coupling, pitch link cant angle, pitch-lag and pitch-flap kinematic couplings, lag damping and blade frequency changes, subsequent to contract closure.

I. Helicopter Conceptual Design Optimization Methodology
(ARO Fellow A. Trainer; Faculty Supervisor; G. Gabriele)

This project was motivated by the need for tools for the conceptual design of rotorcraft. Integrated, computer aided design methods did not exist that could assist the designer in more rapidly arriving at rotorcraft designs, in the conceptual stage, which are "best", according to predefined criteria and which satisfy certain predefined constraints. Improvements expected to help achieve this goal included standardizing the application of existing software, eliminating manual data transfer and automating other routine tasks, defining design parameters more consistently, increasing accessibility to more extensive design databases, and providing better means of data management. The designer would, if this research were successful, be able to examine more design alternatives in less time and gain confidence that promising variants have not been missed.

Fundamental to the approach was the choice of a design process model, eg hierarchical, network or hybrid [67,68]. Secondary considerations included the number and degree of abstraction levels for analysis calculations, how the user interfaces should be arranged and how knowledge bases can be incorporated [eg; 69,70].

A prototype tool was constructed, as a first step, on a highend PC, using an advanced language which implements the principles of object-oriented programming. Application of this tool was expected to provide substantial insight into some of the issues outlined above.

Recognizing that the design process consists of a series of iterative steps, we proposed that definition of a rotorcraft design be divided into six models, each of which would be based on the specification; then synthesized, analyzed, evaluated and iterated (through some or all of these 4 steps), until the specification is satisfied and/or an optimum design achieved. The six models would be (a) the concept development model, (b) the component layout model, (c) the component functional model, (d) the knowledge-based expert model, (e) the design goal model, and (f) the system management model. These models were formulated to describe the conceptual design process tasks in the context of object-oriented and AI approaches. They were seen as largely determining the structure of the computer aided design tool which is the objective of this research, and were described as follows:

- The concept development model would define the "general arrangement" or configuration of the overall design.

- The component layout model would provide all parameters needed to establish the geometry of the component objects of the concept model as solid bodies.

- The component functional model would establish abstractions of the functional aspects of and interactions between, (i.e., the behavior of) components of the concept model quantitatively, through algorithms and/or data and procedures of the component object hierarchy.

- The knowledge-base model would provide a means of applying "Expert System" techniques to support synthesis, analysis and evaluation of components and concepts in their functional aspects, implementing "rules of thumb" or company design policy, for example.

- The design goal model would be the embodiment of "automated goal analysis" to a specific design task. By stipulating weighting factors or figures of merit to specific goals, its use could suggest specification changes.

- The system management model would function as administrator of the remainder of the system, fulfilling user interface, hardware control and knowledge-base management tasks, among others.

Efforts focused on establishing an appropriate structure to house the design knowledge data base - including knowledge about design configurations, how they function and how to vary parameters to achieve the best possible design - concluded that the PRIDE system should be chosen for the rotorcraft design domain. The method known as the Fuel Weight Ratio (R_f) design approach [71] was also chosen as the sizing technique for particular range/payload mission requirements. The R_f method was then recast as a system of hierarchical goals and extended for the purposes of rotorcraft conceptual design. Care was taken to form the goals in such a way that a uniform level of abstraction was achieved at any given level of the goal tree. The intent in making these definitions was to keep design goals and design components compatible and to assign them to one of three abstraction levels.

Data structures for both components and goals were created, including 31 design component objects and 33 design goal objects; see Figs. 45 and 46. During this process, a need to modify the goal structure was recognized. This structure was originally pictured as a unified, homogeneous entity, but advantage subsequently appeared to separating it into categories, based on which design subprocess - synthesis, analysis, or evaluation - they belong to. Studies were conducted simultaneously as to how to manage designer interaction with the design knowledgebase. This was first accomplished by prototyping a Macintosh-based, HyperCard approach. In HyperCard [72], knowledge elements are known as "card" objects. These cards are organized into "stacks" of related cards. Although cards are related by virtue of their inclusion in a stack, they may also contain links to other cards or stacks. This approach appeared to have the advantage of allowing rapid exploration and modification of the data structures and interaction between data structures.

Mechanisms were also examined which would allow a design to be validated with respect to requirements, using a functional approach. Validation in the synthesis phase was foreseen as recasting each requirement in the specification in terms of functions, allowing comparison with the output of applicable predictions for the design model. A total of 42 domain-specific functions were developed, with major effort devoted to three areas; (1) insuring that functions are independent of their solution principle, so as to avoid bias in solutions; (2) insuring that function inputs and outputs are compatible; and (3) correlating requirements and solutions.

The investigation of system-user interface capabilities using the HyperCard approach, led to the conclusion that a goal-based approach to the conceptual design process was valid. Use of selectable design goals appeared to provide a structured environment in which to conduct the design process and included a feedback mechanism to ensure that no part of the process would be overlooked. It also allowed the designer some flexibility as to how the design process could be pursued; allowing the design process to be done, for example, in a manner familiar to him or her. Limitations in the HyperCard environment prompted an effort to adapt a more robust software platform, and the system was then recoded in Object Pascal [73], which provided multiple windows, as one additional feature, through which the designer can view and manipulate the design process.

In addition, MacBRAVO! [74], a commercially available solid modeling package, was chosen to provide a mechanism for displaying and manipulating candidate configurations (design models) and the collections of candidate components or groups (design objects) which make up the configurations. MacBRAVO! was chosen because it was already operational "in-house" and because an add-on module called the Flexible Interface Tool ("FIT") was available. The FIT allowed applicaton-specific, graphic user interfaces to be developed and overlaid onto the basic MacBRAVO! package. MacBRAVO! and FIT were used to create several graphic interface elements for the prototype design tool, including pull-down menus, icon-pallettes of design objects, dialog boxes for viewing and modifying design object parameters, and "alert boxes" for issuing warnings and design advice to the user.

Knowledge representation structures for goals and design objects were also modified, the goal structure being reduced to two levels, to better reflect industry practice. Goals previously shown in the third level were incorporated into second level goals. Similar changes were made to the design object structure. Engine and Engine Losses were combined into, and all subcomponent objects consolidated under, a single Powerplant design object; an Armament design object was added to the Fixed Equipment design object category; and the components of the Fuel System design object were changed to represent internal (permanent) fuel tankage or external (jettisonable) fuel pods. Categorization of Payload objects was revised to separate internal Payload into Passengers and Cargo and to separate External Payload into External Cargo and Ordnance. Finally, Rotor objects were reclassified to better reflect their design function, so that they could be classified as Lifting Rotors, Thrusting Rotors, Convertible Rotors, and Control Rotors.

In early CY 1991 the concept of simultaneously storing and manipulating multiple design models was investigated. The methodology developed for this purpose was based on the NAD/OR tree. It allowed the designer to include alternative concepts at either the system level or the component level. The prototype tool then would search the model tree and store all possible combinations of alternatives in a table. Analyses and evaluations of these alternatives would then be performed by generating and presenting a decision matrix to the designer. This decision matrix would display each design alternative as compiled by the tool, along with the values of designer-selected criteria. Decision criteria may be in the form of numeric quantities, such as gross weight or system productivity, computed from the design model or may be in the form of qualitative rankings of each alternative. The designer could then select from the decision matrix those alternatives which should be retained for refinement or removed from further consideration.

Different categories of design knowledge were included in this system. Design knowledge was introduced which may be classified as statistical trend data, design "rules-of-thumb", or abstractions of design sub-system or design object functionality or performance. Examples of such design knowledge included group weight trends or "rules-of-thumb" for locating or sizing design objects. Approximately two dozen statistical trends and one dozen design "rules-of-thumb" were identified and incorporated into the prototype tool.

At this point, this research project was viewed as essentially complete, and funding under the ARO contract terminated.

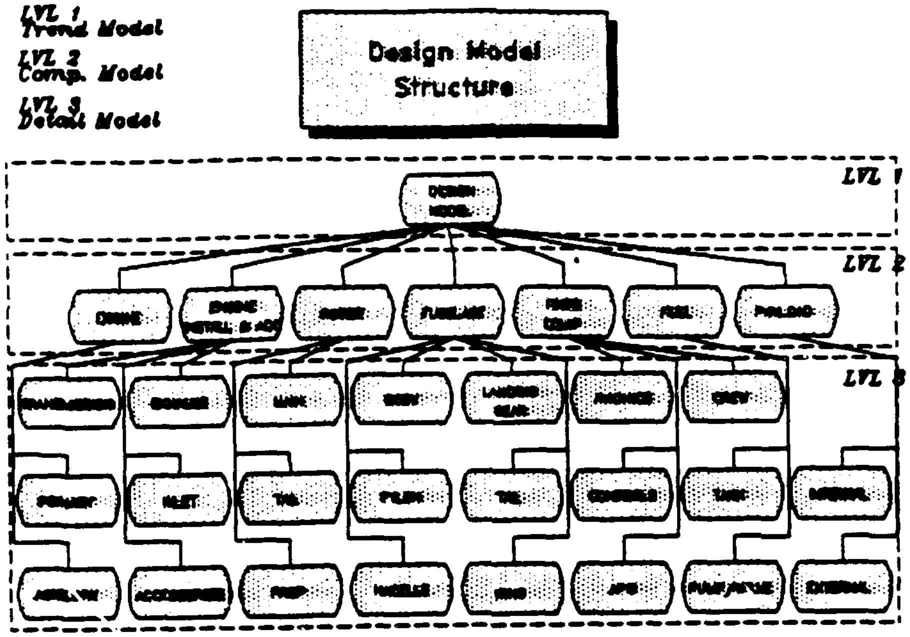

LVL 1 Trend Model
LVL 2 Comp. Model
LVL 3 Detail Model
Design Model Structure
LVL 1
LVL 2
LVL 3

Fig. 45

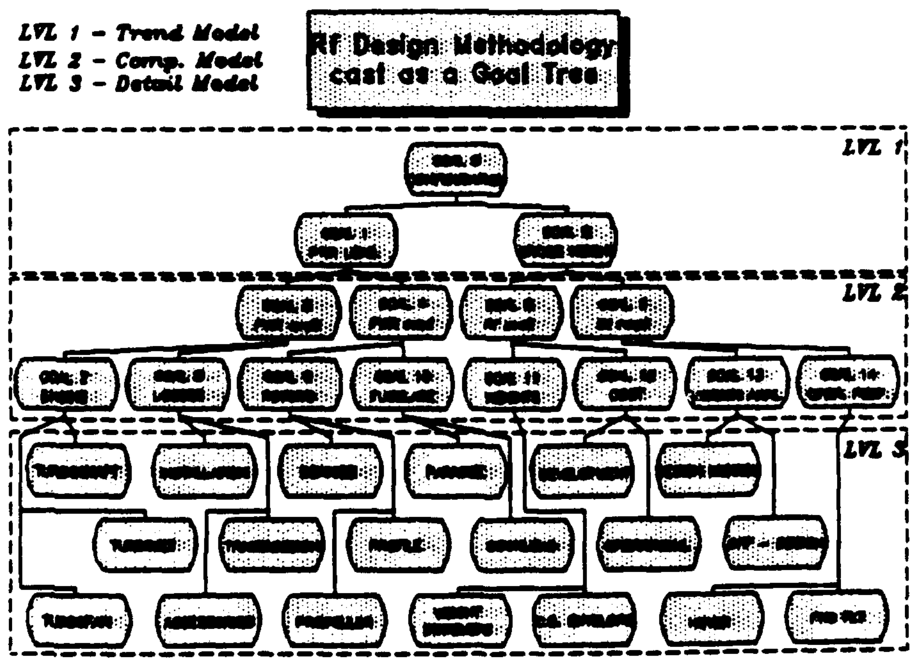

LVL 1 - Trend Model
LVL 2 - Comp. Model
LVL 3 - Detail Model
Rf Design Methodology cast as a Goal Tree
LVL 1
LVL 2
LVL 3

Fig. 46

J. Structural Identification for Fuselage Vibratory Characteristics
(ARO Fellow J. H. Gordis; Faculty Supervisor R. Bielawa)

Because of its importance to helicopter fuselage design, research was conducted to improve methods for structural system identification and modification as regards structural dynamics. A new general theory for frequency-domain structural synthesis was formulated, which encompasses and extends capabilities developed by prior investigators. It was based on a newly developed structural synthesis transformation and provided exact solutions for its various operations. The transformation, due to its generality, makes plain the equivalence of substructure coupling and structural modification, and allows any combination of said operations to be performed simultaneously. An important new feature of the transformation is the ability to include distributed (finite) elements in structural synthesis. Any number and type of new elements may be installed into an existing finite element model, eliminating the need for re-assembly. Further, implementation of the theory is straightforward.

Sample calculations were performed to show the practicality of the numerical procedures. A five segment, finite element model of a cantilever-free beam was postulated as representing a helicopter fuselage. Two segments of this beam were arbitrarily changed, as regards mass, stiffness and damping, to provide differing dynamic characteristics as might be typical of data obtained in tests of the first beam. The frequency domain structural synthesis transformation allowed the differences between the two descriptions to be decomposed into an "error" impedance matrix. This "error" impedance matrix itself was then decomposed into its component mass, stiffness and damping matrices. As this procedure can be performed on a frequency by frequency basis, any frequency-dependent mechanisms inherent in the actual structure can be accommodated inherently. This demonstration of the synthesis transformation showed that an exact solution for "physical" error parameters is available directly from response data. No eigensolution or modal parameter identification need be performed.

This research was concluded at the close of CY 1991, with presentations at regional and national competitions, which led to J.H. Gordis receiving the Robert L. Lichten Award during the American Helicopter Society Forum, in Washington, D.C., 23 May '90. Presentation was also made at the 16th European Rotorcraft Forum on 18 September 1990.

VI Technology Transfer

The research results generated on a campus will be considerably less likely to be useful if the faculty conducting that research are not continuously aware of the programs being undertaken and problems encountered by both researchers and practitioners in industry and government. Similarly, the most potentially useful university research result will lie fallow unless that same research, development, and user community beyond the campus is informed of the advances made on the campus in a timely manner. Both aspects call for technology transfer activities.

The former objectives have been furthered under the subject contract by faculty, staff and student attendance at professional society meetings and visits to government and industry sites, and by seminars on rotorcraft related subjects given on our campus on the part of members of government, industry and the faculties of other universities. Summaries of attendance at professional society meetings at national or international level, associated with Rensselaer RTC program objectives, is given in Table 12 and of RRTC visits to rotorcraft community organizations beyond the campus in Table 13. A similar summary of pertinent visits to our campus is contained in Table 14, showing seminars, workshops and technical discussions held with members of the rotorcraft community from beyond the campus.

The latter objectives, that is, transfer from the Rensselaer RTC to members of the rotorcraft technology community beyond the campus, is done in many ways. Among them are presentations made, papers published and presented, technical discussions held on and off campus, special courses offered for other than Rensselaer students (usually summer "short courses" as party of a continuing education program) individual faculty consulting and service on government advisory committees, and -- the most effective all-around measure -- placement of Rensselaer RTC graduates in rotorcraft technology organizations beyond the campus.

Table 15 lists papers published reporting results of the Rensselaer RTC program. This list includes those in refereed journals, proceedings of major professional society meetings, and the special Rensselaer RTC reports distributed to pertinent members of the rotorcraft community. Table 16 summarizes presentations made of similar results which have come about through the activities of the Center. Note that many of these presentations have been indicated in the listing of professional society meetings attended in Table 12.

Special short courses were given on campus during the contract period in two technology areas within which the Center has concentrated its research. These were "Advanced Composite Materials & Structures" and "Rotor Structural Dynamics, Aeroelasticity and Vibration". A summary of the dates of these offerings and the faculty involved is given in Table 17. Lists of attendees are given in Appendix D.

In September 1989 a second international workshop on Composite Materials and Structures for Rotorcraft was held on the campus, under the auspices of the Army Research Office, the American Helicopter Society and the RRTC. Pertinent committees, the workshop program and a list of participants are given in Appendix E.

Faculty members of the RRTC continued to take part during the contract period in the activities of organizations which contribute to the well-being of the wider rotorcraft community. A partial listing includes:

O. Bauchau	• Associate Editor for Structures, AHS Journal
R. Bielawa	• Member, Dynamics Technical Committee, AHS
M. Crespo da Silva	• Chairman, Third Pan American Congress on Applied Mechanics, Sao Paulo, Brazil, Jan. 1993.
R. Diefendorf	• Chairman, ARO Materials Science Fellowship Selection committee • Chairman, 2nd International Workshop on Composite Materials & Structures for Rotorcraft, Troy, NY, Sept. 1989.
P. Hajela	• Associate Editor, AIAA Journal • Member, AIAA Technical Committee on Multidisciplinary Design Optimization (Chair, Education Subcommittee) • Member, Editorial Boards: "Engineering Optimization" "Computing Systems in Engineering"
R. Loewy	• Member, Board of Directors, Vertical Flight Foundation • Member, Editorial Board, Vertica • Honorary Member, Dynamics Technical Committee, AHS • Member, Army Science Board ad hoc Committee on Comanche Internationalization
S. Sternstein	• Chairman, Sixth Technical Conference of the American Society of Composites, Albany, NY, Oct. 1991 • Member, Manufacturing and Product Assurance Technical Committee, AHS

Placement of graduates from the inception of the Rensselaer Rotorcraft Technology center program to the end date of the current contract are as shown in Table 18.

VII References

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3. Report of the Ad Hoc Committee to Review the Undergraduate Aeronautical Engineering Curriculum, Rensselaer Polytechnic Institute, Department of Mechanical Engineering, Aeronautical Engineering & Mechanics, September 1991.

