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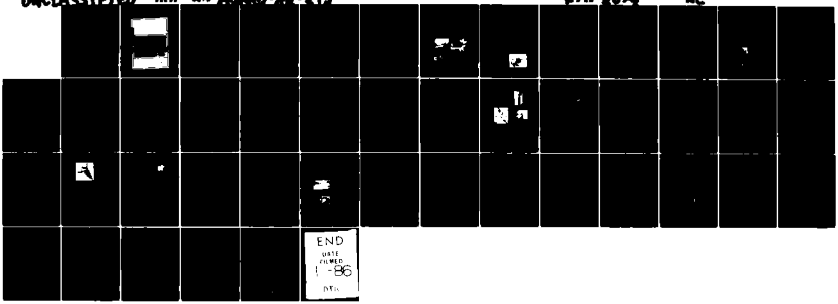

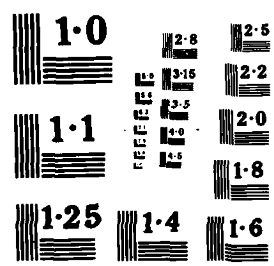
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AGARD Advisory Report No.213

TECHNICAL EVALUATION REPORT

on the

FLUID DYNAMICS PANEL SYMPOSIUM

on

AERODYNAMICS AND ACOUSTICS OF PROPELLERS

by

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TECHNICAL EVALUATION REPORT OF THE AGARD/FDP SYMPOSIUM ON "AERODYNAMICS AND ACOUSTICS OF PROPELLERS"

by

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I - INTRODUCTION

The propeller has become a focus of attention after beeing neglected for many years; that is why this topic was both relevant and timely for an AGARD Symposium.

The Fluid Dynamics Panel was able to convene a large number of experts from the NATO countries to discuss mainly aerodynamics and acoustic of new high speed propellers, but also to generally review the "State of the Art" on propellers, very useful for a non-specialist.

That is why it is convenient to begin this evaluation report with a short history of a ten year Research effort on high speed propellers, summarized on Fig. 1 for the impressive US activity.

The beginning of the story was "the rapid escalation of fuel costs in the mid 70's which caused a serious re-appraisal of fuel efficiency in commercial Aircraft Applications where the impact on operating economics was very high [23] : military users were also seriously concerned with both the amount and cost of fuel required for normal operations."

"Although at the present time, the upward trend in fuel prices has halted, this can at best be a lull in what is a potentially very unstable system: it is therefore important to continue the search for high fuel efficiency."

It is fair to acknowledge the leading role of the NACA up to the mid 1950's on "Conventional" Propeller Research, and then of the NASA since the mid 1970's on high speed propeller Research [12]:

In 1975, NASA-Lewis initiated Research activity on a high-speed propeller concept proposed by Hamilton Standard/United Technologies; this concept, called the Prop-fan, has emerged as a fuel conservative competitor to the high by-pass ratio Turbo-fan in powering commercial transport applications [30, 33].

The results of these ten years of Research, which were frequently commented on during this Symposium, are illustrated briefly on the next two Figures 2 and 3, from the NASA-Lewis presentation [12]:

- A comparison of the installed cruise efficiency of Turbo-prop and Turbo-fan powered propulsive system is shown in Fig. 2 over cruise speed; the efficiencies include the installation losses for both systems (nacelle drag for Turbo-prop, cowl and internal losses for Turbo-fan, etc.).

A "conventional" low speed Turbo-prop has an installed efficiency level near 80% up to about Mach 0.5, and then drops, due to compressibility losses (thick blades operating at high helical-tip Mach numbers).

On the other hand, the advanced high-speed Turbo-prop has the potential to delay these compressibility losses (thin blades, swept tips, etc.) to much higher cruise speed, up to Mach 0.8 cruise. with about the same efficiency; at this Mach 0.8, a high by-pass ratio Turbo-fan exhibit only about 63% efficiency compared to about 77% for a "Single Rotation" (SR) Turbo-prop; such SR Prop-fan has a very high power loading (300 kW/m^2, with 8 blades, working at 240 m/sec. tip speed), which is about three times the loading on the last "conventional" propellers (on Lockheed Electra, Breguet Atlantic,...); its equivalent by-pass ratio is about 90 compared to 5 to 7 for an advanced Turbo-fan.

A full-scale SR Prop-fan nacelle will be tested in flight by NASA on an experimental Gulfstream II Aircraft modified by Lockheed-Georgia and fitted with a Hamilton Standard 9-foot diameter propeller, in front of the left wing ([1] and Fig. 1).

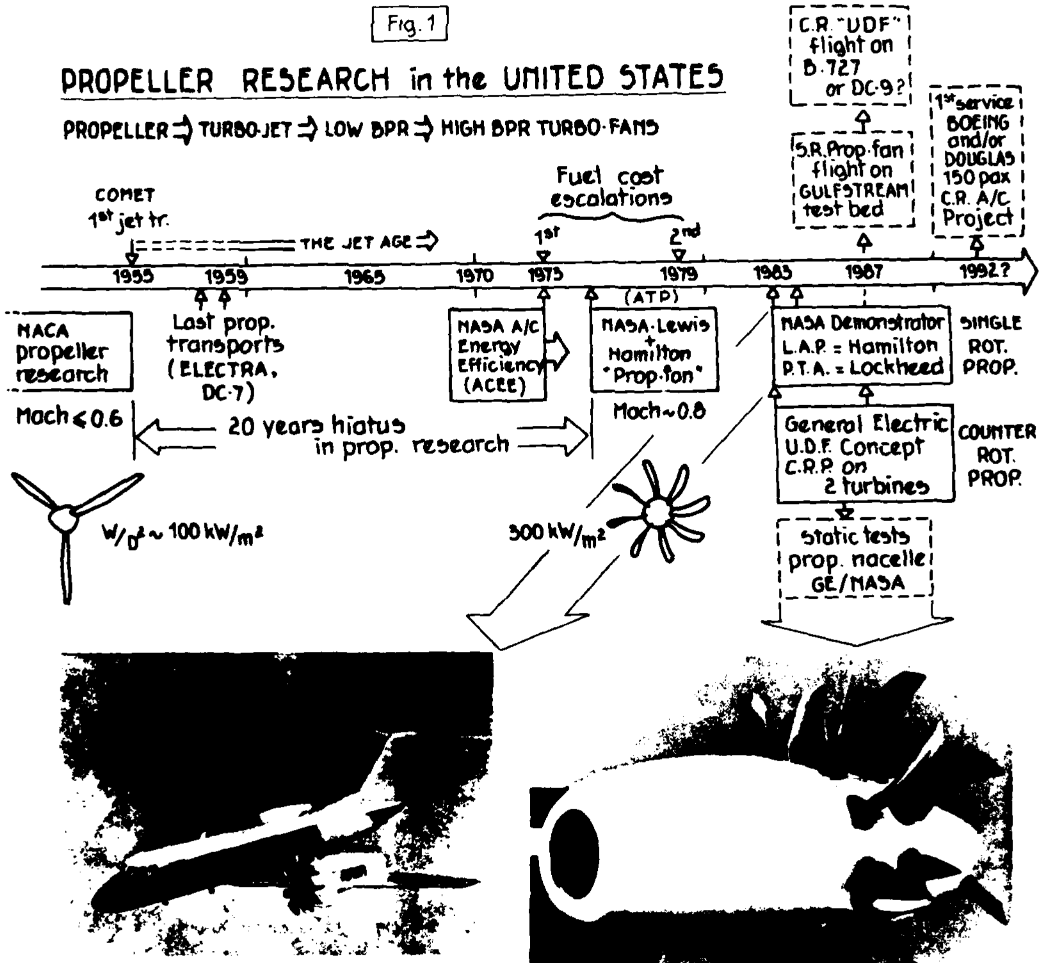
In the mean time, the "Counter-Rotation" (CR) scheme open a new way of Research, also supported by NASA since 1983, with Hamilton Standard and with General Electric.

General Electric has proposed a new propulsive nacelle concept, the "UnDucted Fan" (UDF), with CR Turbine and CR Propeller working together [34] ; a NASA-GE contract covers design and ground testing of the experimental engine (20 000 HP and 12 000 kg Thrust) to evaluate its aeroelastic, acoustic and performance characteristics; both Boeing and McDonnel Douglas Companies are working on a new 150 passengers transport for the next decade, using this concept: a flying "demonstrator" with an UDF nacelle on a B-727 or a DC-9 is scheduled for 1987 (Fig. 1).

About the potential interest of this new type of propulsion, Figure 3 [33] gives the Fuel Savings Trends of advanced Turbo-prop Aircraft over comparable Turbo-fan Aircraft, as a function of their range, and for two cruise Mach numbers, 0.7 and 0.8: the larger gains occur at the shorter operating range (climb and descent dominates), and then at very large range with a lower speed (M = 0.7); the Counter Rotation configuration at M = 0.8 is very promising compared to the Single Rotation prop-fan, due to 5-10% higher efficiency.

Fig. 1

PROPELLER RESEARCH in the UNITED STATES



LOCKHEED/Georgia test-bed system :
- Hamilton D = 2.75 m prop-fan,
- Allison turbo-shaft, W = 8 000 HP sls,
- Gulfstream II Aircraft, M = 0.8.

General Electric nacelle,
F-404 core, C.R. U.D.F.
D = 3.6 m, W = 20000 HP

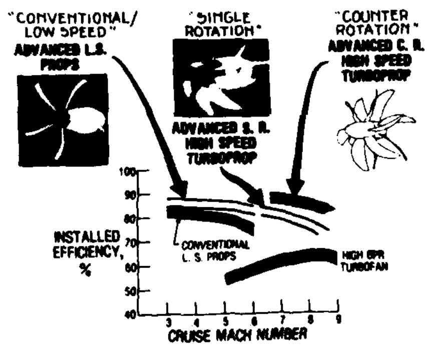


Fig. 2 - Installed cruise efficiency trends.

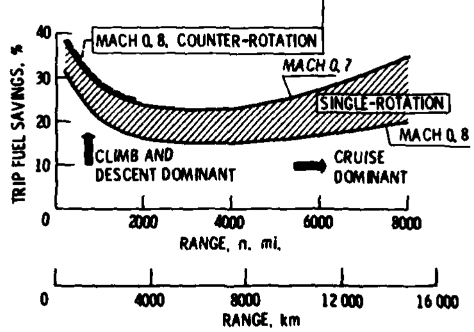
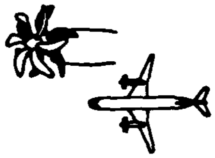


Fig. 3 - Fuel savings trends of advanced turboprop aircraft over comparable turbofan aircraft.

A preliminary estimation of prop-fan transport efficiency (with twin geared SR and CR respectively) compared to a conventional Turbo-fan transport has been conducted by Hamilton Standard P & W [33], which shows (Fig. 4) a dramatic advantage for the prop-fan configurations on the specific consumption (-39% and -46% for SR and CR) and on the fuel burn DOC, for a typical 400 nM mission.