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Table 12

Summary of Pertinent Professional Meetings Attended
During the Contract Period
Rensselaer Rotorcraft Technology Center

Date	Meeting	RRTC Personnel
1988		
1/11-14	AIAA 26th Aerospace Sciences Mtg. Reno, NV	R. Duffy H. Nagamatsu J. Straus*
2/16-18	2nd Int'l Conf. on Basic Research Univ. of Maryland, College Pk, MD	R. Bielawa R. Loewy S. Winckler
6/1-3	2nd Conf. on Non-Linear Vibrations, Stability & Dynamics of Structures & Mechanics, VPI & SU, Blacksburg, VA	M. Crespo da Silva
6/16-18	44th AHS Annual Forum Washington, D.C.	O. Bauchau M. Darlow J. Diefendorf R. Loewy P. Jones** R. Kraus*
8/2-3	Methodology Assessment Phase 2 Workshop, Ames RC, Moffett Field, CA	R. Loewy O. Bauchau M. Crespo da Silva
10/24-25	E.I. duPont, Advanced Materials Conf. Wilmington, DE	J. Diefendorf
10/25-27	AHS Nat'l Technical Specialists' Mtg on Advanced Rotorcraft Structures Williamsburg, VA	P. Jones** R. Kraus*
11/16-17	PERDA Review, WPAFB, Dayton, OH	J. Diefendorf
12/12	ARO Workshop on Multi-Body Dynamics Durham, NC	O. Bauchau

* ARO Fellow
** Graduate Student

<u>1989</u>

1/1-6	Pan-American Congress of Applied Mechanics, Rio de Janeiro, Brazil	M. Crespo da Silva
1/9-12	AIAA 27th Aerospace Sciences Mtg. Reno, NV	H. Nagamatsu
2/22-23	Workshop on Composite Materials, AFML Dayton, OH	J. Diefendorf
4/13-14	AIAA Student Conference, McGill Univ. Montreal, Canada	H. Nagamatsu
5/1-5	ASCE Structures Congress San Francisco, CA	M. Crespo da Silva
5/22-23	Workshop on Carbon Composites at Institute for Defense Analyses Washington, DC	J. Diefendorf
5/22-24	45th AHS Annual Forum Boston, MA	O. Bauchau R. Bielawa J. Diefendorf R. Loewy
6/12-15	AIAA Thermophysics, Fluid Dynamics Plasma, Computational Fluid Dynamics Conf., Buffalo, NY	H. Nagamatsu
6/26	19th Biennial Conf. on Carbon Penn State, PA	J. Diefendorf
9/7	Japanese High Temperature Composites Technology, Washington, DC	J. Diefendorf
9/17-21	12th Biennial Vibrations Conf. of the ASME, Montreal, Canada	M. Darlow
9/14-15	2nd International ARO/AHS/RPI Workshop on Composite Materials & Structures for Rotorcraft, R.P.I. Troy, NY	O. Bauchau M. Crespo da Silva J. Diefendorf R. Loewy B. Mathew* V. Paedelt
11/13-14	AHS Nat'l Specialists Mtg on Rotorcraft Dynamics, Ft. Worth, TX	O. Bauchau R. Loewy
11/27-12/1	Japanese High Temperature Composites Technology, Japan	J. Diefendorf

* Post-doctoral Fellow

1990

1/8-11	AIAA Aerospace Sciences Mtg Reno, NV	H. Nagamatsu
3/12-14	ARO-Duke Univ. Workshop on Rotorcraft Structural Dynamics & Aeroelasticity, Durham, NC	R. Loewy M. Crespo da Silva
3/28-29	Mtg of the Aerospace Engineering Bd of the Nat'l Res. Council, NASA Dryden Flight Research Facility	R. Loewy
4/2-4	31st Structures, Dynamics & Mat'ls Conf., Long Beach, CA.	R. Loewy
4/1-4	Int'l Conf. on Rotordynamics & Transport Phenomena, Honolulu, HA	M. Darlow
5/21-23	46th Annual AHS Forum, Washington, DC	R. Loewy R. Bielawa
6/12-13	Mtg of the Aerospace Engineering Bd of the Nat'l Res. Council, Washington, DC	R. Loewy
6/18-20	21st Fluid Dynamics Conf, AIAA, Seattle, WA	H. Nagamatsu
8/28	2nd World Congress on Computational Mechanics, Stuttgart, FRG	M. Shephard
9/18-19	Mtg of the Aerospace Engineering Bd of the Nat'l Res. Council, Washington, DC	R. Loewy
9/24-26	3rd Air Force NASA Symposium on Recent Advances in Multidisciplinary Analysis & Optimization, San Francisco, CA	P. Hajela
10/18-19	Mtg, Committee on Aeronautics Technology of the AeroSpace Engineering Bd, Nat'l Res. Council, Washington, DC	R. Loewy
11/7	Symposium on Computational Technology for Flight Vehicles, Washington, DC	M. Shephard
11/27	ASME Winter Annual Mtg, Dallas, TX	M. Shephard
11/27-28	Mtg, Committee on Aeronautics Technology of the AeroSpace Engineering Bd, Nat'l Res. Council, Washington, DC	R. Loewy

12/11-12	AIAA Nat'l Coalition for a Composites Plan of Action, Seven Corners, VA	S. Sternstein

<u>1991</u>

1/1-5	Gordon Conference on Composites Ventura, CA	S. Sternstein
1/2-4	II PACAM Congress on Applied Mechanics, Valparaiso, Chile	P. Hajela
1/30-2/15	ARO Conference on Polymers Asilomar, CA	S. Sternstein
3/25-27	Int'l Specialist Technical Mtg. on Rotorcraft Basic Research, GIT Atlanta, GA	R. Loewy O. Bauchau
4/8-10	32nd Structural Dynamics & Materials Conf., Baltimore, MD	P. Hajela
5/6-8	47th Annual Forum AHS, Phoenix, AZ	R. Loewy S. Hill* A. Peck** M. Zotto** A. Trainer**
7/15-19	Eighth Int'l Conf. on Composite Materials (ICCM/VIII), Honolulu, HI	S. Winckler
7/21-24	First U.S. Congress on Computational Mechanics, Chicago, IL	M. Shephard
9/23-26	AIAA/AHS Aircraft Design, Systems and Operations Mtg., Baltimore, MD	A. Trainer**
10/7-9	Sixth Technical Conf. of the American Society of Composites, Albany, NY	A. Peck* O. Bauchau
11/19-21	4th Workshop on Rotational Dynamics & Aeroelastic Stability Modeling, University of Md, College Park, MD	O. Bauchau M. Zotto*
12/3-7	Annual Winter Conf. of the ASME, Atlanta, GA	M. Shephard

* Graduate Student
** ARO Fellow

1992

4/21-24	AIAA/ASME/ASCE/AHS Structures, Structural Dynamics, & Material Conf. Dallas, TX	P. Hajela
4/30	ASME Materials & Aerospace Summer Mtg., Tempe, AZ	M. Shephard
5/14	3rd Int'l Conf. on CAD in Composite Material Technology, Newark, DE	M. Shephard
5/18-21	U.S. Army Aerostructures Mtg, Langley Research Ctr., Hampton, VA	R. Loewy R. Bielawa
6/3-5	48th Annual Forum AHS, Washington, DC	O. Bauchau R. Bielawa R. Loewy T. Butler** H.S. Chen Y. Cho* N.K. Kang* B. Webster**
6/7-11	4th Conf. on Nonlinear Vibrations, Stability & Dynamics of Structures & Mechanisms, V.P.I. & State Univ.	M. Crespo da Silva
6/21-23	IMACS-PDE 7 Conf. at Rutgers Univ. New Brunswick, NJ	B. Webster**
6/21-25	NATO Advanced Research Workshop on the "Topology Design of Structures" Sesimbra, Portugal	P. Hajela
6/22-23	ASME 1992 PVP Conference, New Orleans, LA	M. Shephard
6/22-24	AIAA 10th Applied Aerodynamics Conference, Palo Alto, CA.	Z. Rusak
8/18-19	Mesh Generation Round Table, Northwestern U., Evanston, IL	M. Shephard
9/21-23	4th AIAA/USAF/NASA Conference on Multidisciplinary Analysis and Design, Cleveland, OH	P. Hajela
9/28-10/2	AGARD Lecture Series on Unstructured Grid Methods for Advection Dominated Flows, Mountain View, CA.	M. Shephard

* Graduate Student
** ARO Fellow

10/13	Beamology Workshop, NASA Ames RC Moffett Field, CA	O. Bauchau
11/9-13	ASME Winter Annual Mtg, Anaheim, CA	O. Bauchau M. Shephard
11/9-11	3rd International Conference on Adaptive Structures, San Diego, CA	R. Loewy
12/7-8	Symposium on High Performance Computing for Flight Vehicles Washington, DC	M. Shephard P. Hajela
<u>1993</u>		
1/11-14	31st Aerospace Sciences Mtg., Reno, NV	B. Webster

Table 13

Summary of Visits to Off-Campus Rotorcraft Technology Related Organizations
During the Contract Period
Rensselaer Rotorcraft Technology Center

Date	Purpose of visit	Place	RRTC Personnel
1988			
1/14	Discuss Development of the Rotor Impedance Test Rig	Aeroflightdynamics Directorate, AVSCOM and NASA, Ames R.C.	R. Bielawa
5/3-4	Participate in DAMVIBS Workshop	NASA Langley R.C.	R. Bielawa
5/10-12	Presentation of Contract Program Plans to ARO Monitors & Evaluation Com.	Army Research Off. Durham, N.C.	O. Bauchau R. Diefendorf R. Kraus* R. Loewy S. Winckler
6/18	Mtg of Board of Trustees Vertical Flight Fdtn	A. H. S. Alexandria, VA	R. Loewy
8/3	Discussion of Rotorcraft R & D with Dr. R. Carlson	U.S.A. Aviation Directorate, Ames R.C., CA	R. Loewy
8/4	Discussion of Rotor Aero-dynamics as Applied in Helicopter Maneuvers with Dr. Chee Tung	U.S.A. Aviation Directorate, Ames R.C.	R. Loewy
8/5	Discussion of the Computer Program, "General Tilt Rotor" with Dr. Gary Churchill	NASA Ames R.C.	R. Loewy
9/26-27	Attend Mtg of Aerospace Engineering Board	National Research Council, Washington, DC	R. Loewy
9/29-30	Attend Mtg of Board on Army Science & Technology	National Research Council, Washington, DC	R. Loewy
10/13	Technical Discussion on Finite Element Modeling of Helicopter Blades	Sikorsky Aircraft Stratford, CT	O. Bauchau
12/15	Technical Discussion of Dynamics of Free Rotors	UTRC Hartford, CT	O. Bauchau

* Graduate Student

1989

2/14	Technical Discussion with B. Sopher	Sikorsky Aircraft Stratford, CT	O. Bauchau
2/21	Presented talk on "High Performance Composites"	G.E. R&D Center G.E. Aircraft Engine Div., Lynn, MA	J. Diefendorf
3/6-9	Attended a Rotorcraft Research Review	NASA Langley R.C. Hampton, VA	R. Bielawa
3/22	Presented talk on "Filament Winding of Complex Shapes"	Nippon Steel Tokyo, Japan	J. Diefendorf
3/29	Presented talk on "High Performance Fibers" as part of Distinguished Lecture Series	Pittsburgh Plate Glass, Pittsburgh, PA.	J. Diefendorf
4/24	Technical Discussion with L. Dineau	Lord Corp. Erie, PA	O. Bauchau
4/28	High Performance Composites Review	AFML, Dayton, OH	J. Diefendorf
5/10	Rotor Dynamics Discussion with B. Sopher	Sikorsky Aircraft Stratford, CT	O. Bauchau
5/15	Presented Seminar on Symbolic Computation Applications	G.I.T. Atlanta, GA	M. Crespo da Silva
6/2	Discussion regarding Rotor Impedance Test Rig with B. Gatzen	Hamilton Std. Hartford, CT	R. Bielawa
6/2	Discussion regarding Rotor Impedance Test Rig with E. Fradenburgh	Sikorsky Aircraft Stratford, CT	R. Bielawa
6/12	Discussion of Rotor/ Propeller Dynamics with B. Gatzen	Hamilton Std. Hartford, CT	O. Bauchau R. Bielawa
6/30	Rotor Aeroelasticity Discussion with B. Sopher	Sikorsky Aircraft Stratford, CT	O. Bauchau
7/12	Discussion of Advanced Advanced Matls and Applications	Lord Corp Erie, PA	O. Bauchau

7/19	Interfacing of the Finite Element Based Modal Analysis with R-Dyne	Sikorsky Aircraft Stratford, CT	O. Bauchau
8/14	Discussion regarding Nonlinear Aerodynamics with C. Tung & Y. Yu	U.S. Army Aeroflightdynamics Directorate, Ames R.C.	R. Loewy
8/21-23	Conducted mtg (as Chairman) of National Materials Advisory Board Committee on Fibers	Woods Hole, MA	J. Diefendorf
8/23	Technical Discussion of Helicopter Related Res.	UTRC, Hartford, CT	O. Bauchau
9/22	Presented Talk on Nonlinear Blade Dynamics Solution Methodologies	U.S. Army Aeroflightdynamics Directorate, Ames R.C.	M. Crespo da Silva
11/21	Interfacing the Finite Element Based Modal Analysis with R-Dyne	Sikorsky Aircraft Stratford, CT	O. Bauchau
11/15-16	Attended Mtg of Board on Army Science & Technology	U.S. Army Combined Arms Center, Ft. Leavenworth, KS	R. Loewy
12/11	Discussion Regarding NASA Rotorcraft Research with R. Whitehead	NASA HDQS Washington, D.C.	R. Loewy
12/12	Discussion of Advanced Matls & Concepts for Helicopter Hub Components	Lord Corp. Erie, PA	O. Bauchau
12/16	Discussion of Various Helicopter Research Projects	UTRC, Hartford, CT	O. Bauchau
<u>1990</u>			
2/7	Discussion of Composite Fabrication Methods	Automated Dynamics Corp., North Greenbush, NY	R. Loewy
3/7	Discussion of Composite Materials & Structures with Dr. J. Whiteside	Grumman Corp. Bethpage, NY	R. Loewy S. Sternstein
5/3	Discussion Regarding ARO COE Operations	AHS Headquarters Alexandria, VA	R. Loewy

7/19	Interfacing of the Finite Element Based Modal Analysis with R-Dyne	Sikorsky Aircraft Stratford, CT	O. Bauchau
7/19	Delivered Composites Seminar	G.E. Aircraft Engine Co. Evandale, OH	S. Sternstein
7/25	COE Presentation (with Profs. A. Gessow & D. Schrage) to ARO Director Dr. G. J. Iafrate, Drs. Singleton, Anderson, et al.	A R O, Research Triangle Park, NC	R. Loewy
7/26	Discussion of Ground/Air Resonance Problems of Helicopters with Prof. Peretz Friedmann	U C L A, Los Angeles, CA	R. Loewy
9/12	Discussion of Low-Disc-Loading U.A.V's with Messers C. Heber & R. Johnston	DARPA, Roslyn, VA	R. Loewy
11/7,8	ARO Disclosure Conference for Industry & Government Lab. Engineer/Scientists	A.R.O., Research Triangle Park, NC	O. Bauchau M. Darlow P. Hajela R. Loewy S. Sternstein S. Winckler M. Zotto* A. Peck*
11/29	Discussion of Rotorcraft Conceptual Design Process with Messers A. Schoen, H. Rosenstein, et al.	Boeing Helicopter Co., Philadelphia, PA	A. Trainer*
12/19	Discussion of Rotorcraft Conceptual Design Process with Messers J. Ferraro, J. Olson, et al.	Sikorsky Aircraft Stratford, CT	A. Trainer*
<u>1991</u>			
1/24	Review of Program on Aeronautical Materials & Structures	NASA Langley R.C. Hampton, VA	R. Loewy

* Graduate Student, ARO Fellow

1/29	Review of Program on Aeronautical Materials & Structures	NASA Lewis R.C. Cleveland, OH	R. Loewy
3/21	Discussion of Empirical Factors for Accurate Prediction of Elastic Modulus of Woven Composites	U.S. Composites East Greenbush, NY	S. Winckler
3/28	Presented Seminar on "Automatic Generation and Control of Finite Element Models"	U.S. Army Materials Technology Lab., Watertown, MA	M. Shephard
4/17	Present Seminar on Smart Structures - Stabilized, Unstable Surface Study Results	AFDL, WPAFB, OH	R. Loewy
4/18	Discussion of Smart Materials & Structures Developments	Grumman Aircraft Bethpage, NY	R. Loewy
5/25-6/16	Acted as Visiting Scientist for Dr. James McCroskey, Applying Advanced CFD Methods to Elastic Rotor Blades	NASA Ames R.C. Palo Alto, CA	O. Bauchau
6/21	Discussion of Composite Laminate Theory as Applied to Drive Shaft Coupling Analyses	General Composites Cohoes, NY	S. Winckler
7/30	Made Presentation and Lead Discussion on "Smart Structures-Stabilized Unstable Control Surfaces"	NASA Langley RC Hampton, VA	R. Loewy
8/12	Discussion of Rotorcraft Research Topics Related to Composites	Sikorsky Aircraft Stratford, CT	O. Bauchau R. Loewy M. Shephard S. Sternstein
8/14	Discussion of F.E. Methods for CFD with Prof. T. Hughes	Stanford Univ. and Centric Engrg Palo Alto, CA	M. Shephard B. Webster*
8/15	Gave Seminar, "Issues in Automatic Mesh Generation: Finite-Octree Based Solutions"	NASA Ames RC, Moffett Field, CA	M. Shephard

* Graduate Student, ARO Fellow

8/15	Discussion of F.E. Methods for CFD with Drs. J. McCrosky and R. Strawn	NASA Ames RC, Moffett Field, CA	M. Shephard B. Webster*
10/1	Discussion of F.E. Mesh Generation with Drs. A. Noor and R.E. Smith	NASA Langley RC, Hampton, VA	M. Shephard
10/1	Gave Seminar "Automation, Generation and Control of Engineering Analysis Models"	NASA Langley RC, Hampton, VA	M. Shephard
10/2	Discussion of Various Rotorcraft Research Topics	Sikorsky Aircraft Stratford, CT	O. Bauchau R. Loewy S. Winckler
10/14	Tour of Facilities & Discussion of RRTC Research	Robinson Heli-copters, Torrance CA	R. Loewy
10/18	Discussion of Various Rotorcraft Research Topics	Sikorsky Aircraft Stratford, CT	R. Loewy S. Sternstein & Ctr for Mfg Productivity Personnel
11/19	Gave Seminar in C.G. Johnson Colloquium Series "Aeroelasticity and the Tilt Rotor VTOL Aircraft"	Worcester Poly. Institute, Worcester, MA	R. Loewy
<u>1992</u>			
1/3	Discussed Rotorcraft Research at RPI with Dr. K. Rosen and Mr. E. Fradenburgh	Sikorsky Aircraft Stratford, CT	R. Loewy
1/8	Discussion of Rotorcraft Research Topics with Lt. Col. S. T. Fisher, USMCR	F A A Washington, DC	R. Loewy
1/13	Gave Seminar "Research Topics on Vortex Stability and Transonic Aerodynamics"	NASA Langley RC, Hampton, VA	Z. Rusak
2/4	Gave Seminar "Application of Neural Networks in Structural Design, including Application to Rotorcraft Structures"	Worcester Poly. Institute, Worcester, MA	P. Hajela