Fig. 4

PRELIMINARY ESTIMATION OF PROP-FAN TRANSPORT EFFICIENCY COMPARED TO A CONVENTIONAL TURBO-FAN A/C (1988 TECHNOLOGY), REF. HAMILTON/P. AND W. :



- 120 PASSENGER TWIN-ENGINE. DESIGNED FOR 1800 NM RANGE AND 400 NM MISSION
- 0.75 MACH NUMBER CRUISE AT 35 000 FT
- TAKE-OFF FIELD LENGTH : 7000 F. SEA-LEVEL. 29°C (84°F).
- PROPULSIVE NACELLES :

	TURBO-FANS	PROP-FANS. WITH GEARBOX	
		SINGLE ROTATION	COUNTER ROTATION
- ENGINE TAKE-OFF THRUST/POWER :	7520 KG (16 600 LB)	11.560 HP	10.060 HP
- BY-PASS RATIO :	7	90	80
- MAX TURBINE ENTRY TEMP. :	1460°C (2 260°F)	1460°C (2 600°F)	1426°C (2 600°F)
- DISC DIAMETER : (NR OF BLADES, TIP SPEED)	1.37 M	4.00 M (10 BL. 244 M/SEC)	3.48 METRES (6 + 6. 229 M/SEC)
- NACELLE LOCATION :	UNDERWING POD	TRACTOR PROP-FAN IN	FRONT/ABOVE WING
- PROP SYSTEM WEIGHT :	BASE	+ 9 %	- 7 %
- A/C OPERATING EMPTY WEIGHT :	BASE	+ 4 %	+ 0.5 %
- A/C T.O. GROSS WEIGHT : (INCLUDING ACOUSTIC PROTECTION OF FUSELAGE)	BASE	- 0.5 % GW (+ 1.8 % GW)	- 5 % GW (+ 2.0 % GW)
- SPE. FUEL CONSUMPTION T.S.F.C. — SEA-LEVEL/MACH 0.2	BASE	- 39 %	- 46 %
— 35 000 FT/MACH 0.75	BASE	- 16 %	- 24 %
- 400 NM MISSION — FUEL BURN	BASE = 1758 KG	- 21 %	- 31 %
— D.O.C. ($ 1.5/GALL.)	BASE	- 10 %	- 14 %

REF : ICAS. TOULOUSE. SEPT. 1984 [33]

The main objective of this unusually long introduction was to highlight the expected gains obtainable with a new family of high speed propellers. Now we must look at several technical problems to be solved before their introduction on civil and military transport Aircraft.

This Symposium was particularly informative on two main subjects: Aerodynamic design and acoustic problems related not only to prop-fan concepts but also to "conventional" improved propellers (General Aviation, Commuter Aircraft,...). The 31 papers were given inside four Sessions:

- Propeller analysis and design,
- Propeller testing,
- Propeller airframe integration,
- Propeller acoustic,

which are briefly analysed in the four next chapters, including discussions during the sessions and comments at the final Round Table; a fifth chapter is also added in this TER which deals with the development of modern Turbo-prop engines [23], including installation problems (mechanical gearbox and gearless concepts, inlet and exhaust locations,etc.).

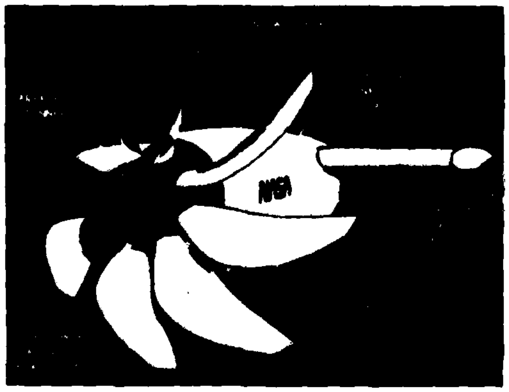


Fig 5

Advanced turboprop propulsion system.

II - PROPELLER ANALYSIS AND DESIGN

The ten papers given in this first session will be reviewed in Section II,2, prior to this review a summary of the calculation methods is given, which is based on the excellent contribution of Dr. Tijdeman to the Round Table Discussion [32]. Comments on some tests results, on some aerodynamic interference or acoustic aspects will be discussed later on in chapters III, IV and V.

II.1 - Theoretical approaches for propeller analysis

In the recent development of calculation methods for propeller design, roughly three phases may be distinguished:

- an exploratory phase that started in the mid 70's,
- an assessment/development phase that is going on at present in several nations,
- an application phase, in which the advanced propeller technology is ripe for application on Aircraft in the 90's.

A very similar development occured a number of years ago (1960-80) in the supercritical wing technology, using the most recent development of computational fluid dynamics available at that time; it is still the same process for propeller design, illustrated during this first session:

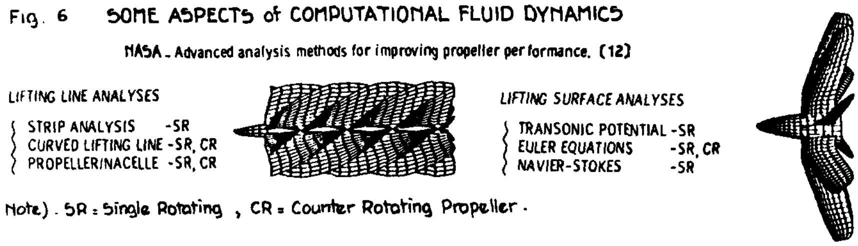
. The application of 2Dim. advanced blade sections, obtained via CFD methods have been illustrated in a number of papers [5, 6, 14, 16, 30], showing a mature and efficient approach confirmed by experiments.

. Computational methods for 3Dim. propellers are clearly in a less-developed stage; they can be classified in three groups: methods for axisymmetric flow, for non-symmetrical flow, and methods for computing dynamic loads; as an example, *Figure 6 illustrates* the various advanced analysis methods applied for both single and counter rotation propellers by NASA-Lewis [12].

A summary of the various methods presented during the symposium is presented in the four following Tables A to D.

Fig. 6 SOME ASPECTS of COMPUTATIONAL FLUID DYNAMICS

NASA - Advanced analysis methods for improving propeller performance. (12)



Note). SR = Single Rotating , CR = Counter Rotating Propeller.

TABLE A

3 DIM. METHODS FOR AXISYMMETRIC FLOW

"STEADY" LOADS ON PROPELLER ⟹ LOADS ON AIRFRAME COMPONENTS

PURPOSES : DESIGN, ANALYSIS, INPUT FOR NOISE COMPUTATIONS

METHODS :	PAPER :		WAKE STRUCTURE (*) :
. NAVIER-STOKES EQUATIONS	[12] NASA/Lewis (Bober)	NON-LINEAR	PART
. FULL EULER EQUATIONS	[2] ONERA (Rousquet) [12] NASA/Lewis		OF THE
. FULL POTENTIAL EQUATIONS	[2] ONERA * [3] LIMSI/Orsay ** (Luu)		SOLUTION
. LINEARIZED EULER EQ/LIFTING SURFACE	[7] NLR (Schulten) [9] DFVLR/BR (Das) [10] NASA/Langley (Farassat) [11] Lockheed/Calif. (Long)	LINEAR	INHERENTLY INCLUDED
. (CURVED) LIFTING LINE + 2 DIM. AIRFOIL AND SIMPLER METHODS	[5] ARA (Bocci) + ONERA [2] [12] NASA/Lewis [16] DORNIER/DFVLR-Br/Hoffmann (Zimmer)		TO BE PRESCRIBED **

(*) EFFECT OF WAKE ON A/C COMPONENTS IN :

[8] CRANFIELD I.T. (Esherby)
[20] Un. of Southampton (Lilley)
[22] Old Dom. Un. NASA-Langley (Prabhu, Liu)

ESTIMATE : NON-LINEAR METHODS (INCLUDING VISCOUS EFFECTS) ARE ESSENTIAL FOR PROP-FAN ANALYSIS.

A) In the axisymmetric flow case, the loads relative to the rotating axis system of the propeller are "steady". This case is important for Aerodynamic Design and Analysis of the propeller itself, for the wake flow, and for installation effects (spinners, hubs); the "steady" loads are also inputs for noise computations.

On Table A, the various approaches are listed in their order of sophistication: the most advanced method imply to solve the Navier-Stokes equations [12]; impressive results based on the full Euler equations were presented by ONERA [2] and NASA [12] -see Fig. 6 . Solutions of the full potential equation were given in paper [2] and by the LIMSI Orsay Univ. [3]; these three approaches are of a non-linear nature.

In the second category (small perturbations assumed), several papers were presented [7, 9, 10, 11], based on Euler equations/lifting surface.

The third group is based on simpler approximations (lifting line, etc. [5, 12, 16]).

Lastly, the effect of the wake on Aircraft components has been treated in three papers [20, 22, 8], also commented later on in section IV,1.

It can be expected that, like in wing design and analysis, the aerodynamic analysis of advanced propellers, non-linear methods are required; while, for the design approach, a linearized method probably will be sufficient.

B) The non-symmetric flow case (the usual situation for installed propeller) requires a time-dependant computation for obtaining the loads on the propeller (I-P and multiple P-loads), the time-dependant contents of the wake, which is a source of excitation on Airframe components, and the noise propagation; Table B shows that most of the methods presented [7, 9, 10, 11, 30] were based on the linearized Euler equations, closely related to those using acceleration potential. For Advanced installed propellers, probably a non-linear method is required because the disturbances are no-longer "small".

TABLE B

3 DIM. METHODS FOR NON-SYMMETRIC FLOW

PURPOSE : TIME DEPENDENT LOADS ON PROPELLER A.O. 1-P LOADS, EXCITATION OF THE AIRCRAFT, INPUT FOR NOISE-COMPUTATION

METHODS :	PAPER :
. NAVIER-STOKES EQUATIONS	not presented
. FULL EULER EQUATIONS	
. FULL POTENTIAL EQUATIONS	
. LINEARIZED EULER EQU, ACCELERATION POTENTIAL	[7] NLR (Schulten) [9] DFVLR/Br. (Das) [10] NASA-Langley (Farasat) [11] LOCKHEED-Calif. (Long) [30] HAMILTON St. (Metzger)
. LIFTING LINE	

ESTIMATE : PROBABLY NON-LINEAR APPROACH REQUIRED FOR PROP-FAN.

C) The dynamic (i.e. motion-induced) loads are important for whirl-flutter studies (a quasi-steady way is allowed) and for blade-flutter (a fully unsteady approach is necessary). These two aspects have been presented by NASA-Lewis [12] and will be commented in section III,4 (see Fig. 19, relative to their propeller aeroelastic Research).

With respect to dynamic loads (Table C), the guess is that linear methods will do the job, if linearized around the correct "mean steady" flow field.

TABLE C

METHODS FOR DYNAMIC LOADS

PURPOSE : MOTION INDUCED

- WHIRL FLUTTER : LOW-FREQUENCY (QUASI-STEADY)
- BLADE FLUTTER : HIGHER FREQ. (UNSTEADY)

PAPER :

[12] NASA-Lewis (Bober)

ESTIMATE : LINEAR METHODS APPLICABLE (IF LINEARIZED AROUND CORRECT "MEAN STEADY" FLOW).

D) The noise problem is most important for an accepted application of Prop-fan scheme.

Noise computations require, as an imput, the "steady" aerodynamic loads on the propeller, and the "time-dependant" loads due to flow assymetry, which give the noise field. A complicated additional step is the translation into interior noise, taking into account the transmission through the fuselage structure; several Propeller Acoustic problems are commented in chapter V.

All the prediction methods presented at the symposium -see Table D- are based on the linearized Euler equations or acceleration potential equations.

Probably linearized theory will be sufficient for obtaining noise prediction results for practical applications, provided that the aerodynamic blade loading is computed using non linear methods.

"Further verification and development of computational tools is essential for a successful introduction of the advanced propeller technology; but these tools should be able to solve rather complex flow patterns."
"The last 10 years of exponential development in CFD methods and in computer technology gives us an excellent base for further progress; but the last "round", oriented to applications, will be very challenging !"

TABLE D

NOISE COMPUTATIONS

"STEADY" LOADS ON PROPELLER (TABLE A) ⟹ NOISE COMPUTATION ⟨ FAR FIELDS. / NEAR FIELD NOISE

INPUT : TIME - DEPENDANT ON PROPELLER (TABLE B)

INTERIOR NOISE (DIFFRACTION PROBLEMS !)

METHODS :

LINEARIZED EULER EQUATIONS
ACCEL. POTENTIAL EQ.

PAPER :

[7] NLR (Schulten)
[9] DFVLR/Br. (Das)
[10] NASA-Langley (Farassat)
[11] LOCKHEED-Calif. (Long)
[10] HAMILTON St. (Metzger)

Note : results for axisymmetric flow presented in [12] (Farassat Method) and in [30].

ESTIMATE : LINEARIZED METHODS WILL SUFFICE (IF CORRECT BASIC FLOW FIELD US ACCOUNTEL FOR).

II.2 - Progress on Propeller Design

In recent years, major progress on propeller design have been obtained in various countries, amply reflected in numerous papers at this Symposium; in this section, these papers are briefly analysed for each country: USA, France, United Kingdom, Germany and Holland.

II.2.1 - US High-speed propeller Research

This theme was introduced in a review paper by Roy Lange, from Lockheed-Georgia Company [1] and then detailed in the Summary paper of recent NASA Propeller Research by L. Bober et al. [12]; a typical high speed Single-Rotation turbo-prop nacelle is shown in Figure 5; in such a system, the propeller efficiency would be kept high by minimizing or eliminating compressibility losses; this would be accomplished by using thin swept blades integrally designed, with an area ruled spinner and nacelle: these concepts are illustrated in Figure 7, based on a cruise condition of Mach 0.8, and showing the propeller blade section Mach number (vector sum of axial and rotational components) as it varies from hub to tip:

- curve A is relative to the Mach distribution encountered by a straight blade, with a front Mach number always larger (M = 0.82 to 1.14 for hub to tip) than that corresponding to the drag rise Mach numbers (MD) of each blade airfoil section (from 15% to 2% thickness) obtained from two-dim. transonic data; in such a case the compressibility losses would be very high all along the blade radius. The first attempt to reduce these losses was to give a sweep effect at the blade tip to reduce the effective Mach number (curve B) below MD curve (also effective to reduce the tip blade noise); but, in the hub region, the spinner-nacelle body must be tailored to increase the effective blockage behind the propeller by spinner area-ruling (curve C, Fig. 7). In fact, for these very highly loaded propellers, with 8 to 12 blades, the hub blade sections operate as a cascade and this important spinner area ruling is mandatory to prevent blade-to-blade choking, as illustrated on Figure 8 from NASA-Lewis tests [12] and ONERA theoretical approach [2].

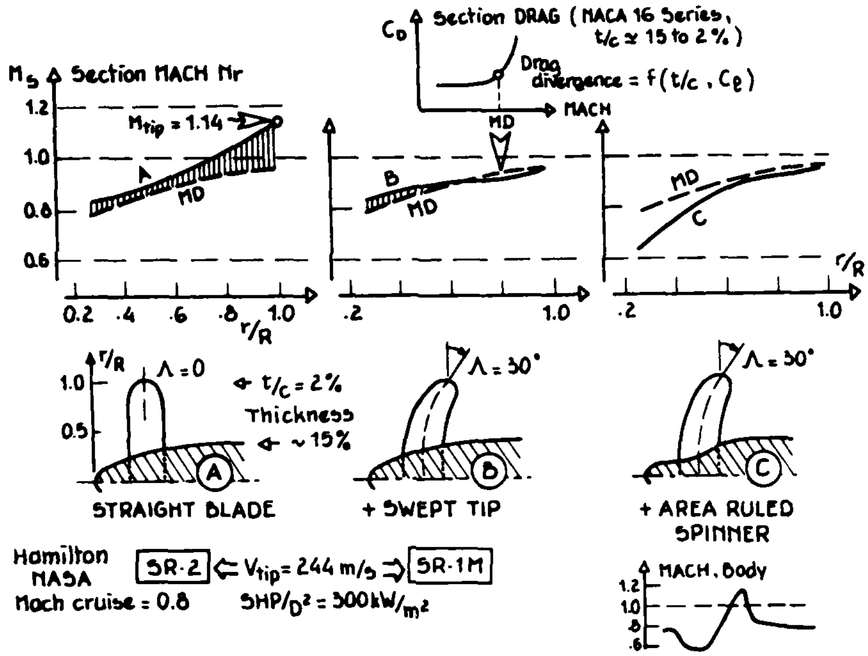


Fig. 7 EFFECTS of ADVANCED AERODYNAMIC CONCEPTS on BLADE SECTION MACH NUMBER DISTRIBUTIONS [12]

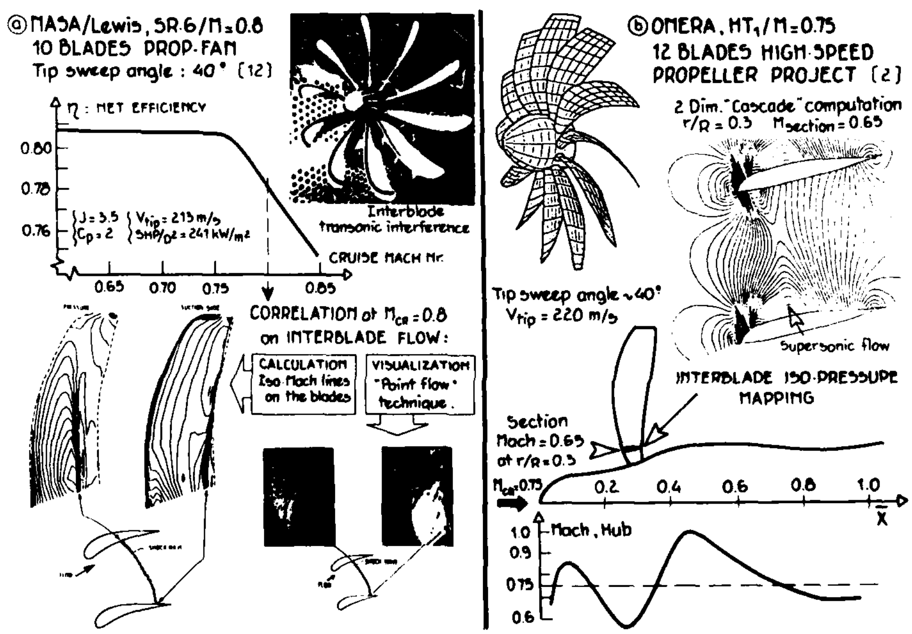
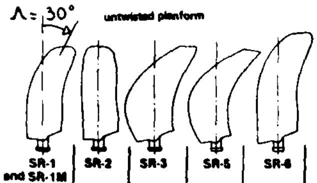


Fig. 8 INTERBLADE FLOW PROBLEMS near the hub, for multibladed prop-fan configurations.

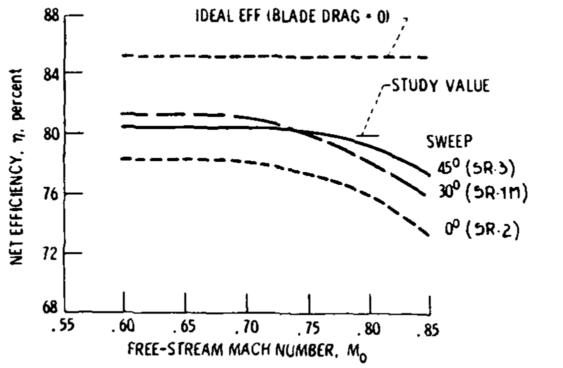
In a cooperative program between NASA-Lewis and Hamilton Standard, these concepts were used to design a series of propeller models for testing in the Lewis transonic tunnel (6 x 8 ft section, see section III,2): four Models SR-1 to SR-5 were designed by Hamilton, and the last -SR-6- by Lewis Center. The characteristics of the first three, with 8 blades, with the same tip speed and power loading are given on Figure 9a, with their shapes (tip sweep of 0°, 30°, 45°); SR-5 has the largest tip sweep and 10 blades with a much lower tip speed and power loading; lastly, the SR-6 model has also 10 blades but intermediate power loading and tip speed, and was designed for increasing its performance and for lowering its noise (see Fig. 8a).

The wind-tunnel results on the efficiency for the eight-bladed propellers as a function of Mach numbers are given on Figure 9b; the difference between the predicted ideal efficiency and the experimental curves represents viscous and compressibility losses, choking losses and non optimal loading distribution; these losses increase with Mach number, and sooner for decreased blade sweep. The SR-3 propeller with 45° swept tip blades reaches 78,7% efficiency at M 0.8, very close to the study value.

The SR-6-ten-bladed-propeller efficiency is given on Figure 8a ; it is higher than for the SR-3 up to Mach 0.75; but above this Mach number, a rapid loss of efficiency is explained by a large extent of interblade choking well visualized by paint flow techniques.



	SR-1 and SR-1M	SR-2	SR-3	SR-5	SR-6
Nr of BLADES	8	8	8	10	10
POWER LOADING SHP/D², kW/m²	301	301	301	209	241
TIP SWEEP ANGLE, deg.	30	0	45	60	40
TIP SPEED, m/s	244	244	244	183	213



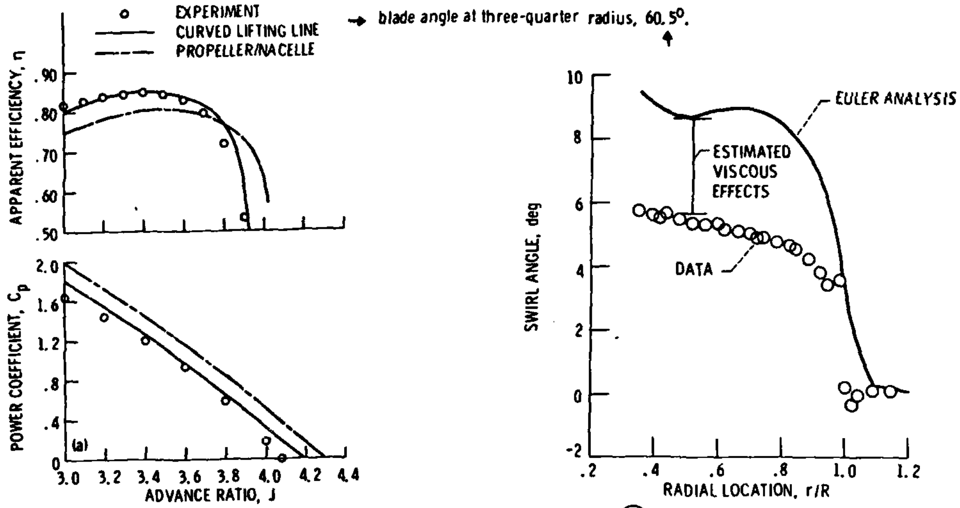
(a) DESIGN CHARACTERISTICS of NASA/Hamilton PROP-FANS MODELS (D_p~2ft) tested in the Lewis Transonic Tunnel (6x8 ft).

(b) EFFICIENCY versus MACH NUMBER, for the 8 blades prop-fans, J=3.06, Cp=1.7, area ruled spinner.

Fig. 9 NASA-Lewis SR PROP-FAN EXPERIMENTAL PROGRAM [12].