* Graduate Stuent, ARO Fellow

2/5	Discussion of Research on Composite Structures Applications to Rotorcraft	Boeing Helicopters Philadelphia, PA	R. Loewy H.S. Chen*
2/11	Discussion of Finite Element Models for Rotor Blades with R. Sopher	Sikorsky Aircraft Stratford, CT	O. Bauchau
2/14	Discussion of Activities of RPI's Scientific Computation Research Center	Theory Center, Cornell National Supercomputer Facility, Cornell University	M. Shephard
2/19	Discussion on Optimal Design of Rotor Blades Using Genetic Search	Boeing Helicopters Philadelphia, PA.	P. Hajela
3/25	Discussion of Rotorcraft Research	Schweizer Aircraft and IBM Defense System Div. Owego, NY	R. Loewy R. Bielawa
4/11-12	Gave Short Course "Optimal Design in Multidisciplinary Systems"	AIAA Professional Studies Series, Dallas, TX	P. Hajela
5/6	Gave Seminar "Automated Generation and Control of Analysis Discretizations for Solving Partial Differential Equations"	Minnesota Supercomputer Institute, Minneapolis, MN	M. Shephard
5/25	Discussion of Issues and Advances in Automatic 3-D Mesh Generation with Emphasis on Octree-Based Techniques	Norwegian Inst. of Technology, Trondheim, Norway	M. Shephard
6/6	Discussion of Potential CFD Research Collaboration on Automated Finite Element-Modeling Tools	UTRC E. Hartford, CT	M. Shephard B. Webster*
6/18	Discussion of Finite Element Models for Rotor Blades with R. Sopher	Sikorsky Aircraft Stratford, CT	O. Bauchau
6/25	Gave Seminar "Research Topics on Transonic Aerodynamics"	NASA, Ames RC,	Z. Rusak

* Graduate Student

7/8	Discussion of RRTC Research	Boeing Helicopters Philadelphia, PA	O. Bauchau P. Hajela R. Loewy S. Winckler B. Webster*
7/13	Discussion of RRTC Research	Sikorsky Aircraft Stratford, CT	R. Loewy O. Bauchau M. Shephard S. Winckler B. Webster*
7/28	Discussion of RRTC Research	Bell Helicopter Co	O. Bauchau R. Loewy B. Thompson B. Webster*
8/3-4	Discussion of RRTC Research	McDonnell Douglas Helicopter Co., Mesa, AZ	P. Hajela R. Loewy B. Webster*
8/5	Plant Tour and Discussion of Helicopter Maintenance	Air Services Int'l Scottsdale, AZ	R. Loewy
8/20-21	Gave Short Course "Optimal Design in Multidisciplinary Systems"	AIAA Hampton Roads Section, VA	P. Hajela
10/2	Made Presentation on Advances in Automatic 3-D Mesh Generation, Part of AGARD Lecture Series	NASA, Ames RC	M. Shephard B. Webster
10/22	Discussion of Rotor Dynamics with R. Sopher	Sikorsky Aircraft Stratford, CT	O. Bauchau
11/12	Discussion of Future NASA Research Program in Aeronautics with Administrator, Center Directors	NASA Hdqs Washington, DC	R. Loewy

* Graduate Student, ARO Fellow

Table 14

Visits By "Off Campus" Engineer/Scientists
to the Rensselaer Campus
on Rotorcraft Related Matters

During the Contract Period

Date	Subject	Visitor
1988		
3/8	Review of RRTC Programs & Plans in Rotorcraft Technology Research with Engineers of Sikorsky Aircraft and UTRC	D. Jenney P. Arcidiacono R. Carlson K. Furnes G. Schneider A. Schwabenbauer W. Twomey, all of Sikorsky; R. Chi M. Davis R. Olson W. Weller, all of UTRC
4/21	Seminar: Nonlinear Effects in the Static and Dynamic Behavior of Beams and Rotor Blades	D. Hodges, School of Aerospace Engrg, G.I.T.
5/4	Seminar: Modal Interactions in the Nonlinear Response of Structural Elements, Theory and Experiment	A. Nayfeh, Dept. of Engrg Sc & Mechanics V.P.I. & State Univ.
5/6	Seminar: Analysis of Elastic and Viscoelastic Composites with Growing Damage	R. A. Schapery, Mechanics & Materials Center, TX A&M Univ
5/24	Seminar: Dynamic Fracture Character-zation of Brittle Materials	K-H. Yang, Dept. of Civil Engrg. Univ of Washington
6/6-10	Summer Short Course on Rotor Structural Dynamics, Aeroelasticity & Vibrations	See Appendix D for list of Attendees
6/14	Seminar: Influence of Stresses on Ferromagnetic Hysteresis and Its Use As a Means of Nondestructive Testing	G. A. Maugin, Pierre-et- Marie Curie Laboratoire de modélisation en Mécanique, Paris, FR

6/21	Review of RRTC Research in Composites, Structural Dynamics, Vibrations and Aeroelasticity	R. Ormiston Aeroflightdynamics Directorate, AVSCOM, Ames RC
7/18-22	Summer Short Course on Composite Materials & Structures	See Appendix D for list of Attendees
9/22	Review of RRTC Educational & Research Programs	Messrs. P. Sintes, Director & G. Unternachrer, Assoc. Director School of Engineering, Univ. of Toulouse, FR
10/20	Site Visit to Review ARO Center of Excellence Program in Rotorcraft Technology	Drs. G. Anderson & F. Oertel
11/1	Seminar: Analytical and Numerical Study of Interaction Between Parametric & External Excitations	D. T. Mook V.P.I. & SU Blacksburg, VA
1989		
1/23	Vollmer W. Fries Lecture: "The Amazing Complexity Generated by Simple Processes"	Prof. J. Hubbard, Cornell Univ., Ithaca, NY
3/7	Seminar: Problems & Methods in Multidisciplinary Analysis and Design	Dr. P. Hajela, Univ. of Florida, Gainesville, FL
3/14	Seminar: State of Flight Technology at McDonnell Douglas Helicopter Co.	Dr. Joyanto Sen & Ms. Marilyn Smith, McDonnell-Douglas Helicopter Co., Flight Technology Dept, Mesa, AZ
3/15	Seminar: A Hybrid Perturbation Galerkin Technique with Applications to Differential Equations	Dr. James F. Geer, State University of NY, Binghamton
4/18-19	Site Visit to Review ARO Center of Excellence Program in Rotorcraft Technology	Drs. R. Singleton, G. Anderson, T. Doligalski, F. Oertel, (ARO); Dr. F. Bartlett, Mr. E. Austin, Dr. R. Strawn, (AVSCOM); Dr. G. D'Andrea (Watervliet Arsenal)

5/2	Annual P.E. Hemke Lecture: "Development of the Model 360 Advanced Composite Helicopter"	Kenneth Grina, former Vice President, Research & Engineering, Boeing Helicopter Co.
6/5-9	Special Short Course on Rotorcraft Structural Dynamics, Vibrations & Aeroelasticity	See Appendix D for list of Attendees
9/22	Seminar: The Part-Mating Function in CAD/CAM Systems	Profs. A. Clement & J. Pegna, Institut Superieur des Materiaus, St. Ouen, France and U. of Cal., Irvine, respectively.
10/12	Seminar: Damage Mechanisms in Continuous Fiber Reinforced Titanium Matrix Composites	Dr. W. Steven Johnson NASA, Langley RC
10/19	Seminar: Helicopter Vibration Reduction and a Quick Look at Tilt-Rotors (Jointly with Student Chapter, AHS)	Frank J. Tarzanin, Manager, Dynamics Projects, Boeing Helicopter Co.
11/3	Seminar: Investigations of Layered Composite Shells by Nonlinear Finite Element Methods	Dr. K. Dorninger, Vienna Technical Univ. Vienna, Austria
<u>1990</u>		
1/30	Review of Rotorcraft Center and Composites Lab	Profs. A. Nurick and J. Martins, Univ. of Witwatersrand, Johannesburg, South Africa
3/22	Review of Rotorcraft Center Activities	Mr. Dean Kamen, Chairman, Enstrom Helicopter Corp., Menominee, MI
5/8-9	Seminar: Viscoplasticity of Materials, and Discussion of Rotorcraft Technology	Profs. N. Cristescu & V.N. Constantinescu, Rectors of University of Bucharest & Polytechnic Institute of Bucharest, respectively

5/30	Seminar: On Experimental Investigation of Vortex Pair Interaction with a Clean or Contaminated Free Surface	Dr. Amir Hirsa University of Michigan
6/29	Site Visit to Review ARO Center of Excellence Program in Rotorcraft Technology	Drs. R. Singleton, G. Anderson, T. Doligalski F. Hurley - ARO; Col. A. Dull - USMA; Dr. G. D'Andrea, Watervliet Arsenal
7/9-13	Special Short Course on Rotorcraft Structural Dynamics, Vibrations & Aeroelasticity	See Appendix D for list of Attendees
7/23-27	Special Short Course on Advanced Composite Materials & Structures	See Appendix D for list of Attendees
8/8	Discussion of RPI Composite Materials & Structures Research	Dr. J. Whitesite & Mr. J. Anderson - Grumman
10/3	Seminar: Low Vibration Rotors - Proof of Concept	Mr. F. Tarzanin, Mgr. Dynamics Projects, Boeing Helicopter Co.
11/9	Seminar: Comprehensive 'Puma' Correlation Consortium Results to Date	Mr. W. Bousman, U.S. Army Aeroflight-dynamics Directorate, NASA Ames RC
12/12	Seminar: Basic Research Trends in Solid Mechanics	Dr. G. Haritos, Acting Director, Aerospace Sciences U.S. AFOSR
<u>1991</u>		
1/16	Review of Rensselaer Rotorcraft Technology Center	Mr. G. Singley, Deputy ASARDA, Dr. I. Iafrate, Director, ARO
2/15	Seminar: Composite Structures Designed for Impulsive Pressure Loads	Mr. Glenn Rossi, Boeing Helicopter Co.
3/4	Seminar: Studies of Lifting Rotors in Hover, Using Advanced Free Vortex Methods	Dr. Todd Quackenbush, Continuum Dynamics, Inc., Princeton, NJ
4/23	Seminar: Aircraft Combat Survivability as a Design Discipline - Fundamentals for Rotorcraft	Mr. N. Caravasos Boeing Helicopter Co.

4/24	Seminar: Computational Models for Multilayered Composite Plates and Shells	Prof. Ahmed K. Noor, NASA Langley RC
4/30	Seminar: Experimental Investigations of Turbulence and Its Control	Prof. T. Wei Rutgers Univ.
5/15	Site Visit to Review ARO Center of Excellence Program in Rotorcraft Technology	Drs. R. Singleton, G. Anderson, T. Doligalski - ARO; Dr. R. Strawn - AVSCOM, Ames RC
6/6	Seminar: Similarity in Fracture Mechanics & Scaling Laws for Fully Developed Turbulence	Prof. G. I. Barenblatt Shirshov Institute of Oceanology, Academy of Sciences, Moscow
7/18	Presentation - Rotorcraft Technology as a Field of Endeavor	PREFACE Program Participants. (Economically or educationally disadvantaged secondary school students.)
9/25	Seminar: Overview of Stability of Elastic Structures Subjected to Nonconservative Forces	Prof. A. Guran, Univ. of Toronto, Toronto, Canada
9/27	Review of Rensselaer Rotorcraft Technology Center (RRTC)	Dr. R. Chait, Chief Scientist, Army Material Command
10/7	Visit to Observe the Modus Operandi, Facilities & Faculty of the RRTC	Dr. F. Snyder & Ms. D. Buckanin, FAA Technical Ctr.
10/24	Seminar: Low Vibration Rotor Research	Mr. R. Gabel, Dynamics Technology Mgr, Boeing Helicopter Co.
10/30	Seminar: Computational Aspects of the the Homogenization Method for Study of Composite Materials	Prof. N. Kikucki, Univ. of Michigan, Ann Arbor, MI
10/31	Seminar: Dynamic System Modeling & Forecasting, Using System Identification on Neural Nets	Dr. R. Mehra, Scientific Systems, Woburn, MA

<u>1992</u>

1/8	Discussion of CFD Meshing Methodology	S. Lamson & G. Holmes - GE Corporate R&D
4/2	Discussion of CFD Meshing Methodology	Drs. L. Couchman, J. Grannell & J. Shirron, Naval Res. Lab.
6/24	Examination and Discussion of Model Rotor Impedance Test Rig	Messrs. P. Mirick & K. Dawson - NASA Langley RC.
10/5	Discussion of RRTC Research	Mr. F. Tarzanin, Mgr, Dynamics Projects, Boeing Helicopter Co.
10/6	Site Visit Review ARO Center of Excellence Program in Rotorcraft Technology	Drs. R. Singleton, G. Anderson, T. Doligalski, ARO
10/7	Seminar: Useful Applications of Smart Structures	Prof. D.J. Inman, V.P.I. & S.U., Blacksburg, VA
10/23	Seminar: The Possibilities for Active Noise Control	Dr. G.C. Maling, Jr. Noise Control F'd't'n Poughkeepsie, NY
11/20	Seminar: Business Directions and Materials Challenges for the Aircraft Engine Industry	Dr. J.C. Williams, G.E. Aircraft Engines
12/4	Discussion of Minimum-fuel Trajectory Computer for Helicopters	Messers C. Richardson, R. Kilmer, N. Kachman, F. Kilmer, IBM, Tech. Systems Co., Owego, NY
12/15	Seminar: Frontiers of Composites Research at ONERA	Dr. O. Sudre, Director of Materials, Onera, Paris, FR

<u>1993</u>

1/14	Seminar: Scaling Laws and Nonlocal Concepts for Mechanics of Damage	Dr. Z.P. Bazant Northwestern Univ.

Table 15

Rotorcraft Technology Papers Published During the Contract Period

Rensselaer Rotorcraft Technology Center

"Generalized Frequency Domain Substructure Synthesis", B. Jetmundsen, R.L. Bielawa and W.G. Flannelly, Journal of the American Helicopter Society, January 1988.

"Adaptive Analysis for Automated Finite Element Modeling", M. Shephard, Mathematics of Finite Elements and Application, J. Whiteman, Editor, Academic Press, 1988.

"Airfoil Pressure Measurements During a Blade-Vortex Interaction and a Comparison with Theory", J. Straus, P. Renzoni and R.E. Mayle, 26th AIAA Aerospace Sciences Meeting, Jan. 11-14, 1988, Reno, NV., AIAA Paper No. 88-0669, 1988.

"A Theoretical and Experimental Study of the Snap-Through Airfoil and Its Potential as a Higher Harmonic Control Device", R.E. Duffy, J. Dubben, J. Nickerson and J. Colasante, 26th AIAA Aerospace Sciences Meeting, Jan. 11-14, 1988, Reno, NV, AIAA Paper No. 88-0668, 1988.

"Experimental Verification of Optimized Helicopter Driveshaft Designs", R.F. Kraus, M.S. Darlow, W.P. Conley and P. L. Jones, Proceedings of the 2nd International Conference on Rotorcraft Basic Research, University of Maryland, College Park, MD, Feb. 16-18, 1988.

"Passive Transonic Drag Reduction of Supercritical and Helicopter Rotor Airfoils", H.T. Nagamatsu and T.W. Trilling, Proceedings of the 2nd International Conference on Rotorcraft Basic Research, University of Maryland, Feb. 16-18, 1988.

"Developmental Status of the RPI Model Rotor Impedance Test Facility", R.L. Bielawa, K.D. Hsueh, R.D. Martin and J-L. Terng, Proceedings of the Second International Conference on Rotorcraft Basic Research, University of Maryland, College Park, MD, Feb. 16-18, 1988.

"Torsional Buckling Analysis and Damage Tolerance of Graphite/Epoxy Shafts", O.A. Bauchau, T.M. Krafchak and J.F. Hayes, J. Composite Materials, Vol. 22, March 1988, pp. 250-270.

"Nonlinear Composite Beam Theory", O.A. Bauchau and C.H. Hong, J. Applied Mechanics, Vol. 55, No. 1, March 1988, pp. 156-163.

"Structural Dynamics of a Helicopter Rotor Blade System", A.V. Srinivasan, D.G. Cutts, H.T. Shu, D.L. Sharpe and O.A. Bauchau, Proceedings of the 44th AHS Forum and Technology Display, Washington, DC, June 16-18, 1988.

"Nonlinear Flexural-Flexural-Torsional-Extensional Dynamics of Beams: I. Formulation", M.R.M. Crespo da Silva, Int. Journal of Solids and Structures, Vol. 24, No. 12, pp. 1225-1234, 1988.

"Nonlinear Flexural-Flexural-Torsional-Extensional Dynamics of Beams: II. Response Analysis", M.R.M. Crespo da Silva, Int. Journal of Solids and Structures, Vol. 24, No. 12, pp. 1235-1242, 1988.

"Nonlinear Effects in the Static and Dynamic Behavior of Beams and Rotor Blades", D.H. Hodges, M.R.M. Crespo da Silva and D.A. Peters, Vertica, Vol. 12, No. 3, pp. 243-256, 1988.

"Uniaxial and Biaxial Fatigue Properties of Thin-Walled Composite Tubes", E. Krempl, D.M. Elzey, B.Z. Hong, T. Ayar and R.G. Loewy, Journal of the American Helicopter Society, Vol. 33, No. 3, pp. 3-10, July 1988.

"Nonlinear Response and Stability Analysis of Beams Using Finite Elements in Time", O.A. Bauchau and C.H. Hong, AIAA Journal, Vol. 26, No. 9, Sept. 1988, pp. 1135-1142.

"Design Strategies for the Development of a Model Helicopter Rotor Impedance Test Facility", R. Bielawa and K. Hseuh, VERTICA, Vol. 12, No. 1/2.

"Oscillating Flow Field Simulation in a Blow-Down Wind Tunnel and the Passive Shock Wave/Boundary Layer Control Concept", T. Mitty, H.T. Nagamatsu and G. Nyberg, Proceedings of 27th AIAA Aerospace Sciences Meeting, January 1989, Reno, NV.

"Validation of a Method for Air Resonance Testing of Helicopters at Model Scale Using Active Control of Pylon Dynamic Characteristics", R.L. Bielawa, Journal of the American Helicopter Society, Vol. 34, No. 2, April 1989.

"Analysis of the Non-Planar Response of a Cantilever with the Aid of Computerized Symbolic Manipulation", M.R.M. Crespo da Silva, Computer Utilization in Structural Engineering, Proceedings of the Structures Congress, ASCE, pp. 61-70, May 1-5, 1989.

"Torsional Buckling Analysis and Damage Tolerance of Graphite/Epoxy Shafts", Proceedings of the 45th AHS Annual Forum, O.A. Bauchau and A.W. Peele, May 22-24, 1989, Boston, MA.

"Helicopter Ground/Air Resonance Including Rotor Shaft Flexibility and Control Coupling", R.G. Loewy and M. Zotto, Proceedings of the 45th AHS Annual Forum, May 22-24, 1989.

"An Efficient Algorithm for the Demodulation of Narrow Band AM Signals - Theory and Implementation", R.L. Bielawa and K.D. Hsueh, Journal of Sound and Vibration, Vol. 134, No. 3, 1989.

"Analytical Failure Prediction of Bolted Connections in Composite Shafts", K.M. Furnes and D.B. Goetschel, Journal of the American Helicopter Society, Vol. 34, No. 3, July 1989.

"The Use of Functional Models to Control Engineering Idealizations", R. Wentorf, M.S. Shephard and E.V. Korngold, Computers in Engineering, Vol. 1, ASME, 1989, pp. 63-70.

"Analysis and Design of Curved Composite Beams", A. Peck and O. Bauchau, Proceedings 2nd ARO-AHS-RPI International Workshop on Composite Materials & Structures for Rotorcraft, Troy, NY, 9/14-15/89.

"Biaxial Fatigue of Epoxy Matrix Composites", E. Krempl, Proceedings 2nd ARO-AHS-RPI International Workshop on Composite Materials & Structures for Rotorcraft, Troy, NY, 9/14-15/89.

"Compression Failure and Delamination in Thermoplastic Composites", S.S.Sternstein, Proceedings 2nd ARO-AHS-RPI International Workshop on Composite Materials & Structures for Rotorcraft, Troy, NY, 9/14-15/89.

"Demonstration of a Supercritical Composite Helicopter Power Transmission Shaft", P.L. Hetherington, R.F. Kraus and M.S. Darlow, Journal of the American Helicopter Society, Vol. 35, No. 1, January 1990.

"Structural Dynamics of a Helicopter Rotor Blade System", A.V. Srinivasan, D.G. Cutts, H.T. Shu, D.L. Sharpe and O.A. Bauchau, Journal of the American Helicopter Society, Col. 35, No. 1, January 1990.

"Airfoil Pressure Measurements During a Blade-Vortex Interaction and a Comparison with Theory", J. Straus, P. Renzoni, R.E. Mayle, J. AIAA, Vol. 28, No. 2, Feb. 1990.

"Nonlinear Effects in Helicopter Rotor Forward Flight Forced Response", M.B. Mathew and R.G. Loewy, Vertica, Vol. 14, No. 1, 1990.

"Dynamics of Rotor Blades in Curved Steady Maneuver", W.C. Hassenpflug and M.R.M. Crespo da Silva, Proceedings of the Dynamics and Aeroelastic Stability Modeling of Rotorcraft Systems Workshop, Duke University, Durham, NC, March 12-14, 1990.

"The Rotorcraft Center of Excellence at RPI", R.G. Loewy, Proceedings of the Dynamics and Aeroelastic Stability Modeling of Rotorcraft Systems Workshop, Duke University, Durham, NC, March 12-14, 1990.

"Dynamic Analysis of Rotor Blades with Rotor Retention Design Variations", R.G. Loewy, A. Rosen, M.B. Mathew and M. Zotto, Proceedings of the 31st Structures, Structural Dynamics and Materials Conference, Long Beach, CA, April 2-4, 1990.

"Idealization in Engineering Modeling and Design", M.S. Shephard, Research in Engineering Design, Vol. 1, 229-238, 1990.

"Decomposition Methods in Quasi-Procedural Design", P. Hajela and N. Shankar, Proceedings of the 3rd Air Force/NASA Symposium on Recent Advances in Multidisciplinary Analysis and Optimization, September 1990, San Francisco, CA.

"Neural Networks in Multidisciplinary Aircraft Design", P. Hajela and S. Sharma, Proceedings of the II Pan American Congress on Applied Mechanics, Valparaiso, Chile, January 2-4, 1991.

"Damage Detection in Structural Systems", F.J. Soeiro and P. Hajela, Proceedings of the II Pan American Congress on Applied Mechanics, Valparaiso, Chile, January 2-4, 1991.

"Multicriterion Optimal Design of Structural Composites for Enhanced Damping Characteristics", P. Hajela and C. Y. Lin, Proceedings of the II Pan American Congress on Applied Mechanics, Valparaiso, Chile, January 2-4, 1991.

"Effects of Approximations on the Static and Dynamic Response of a Cantilever with a Tip Mass", M.R.M. Crespo da Silva, C.L. Zaretzky and D.H. Hodges, International Journal of Solids and Structures, Vol. 27, No. 5, pp. 565-583, 1991.

"The Reduction of Environmental Effects on Tension-Twist Coupled Composite Rotor Blades", S.C. Hill and S.J. Winckler, Proceedings of the International Technical Specialists' Meeting on Rotorcraft Basic Research, GIT, Atlanta, GA, March 25-17, 1991.

"Nonlinear Analysis of Anistropic Beams Including Warping Using Generalized Coordinates", R.G. Loewy, A. Rosen and M.B. Mathew, Proceedings of the International Technical Specialists' Meeting on Rotorcraft Basic Research, GIT, Atlanta, GA, March 25-17, 1991.

"On the Choice of Appropriate Bases for Nonlinear Dynamic Modal Analysis", O.A. Bauchau and N.K. Kang, Proceedings of the International Technical Specialists' Meeting on Rotorcraft Basic Research, GIT, Atlanta, GA, March 25-17, 1991.

"Dynamic Analysis of Rotor Flex-structures Based on Nonlinear Anisotropic Shell Models", O.A. Bauchau and W.Y. Chiang, Proceedings of the International Technical Specialists' Meeting on Rotorcraft Basic Research, GIT, Atlanta, GA, March 25-17, 1991.

"Genetic Search Strategies in Multicriterion Optimal Design", P. Hajela and C-Y. Lin, Proceedings of the 32nd SDM Mtg, Baltimore, MD, April 8-10, 1991.

"Evaluation of an Advanced Finite Element Analysis for Rotor Blades", S.Y.Chen, O.A. Bauchau and R. Sopher, Proceedings of the 47th Annual Forum of the American Helicopter Society, Phoenix, AZ, pp 1385-1397, May 6-8, 1991.

"A Unified Treatment for Dealing with Auxiliary Conditions in Blade Dynamics", A. Rosen, R.G. Loewy and M.B. Mathew, AIAA Journal, Vol. 29, No. 7, June 1991.

"Minimizing Hygrothermal Effects on the Dimensional Stability and Mechanical Properties of Composite Plates and Tubes", S. Hill and S.J. Winckler, Proceedings of the Eighth International Conference on Composite Materials, Honolulu, HI, July 15-19, 1991.

"Design and Implementation of a Goal and Analysis Manager for the Control of Analysis Idealizations", M. Shephard, Proceedings of the First U.S. National Congress on Computational Mechanics, Chicago, IL, July 22, 1991.

"Computational Geometry Issues in Automatic Mesh Generation: Finite Octree and Octree/Delaunay Based Solutions", M. Shephard, Proceedings of the First U.S. National Congress on Computational Mechanics, Chicago, IL, July 23, 1991.

"Explicit Node Point Smoothing", M. Shephard, Proceedings of the First U.S. National Congress on Computational Mechanics, Chicago, IL, July 23, 1991.

"Computer-Aided Conceptual Design of Rotorcraft", A. Trainer, Proceedings of the AIAA/AHS Aircraft Design, Systems and Operations Meeting, Baltimore, MD, Sept. 23-25, 1991.

"Automatic Three-Dimensional Mesh Generation by the Finite Octree Technique", M.S. Shephard and M.K. Georges, Int. J. Num. Meth. Engrg, Vol. 32, No. 4, pages 709-749, Sept. 1991.

"Advanced Finite Element Formulations for Composite Shells", M.W. Beall and M. Shephard, Proceedings of the 6th Technical Conference of the American Society for Composites, Albany, NY, Oct. 7-9, 1991.

"Design & Optimization of Curved Composite Beams", O.A. Bauchau and A. Peck, Proceedings of the 6th Technical Conference of the American Society of Composites, Albany, NY, Oct. 7-9, 1991.

"Stresses and Deformations in Thickwall Cylinders Subjected to Combined Loading and a Temperature Gradient", N. Tutuncu and S.J. Winckler, Proceedings of the 6th Technical Conference of the American Society of Composites, Albany, NY, Oct. 7-9, 1991.

"Passive Drag Reduction of a Helicopter Airfoil in an Unsteady Transonic Flow", H.T. Nagamatsu, M.A. Weston, A. Feingold and R.A. Smith, Proceedings of the International Technical Specialists Meeting on Rotorcraft Acoustics and Rotor Fluid Dynamics, Co-Sponsored by the American Helicopter Society and Royal Aeronautical Societies, Philadelphia, PA, Oct. 15-17, 1991.

"Toward Reliable Automated Analysis: Mesh Generation Developments", M. Shephard, Proceedings of the Second Workshop on Reliability and Adaptive Methods in Computational Mechanics, Krakow, Poland, Oct. 16, 1991.

"Multicriterion Optimal Design of Structural Composites for Enhanced Damping Characteristics", P. Hajela and C.Y. Lin, Applied Mechanics Review, Oct. 1991.

"Equations for Nonlinear Analysis of 3D Motions of Beams", M.R.M. Crespo da Silva, Applied Mechanics Review, Oct. 1991.

"A General Theory for Frequency Domain Structural Synthesis", J.H. Gordis, R.L. Bielawa and W.G. Flannelly, Journal of Sound and Vibration, pp 139-158, Oct. 1991.

"Multibody Formulation for Helicopter Nonlinear Dynamic Analysis", O.A. Bauchau and N.K. Kang, Proceedings of the Fourth Workshop on Dynamics and Aeroelastic Stability Modeling of Rotorcraft Systems, University of Maryland, College Park, MD, Nov. 19-21, 1991.

"Direct Integration of Helicopter Rotor Nonlinear Finite Element Dynamic Equations", O.A. Bauchau, Proceedings of the Fourth Workshop on Dynamics and Aeroelastic Stability Modeling of Rotorcraft Systems, University of Maryland, College Park, MD, Nov. 19-21, 1991.

"Influence of Pitch/Lag Couplings on Damping Requirements for 'Ground/Air Resonance' Stability", M. Zotto, Proceedings of the 4th Workshop on Dynamics & Aeroelastic Stability Modeling of Rotorcraft Systems, University of Maryland, College Park, MD, Nov. 19-21, 1991.

"Lamina Level Nonlinear Composite Mixing Models in Finite Element Computations", M.W. Beall, J.F. Wu and M.S. Shephard, Enhancing Analysis Techniques for Composite Materials, J.N. Reddy, Editor, New York, 1991.

"Static Strain Description & Vibration Characteristics of a Metal Semimonocoque Helicopter Tail Cone of Moderate Size", R.L. Bielawa, R.E. Hefner and A. Castagna, Rotorcraft Technology Center, Rensselaer Polytechnic Institute, RTC Report No. D-991-1 (republished as NASA CR 187576), 1991.

"Automatic Generation of Coarse Three-Dimensional Meshes Using the Functionality of a Geometric Modeler", M.S. Shephard and J.A. Lo, Advances in Engineering Software, 13(5/6):273-286, 1991.

"Two Prototypes Testing the U[illegible] of an Expert System in the Control of Structural Analysis Idealizations", R. Wentorf, A. [illegible]dhiraja, R.R. Collar, M.S. Shephard and P.L. Baehmann, Intelligent Scientific Software, [illegible]. Houstis, J.R. Rice, and R. Vichnevetsky, editors, pages 283-326, North Holland, Amste[illegible]m, 1992.

"A Posteriori Error Estimation For Triangular and Tetrahedral Quadratic Elements Using Interior Residuals", P.L. Baehmann, M.S. Shephard and J.E. Flaherty, Int. J. Numer. Engrg., 34:979-996, 1992.

"Analysis Idealization Control From Composite Materials with Nonlinear Materials", M.S. Shephard and M.W. Beall, Computer Aided Design in Composite Materials Technology III, S.G. Advani, W.R. Blain, W.P. de Wilde, J.W. Gillespie, Jr., and O.H. Griffin, Jr., editors, pages 313-330. Computational Mechanics Pub. and Elsevier Applied Science, 1992.

"Interaction of Functional and Geometric Models in Support of Analysis Idealization", M.S. Shephard, P.L. Baehmann, R. Wentorf and R.R. Collar, Computer Technology 1991: Advances and Applications, pages 21-30, ASME.

"The Subsonic and Transonic Flow Around the Leading Edge of a Thin Airfoil with a Parabolic Nose", Z. Rusak, Proceedings of the AIAA 10th Applied Aerodynamics Conference, Palo Alto, CA, June 1992.

"On the Design and Optimization of Curved Composite Beams", A.W. Peck and O.A. Bauchau, Proceedings of the 48th Annual Forum of the American Helicopter Society, Washington, DC, June 3-5, 1992.

"An Adaptive Finite Element Methodology for Rotorcraft Aerodynamics", B. Webster, Proceedings of the IMACS-PDE 7 Conference at Rutgers University, New Brunswick, NJ, June 21-23, 1992.

"Genetic Algorithms in Structural Topology Optimization", P. Hajela, E. Lee and C-Y. Lin, Invited Lecture, NATO Advanced Research Workshop, Sesimbra, Portugal, June 22-28, 1992, Topology Design of Structures, eds. M.P. Bendsoe and C.A. Mota-Soares, Kluwer Academic, 1992.

"Rotary Wing Structural Dynamics and Aeroelasticity", R.L. Bielawa, AIAA Education Series, 1992.

"Dynamic Analysis of Bearingless Rotor Blades Based on Nonlinear Shell Models with Drilling Degrees of Freedom", O.A. Bauchau and W.Y. Chiang, in Recent Advances in the Structural Dynamic Modeling of Composite Rotor Blades and Thick Composites, edited by P.P. Friedmann and J.B. Kosmatka, ASME, AD-Vol. 30, November 1992.

"Reliability of Automatic 3-D Mesh Generation", M.S. Shephard and M.K. Georges, Comp. Meth. Appl. Mech. Engng., 101:443-462, 1992.

"Idealization Control for the Analysis of Composite Materials", M.S. Shephard, J. Fish and M.W. Beall, Computing Systems in Engng., 3(1-4):443-456, 1992.

"A Multibody Formulation for Helicopter StrucDynamic Analysis", O.A. Bauchau and N.K. Kang, Journal of the American Helicopter Society: accepted for publication.

"Space-Time Perturbation Modes for Nonlinear Dynamic Analysis", O.A. Bauchau and C. Bottasso, Journal of Nonlinear Dynamics: accepted for publication.

"Dynamic Analysis of Bearingless Tailrotor Blades Based on Nonlinear Shell Models", O.A. Bauchau and W.Y. Chiang, Journal of Aircraft: accepted for publication.

"A Multibody Formulation for Helicopter Structural Dynamic Analysis", O.A.Bauchau and N.K. Kang, Journal of the American Helicopter Society, accepted for publication.

Table 16

Rotorcraft Technology Papers Presented During the Contract Period

Rensselaer Rotorcraft Technology Center

"Airfoil Pressure Measurements During a Blade-Vortex Interaction and a Comparison with Theory", J. Straus, P. Renzoni and R.E. Mayle, 26th AIAA Aerospace Sciences Meeting, Jan. 11-14, 1988, Reno, NV.

"A Theoretical and Experimental Study of the Snap-Through Airfoil and Its Potential as a Higher Harmonic Control Device", R.E. Duffy, J. Dubben, J. Nickerson and J. Colasante, 26th AIAA Aerospace Sciences Meeting, Jan. 11-14, 1988, Reno, NV.

"Experimental Verification of Optimized Helicopter Driveshaft Designs", R.F. Kraus, M.S. Darlow, W.P. Conley and P. L. Jones, 2nd International Conference on Rotorcraft Basic Research, University of Maryland, College Park, MD, Feb. 16-18, 1988.

"Developmental Status of the RPI Model Rotor Impedance Test Facility", R.L. Bielawa, K.D. Hsueh, R.D. Martin and J-L. Terng, Second International Conference on Rotorcraft Basic Research, University of Maryland, College Park, MD, Feb. 16-18, 1988.

"Applications of Composite Materials to Helicopter Structures", O.A. Bauchau, Center for Composite Materials and Structures Overview, Rensselaer Polytechnic Institute, March 2-3, 1988.

"Unsymmetric Composites", S.J. Winckler, Center for Composite Materials and Structures Overview, Rensselaer Polytechnic Institute, March 2-3, 1988.

"Nonlinear Dynamic Analysis of Composite Helicopter Rotor Blades", O.A. Bauchau, Invited Seminar at Syracuse University, Syracuse, NY, March 4, 1988.

"Nonlinear Effects in the Static and Dynamics Behavior of Beams and Rotor Blades", D.W. Hodges, M. Crespo da Silva and D.A. Peters, Second Conference on Non-Linear Vibrations, Stability, and Dynamics of Structures and Mechanisms, Virginia Polytechnic Institute and State University, Blacksburg, VA, June 2, 1988.

"Nonlinear Flexural-Flexural-Torsional Extensional Dynamics of Beams: Formulation and Response", M. Crespo da Silva, Second Conference on Non-Linear Vibration s, Stability, and Dynamics of Structures and Mechanisms, Virginia Polytechnic Institute and State University, Blacksburg, VA, June 2, 1988.

"Nonlinear Modal Coupling in the Response of Inextensional Beams", M. Crespo da Silva and C.L. Zaretzky, Second Conference on Non-Linear Vibrations, Stability and Dynamics of Structures and Mechanisms, Virginia Polytechnic Institute and State University, Blacksburg, VA, June 2, 1988.

"Structural Dynamics of a Helicopter Rotor Blade System", A.V. Srinivasan, D.G. Cutts, H.T. Shu, D.L. Sharpe and O.A. Bauchau, 44th AHS Forum and Technology Display, Washington, DC, June 16-18, 1988.

"Lift Deficiency Functions for Rotors with Blade Aspect Ratios of 6, 12 and 18 at Advance Ratios of 0 to 0.4", R.L. Milliken and R.E. Duffy, AIAA-AHS-ASEE Meeting on Aircraft Design and Operations, Atlanta, GA, Sept. 7-9, 1988.

"Demonstration of a Supercritical Composite Helicopter Power Transmission Shaft", P.L. Jones, R.F. Kraus and M.S. Darlow, AHS National Technical Specialists' Meeting on Advanced Rotorcraft Structures, Williamsburg, VA, Oct. 25-27, 1988.

"Oscillating Flow Field Simulation in a Blow-Down Wind Tunnel and the Passive Shock Wave/Boundary Layer Control Concept", T. Mitty, H.T. Nagamatsu and G. Nyberg, 27th AIAA Aerospace Sciences Meeting, January 1989, Reno, NV.