Lastly, the SR-5-ten-bladed-propeller has encountered, during high speed ($0.6 < M < 0.85$) tests, a classical coupled bending-torsion flutter phenomena, when the blade helical tip Mach number reached Mach one. Theoretical approach and experiments have shown that both large blade sweep and aerodynamic cascade effects have a strong destabilizing influence on the flutter boundary (see Fig. 19, and section III,4 on structural testing); these very important aeroelastic behaviour will be one of the objectives of the NASA program (LAP/PTA) on a full-scale demonstrator (Hamilton St. SR-7 propeller, D = 9ft, to be tested on a static rig, in wind-tunnel, and then in Flight on a Gulfstream II, see Fig. 1). On the performance prediction side, the NASA prop-fan program has included an evolutional analytical Research activity with the US Manufacturers in parallel with the development of the experimental propeller models, illustrated on Figure 6; these analysis methods range from simple lifting line (ex. strip analysis for single-rotation prop/Goldstein approach), to more sophisticated-computer-consuming-programs such as lifting surface analysis solving the five Euler Equations.

The more recent curved lifting line analysis represents the wake by a finite number of helical vortex filaments instead of the continuous sheet of vorticity used by Goldstein; the propeller-nacelle interaction analysis also represents the wake by a finite number of vortex filaments, but placed along stream surfaces of the axisymetric nacelle. The results of those calculations [12] compared to the experimental W-T results on the SR-3 propeller model are shown on Figure 10a for a Mach 0.8 cruise: for both efficiency and power coefficients, as a function of the advance ratio. The curved lifting line analysis gives a quite good prediction; but the propeller-nacelle interaction analysis is still poor, the difference between the two methods being mainly due to different approaches used for obtaining lift. The Euler analysis of swirl angle downstream of the propeller is compared, on Figure 10b, with the experimental values measured (0.21 diameters downstream) with an instrumented wedge mounted on a translating probe in the 8 x 6 foot NASA-Lewis tunnel: the predicted results are much higher than the experiments (Δ swirl ~ 4°); this large discrepancy is presumed due to the viscous flow/shock wave effects which reduce the blade loading and then the swirl angle; as expected the power coefficients are also over-predicted.



(a) - Comparison of analytical and experimental results for the SR-3 propeller at free stream Mach number of 0.8. Camber, drag, nonuniform inflow and centrifugal effect on twist included.

NASA-Lewis SR-3 Prop-fan [12]

Fig. 10

(b) - Comparison of predicted and measured swirl angle downstream of the SR-3 propeller blade. Axial location, 0.21 diameters downstream of the pitch change axis; free stream Mach number, 0.8; advance ratio, 3.06

To recover a large part of this very large swirl loss, the counter-rotating propeller concept seems very attractive and is the subject of important new Research programs both by NASA and by US Manufacturers. The calculated ideal efficiency for a CR versus a SR propeller is 6 to 9% higher at power loading from 200 to 320 kW/m², and this "gain" is accompanied by a reduction of the propeller diameter and the number of blades (and weight); we have seen previously that some Hamilton Standard preliminary design have shown an important avantage of the CR aircraft versus SR aircraft (Fig. 4: Fuel burn = -10%, Δ DOC = -4%), see ref. [33]).

Unfortunately, this crucial subject of the counter-rotating prop-fan was not discussed in depth during the *symposium*; however, some interesting theoretical approaches have been recently published by Boeing/General Electric in an interesting AIAA Paper [38]; this paper gives some preliminary calculations of the performance of a counter-rotating propeller, assuming quasi-steady interference effects between rotors; a simple lifting line (strip theory) method gives interesting results, even for partially supersonic swept blades by using "synthetic" blade section data that include sweep and compressibility effects implicitly. Figure 11 illustrates such calculations for a CR propeller having the same planform and section distribution that the NASA/Hamilton SR-3 propeller, and five plus five blades of the same diameter (instead of eight blades for the SR-3). For the same advance ratio $J \approx 3.06$, the calculated efficiency at Mach 0.8 cruise increases from 0.79 to 0.85 at 35% greater thrust; but at constant power loading $W/D^2 = 381$ kW/m², it is possible to keep the same 85% efficiency with the tip speed reduced from 244 m/sec. to 207 m/sec.; a significant noise reduction could then be expected. Note that, in this preliminary exercise, the blade design was not optimized; but it will be interesting to compare these predictions with future CR testing.

This trend favoring the counter-rotating scheme was already shown by René Hirsch in France, in an unpublished report (1980), where a comparative calculation between CR and SR solutions designed for Mach 0.8 cruise (Z = 35 Kft, V_t = 220 m/sec) has given a much better cruise efficiency for the CRP: 84% instead of 76%; moreover, the calculated take-off thrust was T ≈ 15500 daN versus only 10000 daN for the SRP, both installed on a propulsive nacelle equipped with a 14700 kW turbine; the CR propellers had a 5.5 m diameter and 2 x 8 blades with swept tips.

The two other US papers given during the first session were related to theoretical Acoustics and Aerodynamics approaches for high speed propellers:

The F. Farassat (NASA-Langley) paper [10] presents the derivation of a formula for prediction of the noise of supersonic propeller using time domain analysis: it is a solution of the Ffowcs Williams-Hawkings equation. The blade geometry, motion and surface pressure are needed for noise calculations. To obtain the blade surface pressure, the observer is moved into the blade surface, and a linear singular integral equation is derived, solved numerically; the computer program is still at the stage of development at *NASA-Langley. An example of the comparison of predicted and measured* pressure and noise signatures in the nearfield of a SR-3 propeller is commented on Section V,1 and illustrated in Figure 30.

A general theory of arbitrary motion Aerodynamics using an Aeroacoustic approach was given by L.N. Long and G.A. Watts/Lockheed-California [11]: this paper describes a new unsteady aerodynamics method using time-domain aeroacoustic integral equations; the effects of thickness, compressibility, and arbitrary motions may be calculated for subsonic and supersonic flows: by solving the wave equation instead of Prandtl-Glauert equation, the governing equation remains hyperbolic in both speed regimes. The authors have summarized their approach and the claimed advantages in the following tables:

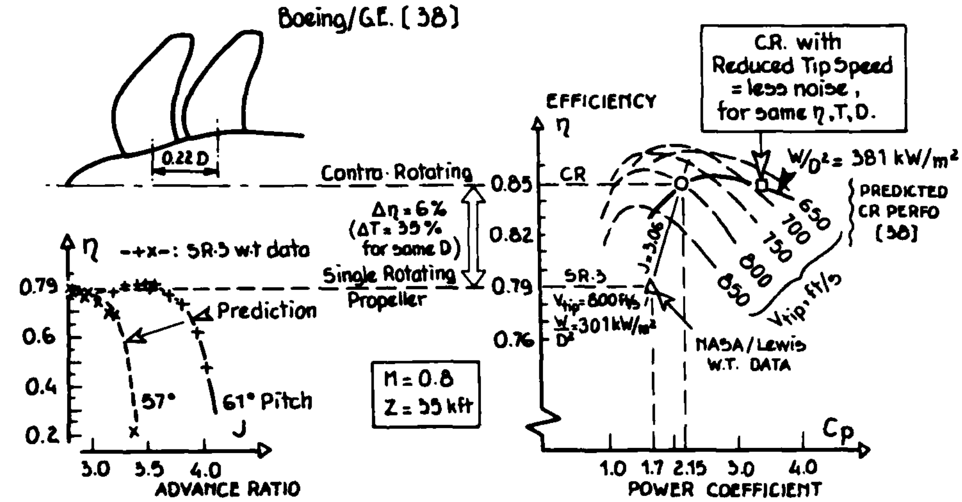
Ⓐ RELATIONSHIP OF AEROACOUSTIC APPROACH TO OTHER UNSTEADY AERODYNAMICS METHODS

- PRESENT METHOD IS ESSENTIALLY AN ACCELERATION POTENTIAL METHOD.
- ASSUMING ZERO THICKNESS REPRODUCES DAY'S EQUATION.
- CHANGING TO BODY-FIXED COORDINATES REPRODUCES KUSSNER'S EQUATION.
- TRANSFORMING TO THE FREQUENCY DOMAIN REPRODUCES DOUBLET LATTICE METHOD.

Ⓑ ADVANTAGES OF AEROACOUSTIC APPROACH

- VALID FOR SUBSONIC AND SUPERSONIC FLOWS (HYPERBOLIC IN BOTH REGIMES)
- VALID FOR HIGH REDUCED FREQUENCY
- TIME-DOMAIN FORMULATION ALLOWS ARBITRARY MOTIONS
- TIME DOMAIN FORMULATION IS A PREREQUISITE TO INCLUDING NONLINEAR TERMS
- EASILY ACCOMODATES THICKNESS EFFECTS
- ROLE OF NONLINEAR TERMS IS APPARENT IN FW-H EQUATION
- WAKE IS ACTUALLY TIME-HISTORY OF LIFTING SURFACE
- PREVIOUS THEORIES ARE SPECIAL CASES OF PRESENT METHOD
- PHYSICS OF PROBLEM ARE MORE EASILY UNDERSTOOD

Fig. 11 PRELIMINARY COUNTER ROTATION PROPELLER PERFORMANCE PREDICTION
Boeing/G.E. [38]



CORRELATION of STRIP THEORY/SYNTHETIC SECTION DATA [38] with W.TUNNEL DATA on eight blades. $\Lambda_t = 45°$, SR-3 Prop.fan [12].

PRELIMINARY PREDICTION for a COUNTER-ROTATION PROPELLER with 5+5 blades similar to SR-3 blades.

II.2.2 - French High-speed propeller Research

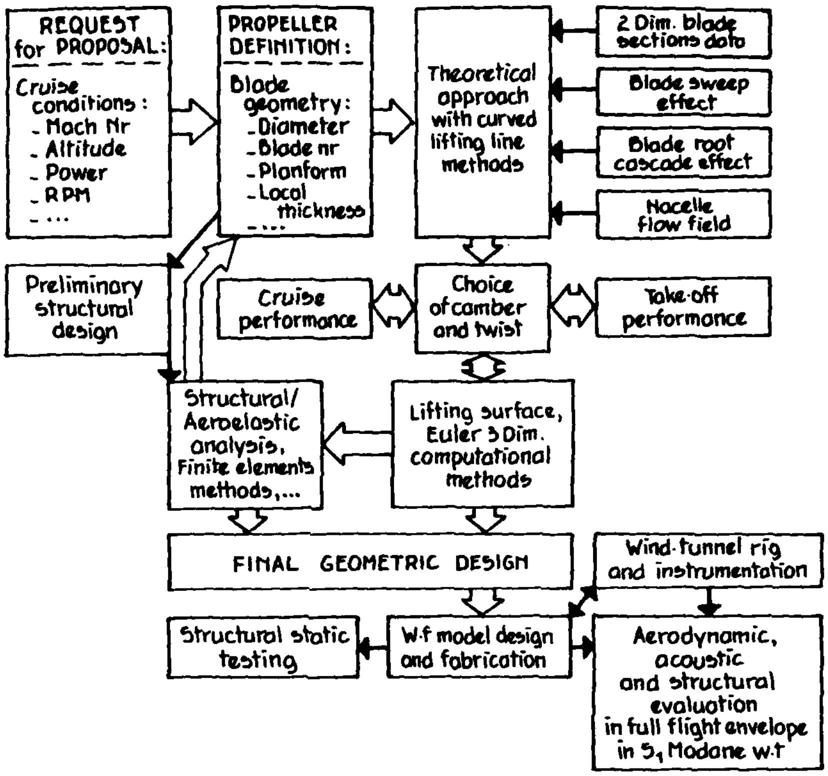
Two papers were given by J.M. Bousquet/ONERA [2] and by T.S. Luu and R. Collercandy/LIMSI-CNRS [3] which summarize propeller design concepts and performance prediction methods recently developed in France for High speed propellers (cruise Mach numbers 0.75-0.80). The first theoretical Research was launched at ONERA in 1979 as a feasibility study of an advanced multiblade propeller designed for cruise Mach number of 0.75. Following this preliminary phase, a national Research program was launched in 1982 by the French Authorities (Ministries of Defence and of Civil Aviation) with a joint team of:

- ONERA (theoretical methods for Aerodynamics/Aeroelasticity/Acoustics, Aerodynamic design, Structural testing, Demonstrator testing in S1 Modane tunnel in 1985 on a 1 m diameter model);
- Aérospatiale Company (Aircraft Division for Airplane Projects, and Helicopter Division for Structural Design/Manufacturing of the one meter diameter propeller Demonstrator);
- Ratier Company (Mechanical Design and test rig installation for the Demonstrator).