"The Status of University Programs Supporting the Rotorcraft Industry", R.G. Loewy, Philadelphia, PA, Chapter, American Helicopter Society, January 10, 1989.

"High Performance Fibers", R.J. Diefendorf, St. Louis Chapter ASM, McDonnell Douglas Aircraft Corp., Feb. 16, 1989.

"Compatible Composite Systems" and Oxidation of Carbon Fibers", R.J.Diefendorf, Workshop on Composite Materials, AFML, Dayton, OH, February 22-23, 1989.

"Transonic Passive Drag Reduction of a NACA 0012 Airfoil at a 2° Angle of Attack and a Mach Number of 0.86", L. Iman and H.T. Nagamatsu, AIAA Student Conference Competition, McGill Univ., Montreal, Canada, April 13-14, 1989.

"Analysis of the Non-Planar Response of a Cantilever with the Aid of Computerized Symbolic Manipulation", M.R.M. Crespo da Silva, Computer Utilization in Structural Engineering Congress, ASCE, pp. 61-70, May 1-5, 1989.

"DYMORE: A Finite Element Based Modal Analysis for Rotorcraft Aeroelastic Analysis", O.A. Bauchau, Sikorsky Aircraft, Stratford, CT, May 10, 1989.

"Torsional Buckling Analysis and Damage Tolerance of Graphite/Epoxy Shafts", 45th AHS Annual Forum, O.A. Bauchau and A.W. Peele, May 22-24, 1989, Boston, MA.

"Helicopter Ground/Air Resonance Including Rotor Shaft Flexibility and Control Coupling", R.G. Loewy and M. Zotto, 45th AHS Annual Forum, May 22-24, 1989.

"Mechanical Testing of Carbon Fibers", S.S. Tzeng and R.J. Diefendorf, 19th Biennial Conference on Carbon, Penn State Univ., PA, June 26, 1989.

"The Use of Functional Models to Control Engineering Idealizations", R. Wentorf, M.S. Shephard and E.V. Korngold, ASME Computers in Engrg. Conf., Anaheim, CA, July 31, 1989.

"Design Modeling Systems for Engineering Idealizations", M.S. Shephard, Northrop Aircraft Division, Los Angeles, CA, Aug. 2, 1989.

"The Reduction of Hygrothermal Effects on Tension-Torsion Coupling in Composite Rotor Blades", S. Hill, 2nd ARO-AHS-RPI International Workshop on Composite Materials & Structures for Rotorcraft, Troy, NY, 9/14-15/89.

"Analysis and Design of Curved Composite Beams", A. Peck and O. Bauchau, 2nd ARO-AHS-RPI International Workshop on Composite Materials & Structures for Rotorcraft, Troy, NY, 9/14-15/89.

"Biaxial Fatigue of Epoxy Matrix Composites", E. Krempl, 2nd ARO-AHS-RPI International Workshop on Composite Materials & Structures for Rotorcraft, Troy, NY, 9/14-15/89.

"Compression Failure and Delamination in Thermoplastic Composites", S.S.Sternstein, 2nd ARO-AHS-RPI International Workshop on Composite Materials & Structures for Rotorcraft, Troy, NY, 9/14-15/89.

"Dynamics of Rotor Blades in Curved Steady Maneuver", W.C. Hassenpflug and M.R.M. Crespo da Silva, Dynamics and Aeroelastic Stability Modeling of Rotorcraft Systems Workshop, Duke University, Durham, NC, March 12-14, 1990.

"The Rotorcraft Center of Excellence at RPI", R.G. Loewy, Dynamics and Aeroelastic Stability Modeling of Rotorcraft Systems Workshop, Duke University, Durham, NC, March 12-14, 1990.

"Dynamic Analysis of Rotor Blades with Rotor Retention Design Variations", R.G. Loewy, A. Rosen, M.B. Mathew and M. Zotto, 31st Structures, Structural Dynamics and Materials Conference, Long Beach, CA, April 2-4, 1990.

"Rensselaer's Center of Excellence in Rotorcraft Technology - the Who, What, Why, When and Where", R.G. Loewy, Univ. of Vt., Burlington, VT, April 1990.

"A Frequency Domain Theory for Structural Identification", J.H. Gordis, Winner, American Helicopter Society 1990 Robert L. Lichten Award Competition, 46th Annual AHS Forum, Washington, DC, May 23, 1990.

"Effects of Approximation on the Nonplanar Response of a Cantilever with a Large Tip Mass", M.R.M. Crespo da Silva, C.L. Zaretzky, 3rd Conference on Nonlinear Vibrations, Stability and Dynamics of Structures and Mechanisms, V.P.I., Blacksburg, VA, June 25-27, 1990.

"Nonlinear Flexural-Torsional Interactions in the Dynamic Response of Inextensional Beams", M.R.M. Crespo da Silva and C.L. Zaretzky, 3rd Conference on Nonlinear Vibrations, Stability and Dynamics of Structures and Mechanisms, V.P.I., Blacksburg, VA, June 25-27, 1990.

Nonlinear Vibrations of a Plane Frame Under Support Motion", J.C. Andre and M.R.M. Crespo da Silva, 3rd Conference on Nonlinear Vibrations, Stability and Dynamics of Structures and Mechanisms, V.P.I., Blacksburg, VA, June 25-27, 1990.

"Decomposition Methods in Quasi-Procedural Design", P. Hajela and N. Shankar, 3rd Air Force/NASA Symposium on Recent Advances in Multidisciplinary Analysis and Optimization, September 1990, San Francisco, CA.

"Finite Element Modeling and Ground Vibration Testing of a Helicopter Tailboom", R. Bielawa, Langley DAMVIBS and High-Speed Rotorcraft Technology Mtg., Langley Research Center, Sept. 11-12, 1990.

Nonlinear Dynamics of Flexible Multibody Systems with Rotating Components", O. Bauchau, Langley DAMVIBS and High-Speed Rotorcraft Technology Mtg., Langley Research Center, Sept. 11-12, 1990.

"Computer-Aided Conceptual Design of Rotorcraft", A. Trainer, 1991 AHS Lichten Competition, Northeast Region, Stratford, CT, January 8, 1991.

"Neural Networks in Multidisciplinary Aircraft Design", P. Hajela and S. Sharma, II PACAM Congress on Applied Mechanics, Valparaiso, Chile, January 2-4, 1991.

"Damage Detection in Structural Systems", F.J. Soeiro and P. Hajela, II PACAM Congress on Applied Mechanics, Valparaiso, Chile, January 2-4, 1991.

"Multicriterion Optimal Design of Structural Composites for Enhanced Damping Characteristics", P. Hajela and C. Y. Lin, II PACAM Congress on Applied Mechanics, Valparaiso, Chile, January 2-4, 1991.

"Delamination and Compression Strength of Composites", S.S. Sternstein, Invited Participant and Lecturer in ARO Asilomar Conference on Polymers, Jan. 30-Feb. 2, 1991.

"The Reduction of Environmental Effects on Tension-Twist Coupled Composite Rotor Blades", S.C. Hill and S.J. Winckler, International Technical Specialists' Meeting on Rotorcraft Basic Research, GIT, Atlanta, GA, March 25-17, 1991.

"Nonlinear Analysis of Anistropic Beams Including Warping Using Generalized Coordinates", R.G. Loewy, A. Rosen and M.B. Mathew, International Technical Specialists' Meeting on Rotorcraft Basic Research, GIT, Atlanta, GA, March 25-17, 1991.

"On the Choice of Appropriate Bases for Nonlinear Dynamic Modal Analysis", O.A. Bauchau and N.K. Kang, International Technical Specialists' Meeting on Rotorcraft Basic Research, GIT, Atlanta, GA, March 25-17, 1991.

"Dynamic Analysis of Rotor Flex-structures Based on Nonlinear Anisotropic Shell Models", O.A. Bauchau and W.Y. Chiang, International Technical Specialists' Meeting on Rotorcraft Basic Research, GIT, Atlanta, GA, March 25-17, 1991.

"Automatic Generation and Control of Finite Element Models", M. Shephard, U.S. Army Materials Technology Laboratory, Watertown, MA, March 28, 1991.

"Genetic Search Strategies in Multicriterion Optimal Design", P. Hajela and C-Y. Lin, 32nd SDM Mtg, Baltimore, MD, April 8-10, 1991.

"Design & Optimization of Curved Composite Beams", A. Peck, Univ. of Notre Dame, South Bend, IN, March 1991, Univ. of Wyoming, Laramie, WY, April 1991, and Pennsylvania State University, State College, PA, May 1991.

"Minimizing Hygrothermal Effects on the Dimensional Stability and Mechanical Properties of Composite Plates and Tubes", S. Hill and S.J. Winckler, Eighth International Conference on Composite Materials, Honolulu, HI, July 15-19, 1991.

"Design and Implementation of a Goal and Analysis Manager for the Control of Analysis Idealizations", M. Shephard, First U.S. National Congress on Computational Mechanics, Chicago, IL, July 22, 1991.

"Computational Geometry Issues in Automatic Mesh Generation: Finite Octree and Octree/Delaunay Based Solutions", M. Shephard, First U.S. National Congress on Computational Mechanics, Chicago, IL, July 23, 1991.

"Explicit Node Point Smoothing", M. Shephard, First U.S. National Congress on Computational Mechanics, Chicago, IL, July 23, 1991.

"Design and Test of an Electromagnetic Eddy Current Damper for a High-Speed Rotor", J. Frederick and M.S. Darlow, International Modal Analysis Conference, Florence, Italy, Sept. 16, 1991.

"Operation of a Torsionally-Loaded, Composite Shaft Above Two Flexural Critical Speeds", J. Frederick and M.S. Darlow, ASME Vibrations Conference, Miami, FL, Sept. 23, 1991.

"Computer-Aided Conceptual Design of Rotorcraft", A. Trainer, AIAA/AHS Aircraft Design, Systems and Operations Meeting, Baltimore, MD, Sept. 23-25, 1991.

"Application of Piezoelectric Elements in Panel Flutter Suppression", P. Hajela and R. Glowasky, AIAA/AHS/ASEE Aircraft Design Mtg., Baltimore, MD, Sept. 1991.

"Advanced Finite Element Formulations for Composite Shells", M.W. Beall and M. Shephard, 6th Technical Conference of the American Society for Composites, Albany, NY, Oct. 7-9, 1991.

"Design & Optimization of Curved Composite Beams", O.A. Bauchau and A. Peck, 6th Technical Conference of the American Society of Composites, Albany, NY, Oct. 7-9, 1991.

"Stresses and Deformations in Thickwall Cylinders Subjected to Combined Loading and a Temperature Gradient", N. Tutuncu and S.J. Winckler, 6th Technical Conference of the American Society of Composites, Albany, NY, Oct. 7-9, 1991.

"Passive Drag Reduction of a Helicopter Airfoil in an Unsteady Transonic Flow", H.T. Nagamatsu, M.A. Weston, A. Feingold and R.A. Smith, International Technical Specialists Meeting on Rotorcraft Acoustics and Rotor Fluid Dynamics, Co-Sponsored by the American Helicopter Society and Royal Aeronautical Societies, Philadelphia, PA, Oct. 15-17, 1991.

"Toward Reliable Automated Analysis: Mesh Generation Developments", M. Shephard, Second Workshop on Reliability and Adaptive Methods in Computational Mechanics, Krakow, Poland, Oct. 16, 1991.

"Multibody Formulation for Helicopter Nonlinear Dynamic Analysis", O.A. Bauchau and N.K. Kang, Fourth Workshop on Dynamics and Aeroelastic Stability Modeling of Rotorcraft Systems, University of Maryland, College Park, MD, Nov. 19-21, 1991.

"Direct Integration of Helicopter Rotor Nonlinear Finite Element Dynamic Equations", O.A. Bauchau, Fourth Workshop on Dynamics and Aeroelastic Stability Modeling of Rotorcraft Systems, University of Maryland, College Park, MD, Nov. 19-21, 1991.

"Influence of Pitch Lag Couplings on Damping Requirements for 'Ground/Air Resonance' Stability", M. Zotto, 4th Workshop on Dynamics & Aeroelastic Stability Modeling of Rotorcraft Systems, University of Maryland, College Park, MD, Nov. 19-21, 1991.

"Lamina Level Nonlinear Mixing Models in Finite Element Computations", M. Shephard, ASME, Atlanta, GA, Dec. 6, 1991.

"An Adaptive Finite Element Methodology for Rotorcraft Aerodynamics", B. Webster, 1992 Robert L. Lichten Award Competition Entry Representing the Northeast Region of the American Helicopter Society, March 1, 1992.

"The Subsonic and Transonic Flow Around the Leading Edge of a Thin Airfoil with a Parabolic Nose", Z. Rusak, AIAA 10th Applied Aerodynamics Conference, Palo Alto, CA, June 1992.

"Genetic Algorithms in Structural Topology Optimization", P. Hajela, Invited Lecture, NATO Advanced Research Workshop, Sesimbra, Portugal, June 22-28, 1992.

"Finite Octree Automatic Mesh Generation: Overview and Some Recent Developments", M. Shephard, Mesh Generation Round Table, Northwestern University, Evanston, Ill, Aug. 18, 1992.

"Issues and Advances in Automatic 3-D Mesh Generation with Emphasis on Octree-Based Techniques, and Adaptive Unsteady Aerodynamics Using the Time-Discountinuous gls Finite Element Method", M. Shephard, AGARD Lecture Series on Unstructured Grid Methods for Advection Dominated Flows, NASA AMES Research Laboratoties, Mountainview, CA, Oct. 2, 1992.

"Structural Models for Comprehensive Rotorcraft Analysis", O. Bauchau, Beamology Workshop, NASA Ames Research Center, Moffett Field, CA., Oct. 13, 1992.

"Dynamic Analysis of a Helicopter Tailrotor Based on Nonlinear Shell Models", O. Bauchau, ASME Winter Annual Meeting, Anaheim, CA, Nov. 9-13, 1992.

"Idealization Control for the Analysis of Composite Materials", M. Shephard, Symposium on High-Performance Computing for Flight Vehicles, Washington, D.C., Dec. 8, 1992.

Table 17

Short Courses Given During the Contract Period under RRTC Auspices

Topic	Dates	Lecturers	
Rotor Structural Dynamics, Aeroelasticity & Vibrations	June 6-10, '88; June 5-9, '89; and July 9-13, '90	O. Bauchau R. Bielawa D. Bliss F. Caradonna R. Loewy	RRTC RRTC Duke U US Army Aeroflight- dynamics Dir. RRTC
Composite Materials & Structures	July 18-22, '88 and July 17-21, '89	O. Bauchau R. Diefendorf G. Dvorak R. Loewy V. Paedelt	RRTC RRTC CE, RPI RRTC RRTC
	July 23-27, '90	O. Bauchau S. Dastin R. Diefendorf G. Dvorak R. Loewy V. Paedelt S. Tsai	RRTC Grumman A/C RRTC (Clemson U.) CE, RPI RRTC RRTC Stanford U.

Table 18

<u>Rotorcraft Related Placement of Graduates Since ARO RTC was Established</u>

Rensselaer Rotorcraft Technology Center

Year Organization	82/83	83/84	84/85	85/86	86/87	87/88	88/89	89/90	90/91	91/92
Bell Helicopter			D. Speaker[1]			R. Milliken*[3] K. Hsueh[3]				
Boeing Helicopter		M. Jenks*[2] R. Smith*[2] M. Niederer[2] A. Bertolazzi[2]	P. Welles[1] R. Tomlin*[2] M. Cawthorne[2]	J. Doran[2] J. Hayes*[2] J. Nickerson[2]			B. Mathew*[3]	T. Zientek*[2] R. Hymmen[2]	A. Trainer*[2]	A. Peck*[3]
Central Italian Aero Res.						P. Renzoni*[3]				
Corning Glass				R. Bergman*[2]				S. Robinson[1]	H. Gill[1]	
Det Norske Veritas, Norway				B. Jetmundsen*[3]						
Eastern Molding							C. Bonner*[2]			
ERA			J. Benario[1]‡							
FMC Corp.										J. Creonte*[2]
Garrett Turbine					T. Harris[1] M. Morris[1] R. Musiol[1]					
G.E. (Turb. or A/C Eng.)		D. Elzey*[2]	E. Degen*[3]		J. Carboni[1]				G.DeLeonardo[2] J.Korzendorfer[1] A. Lockhart[1]	P. Gendron*[2] D.T. Dang[1]
General Motors							P. Jones*[2]	B. Brosokas*[1]	D Kogut[1]	
Grumman				J. Colassante[2]						
Hamilton Standard								J. Connor[1] E. Scranton[1]		R. Cardona[2]
Helicopter Pilot Train.					M. O'Connor[2]					
H. Power										J. Straus*[3]
Kaman		P. Vrionides[2]								R. Walker[1]
LSI – Logic Corp.				B. Gregory*[2]						
Link-Singer			S. Garing*		G. Feder[2] P. Lewis[2]					
Lycoming							J. Ives[1]	P. Tangredi[2]		
Mat'l Proc Lab (Schenectady)							R. Kraus*[3]			

‡ Current, first USN Helicopter Columnist for RCM (radio control modeler)

<u>Rotorcraft Related Placement of Graduates Since ARO RTC was Established</u>

Rensselaer Rotorcraft Technology Center

Continued

Year / Organisation	82/83	83/84	84/85	85/86	86/87	87/88	88/89	89/90	90/91	91/92
MDHC (formerly Hughes)			J. Schorn[1] S. Casabella[1]			C. Pena				
MPR Assoc's (Wash, DC)								S. Bonner[1]		
NASA LaRC		C. Rumsey*[2]				J. Garrison[1] J. Hannon[1] W. Sasamoto[1]	M. DiFulvio			
NASA LeRC							J. Richard[3] I. Serbecti[3]	R. Goldberg[3] J. Moder[3]		
Robinson Helicopter Co.									R. Maciolek[2]	
RPI				S. Winckler*[3]	B. Mathew*[3]					
Sikorsky	P. Bogucki[1] P. Novoa[1] P. Dripnak[1]	W. Kim[3] J. Rios[1] S. Baxter[1] K. Furnes[2] P. Zoons[2]	R. Martin[1] J. Philcox[1] A. Trudeau[2] T. Kron[2] W. Beck[2]	S. Morris[1] S. Poulin[1] S. Sammatro[1]	D. Belluardo[1] S. Clarkson[1] M. Consolini[1] P. Dansreau[1] R. Halvorson*[2] C. Jaran*[3]	K. Deyo[2]			D.Goldschmidt[1] E. Mallen[1] M.E. Mudrick[1]	R. Heines[2] S. Kaluczky[1]
Structural Dyn'cs Res. Corp.								J. Gordis[3]		
SUNY Auditory Res Lab						K. Hsueh*[3]				
USA St. Louis & West Point			J. Planchak[2]							T. Hood[3]
US Air Force				T. Bidlack*[3]				R. Hall[3]	F. Stotz[1]	
US Coast Guard Acad								R. Yotto[2]		
UTRC		M. Malorin[1] J. Regelman[1]						A. Marchese[1]	T.D. Strayer[3]	W. Harrison[2]
Grad. Programs Elsewhere		F. Czajkowski*[2] (MIT)	J. Lim*[2] (U of MD)		T. Mitty*[2] (Princeton)		S. Liu[2] (RPI)	A. Dean (Penn State)		N. Alura[2] (Stanford)

*With support under ARO contract.