The Design Methodology, summarized on Figure 12, is used for obtaining the propeller performance (Cp, C_T and η) as a function of the Advance Ratio for two design points requirement (cruise and take-off regimes). The table shown on Figure 13a presents the various theoretical approaches used during this program from the simplest to the more sophisticated 3Dim. methods:

- For a preliminary design, the lifting line method is well suited; the induced velocities are calculated by the R. Hirsch formulae and the 2Dim. section characteristics are interpolated from existing or new data bases; for taking into account the sweep effect, the oblique attack on each section is used, and a curved lifting line scheme is introduced in the vortex flow calculation; then, the nacelle interaction is taken into account.

Fig. 12 ONERA. ADVANCED PROPELLER DESIGN METHODOLOGY



- The lifting surface method in incompressible flow was developed some years ago for ship propellers; in the Luu paper [3], this method, based on panel method applied to the lifting surface theory, is used as a design tool; singularity distributions are used for modelling the blade (thickness effect with sources, camber effect with doublets) and the wake (doublets distribution); the chordwise distribution of the loading is adjusted to give any desired pressure distribution over the blade (to avoid boundary layer separation); and the load distribution can be imposed to avoid abrupt changes in circulation to minimize the noise; this analysis permits a preliminary performance estimation. To introduce the compressibility, Luu has also developed a full potential transonic finite difference method in a body-fitted grid system; this new code is able to calculate the performance at design and off-design condition; both 2Dim. and 3Dim. results are given in the paper [3] for Mach 0.8.

- In the 3Dim. compressible method developed by J.J. Costes/ONERA, the 3Dim. flow without shock around the blade is calculated by solving the small perturbations of the velocity potential by finite differences in the interblade domain.

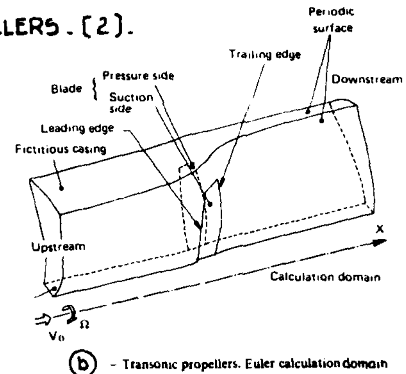
- To check the propeller performance in transonic flow, the method developed at ONERA that solves the Euler equations for turbomachinery has been extended to propellers. The calculated domain used is shown on Figure 13b, which is limited to the spacing between two consecutive blades, the lower boundary fits the axisymetrical form of a hub fairing. The meshes used have about 12000 points, 300 of them being on the blade itself; thus Mach number distributions on the blade are obtained which indicate for example if the flow is locally choked near the hub, as shown on Figure 13d1 for a cylindrical fairing at $M_0 = 0.7$, $J = 3.06$; the advantage of an area ruled hub fairing is evident on Figure 13d2 for the same regime; this optimized hub shape improves the flow over the entire blade; another calculated case was already given on Figure 8b at the cruise regime ($M_0 = 0.75$), with a subsonic flow along this well streamlined hub.

Fig. 13 ONERA RESEARCH on HIGH SPEED PROPELLERS. [2].

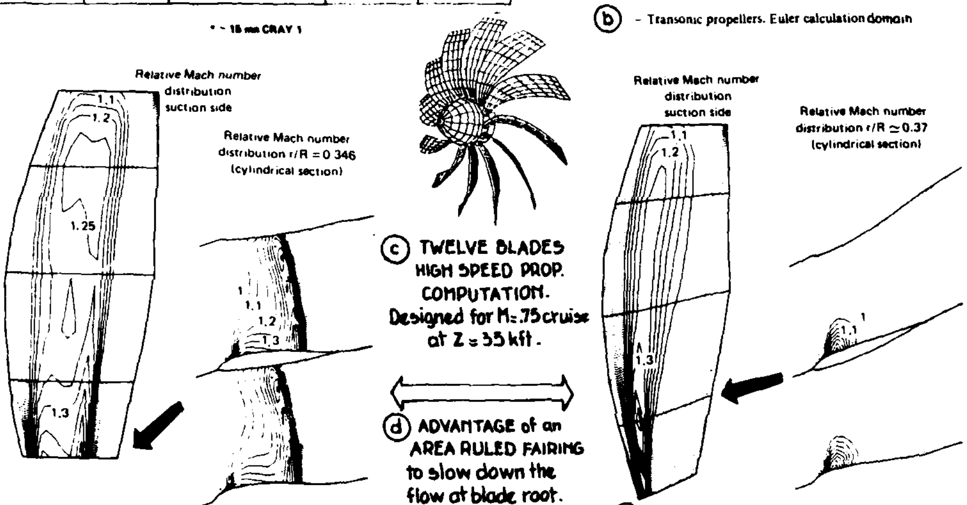
(a) 3D CODES FOR PROPELLER CALCULATION

EQUATION		HYPOTHESES	CODE	CPU CYBER 750
EULER		• INVISCID	EULER 3D	~ 3 HOURS*
POTENTIAL	FULL	• IRROTATIONAL • SLIPSTREAM GEOMETRY	LUU/LIMSI	
	LINEARISED	• THIN AIRFOILS • SUBSONIC	J.J. COSTES (ONERA)	~ 15 mn
SINGULARITIES	LIFTING SURFACE	• INCOMPRESSIBLE • SLIPSTREAM GEOMETRY	LUU/LIMSI	
	LIFTING LINE	• COMPRESSIBILITY AND VISCOUS EFFECTS - 2D AIRFOILS	LL Curved LL	~ 10 s

* ~ 15 mn CRAY 1



(b) - Transonic propellers. Euler calculation domain



(d1) - Calculation of the flow over a combined propeller-cylindrical fairing assembly.

(d2) - Calculation of the flow over a combined propeller-variable section fairing assembly.

The three previous methods (Luu, Costes and Euler) give similar results on the radial lift distribution along the blade of the twelve bladed propeller HT1 project; the curved lifting line method overestimates the local C_L and the simple lifting line method is quite misleading for the shape and the level of the C_L distribution. After a detailed parametric analysis, a final twelve bladed propeller has been defined as the HT-3 model, which satisfies the requirements:

- cruise at M = 0.75 and Z = 35 kft altitude, disc loading W/D^2 = 250 kW/m^2, and tip speed V_t = 220 m/s;
- a specific thin blade section (t/c = 3.5%) has been calculated and tested, which gives better C_{Lmax} and drag divergence Mach number than the conventional NACA 16 series of the same thickness. During the propeller design development, structural calculations were included to obtain the aeroelastic deformation under aerodynamic and centrifugal loads;
- the testing conditions in S1 Modane are described in Section III,2,a and on Figure 16.

A third French paper by ONERA and Ratier [6] deals with the theoretical design of a family of advanced blade sections suited for more conventional propellers. The requested specifications were aimed at increasing the maximum lift and the lift/drag ratio over the NACA 16 series profiles, while keeping about the same drag divergence Mach numbers. Four sections were calculated with relative thickness of 4, 7, 12 and 20%; the numerical optimization method used for designing these airfoils is obtained by coupling a transonic viscous flow analysis program with a constrained minimization function routine; the inviscid flow is computed by a method using a finite difference scheme to solve the full potential equation in non-conservative form; the viscous effects are taken into account by adding the displacement thickness of the boundary layer to the initial shape. The 2Dim. testing of these sections have been made by ONERA and some results are given on Figure 15a, which are commented in section III,1.

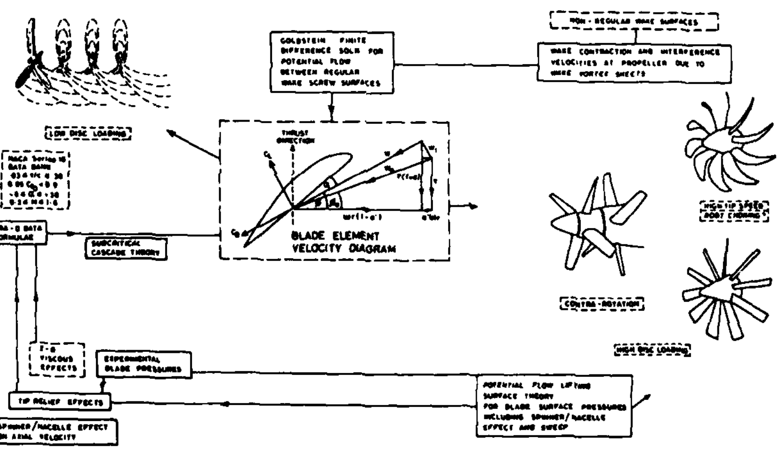
II.2.3 - United Kingdom High-Speed propeller Research

Two British papers were given at this first session: the first one by the Aircraft Research Association deals with a review of ARA Research into propeller Aerodynamic prediction methods [5], the second one, by the Cranfield Institute of Technology, on the Aerodynamics of installed propellers will be commented in section IV; a third British survey paper on propeller Aero-acoustic Research conducted at the RAE, including theoretical Aerodynamic aspects [25], was given in Session IV and will be analysed in Section V,2,3.

In recent years, the British Manufacturer Dowty-Rotol has developed for a number of Aircraft a family of propellers incorporating ARA-D blade airfoils, which were developed in the context of classical wake methods of propeller performance prediction; subsequent work at ARA [5] has involved the development of more advanced methods. The main objective was to ensure that the ARA-D airfoils -or developments of these sections- are applied in most appropriate manner to the blades of a wide range of configurations, including the cases with high disc-loading, high tip-speeds, swept tips or contra-rotation. Figure 14 illustrates the scheme of this aerodynamic Research; the boxes defined by solid lines indicate the particular area of Research effort analysed in the paper: a method has been developed to provide a finite difference solution for the flow between regular wake surfaces, following Goldstein but without limiting assumptions; the performance is given by linking inflow velocities given by the wake solution to blade element lift and drag data, according to the velocity diagram.

The Dowty-Rotol NACA Series 16 data bank is already very comprehensive and is now completed with a relatively limited number of ARA-D airfoils 2Dim. test data; they are used with semi empirical formulae for interpolation and extrapolation purposes.The 2Dim. data are modified to take account of conditions of the finite rotating blade, including tip relief correction and the influence of spinner and nacelle shaping and "cascade" effects toward the blade root; the wake methods assume a regular screw surface for downstream of the same diameter as the propeller; a method has been developed to calculate the flow induced by a prescribed wake vortex sheet; finally, 3Dim. methods involving solution of the compressible flow have been investigated.

Fig. 14 ARA RESEARCH into PROPELLER AERODYNAMIC PREDICTION METHODS [5].



Some comparisons of these theoretical approaches with pressures measurements on NACA propeller blades show that the calculated lift is overestimated at supercritical regimes; these discrepancies are probably due to a deficient modelling of the viscous flow in the calculation process.

In fact, during the round-table discussion [32], two comments, by Dr. Landon (ARA) and Bass (Dowty-Rotol), were given on the centrifugal effects on the boundary layer development along the blade; some experiments by Dowty on a propeller model, working at the same blade tip Mach number and same Reynolds number but at different RPM, have shown very large difference in performance, which are, by inference, due to centrifugal effects. At the same round-table discussion [32] an interesting presentation was given by A. Bagnall about the Rolls-Royce work on high speed propellers, using theoretical methods already applied in Turbomachinery (Fans); a 3Dim. Denton code was used (a time marching unsteady Euler equation) which iterates in time to end up with the steady solution; a fair comparison of this approach with NASA experiments on the SR-3 propeller was presented, with several Mach number mappings along the hub and in the interblade region showing typical supersonic and choked flow which disappear with a spinner area ruling (see similar trends on Fig. 8 and 13 obtained by NA. and ONERA).

II.2.4 - German propeller Research

The main German activity about propellers deals with advanced General Aviation with a view of improving their efficiency and reducing their noise; in the first session, a more general paper was given by the DFVLR-Braunschweig [9] on an unified approach for the Aerodynamics and Acoustics of propellers in forward motion:

Starting from the fundamental equations of wave propagation from moving singularities, a computational procedure is developed to solve both the aerodynamic and acoustic problems of moving bodies in an unified way: this approach includes the spatial and temporal dilatations in the propagation field of singularities, a generalized solution of the linearized wave equation in terms of pressure potential and the extension of the sweep technique for calculating the induced fields of singularity surfaces undergoing helical motion. As a test case the pressure distribution on a moving wing is given, but a numerical code for the propeller motion is still in progress.

On the experimental side, and in the General Aviation field, a joint paper [16] was given by Dornier Hofmann DFVLR-Braunschweig; several advanced "conventional" propellers have been designed and theoretically and experimentally analysed. At first, a new family of four blade sections were calculated by DFVLR: from prescribed velocity distribution on the airfoil the section contour and aerodynamic coefficients are obtained by inverse method using a modified computer code from Eppler and Sommers extended to compressible flow; for transonic flow the BGK-III method is used; the viscous effects are included by adding boundary layer displacement thickness to the airfoil contour. The tests on this four shapes were carried out in the TWB-2Dim.-tunnel: the results are commented in section III.1 and illustrated on Figure 15c; a very thick section was also developed for the blade root which gives a very high $C_{lmax} = 2$. For the calculation of the new propellers, a blade element vortex wake method was used, where the radial contraction and the axial displacement of the blade tip vortices is prescribed according to the local downwash. Two four-blades propeller models were designed and tested in the DFVLR tunnel. Then two full-scale propellers were tested in flight on the twin-engine DO-228 commuter Aircraft (ZKP program); compared with well known production propellers, these advanced configurations give much better static thrust (+19%), better take-off and climb performance (+10 to 16% on one-engine case) and cruise speed (+2%). The next step will be the design of a relatively highly loaded propeller for M = 0.6 cruise regime using these advanced airfoils; the calculated propulsive efficiency is quite impressive: $\eta \sim 0.9$ (four blades, D = 1.85 m, AF = 150, $M_{tip} = 0.84$).

II.2.5 - Dutch propeller Research

Like already seen on the German side, the main activity is connected with "conventional" propellers for short range transport Aircraft (for example the Fokker twin turbo-prop F-27 F-50): a joint paper by Dowty/Fokker/NLR on propeller testing [17] will be commented in sections III.2 and III.4.

On the theoretical side, a NLR paper was given on Aerodynamics of wide-chord propellers in non-axisymetric flow [7]: usually such conditions prevail for propellers installed on Aircraft, wing upwash being the most common flow asymetry; in fact, stronger inflow distortions may be expected in less usual configurations such as pusher and counter-rotation propellers, which are well covered by the present analysis. A non-helicoïdal unsteady lifting surface theory is formulated for propellers in a non-axisymetric flow; in particular, the method applies to wide-chord propellers with blades that may be swept both axially and azimuthally; in the analysis, the Euler equations linearized about an uniform subsonic main flow are solved after separation of variables in cylindrical coordinates, via integral equation for the force distribution over the two faces of the blades; the boundary condition of vanishing normal velocity is applied at the actual blade surfaces, i.e. a non-helicoïdal unsteady lifting theory. There is no inherent limitation to the propeller tip Mach number. Apart from the calculation of the unsteady blade loading, expressions for the velocity and pressure fields are derived, in which the propeller slipstream appears explicitly as part of the whole velocity field well suited for wing interference calculations.

III - PROPELLER TESTING

In the framework of this FDP Symposium, mainly Aerodynamic and Acoustic Testing were discussed, but Structural Testing methods and results were also presented in three papers [12, 13, 17], which are analysed later on in section (III,4).

About Aerodynamic Testing, the revival of interest in propellers has meant that an increasing number of wind-tunnels are being used for this purpose [32], both for 2Dimensional Testing on blade sections, and for 3Dim. testing on propeller mounted on a "minimum body", or in front of a simulated nacelle shape, or on a complete motorized Aircraft model configuration (see sections III.1,2,3).

III.1 - Two-Dim. Testing on blade sections are performed in many laboratories, taking advantage of new CFD methods (see ch. II) for developing better sections than the well known NACA-16 series, for a very wide range of thickness (2% to 20%), of Mach numbers (0.2 to about 1), and of angles of attack (up to post-stall).

The same 2Dim. Tunnels, used for developing new generations of "supercritical" sections for Aircraft wings and Helicopter blades, are also convenient for propeller blade sections; and the Reynolds numbers reached are usually large enough to duplicate easily the full-scale values; but, sometimes, the main problem is the manufacturing of very thin sections (up to 3% $\frac{t}{c}$) with enough stiffness and equipped with numerous pressure taps along their chord!

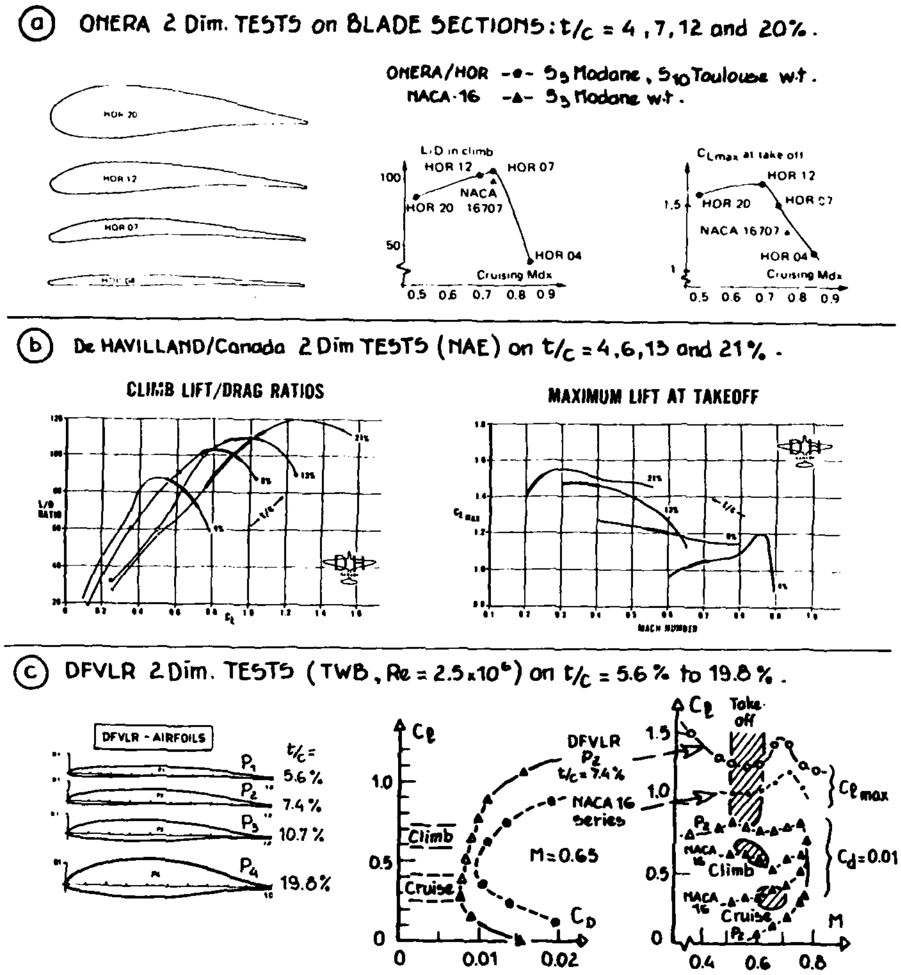


Fig. 15 DEVELOPMENT of NEW FAMILIES of PROPELLER BLADE SECTIONS calculated by ONERA [6] De HAVILLAND/Canada [18] DFVLR [16] for Advanced General Aviation.

a For example, ONERA has used the S3 Modane blow-down transonic tunnel for testing several families of blade sections designed either for "Conventional" propeller Aircraft 5 or for Prop-fan development 2 ; the blade sections, usually 0.2 m chord, and equipped with up to 90 pressures taps (for a good definition of C_L and C_m, and detailed comparison with computed pressure distributions) are mounted between walls (b = 0.56 m); the test section height between top and bottom perforated walls is h = 0.78 m; an automatic traversing rake with multi-probes gives a detailed wake measurement for determining the section drag C_D; the Reynolds numbers are adjusted to those occurring on a full-scale propeller by stagnation pressure adjustment, and the boundary layer is kept "free" (transition location controlled by sublimation process).

The very thick section at the blade root (20%), working at low speed (M 0.35) was tested in the CEAT/Toulouse S-10 tunnel (1 x 2 m²), using a 0.5 m chord model (C_L and C_m from balance and C_D from wake measurements). Usually, a well known "reference" propeller section (from NACA-16 family) is tested in the same conditions to have a direct and fair estimation of some expected gains 5, 2, 18 .

b) In England, the ARA Bedford pressurized-transonic-2Dim.-tunnel ($0.40 \times 0.20\ m^2$) is also used for developing a new family of blade sections (ARA-D, 20% to 4%) at variable Reynolds numbers (1.5 to 3.5×10^6) without blockage problems [5].

c) The DFVLR Braunschweig 2Dim. tunnel TBW ($0.6 \times 0.34\ m^2$), with slotted walls, is used for developing also a family of advanced blade sections ($c = 0.1$ to 0.2 m) at $Re_c = 2.5 \times 10^6$ [10].

d) Lastly, the NAE Transonic tunnel, equipped with a 2Dim. insert ($0.38 \times 1.53\ m^2$) is used for testing one foot chord propeller sections, having 4% to 21% thickness chord ratios, and developed for de Havilland-Canada STOL configurations [18]; this paper gives a very interesting study on the influence of various profile disturbances (roughness, de-icer boots), duplicated on the wind tunnel model: up to 50% increase on the C_D minimum was measured! Similar penalties were observed on a full-scale propeller with such usual protuberances.

A summary of some results about the development of new families of propeller blade sections for Advanced General Aviation in France, Canada and Germany is given on Figure 15; a very similar program is still in progress with the ARA-D blade sections developed in UK [5].

To conclude with the two-dimensional data obtained on propeller sections, it is still very difficult to compare those obtained in different wind tunnels; although some confidence is now obtained on the applied wall-corrections, there are still some important differences between testing methods and model mountings, wall boundary-layer interaction on the model, turbulence level, etc.; and the AGARD Fluid Dynamics Panel has certainly a leading role to play for improving the quality of the 2Dim. testing, which is still very important in the design process of advanced fans, propellers and rotors [32].