[1] B.S., [2] M.S., [3] Ph.D.

Appendix A

AGENDA

Rensselaer Rotorcraft Technology Center
Presentation for the

Evaluative Committee
Army Research Office
Durham, N.C.

5/10/88

(AM)	Topics	Presenter
8:15	RRTC Goals, Organization, Resources	R.G. Loewy
8:30	Educational Aspects: RPI as Setting	R.J. Diefendorf
8:45	Hygrothermal Effects on Elastically Coupled Composite Rotor Blades	S.J. Winckler
9:05	Optimization of Composite Drive Systems	R. Kraus*
9:45	Break	
10:00	Analysis and Design of Composite Fuselage Frames	O. Bauchau
10:30	Unconventional Composite Laminates for Rotorcraft	R. J. Diefendorf
10:50	Helicopter Rotor Loads in Violent Maneuvers	R.G. Loewy
11:30	Optimizing Composite Blades with Design Constraints	O. Bauchau
11:45	Wrap-Up	R.G. Loewy

* ARO Distinguished Fellow

Evaluative Panel
Attendance

Durham, N.C.

May 10, 1988

Dr. R. Singleton	Army Research Office
Dr. G. Anderson	Army Research Office
Dr. T. Doligalski	Army Research Office
Mr. E. Austin	USARTL
Dr. F. Bartlett	Aerostructures Directorate
Dr. C. Tung	AVSCOM - Ames

Agenda

ARO Site Visit 4/18-19/89

April 18

10:25	Arrival, Albany Airport	
	JEC Room 3117	
11:30	Introduction	R. Singleton (ARO)
11:35	Welcome & Overview	R. Loewy
12:00	Working Lunch	
	Interchange Session on Composites	
12:15	Innovative Composites	J. Diefendorf
12:30	Fuselage Frame Design	O. Bauchau
12:50	Composites & Environmental Effects	S. Winckler (with S. Hill*)
1:20	Discussion	
1:35	Composite Technology Transfer and Research Integration	F. Bartlett (Aerostructures)
2:15	Discussion	
2:30	Break	
	JEC Room 3012	
	Interchange Session on Structural Dynamics	
2:50	Damage Tolerance in Drive Shafts	O. Bauchau
3:05	Ground/Air Resonance with Shaft Flex'y	M. Zotto**
3:25	Fuselage Vibration Correlation	R. Bielawa (with J. Gordis**)
3:55	Discussion	
4:10	U.S. Army Dynamics Research Prog.	G. Anderson (ARO)
4:40	Discussion	
	Interchange Session on Rotorcraft Conceptual Design	
4:55	Computer-Aided Method Development	G. Gabriele (with A. Trainer**)
5:15	Discussion	
5:30	Closure	R. Loewy
5:35	Adjourn	
6:00	Dinner (Center Meeting Room)	

* Graduate Student
** ARO Distinguished Fellow

April 19 JEC 3117

Interchange Session on Maneuver Loads

8:00	Review of Integrated Approach	R. Loewy
8:05	Wake Aerodynamics	B. Webster**
8:15	C-60, Modal Analysis Adaptation	B. Mathew
8:35	Discussion	
8:50	U.S. Army Aerodynamics Research	T. Doligalski
9:20	U.S. Army Air ManueverProgram	E. Austin
9:50	Discussion	
10:05	Structural Dynamics Methodology	O. Bauchau
10:25	Aeroelastic Stability	M. Crespo da Silva
10:40	Discussion	
10:55	Closure	R. Loewy
11:00	Executive Session	
Noon	Working Lunch: Feedback	ARO Team and Faculty
12:45	Departure	

** ARO Distinguished Fellow

<u>ARO EVALUATIVE PANEL</u>

for

April 18-19, 1989

Dr. Robert Singleton, Chairman
Director, Engineering Sciences Div. - ARO

Dr. Gary Anderson, Contract Monitor
Chief, Structures & Dynamics Branch - ARO

Mr. Edward Austin
Chief Structures Lab.
AVSCOM - Ft. Eustis

Dr. Roger Strawn
Research Scientist
AVSCOM - Ames

Dr. Thomas Doligalski
Chief, Fluid Dynamics Branch - ARO

Dr. Fritz Oertel, Jr.
Chief, Multidis. Mechanics & Applications - ARO

Dr. Felton Bartlett, Jr.
Chief, Structures Div.
AVSCOM - Langley

Dr. Giuliano D'Andrea
Research Director
Watervliet Arsenal

Final Agenda

Site Visit
ARO Evaluative Panel
Rensselaer Rotorcraft Technology Center

June 29, 1990
JEC 3117

8:00	Welcome		Provost J. Meindl
8:05	Overview		R. Loewy
8:15	Innovative Composites for Rotorcraft		R. Fricke[1] (RJD)[2]
8:35	Fuselage Frame Optimization		A. Peck[1] (O.B.)
8:55	Hybrid Laminates with Elastic Coupling		S. Hill (E.B., S.W.)
9:15	Optimal Design and Demonstration: Supercritical Composite Shaft System		M. Darlow[1]
9:45	Mode Identification & Synthesis (Lab Walk-Through)		J. Gordis[3] (R.B.)
10:15	Break		
10:30	Idealization Control Techniques for Airframe Structural Analysis		M. Shephard[4]
10:50	Helicopter Ground/Air Resonance Analysis		M. Zotto[3] (R.L.)
11:10	R/C Helicopter Model Air Resonance Tests		R. Bielawa[4]
11:30	Lunch		
	Helicopter Maneuver Loads and Stability		
12:15	Introduction		R. Loewy[1]
12:25	FEM/Modal Methods		O. Bauchau[1]
12:45	Advanced Aerodynamic Formulation		B. Webster[3] (O.B.)
1:00	Blade Section Aerodynamics		R. Loewy[1]
1:20	Blade Vortex Interaction		J. Straus[3] (R.M.)
1:35	Aeroelastic Stability		M. Crespo da Silva[1]
1:55	Wrap-Up		R. Loewy
2:00	Break		
2:15	ARO Executive Session	JEC 3012	Drs. R.S., G.A., F.H., T.D.
2:15	RRTC-ITAP Interchange	JEC 3117	
2:45	Evaluation Feed-Back	JEC 3012	ARO-RRTC Exec. Com.
3:15	Adjourn		

NOTES:

1. ARO Contract Items
2. Initials in parentheses indicate responsible faculty member
3. ARO Distinquished Fellows
4. Other than ARO support

Attendance

ARO Evaluative Panel

Robert Singleton
Gary Anderson
Frank Hurley
Thomas Doligalski

Industrial Technical Advisory Panel

Debashis Banerjee
McDonnell Douglas Helicopter Co.

Raymond Carlson
Sikorsky Aircraft Div.

Troy Gaffey
Bell Helicopter Textron, Inc.

Andrew Lemnios
Kaman Aerospace Co.

John Shaw
Boeing Helicopter Co.

Rensselaer Rotorcraft Technology Center Faculty

Olivier Bauchau
Richard Bielawa
Eugene Brunelle
Marcelo Crespo da Silva
Mark Darlow
Prabhat Hajela
Robert Loewy
Henry Nagamatsu
Mark Shephard
Sanford Sternstein
Steven Winckler

Special Guest

Dr. Giuliano D'Andrea
Watervliet Arsenal

Lt. Col. Andrew Dull
U.S. Military Academy

Interim Agenda

Site Visit
ARO Evaluative Panel
Rensselaer Rotorcraft Technology Center

May 15, 1991
JEC 3117

8:00	Welcome & Overview		R. Loewy
8:20	Fuselage Frame Optimization Using Composites		A. Peck[1,2,3] (OB)
8:40	Characterization of Microcracking in Matrix Critical Composites		S. Hill[1,2] (SW)
9:00	Hybrid Laminates with Elastic Coupling		S. Winckler[1]
9:30	Crashworthiness & Innovative Composites		S. Sternstein[1]
10:00	Break		
10:15	Composite Shaft Optimization Studies		J. Creonte[1,2] (MD)
10:35	Shake Tests of Full Scale Components		R. Bielawa[4]
11:05	Flex-Structure Modelling		O. Bauchau[4]
11:35	Helicopter Ground/Air Resonance		M. Zotto[3]
12:00	Lunch		
	Helicopter Maneuver Loads and Stability		
12:30	Introduction		R. Loewy[1]
12:40	MultiBody FEM/Modal Methods		O. Bauchau[1]
1:10	Advanced Aerodynamic Formulations		B. Webster[3]
1:25	Automated FEM CFD Mesh Generator		M. Shephard[1]
1:40	Closing the Loop with Existing Programs		R. Loewy[1]
2:00	Aeroelastic Stability		M. Crespo da Silva
2:15	Research Forecast and Wrap-Up		R. Loewy
2:45	Break		
3:00	ARO Executive Session	CII 4003	
3:00	RRTC-TAP Exchange	JEC 3117	
3:30	Evaluation Feedback	CII 4003	ARO-RRTC Exec. Com.
4:00	Adjourn		

NOTES:

1 ARO Contract Items
2 Initials in parentheses indicate responsible faculty member
3 ARO Distinquished Fellow
4 Other than ARO support

Site Visit
ARO Evaluative Panel
Rensselaer Rotorcraft Technology Center

May 15, 1991

Evaluative Panel

Dr. Robert Singleton	ARO
Dr. Gary Anderson	ARO
Dr. Thomas Doligalski	ARO
Dr. Frank Hurley	ARO

Industry/Government Advisory Panel

Dr. Dev Banerjee	McDonnell Douglas
Mr. Troy Gaffey	Bell Helicopter
Dr. Dave Jenney	Sikorsky Aircraft
Dr. Andy Lemnios	Kaman Aerospace
Dr. John Shaw	Boeing Helicopter
Mr. Robert Huston	NASA Langley (for Dr. Wolf Elber, U.S. Army Aerostructures Directorate)

Final Agenda

Site Visit

Rensselaer Rotorcraft Technology Center

ARO Evaluative Panel

Dr. Gary Anderson
Dr. Thomas Doligalski
Dr. Robert Singleton

October 6, 1992
JEC 5030

7:30	Continental Breakfast	
8:00	Overview Update	R. Loewy
	<u>Composite Materials and Structures</u>	
8:15	Environmental Effects on Coupled Laminates	S. Winckler (S. Hill*)
8:45	Crashworthiness & Innovative Composites	S. Sternstein
9:10	Anisotropic Shell Models for Flexbeams	O. Bauchau
	<u>Optimization Studies</u>	
9:35	Genetic Alogorithms and Nonlinear Optimization	P. Hajela
10:05	Helicopter Blades with Adjustable Masses	O. Bauchau
	BREAK	
	<u>Maneuver Loads</u>	
10:40	Automated Adaptive Finite Element Methodology for Rotorcraft Aerodynamics	B. Webster*
11:10	Multibody Finite Element Methods	O. Bauchau
11:40	Maneuver Blade Load Studies	R. Loewy
12:00	LUNCH (Continued Informal Discussion)	
12:50	Helicopter Ground/Air Resonance	M. Zotto*
1:15	Smart Structure Stabilized Rotor	R. Loewy
1:35	ARO Executive Session	
2:00	Feedback Session	O. Bauchau/Loewy
2:20	Departure	

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* Graduate Students

Appendix B

List of Theses On Rotorcraft Technology Topics Written During the Contract Period

1988

"Passive Shock Wave/Boundary Layer Control on a Complete NACA 0012 Airfoil Model Using a Contoured Transonic Wind Tunnel", T. Trilling, May '88, M.S. Aero. Eng. (Nagamatsu)*

"Finite Element Based Modal Analysis of Helicopter Rotor Blades", S. P. Liu, Dec. 1988, M.S. (Bauchau)

"Design and Experimental Studies on Supercritical Composite Power Transmission Shafting", R. Kraus, Dec. 1988, Ph.D. (Darlow)

"Aerodynamics of a Lifting Rotor due to Near Field Unsteady Effects", R. Milliken, Dec. 1988, Ph.D. (Duffy)

1989

"The Effects of Transverse Shear Deflections on the Flap Bending Natural Frequencies and Mode Shapes of a Cantilever Composite Beam", C. Bonner, May 1989, M.S. (Loewy).

"Performance Verification of a Supercritical Composite Helicopter Power Transmission Shaft", P.L. Jones, May 1989, M.S. (Darlow)

"A Theoretical Study of Passive Drag-Reduction on Transonic Airfoils", B-Y. Kim, May 1989, Ph.D. (Brower)

"Fabrication of a Replacement Composite Longitudinal Floor Beam in the Aerospatiale HH-65A Helicopter", R.P. Yatto, August 1989, M.E. (Winckler)

"The Reduction of Hygrothermal Effects on Tension-Torsion Coupling of Proposed Composite Rotor Blades", S. Hill, Dec. 1989, M.S. (Winckler)

1990

"Effects of Molding and Fiber Continuity in Graphite Epoxy Pin Joints", R. Fricke, May 1990, Ph.D. (Diefendorf)

* Faculty member responsible as thesis advisor is shown in parenthesis.

"Effects of Steady Nonlinear Aerodynamics on Helicopter Maneuver Rotor Loads", M.E. Thesis, T.A. Zientek, May 1990, M.S. (Loewy)

"An Examination of Helicopter Ground/Air Resonance Including Rotor Shaft Flexibility and Associated Kinematic Control Coupling", M. Zotto, May 1990, M.S. (Loewy)

"On Structural Synthesis and Identification in the Frequency Domain", J.H. Gordis, August 1990, Ph.D. (Bielawa)

"The Design and Experimental Verification of an Electromagnetic Eddy Current Damper For Application to a Supercritical Composite Power Transmission Rotor", J. Frederick, August 1990, M.S. (Darlow)

"Development of a Structural Analysis Idealization Environment for Airframes", A. Budhiraja, August 1990, M.S. (Shephard)

"Optimization of Rotor Blades for Minimum Vibration with a Finite Element in Time Nonlinear Analysis", G. DeLeonardo, Dec. 1990, M.S. (Bauchau)

1991

"Thermal Stresses and Deformation in Composite Thin-Walled and Thick-Walled Tubes and Shells", N. Tutuncu, May 1991, Ph.D. (Winckler)

"Pressure and Velocity Measurements About an Airfoil During a Parallel Blade-Vortex Interaction", J. Straus, May 1991, Ph.D. (Mayle)

"On the Choice of Appropriate Bases for Nonlinear Dynamic Modal Analysis", D. Guernsey, May 1991, M.S. (Bauchau)

"Optimal Control and Structural Optimization of a Helicopter Blade Using Finite Elements in Time", V. Questiaux, May 1991, M.S. (Bauchau)

"Dynamics of Rotor Blades in Curved Steady Maneuver", W. Hassenpflug, July 1991, M.Eng., (Crespo da Silva)

"Elimination of Disproportionately Small Finite Element Segments From the Finite Octree Mesh Generator", N. Alura, Aug. 1991, M.S. (Shephard)

1992

"Multidisciplinary Optimal Design of a Helicopter Rotor Blade", M.C. Reed, May 1992, M.S. (Hajela)

"The Optimal Design of Supercritical Composite Drive Shafts with Axially Varying Cross-Section", J. Creonte, May 1992, M.S. (Darlow)

"Structural Dynamic Analysis of a Bearingless Rotor Blade", W. Chiang, August 1992, Ph.D. (Bauchau)

"Design and Analysis of Curved Composite Components for Rotorcraft Fuselage Frames", A. Peck, August 1992, Ph.D. (Bauchau)

"Investigation of Non-Linear Aerodynamic Effects on Helicopter Blade Loads in Maneuvers", P. Gendron, August 1992, M.S. (Loewy)

1993

"An Adaptive Finite Element Method for Unsteady Compressible Rotor Airfoil Aerodynamics", B. Webster, January 1993, Ph.D. (Shephard)

Appendix C

Summary of Brown Bag Lunch Schedules During the Contract Period Rensselaer Rotorcraft Technology Center

Spring 1988

Date	Topic	Resp. Faculty
Jan 18	Administrative Report	R. Bielawa
	Optimizing Composite Drive Systems	M. Darlow
	Use of Elastic Coupling in Blade Design	S. Winckler
Jan 25	Administrative Report	R. Loewy
	Ground Air Resonance	M. Zotto
	Passive Wave Drag Reduction	T. Trilling
Feb 1	Administrative Report	R. Loewy
	Emerging Discipline for Comprehensive Computer Programming	B. Mathew
	Birth of Bell Helicopter (film)	R. Duffy
Feb 8	Administrative Report	R. Bielawa
	Birth of Bell Helicopter (concluded)	R. Duffy
Feb 15	Administrative Report	R. Loewy
	Report on AIAA Aerospace Sciences Mtg.	R. Duffy H. Nagamatsu J. Straus
	Modal Approach to Helicopter Blade Dynamics	O. Bauchau
Feb 22	Administrative Report	R. Loewy
	Report on Int'l Conf. on Basic Rotorcraft Research	R. Bielawa M. Darlow R. Loewy H. Nagamatsu
	New Fabrication Symmetries	R. Diefendorf
Feb 29	Administrative Report	R. Loewy
	Impedance Test Rig	R. Bielawa
	Use of Generalized Coordinates in Blade Dynamics	R. Loewy
Mar 7	Administrative Report	R. Loewy
	Optimizing Composite Drive systems	M. Darlow
	Use of Elastic Coupling in Blade Design	S. Winckler
Mar 14	Administrative Report	R. Loewy
	Transonic Drag Reduction	H. Nagamatsu
	Ground Air Resonance	M. Zotto
Mar 21	Administrative Report	R. Loewy
	Analysis of Composite Helicopter Frames	O. Bauchau
	Vortex Interaction Testing	J. Straus