III.2 - Three-Dimensional Testing of propellers of various sizes -including full-scale- is not so easy and necessitates very special and expensive motorized rigs to be "integrated" in the existing wind tunnel test sections without too large parasitic interferences.

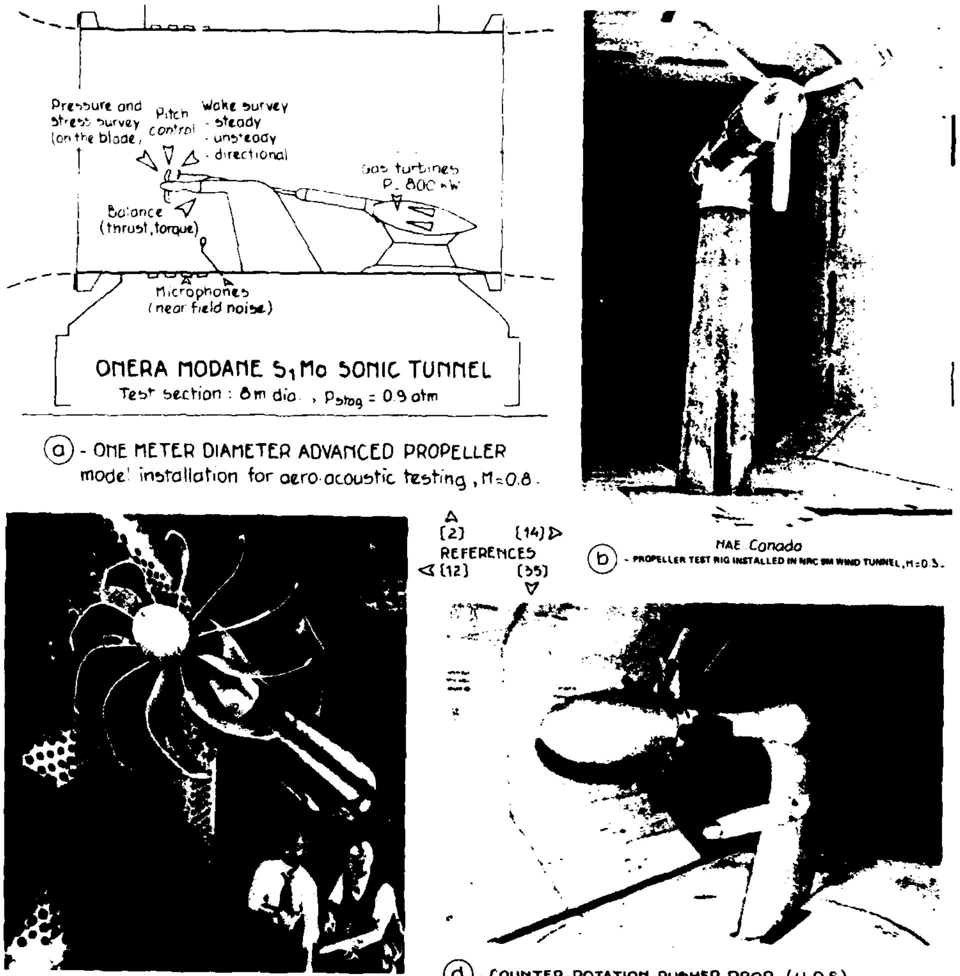
III.2.a - To minimize the propeller/nacelle interaction, ONERA uses in its S1 Modane tunnel a "minimum body" rig [2], powered by a twin gas-turbine (800 kW) group located far behind the propeller; thanks to "area ruled" wall shaping of the closed circular test section, this rig permits testing up to Mach about 0.85 with very low parasitic interference on the propeller itself (Fig. 16a). With the addition of a dummy nacelle shape around this cylindrical minimum body, it is possible to obtain the interference drag, both on the propeller itself and on the nacelle inside the propeller slipstream. Such testing technique is also commented in the AMD/Breguet paper for the Breguet-Atlantic propeller development [19].

Several other rigs with a powered "minimum body" behind the propeller were also discussed:

- The Dornier/Hoffman presentation [16] describes the DFVLR/Göttingen rig in their 3 m low-speed tunnel, used for the propeller development on the Dornier Do-228 Experimental Aircraft,
- The De Havilland-Canada paper [14] describes the NAE/Ottawa rig in the 9 x 9 m low-speed tunnel (Fig. 16b), used for the full-scale testing of 8.5 foot propellers (developed by Hartzell and Dowty-Rotol respectively, for a DHC-Twin Otter class of commuter Aircraft); this rig is powered with a 850 SHP/2000 RPM modified turbine/gearbox PT6 unit driven by compressed air. This paper gives also some very interesting full-scale data on the efficiency losses due to erosion roughness and de-icer boots (-1 to -3%!).
- The Dowty/NLR/Fokker paper [17] describes two different tunnels used for propeller testing:
  . the low-speed NLR/LST tunnel ($2 \times 3\ m^2$), with an isolated nacelle on a faired strut mounted on a floor balance; this rig is used for the calibration of the propellers ($D_p = 0.76$ m) designed for the complete F-50 model tested in the DNW tunnel;
  . the new low-speed Deutch-German DNW tunnel, with several test sections: the $8 \times 6\ m^2$ is used with a closed section for a complete motorized model (Fokker F-27 "RE" at 1/5th scale, see Fig. 25b); the propeller drive unit is a single stage turbine working with compressed air, W = 133 kW. This large tunnel is also used with an open-section ($8 \times 6\ m^2$) for acoustic measurements around rotors and propellers (see section III,4).

III.2.b - A special mention must be given to the development of the Propeller Test Rig (PTR) designed for the NASA-Lewis (8 x 6 ft) Transonic Tunnel, where almost all the new NASA/Hamilton Prop-fan configurations were tested since 1976 [12]; this tunnel has a porous wall test section for transonic tests up to Mach 0.85; the isolated nacelle (PTR) is powered by a 746 kW turbine using compressed air routed through the support strut (Fig. 16c); Axial force and torque on the propeller are measured on a rotating balance located inside of an axisymetric nacelle behind the single-rotation propeller ($D_p = 0.62$ to 0.70 m). A laser velocimeter system is installed in this tunnel to obtain detailed velocities around the propellers (see section III.3).

Recently, NASA-Lewis has initiated an extensive Counter-Rotating Prop-fan program [12], using the 8 x 6 foot tunnel with a new C.R. test rig for both tractor and pusher configurations, and powered by two air turbines (2 x 750 HP).



(c) - Installation of propeller test rig in the 8x6 wind tunnel with the SR-5 turboprop model, M=0.8 - (NASA/Lewis, 6×8 ft)

(d) - COUNTER-ROTATION PUSHER PROP (U.D.F.) tested in the Boeing "Acoustic" Tunnel, M=0.8. (transonic section : 8×12 ft)

Fig. 16 ISOLATED PROPELLER TESTING in LARGE WIND-TUNNELS.

For the same purpose, the Boeing Commercial Airplane Company has also developed a Counter-Rotating Cold Air Turbine Drive (CATD) for C.R. pusher propellers (D = 0.62 m) absorbing 2 x 750 HP (1119 kW) to simulate the GE UDF gearless configuration ([35] and Fig. 16d); this CR CATD rig was recently installed in the Boeing transonic tunnel (2.4 x 3.7 m^2) with a special acoustic treatment fitted on the test-section walls.

To study the interaction between these same "2 foot" propellers and the airframe (wing - fuselage), NASA uses the Ames 14 foot transonic tunnel for $0.6 < M < 0.85$ [1, 12].

III.2.c - The full-scale propeller testing approach in large wind tunnels was advocated by Ph. Poisson-Quinton during the Round Table discussion [32], and is illustrated on Figure 17a: "How to reduce the high risk venture of a Prop-fan development?" An expected answer would be to have a full-scale testing of the propulsive nacelle in the largest existing tunnels before flight; NASA-Ames has of course the largest low-speed tunnel in the world, where it will be possible to test a full-scale complete Aircraft inside the new 120 x 80 foot section; other low-speed large tunnels are also available in Canada: NAE, 9 x 9 m^2 [14], and in Europe : DNW, 8 x 6 m^2 [17], and RAE, D = 24 foot [25] tunnels.

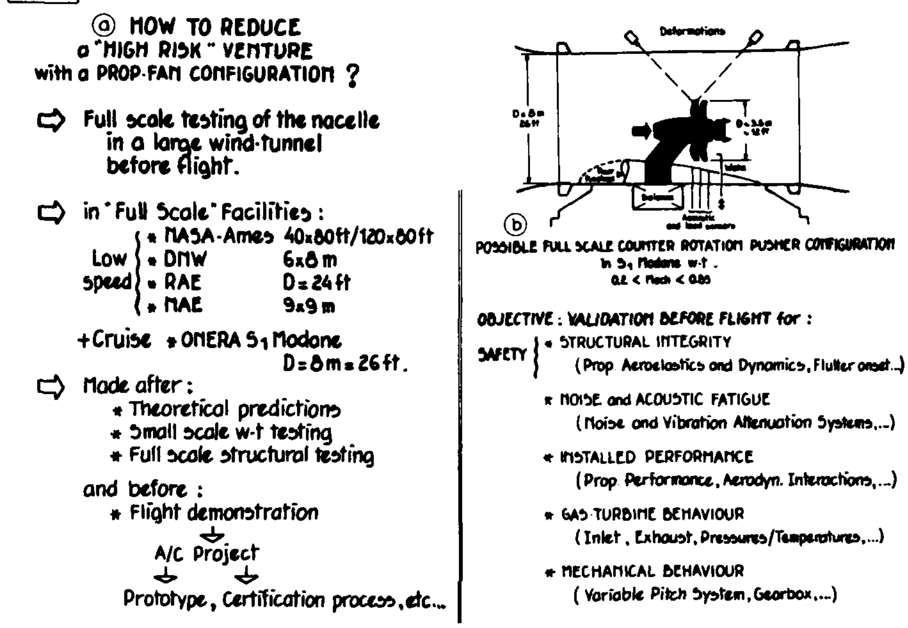
Furthermore, for both low-speed and transonic testing, the ONERA sonic S1 Modane tunnel seems very well suited for full-scale testing of motorized nacelles in its circular 8 m section, as illustrated on Figure 17b. Such expensive tests would be the last phase of ground testing to validate a prop-fan nacelle before experimental flight. The main objectives of such "Full-scale" approach (discussed by Bober (NASA-Lewis) and Poisson-Quinton (ONERA) during the Round Table), are listed on Figure 17b: the most important, for safety, would be to validate the structural integrity of the propeller blades working in realistic environment simulating all the Flight regimes:

- take-off, climb, landing with reverse thrust conditions, in large low speed tunnels,

- cruise and over-speed conditions, in the Modane tunnel (also usable for low-speed testing).

The full-scale validation of various absorbing materials fitted on the adjacent fuselage is also very useful for the Airframe Designer, as well as the observation of the gas turbine transmissions behaviour for the Engine manufacturer.

Fig. 17 FULL SCALE PROPELLER TESTING in LARGE WIND-TUNNELS



III.3 - The flow analysis behind the propeller is very important to study the slipstream characteristics and its interaction with various airframe components (nacelle, wing, tail, pylon...) and also to validate several theoretical approaches.