Mar 28	Spring Break	
Apr 4	Administrative Report	R. Loewy
	Fuselage Shake Testing	R. Bielawa
	Modal Approach to Helicopter Blade Dynamics	O. Bauchau
Apr 11	Administrative Report	R. Diefendorf
	Rotor Unsteady Aerodynamics	R. Duffy
	Optimizing Composite Drive Systems	M. Darlow
Apr 18	Administrative Report	R. Loewy
	Use of Generalized Coordinates in Blade Dynamics	R. Loewy
	New Fabrication Symmetries	R. Diefendorf
Apr 25	Administrative Report	R. Loewy
	Use of Elastic Coupling in Blade Design	S. Winckler
	Vortex Interaction Testing	J. Straus
May 2	Administrative Report	R. Loewy
	Transonic Drag Reduction	H. Nagamatsu
	Ground/Air Resonance	M. Zotto

Fall 1988

Sep 19	Welcome and Administrative Report	R. Loewy
	Ground/Air Resonance with Shaft Flexibility	R. Loewy
	FEM-based Modal Analysis of Rotor Blades	O. Bauchau
Sep 26	Administrative Report	R. Bielawa
	Environmental Effects on Composites	S. Winckler
	Wave Drag Reduction on Blade Tips	H. Nagamatsu
Oct 3	Administrative Report	R.J. Diefendorf
	Unbalanced Laminates	R.J. Diefendorf
	Fabrication of Curved Fuselage Members	O. Bauchau
Oct 10	No Classes	
Oct 17	Administrative Report	R. Loewy
	Update on Boeing Helicopter C-60 Project	B. Mathew
	Transverse Shear Effects on Composite Blade Modes	C. Bonner
Oct 24	General Discussion: What are the major issues in adapting composites to rotorcraft?	R. Bielawa, S. Winckler, O. Bauchau
Oct 31	Administrative Report	R. Loewy
	Recent Results in Non-Linear Blade Analysis	M. Crespo da Silva

Nov 7	Administrative Report	R. Loewy
	FEM in Blade Dynamics	O. Bauchau
	Blade Vortex Interaction	J. Straus
Nov 14	Administrative Report	R.J. Diefendorf
	Rotorcraft Design Optimization	G. Gabriele
	R/C Models for Ground/Air Resonance Res.	R. Bielawa
Nov 21	Administrative Report	R. Loewy
	General Discussion: Control Feedback in Helicopter Vibration	{ R. Loewy R. Bielawa
Nov 28	Administrative Report	R.J. Diefendorf
	Vortex Sheet Modeling, Including Roll-up	R. Duffy
	Affine Transformations in Fluid Mechanics	E. Brunelle
Dec 5	Administrative Report	R. Loewy
	Transonic Drag Reduction	H. Nagamatsu
	Advanced Airframe Structure Design System	M. Shephard
Dec 12	Administrative Report	R. Loewy
	Ground/Air Resonance with Shaft Flexibility	M. Zotto
	Rotor Impedance Test Rig	R. Bielawa

Spring 1989

Jan 16	Administrative Report	R. Loewy
	Hub Forces with Swashplate Motion	R. Loewy
	A Prescribed Wake Model for Rotorcraft Aerodynamic Analysis	O. Bauchau
Jan 23	Administrative Report	R. Loewy
	Linking Finite Element Analysis with Experimental Structural Dynamics	R. Bielawa
	Environmental Effects on Composites	S. Winckler
Jan 30	Administrative Report	R.J. Diefendorf
	Composites for Rotorcraft	R.J. Diefendorf
	FEM-based Modal Analysis of Rotor Blades	O. Bauchau
Feb 6	Administrative Report	R. Loewy
	Capsule History of Advanced Rotorcraft	R. Loewy
Feb 13	Administrative Report	R.J. Diefendorf
	Blade Vortex Interaction	J. Straus
	Ground/Air Resonance with Shaft Flexibility	M. Zotto
Feb 20	Administrative Report	R. Loewy
	Fabrication of Curved Fuselage Members	O. Bauchau
	Wave Drag Reduction on Blade Tips	H. Nagamatsu

Feb 27	Administrative Report Recent Results in Non-Linear Blade Analysis Use of Generalized Coordinates for Swept Blade Design	R.J. Diefendorf M. Crespo da Silva B. Mathew
Mar 6	Administrative Report General Discussion: Where does unsteady aerodynamics of rotors stand?	R. Loewy { R. Loewy A. Rosen O. Bauchau }
Mar 13	Administrative Report Computer-Aided Conceptual Design of Rotorcraft Helicopter Fuselage Vibration Testing	R. Loewy G. Gabriele R. Bielawa
Mar 20	Spring Break	
Mar 27	Administrative Report Environmental Effects on Composites FEM in Blade Dynamics	R. Loewy S. Winckler O. Bauchau
Apr 3	Administrative Report General Discussion: Issues in Applying Composites to Rotorcraft	R. Loewy { R.J. Diefendorf S. Winckler }
Apr 10	Administrative Report Transonic Drag Reduction Advanced Airframe Structure Design System	R. Loewy H. Nagamatsu M. Shephard
Apr 17	Administrative Report Ground/Air Resonance with Shaft Flexibility Rotor Impedance Test Rig	R. Loewy M. Zotto R. Bielawa
Apr 24	Administrative Report Blade Vortex Aerodynamics Unbalanced Laminates	R. Loewy J. Straus R.J. Diefendorf
May 1	Administrative Report Shear Effects in Nonlinear Blade Analysis Generalized Coordinate Analysis Results for Swept Blades	R.J. Diefendorf A. Rosen B. Mathew

<u>Fall 1989</u>

Sep 11	Administrative Report Reducing Hygrothermal Effects on Tension-Torsion Coupled Composite Rotor Blades Analysis & Design of Curved Composite Beams	R.J.Diefendorf S. Hill O. Bauchau

Sep 18	Administrative Report	R. Loewy
	Linking Finite Element Analysis & Experimental Structural Dynamics	R. Bielawa
	Blade Vortex Interaction	J. Straus
Oct 2	Administrative Report	R. Loewy
	Composites for Rotorcraft	R.J. Diefendorf
	FEM-Based Modal Analysis of Rotor Blades	O. Bauchau
Oct 9	Holiday	
Oct 16	Administrative Report	R. Loewy
	General Discussion: Aerodynamics in Comprehensive Rotor Analysis Programs: CAMRAD, C-60, ETC.	O. Bauchau, B. Webster, R. Loewy, T. Zientek
Oct 30	Administrative Report	J. Diefendorf
	Fabrication of Curved Fuselage Members	O. Bauchau
	Computer-Aided Conceptual Design of Rotorcraft	A. Trainer
Nov 6	Administrative Report	J. Diefendorf
	Recent Results in Non-Linear Blade Analysis	M. Crespo da Silva
	Optimization of Composite Shafts	M. Darlow
Nov 13	Administrative Report	J. Diefendorf
	Composites for Rotorcraft	R. Fricke
	Helicopter Fuselage Vibration Testing	J. Gordis
Nov 20	Administrative Report	R. Loewy
	Effect of Root Conditions on Blade Dynamics	R. Loewy
	FEM in Blade Dynamics	O. Bauchau
Nov 27	Administrative Report	R. Loewy
	General Discussion: Nonlinear Effects in Aeroelastic Instabilities	O. Bauchau, R. Bielawa, M. Crespo da Silva, R. Loewy
Dec 4	Administrative Report	R. Loewy
	Transonic Drag Reduction	H. Nagamatsu
	Advanced Airframe Structure Design System	M. Shephard
Dec 11	Administrative Report	R. Loewy
	Ground/Air Resonance with Shaft Flexibility	M. Zotto
	Rotor Impedance Test Rig	R. Bielawa

Spring 1990

Jan 22	Administrative Report	R. Loewy
	Blade Vortex Interaction	R. Mayle/J. Straus
	Blade Root Mechanism Effects on Structural Dynamics	R. Loewy
Jan 29	Administrative Report	R. Loewy
	Blade Root Mechanism Effects on Structural Dynamics (cont'd from 1/22)	R. Loewy
Feb 5	Administrative Report	R. Loewy
	Structural System Identification in the Frequency Domain	J. Gordis
	Stress Reduction Through Fiber Placement Around Holes	R. Fricke
	Visitor: Sharron Lifshitz - Aerospace Engrg Dept., Technion, Haifa, Israel	
Feb 12	Administrative Report	R. Loewy
	Modeling of Hub Kinematic Couplings due to Shaft Flexibility	M. Zotto
	Reduction of Hygrothermal Effects on Tension-Torsion-Coupled Composite Rotor Blades	S. Hill
Feb 19	Administrative Report	R. Loewy
	Computer-Aided Conceptual Design of Rotorcraft	A. Trainer
	Linking Finite element Analysis with Experimental Structural Dynamics	R. Hefner
Feb 26	Administrative Report	R. Loewy
	Curved Composite Beams	A. Peck
	Unsteady Transonic Drag Reduction	H. Nagamatsu
Mar 5	Administrative Report	R. Loewy
	Optimization & Experimental Composite Drive Shafts	J. Frederick
	Bearingless Rotor Blade Structural Dynamics	W.Y. Chiang
Mar 19	Administrative Report	R. Loewy
	Feedback: Rotor Dynamics Workshop at Duke University	M. Crespo da Silva & R. Loewy
	Application of Existing Rotor Aerodynamic Computer Programs to Maneuver Loads	T. Zientek
Mar 26	Administrative Report	R. Loewy
	Blade Root Mechanism Effects on Structural Dynamics	R. Loewy
	Advanced Airframe Structure Design System	M. Shephard

Apr 2	Administrative Report	R. Bielawa
	Stress Reduction Through Fiber Placement Around Holes	R. Fricke
	Acceleration Potential Aerodynamic Theory of Wings	B. Webster
Apr 9	Administrative Report	R. Loewy
	Feedback: 31st Annual Structures, Dynamics & Materials Conference	R. Loewy
	Reduction of Hygrothermal Effects on Tension-Torsion-Coupled Composite Rotor Blades	S. Hill
Apr 16	Administrative Report	R. Loewy
	Dynamics of Rotor Blades in a Curved Steady Maneuver	W. Hassenpflug
	Optimization & Experimental Studies of Composite Drive Shafts	J. Frederick
Apr 23	Administrative Report	R. Loewy
	Structural System Identification in the Frequency Domain	J. Gordis
	Blade Vortex Interaction	J. Straus
Apr 30	Administrative Report	R. Loewy
	Computer-Aided Conceptual Design of Rotorcraft	A. Trainer
	Curved Composite Beams	A. Peck

<u>Fall 1990</u>

Sep 10	Administrative Report	O. Bauchau
	Optimization & Experimental Studies of Composite Drive Shafts	M. Darlow
	Modeling of Hub Kinematic Couplings Due to Shaft Flexibility	M. Zotto
Sep 17	Administrative Report	R. Loewy
	Curved Composite Beams	A. Peck
	Finite Element Methods for Compressible Aerodynamics	B. Webster
Sep 24	Administrative Report	R. Loewy
	Computer Aided Conceptual Design of Rotorcraft	A. Trainer
	Report on DAMVIBS Meeting held at Langley 9/11-12	O. Bauchau, R. Bielawa

Oct 1	Administrative Report	O. Bauchau
	Maintaining Tension-Torsion-Coupling on Composite Rotor Blades	S. Hill
	Optimization of Helicopter Blades	O. Bauchau
Oct 8	Holiday	
Oct 15	Administrative Report	R. Loewy
	Helicopter Maneuver Loads Analysis	R. Loewy
Oct 22	Administrative Report	R. Loewy
	Dynamics of Rotor Blades in a Curved Steady Maneuver	M. Crespo da Silva
	Recent Advances in Optimization Theory	P. Hajela
Oct 29	Administrative Report	R. Loewy
	Advanced Airframe Structure Design System	M. Shephard
	Composites and Crashworthiness	S. Sternstein
Nov 5	Administrative Report	R. Loewy
	Curved Composite Beams	A. Peck
	Ground/Air Resonance with Shaft Flexibility	M. Zotto
Nov 12	Administrative Report	R. Loewy
	Analysis of Flex Structures	W. Chiang
	Finite Element Methods for Compressible Aerodynamics	B. Webster
Nov 19	Administrative Report	R. Loewy
	General Discussion: Low Vibration Rotor Optimization Studies	R. Loewy, P. Hajela, R. Bielawa, O. Bauchau
Nov 26	Administrative Report	O. Bauchau
	Computer Aided Conceptual Design of Rotorcraft	A. Trainer
	Use of R/C Models for Research	R. Bielawa
Dec 3	Administrative Report	R. Loewy
	Maintaining Tension-Torsion Coupling on Composite Rotor Blades	S. Hill
	Advanced Airframe Structure Design System	M. Shephard
Dec 10	Administrative Report	R. Loewy
	Optimization & Experimental Studies of Composite Drive Shafts	M. Darlow
	Optimization of Helicopter Blades	G. DeLeonardo

Spring 1991

Jan 14	Administrative Report	R. Loewy
	Ground/Air Resonance with Shaft Flexibility	M. Zotto
	Curved Composite Beams	A. Peck
Jan 21	Administrative Report	R. Loewy
	Finite Element Methods for Compressible Aerodynamics	B. Webster
	Accounting for Hub Accelerations Modal Blade Analysis	T. Butler
Jan 28	Administrative Report	R. Loewy
	Optimization & Experimental Studies of Composite Drive Shafts	M. Darlow
	Multivariate Control Systems	J. Chow*
Feb 4	Administrative Report	O. Bauchau
	Maintaining Tension-Torsion-Coupling on Composite Rotor Blades	S. Hill
	Modal Methods for Helicopter Rotor Blades	D. Guernsey
Feb 11	Administrative Report	R. Loewy
	General Discussion: Helicopter Crashworthiness	R. Loewy, S. Sternstein, P. Hajela
Feb 18	Administrative Report	R. Loewy
	Nonlinear Dynamics of Rotor Blades	Y. Cho
	Advanced Airframe Structure Design System	M. Shephard
Feb 25	Administrative Report	O. Bauchau
	Curved Composite Beams	A. Peck
	Ground/Air Resonance with Shaft Flexibility	M. Zotto
Mar 4	Administrative Report	R. Loewy
	Recent Advances in Optimization Theory	P. Hajela
	Helicopter Maneuver Airloads	P. Gendron
Mar 11	Spring Recess	
Mar 18	Administrative Report	O. Bauchau
	General Discussion: CFD Methodology	R. Webster, M. Shephard
Mar 25	Administrative Report	S. Sternstein
	Computer Aided Conceptual Design of Rotorcraft	A. Trainer
	Optimization & Experimental Studies of Composite Drive Shafts	J. Creonte

* Electrical, Computer and Systems Engineering Department

Apr 1	Administrative Report	R. Loewy
	Analysis of Flex Structures	W.Y. Chiang
	Summary of 3rd Int'l Conf. on Basic Rotorcraft Research, at G.I.T.	O. Bauchau, S. Hill, R. Loewy
Apr 8	Administrative Report	R. Loewy
	Maintaining Tension-Torsion-Coupling on Composite Rotor Blades	S. Hill
	Composites & Crashworthiness	S. Sternstein
Apr 15	Administrative Report	R. Loewy
	Advanced Airframe Structure Design System	R. Wentorf**
	Optimization of Helicopter Rotor Blades	M.R. Lee
Apr 22	Administrative Report	R. Loewy
	Nonlinear Dynamics of Rotor Blades	Y. Cho
Apr 29	Administrative Report	R. Loewy
	FEM for Rotor Aerodynamics	B. Webster
	Accounting for Hub Accelerations in Modal Blade Analyses	T. Butler

Fall 1991

Sep 16	Administrative Report	R. Loewy
	Ground/Air Resonance Including Kinematic Couplings	M. Zotto
	Computer Aided Conceptual Design of Rotorcraft	A. Trainer
Sep 23	Administrative Report	R. Loewy
	Maintaining Tension-Torsion-Coupling on Composite Rotor Blades	S. Hill
	Helicopter Maneuver Airloads	P. Gendron
Sep 30	Administrative Report	R. Loewy
	Optimization & Experimental Studies of Composite Drive Shafts	J. Creonte
	FEM for Rotor Dynamics	N.K. Kang
Oct 7	Administrative Report	R. Loewy
	Effect of Hub Accelerations on Rotor Blade Stability	W. Hassenpflug
	Accounting for Hub Accelerations in Modal Blade Analysis	T. Butler
Oct 14	Holiday	

** Scientific Computation Research Center

Oct 21	Administrative Report	R. Loewy
	Recent Advances in Optimization Theory	P. Hajela
	FEM for Rotor Aerodynamics	B. Webster
Oct 28	Administrative Report	R. Loewy
	Composites & Crashworthiness	S. Sternstein
	Optimization of Composite Blades	M.R. Lee
Nov 4	Administrative Report	R. Loewy
	Non-Linear Dynamics of Rotors	Y. Cho
	Ground/Air Resonance Including Kinematic Couplings	M. Zotto
Nov 11	Administrative Report	R. Loewy
	Maintaining Tension-Torsion-Coupling on Composite Rotor Blades	S. Hill
	FEM for Aerodynamics	M. Shephard
Nov 18	Administrative Report	R. Loewy
	FEM for Rotor Dynamics	N.K. Kang
Nov 25	Administrative Report	R. Loewy
	Report on 4th Rotor Dynamics Workshop, at U of Md.	O. Bauchau M. Zotto N. Kang
	Optimization & Experimental Studies of Composite Drive Shafts	J. Creonte
Dec 2	Administrative Report	R. Loewy
	Accounting for Hub Accelerations in Modal Blade Analysis	T. Butler
	Helicopter Maneuver Airloads	P. Gendron
Dec 9	Administrative Report	R. Loewy
	Composites & Crashworthiness	S. Sternstein
	Curved Composite Beams	A. Peck

<u>Spring 1992</u>

Jan 20	Administrative Report	R. Loewy
	Ground/Air Resonance Including Kinematic Couplings	M. Zotto
	Curved Composite Beams	A. Peck
Jan 27	Administrative Report	R. Loewy
	Maintaining Tension-Torsion-Coupling on Composite Rotor Blades	S. Hill
	FEM for Rotor Dynamics	N. K. Kang
Feb 3	Administrative Report	R. Loewy
	Optimization of Composite Blades	M. R. Lee
	FEM for Rotor Aerodynamics	B. Webster

Feb 10	Administrative Report	R. Loewy
	General Discussion: Wither Composites for Rotorcraft? (Blades, Fuselages, Transmissions, Shafts)	S. Sternstein O. Bauchau R. Loewy
Feb 17	Administrative Report	R. Loewy
	Accounting for Hub Accelerations in Modal Blade Analysis	T. Butler
	Non-linear Dynamics of Rotors	Y. Cho
Feb 24	Administrative Report	R. Loewy
	Composites & Crashworthiness	S. Sternstein
	Optimization & Experimental Studies of Composite Drive Shafts	J. Creonte
Mar 2	Administrative Report	R. Loewy
	Effect of Hub Accelerations on Rotor Blade Stability	W. Hassenpflug
	Helicopter Maneuver Airloads	P. Gendron
Mar. 9	Spring Break	
Mar 16	Administrative Report	R. Loewy
	FEM for Aerodynamics	M. Shephard
	Hygrothermal Effects on Fatigue Strength of Composite Joints	H. S. Chen
Mar 23	Administrative Report	R. Loewy
	Thermally Activated Composite Structures	S. Winckler
	Feedback-Stabilized Unstable Rotors	S. Tseng
Mar 30	Administrative Report	R. Loewy
	Ground/Air Resonance Including Kinematic Couplings	M. Zotto
	Recent Advances in Optimization Theory	P. Hajela
Apr 6	Administrative Report	R. Loewy
	Accounting for Hub Accelerations in Modal Blade Analysis	T. Butler
	Maintaining Tension-Torsion-Coupling on Composite Rotor Blades	S. Hill
Apr 13	Administrative Report	R. Loewy
	Composites & Crashworthiness	S. Sternstein
	Helicopter Maneuver Airloads	P. Gendron
Apr 20	Administrative Report	R. Loewy
	Nonlinear Dynamics of Rotors	Y. Cho
	FEM for Rotor Dynamics	N. K. Kang
Apr 27	Administrative Report	R. Loewy
	Effect of Hub Accelerations on Blade Stability	W. Hassenpflug
	Optimization of Composite Blades	M. R. Lee

Fall 1992

Sep 22	Administrative Report Feedback Stabilized Unstable Rotor Control Multibody FEM	R. Loewy S. Tseng G. Damilano
Sep 29	Administrative Report Environmental Effects on Bolted Composites Optimization of Composite Blades	R. Loewy H.S. Chen M. R. Lee
Oct 8	Administrative Report Report on ARO Site Visit FEM for Rotor Dynamics	R. Loewy R. Loewy N. K. Kang
Oct 15	Administrative Report Advanced Blade Tracking Research Thermally Activated Composite Structures	R. Loewy R. Bielawa C. Rekow
Oct 20	Administrative Report General Discussion: Smart Structures Applications to Rotorcraft	R. Loewy S. Winckler O. Bauchau R. Loewy I. Tadjbakhsh*
Oct 27	Administrative Report Accounting for Hub Accelerations in Modal Blade Analysis FEM for Rotor Aerodynamics	R. Loewy T. Butler B. Webster
Nov 3	Administrative Report Wake Model for a Manuevering Helicopter Composites & Crashworthiness	R. Loewy N. Theron S. Sternstein
Nov 10	Administrative Report Ground/Air Resonance Including Kinematic Couplings Environmental Effects on Bolted Composites	R. Loewy M. Zotto H.S. Chen
Nov 17	Administrative Report FEM for Rotor Aerodynamics Feedback Stabilized Unstable Rotor Control	R. Loewy M. Shephard S. Tseng
Nov 24	Administrative Report Maintaining Tension-Torsion-Coupling on Composite Rotor Blades Combining FEM-TM for Rotorcraft Analysis	R. Loewy S. Winckler N. Bhutani
Dec 1	Administrative Report Recent Advances in Optimization Theory Accounting for Hub Accelerations in Modal Blade Analysis	R. Loewy P. Hajela T. Butler
Dec 8	Administrative Report Thermally Activated Composite Structures FEM for Rotor Dynamics	R. Loewy C. Rekow N.K. Kang

* Director, ARO URI Project on Smart Materials at Rensselaer

ARO
ROTORCRAFT TECHNOLOGY CENTER
at RPI

Rotor Structural Dynamics, Aeroelasticity and Vibrations Short Course
June 6-10, 1988

List of Attendees

Berezin, Chip
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Domzalski, David B.
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Mesa, AZ

Gaetano, Armando J.
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Natick, MA

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Hansen, A. Craig
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ARO
ROTORCRAFT TECHNOLOGY CENTER
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Composite Materials & Structures
July 18-22, 1988

List of Attendees

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ARO
ROTORCRAFT TECHNOLOGY CENTER
at RPI

Composite Materials & Structures
July 18-22, 1988

List of Attendees

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ARO
ROTORCRAFT TECHNOLOGY CENTER
at RPI

Rotorcraft Structural Dynamics, Vibrations & Aeroelasticity
June 5-9, 1989

List of Attendees

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Gauthier, David
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ARO
ROTORCRAFT TECHNOLOGY CENTER
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June 5-9, 1989

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ARO
ROTORCRAFT TECHNOLOGY CENTER
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Composite Materials & Structures
July 17-21, 1989

List of Attendees

Barcus, Richard
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RPI Continuing Education

ATTENDEE LIST
FOR RSD90

Rotorcraft Structural Dynamics
CII
July 9, 1990 THRU July 13, 1990

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Matthews, William
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RPI Continuing Education

ATTENDEE LIST
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Composite Materials & Structures
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July 23, 1990 THRU July 27, 1990

Buettner, Arthur
Senior Development Engineer
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Ches, Chih-Tsai
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Fisher, David
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Groepler, David
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ANNOUNCEMENT

U.S. Army Research Office
Rensselaer Rotorcraft Technology Center
American Helicopter Society

SECOND INTERNATIONAL WORKSHOP

COMPOSITE MATERIALS & STRUCTURES FOR ROTORCRAFT

September 14 and 15, 1989
on the campus of Rensselaer Polytechnic Institute

General Chairman: Prof. R. J. Diefendorf
Rensselaer Polytechnic Institute, Troy, N.Y. 12180

Steering Committee:

Dr. Gary Anderson, Chairman	-ARO
Mr. Carl Albrecht	-Boeing Helicopter
Mr. G. Reis Alsmiller	-Bell Helicopter
Prof. John Dugundji	-MIT
Dr. Wolf Elber	-U.S. Army AATD
Mr. Samuel Garbo	-Sikorsky Aircraft
Dr. William Krueger	-DuPont
Mr. Andrew Logan	-McDonnell Douglas Helicopter
Mr. John Zugschwert	-AHS

Working Papers and Presentations are requested in the fundamental aspects of the theory, numerical analysis, design, structural analysis, fabrication, testing and qualification of advanced composite structures intended for use in rotorcraft. Examples of applications include , but are not necessarily limited to, rotor blades; drive shafting and transmissions; engine and propulsion group components; fuselages, pylons, fins, and tail surfaces; and landing gear. Examples of topics of interest include, "smart structures" concepts, aeroelastic tailoring; strength and fatigue life; material processing and manufacturing; NDI; toughness and damage tolerance; durability, ballistic damage and energy absorption effects; CAD/CAM and optimization methods; erosion, humidity, temperature and other environmental aspects.

Brief abstracts of such offerings should be received by the General Chairman by April 30, 1989. Attendance will be by invitation only, based solely on technical involvement in the field and on obtaining the widest possible organizational involvement, and limited to about 100, including presenters and session chairmen. Invitations will be sent with the final program by May 30, 1989.

PROGRESS REPORT

U.S. Army Research Office
Rensselaer Rotorcraft Technology Center
American Helicopter Society

SECOND INTERNATIONAL WORKSHOP

COMPOSITE MATERIALS & STRUCTURES FOR ROTORCRAFT

September 14 and 15, 1989
on the campus of Rensselaer Polytechnic Institute

Luncheon Speaker	Mr. Thomas Scarpati, Vice President Composite Business Development, Sikorsky Aircraft
Banquet Speaker	Mr. Allen C. Haggerty, Vice President and Bell-MDHC LHX Team Leader, McDonnell-Douglas Helicopter Company
Keynote	Dr. Thomas L. House, Technical Director, U.S. Army Aviation Systems Command and Technical Director, A.H.S.
Invited Presentations	Dr. A. Barth, Messerschmitt-Boelkow-Blohm, GmbH, "Structural Strength and Stiffness Analysis of Composite Rotor Components for Best Material Efficiency"
	Prof. E. Crawley, K. Lazarus and D. Warkentin, M.I.T, "Composites and Intelligent Structures"
	Mr. K. Stevenson, Bell Helicopter, "Composite Challenges in the V-22"
	Mr. A. Stevenson, Westland Helicopters Limited, "Rotor Blade Root End Design: To Wind or Drill?"

Session Chairmen	Mr. Robert W. Arden	U.S. Army AVSCOM
	Dr. Christian Gunther	Boeing Helicopter Co.
	Prof. Paul Lagace	M.I.T.
	Dr. Kevin O'Brien	U.S. Army Aerostructures Dir.
	Mr. George Schneider	Sikorsky Aircraft Div., UTC
	Prof. Sanford Sternstein	Rensselaer Polytechnic Institute

AGENDA

2nd ARO-AHS-RPI WORKSHOP ON COMPOSITE MATERIALS AND STRUCTURES FOR ROTORCRAFT

Room 4050 CII

September 14th

8:15-8:20 AM	WELCOME - R. *Judd Diefendorf* (Rensselaer Polytechnic Institute)
8:20-8:40 AM	KEYNOTE ADDRESS: *Thomas L. House*, Technical Director, U.S. Army Aviation Systems Command and Technical Director, American Helicopter Society, "Composite Structures for Rotorcraft— Meeting the Military Application Challenge"
SESSION I:	CHAIRMAN - *Christian K. Gunther* (*Boeing Helicopters*) Rotor Technology
8:45-9:15 AM	*"Rotor Blade Root End Design: To Wind or Drill?", A. *Stevenson*, Westland Helicopters Ltd., Yeovil, Somerset, United Kingdom.
9:15-9:45 AM	*"Structural Strength and Stiffness Analysis of Composite Rotor Components for Best Material Efficiency", A. *Barth*, Messerschmitt-Bolkow Blohm, GmbH, Munich, West Germany.
9:45-10:15 AM	"Stress Analysis of Composite Rotor Blades", M. *Borri and G. Ghiringhelli*, Politecnico di Milano, Milano, Italy.
10:15-10:30 AM	B R E A K (CII Lounge)
SESSION II.	CHAIRMAN - *Paul A. Lagace* (*Massachusetts Institute of Technology*) Composite Structural Design
10:30-11:00 AM	*"Composite Challenges on the V-22", M. K. *Stevenson*, Bell Helicopter, Fort Worth, Texas.
11:00-11:30 AM	"Analysis and Design of Curved Composite Beams", *O. A. Bauchau and A. W. Peck*, Rensselaer Polytechnic Institute, Troy, New York.
11:30-12:00 PM	"Dynamic Characteristics of Thin-Walled Composite Beams", *L. W. Rehfield*, University of California-Davis, Davis, California, *A. R. Atilgan and D. H. Hodges*, Georgia Institute of Technology, Atlanta, Georgia.
12:00-12:30 PM	"Evaluation of Composite Components on the Bell 206L and Sikorsky S-76 Helicopters", *D. J. Baker*, Aerostructures Directorate USAARTA AVSCOM, NASA Langley Research Center, Hampton, Virginia.
12:30-1:50 PM	L U N C H (Rensselaer Union, Rm 241-243)
1:15-1:45 PM	LUNCHEON ADDRESS: *Joseph Goldberg*, Program Manager, Sikorsky Aircraft-UTC, "Composite Developments in Rotor Systems"

[CONTINUED on PAGE 2]

September 14th

SESSION III: **CHAIRMAN** - ***Robert W. Arden (U.S. Army AVSCOM)***
Tailored Laminates

2:00-2:30 PM "The Reduction of Hygrothermal Effects on Tension-Torsion Coupling in Composite Rotor Blades", *S. C. Hill*, Rensselaer Polytechnic Institute, Troy, New York.

2:30-3:00 PM "Importance of Elastic Tailoring in Design Analysis of Thin-Walled Composite Beams", *A. R. Atilgan*(*), *L. W. Rehfield*(**), *and D. H. Hodges*(*), (*)Georgia Institute of Technology, Atlanta, GA, (**)University of California-Davis, Davis, California.

3:00-3:30 PM "Toward Understanding the Tailoring Mechanisms for Thin-Walled Composite Tubular Beams", *L. W. Rehfield*, University of California-Davis, Davis, California and *A. R. Atilgan*, Georgia Institute of Technology, Atlanta, Georgia.

3:30-3:45 PM **B R E A K (CII Lounge)**

SESSION IV: **CHAIRMAN** - ***Sanford S. Sternstein (Rensselaer Polytechnic Institute)***
Structural Integrity and Damage Mechanisms

3:45-4:15 PM "Damage Resistance in Rotorcraft Structures", *E. A. Armanios and B. H. Fortson*, Georgia Institute of Technology, Atlanta, Georgia.

4:15-4:45 PM "Biaxial Fatigue of Epoxy Matrix Composites", *E. Krempl*, Rensselaer Polytechnic Institute, Troy, New York.

4:45-5:15 PM "Structural Tailoring Techniques for Increased Delamination Resistance of Laminated Composites", *A. J. Vizzini and W. R. Pogue III*, University of Maryland, College Park, Maryland.

5:15-5:45 PM "Generalized Structural Integrity Assurance: Application to Rotorcraft", *W. T. Matthews*, U.S. Army Materials Technology Laboratory, Watertown, Massachusetts.

6:00-9:00 PM **C O C K T A I L S A N D B A N Q U E T (Sage Dining Hall)**

7:45-8:15 PM ***BANQUET SPEAKER: Jack D. Floyd***, Deputy Director, Super Team LHX Joint Program Office, Bell Helicopter/McDonnell-Douglas Helicopter Co., "LHX— A New Composite Helicopter"

[CONTINUED on PAGE 3]

September 15th

SESSION V: CHAIRMAN - *Jeffrey A. Hinkley (NASA-Langley)*
Thermoplastics versus Thermosets

8:15-8:45 AM "The Adhesion of Carbon Fibers to Thermoset and Thermoplastic Polymers", *W. D. Bascom*, University of Utah, Salt Lake, Utah.

8:45-9:15 AM "Compression Failure and Delamination in Thermoplastic Composites", *S. S. Sternstein*, Rensselaer Polytechnic Institute, Troy, New York.

9:15-9:45 AM "Advanced Thermoplastic Composite Structures for Rotorcraft Applications", *J. F. Pratte*, E. I. DuPont De Nemours & Co., Wilmington, Delaware.

9:45-10:15 AM "Thermoplastic Prepreg Product Forms", *T. L. Greene*, BASF, Charlotte, North Carolina.

10:15-10:45 AM "Advanced Thermoset Resin Systems", *W. T. McCarvill*, Hercules, Inc., Magna, Utah.

10:45-11:00 AM **B R E A K (CII Lounge)**

SESSION VI: CHAIRMAN - *George J. Schneider (Sikorsky Aircraft Division, UT*
Intelligent Structures and Active Control

11:00-11:30 AM *"Embedded Actuation and Processing in Intelligent Materials", *E. F. Crawley, K. B. Lazarus, and D. J. Warkentin*, Massachuset Institute of Technology, Cambridge, Massachusetts.

11:30-12:00 PM "Dynamically-Tunable Smart Composites Featuring Electro-Rheological Fluids", *M. V. Gandhi and B. S. Thompson*, Michigan State University, East Lansing, Michigan.

12:00-12:30 PM *"Active Dynamic Tuning Utilizing SMA Composites", C. A. *Rogers*, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

12:30-1:00 PM "A Review of Active Noise Control Strategies for Reduction of Rotorcraft Interior Noise", *J. D. Jones*, Purdue University, West Lafayette, Indiana.

1:00-2:15 PM **L U N C H (Fac/Staff Center Meeting Room - Sage Dining Hall)**

A D J O U R N

***INVITED PAPERS**

LIST OF ATTENDEES

2nd ARO-AHS-RPI Workshop on Composite Materials and Structures for Rotorcraft

September 14 & 15, 1989
Rensselaer Polytechnic Institute
Troy, NY 12180-3590

Gary Anderson - ARO-Durham, NC
Robert W. Arden - U.S. Army AVSCOM
Ali R. Atilgan - Georgia Tech.
M. Arockiasamy - Florida Atlantic U.
Donald J. Baker - U.S. Army Aerostructures Directorate
Armin Barth - MBB, GmbH
Felton D. Bartlett, Jr. - U.S. Army Aerostructures Directorate
Olivier A. Bauchau - RPI
Marco Borri - Politecnico di Milano
John F. Caccamo - Lord Aerospace
Doug Cairns - Hercules, Inc.
Ramesh Chandra - U. of Maryland
Edward F. Crawley - MIT
Marcelo Crespo da Silva - RPI
Giuliano D'Andrea - Benet Labs., Watervliet Arsenal
Mark S. Darlow - RPI
R. Judd Diefendorf - RPI
John Dugundji - MIT
Jack D. Floyd - Bell Helicopter, Textron
John E. Fontenot - Lord Aerospace
Bryan H. Fortson - Georgia Tech.
Jeff Frederick - RPI
Roland Fricke - RPI
Mukesh V. Gandhi - Michigan State U.
Joseph Goldberg - Sikorsky Aircraft Div., UTC
Tim L. Greene - BASF
Christian K. Gunther - Boeing Helicopter Co.
Stephen C. Hill - RPI
Jeffrey A. Hinkley - NASA Langley Research Center
Thomas L. House - US Army AVSCOM
James D. Jones - Purdue U.
Rakesh K. Kapania - VPI
Erhard Krempl - RPI
William Krueger - DuPont
Paul A. Lagace - MIT
Edward F. Lauser, Jr. - Boeing Helicopter Co.
Robert G. Loewy - RPI
Paul Maloney - KAMAN Aerospace
Leonard J. Marchinski - Leonard Associates
Bobby Mathews - RPI
William T. Matthews - U.S. Army MTL
William T. McCarvill - Hercules
Peter O'Hare - Benet Labs., Watervliet Arsenal
Volker Paedelt - RPI
Ann W. Peck - RPI
James F. Pratte - DuPont
Bill Reinfelder - Sikorsky Aircraft Div., UTC
Craig A. Rogers - VPI
Glenn Rossi - Boeing Helicopter Co.

[Cont'd. - See reverse]

LIST OF ATTENDEES (Cont'd.)

Erik S. Saether - U.S. Army MTL
George J. Schneider - Sikorsky Aircraft Div., UTC
Joyanto K. Sen - McDonnell Douglas Helicopter Co.
Mrityunjay Singh - RPI
Edward C. Smith - U. of Maryland
Sanford S. Sternstein - RPI
Andrew Stevenson - Westland Helicopters
M. Keith Stevenson - Bell Helicopter, Textron
Brian S. Thompson - Michigan State U.
Ralph M. Verette - McDonnell Douglas Helicopter Co.
Anthony J. Vizzini - U. of Maryland
George E. Zahr - DuPont