Various measurement techniques to obtain the three components of a local velocity (Fig. 18a) were discussed:

III.3.a - The laser velocimeter developed by NASA-Lewis for their Prop-fan tests in the 8 x 6 ft tunnel [12] is used for obtaining non-intrusive measurements of detailed velocities ahead of, in between, and behind propeller blades; it is a 15 watt argon laser using a four beam on-axis back scatter optic system; the movement of the measuring volume is remotely computer controlled; the flow in the tunnel is seeded with particles of dioctyl phthalate (DOP); two velocity components are obtained simultaneously: axial and tangential components are obtained by measurements in the horizontal plane and axial plus radial components by measurements in the vertical plane passing through the rotational axis. Ref. [12] gives an interesting example of LV data, using a color computer graphic technique, compared to a theoretical curved lifting line analysis of the exit velocity just behind the eight bladed SR-3 Prop-fan model.

III.3.b - To investigate the interaction of propeller slipstream with nacelle/wing flap combinations, Lockheed-Georgia [21] uses, in their 43 x 30 inch tunnel, a 7 probe - 5 holes-per-probe survey rake exploring various planes behind the propeller; the data are reduced to provide the three components of the wake velocity and the total pressure; these precise data provide a computerized visualization of the slipstream flow and its interaction with airframe parts (Fig. 22), but gives also the main characteristics of the propeller (thrust and power coefficients, blade section lift and drag coefficients), and the torque in the slipstream ("de-rotation" of flow by the presence of the wing, etc.).

III.3.c - The slipstream behind a propeller tested in the Institut de Mécanique des Fluides de Marseille tunnel [15] is measured by exploring the flow with a hot-wire probe (Disa-system with cross wires); the 3 components of the local velocity are automatically mapped through a mini-computer: this detailed experimental Research was conducted in the IMFM low-speed tunnel (Elliptic section 3.3 x 2.2 m, Vmax = 45 m/sec, four blades conventional propeller D_p = 0.85 m); numerous details of the slipstream flow are obtained: trajectories of the blade tip vortices, wake contraction and the mean velocity, the instantaneous radial flow field, (Fig. 18b), from which the tip vortex circulation is obtained.

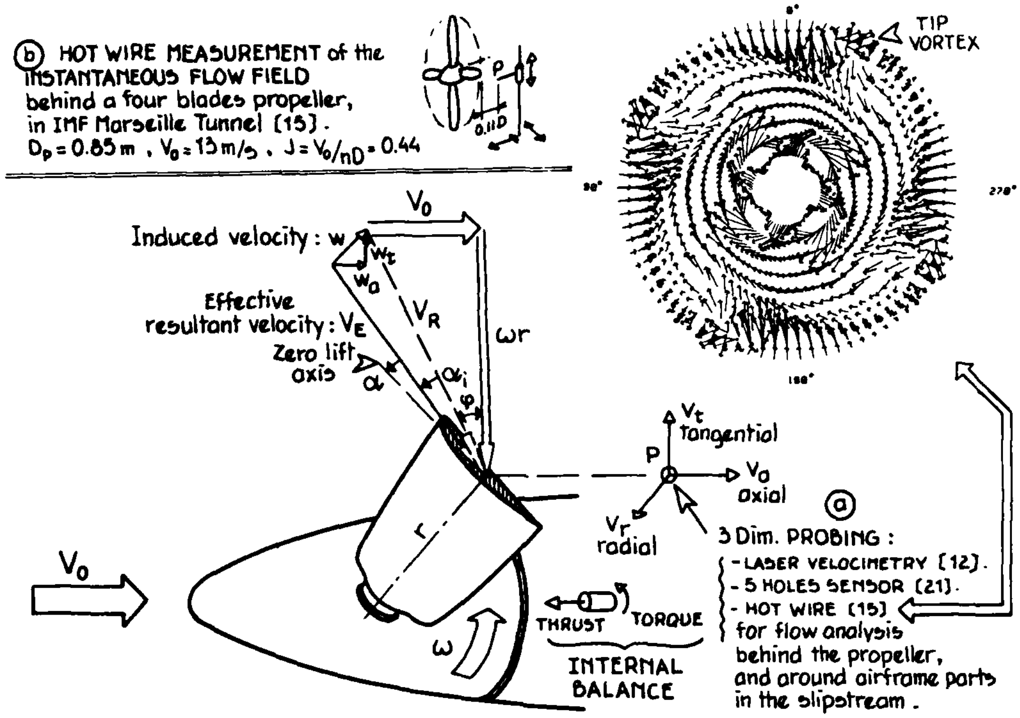


Fig. 18 WIND-TUNNEL PROPELLER TESTING METHODS ; SLIPSTREAM FLOW AUTOMATIC MAPPING.

III.4 - Structural testing

Although this symposium was mainly oriented on Propeller Aerodynamics and Acoustics, it is evident that the STRUCTURAL INTEGRITY must be analysed during the design process and ground testing mainly for the new thin, highly swept and twisted blades used on high-speed prop-fans; then, during the wind-tunnel testing, it is mandatory to have a specific instrumentation on the blades to measure the aeroelastic characteristics and to analyse the dangerous flutter problems.

III.4.1 - The NASA Propeller Aeroelastic Research program was summarized by L. Bober [12] and illustrated on Figure 19: the Aeroelastic Research deals with three phenomena (Fig. 19a):

- the stall flutter (occurring at low flight speed, with high blade incidence and some separated flow;
- the classical flutter (usually occurring at higher speed);
- force excitations (occuring at both low and high speeds because upwash, airframe flow fields distortions and angled inflow).

The aeroelastic analysis methods involve both structural blade models (swept, straight and curved beams, plate finite element structural model) and unsteady aerodynamic models. The NASA experimental Aeroelastic Research program has included three of the prop-fan models (see Fig. 9): 8 blades SR-2 and SR-3 and 10 blades SR-5; these models were not aeroelastically scaled, and the experimental data are compared with specific calculations for their structural characteristics.

The operating procedure in the Lewis 8 x 6 foot tunnel was to incrementally increase the propeller RPM at fixed pitch angle; the limits were blade stress, RPM and rig power or vibration.

To produce forced excitation on the blades, the propeller rig is put at an angle of attack; such tests are illustrated on Figure 19b, where measured and predicted one-P vibratory blade stress are compared for the three prop-fan models tested alone (Lewis 8 x 6 ft tunnel) or installed on a half-swept wing (Ames 14 ft-tunnel): a good agreement is obtained for the unswept propeller SR-2, but the one-P stress is underpredicted for the swept propellers SR-3 and SR-5. On the contrary, for the installed case, the two analysis methods overpredict the measured stress level.

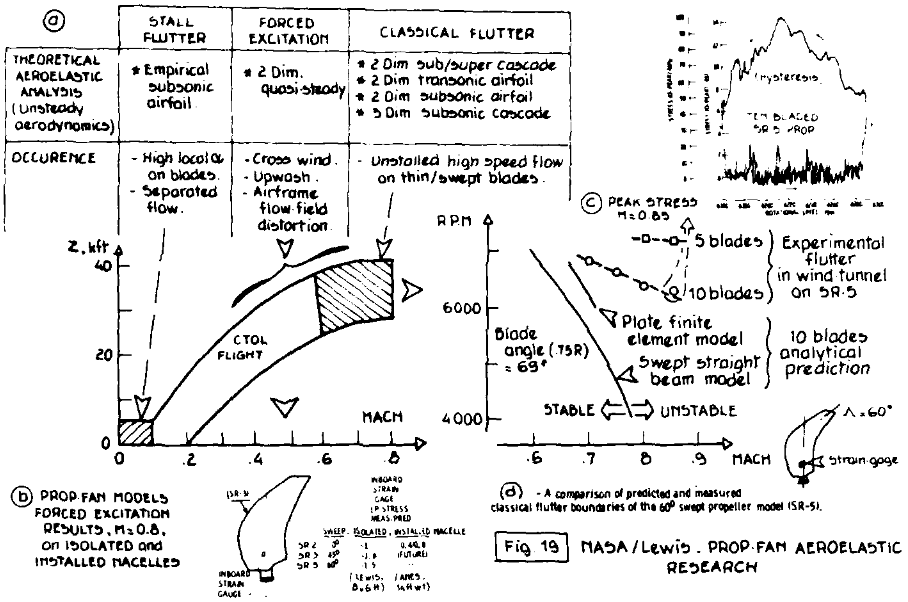


Fig 19 NASA/Lewis. PROP-FAN AEROELASTIC RESEARCH

During the NASA Lewis tunnel tests on the SR-5 (60° sweep) prop. model, a classical coupled bending-torsion flutter was encountered *inside a large range* of Mach numbers (0.6 to 0.85), when the blade helical tip Mach number reached about Mach 1: a very rapid increase of peak stress amplitude on strain-gage signal as a function of RPM: at first low amplitude vibratory signals and then an "explosive" growth near the first blade mode, and finally, a large stress hysteresis phenomena [41], as shown on Figure 19c.

Theoretical trends have shown that high sweep tip and aerodynamic cascade effects have a strong destabilizing influence on this flutter boundary; this "cascade" effect is demonstrated on Figure 19d where are compared specific experimental flutter boundary obtained for ten -and five-bladed configurations; on the other hand, the two theoretical approaches for flutter onset prediction for the 10 bladed prop appeared very conservative compared to the experimental (RPM, Mach) boundary.

III.4.2 - The Dynamic behaviour of a prop-fan model was presented by ONERA/Aérospatiale [13] in the framework of the French high speed propeller program already described in section II,2,2 [2]: this Research was a part of the design study of a demonstrator (D_p = 1 m) to be tested in the S1 Modane transonic tunnel, and included structural analysis for both the isolated propeller and the propeller fitted on the S1 Modane tunnel "minimum body" rig. Furthermore the structural predictions were made for the actual carbon fibre blade structure; the calculations were carried out by finite element method, adapted to the anisotropy of the composite materials the calculations were done with both the SAMCEF code used at Aérospatiale and the ASTRONEF code developed by ONERA. The structural characteristics were found by identification during vibration tests on the actual blade fixed rigidly at its root; Figure 20 shows a typical example of the blade deformation on the first mode (bending) and second mode (torsion); it was found that, for a carbone fibre composite structure, the fibre orientation is a fundamental parameter (few degrees difference strongly modifies the modal deformations: (a precision of about 10% on the natural modes calculation was estimated).

Similar ground vibration testing on the testing rig + propeller will be made to check any parasitic flutter problem before S1 Modane tunnel testing.

III.4.3 - Another structural aspect of wind-tunnel testing was presented in a joint paper by Dowty NLR Fokker [17] describing the development of a 1/5th scaled four bladed model propeller (D_p = 0.76 m) to be calibrated, isolated, in the 3 x 2 m. NLR/LST tunnel, and then put on a F-27"RE" complete model in the DNW 8 x 6 m tunnel (see Fig. 25b).

During initial runs on this complete 1/5th scale twin turbo-prop transport model, one of the blade failed at the root, with some damages to the nacelle and to the W-T test section; fracture surface examination of the aluminium alloy blade have shown that it was due to fatigue cracking due to high dynamic stresses, probably caused by resonance; it was concluded that in the model, the excitation showed itself as an unexpected axial vibration of the propeller shaft.

Following this blade failure of the metal propeller, it became necessary to change the elastic properties of the blades: new propeller blades with high damping were manufactured with *anisotropic composite* materials (carbon fibre oriented laminae), and the program was successfully completed.

To conclude, it is important to notice that composite construction offer two very great advantages:

- Unlike metal, the elastic properties of a blade can be changed without altering its shape, simply by modifiying the fibres orientation;
- Any failure is progressive and readily detectable before ultimate fracture; and even if this were allowed to occur, the energy would be dissipated among a large number of fragments of very low mass.

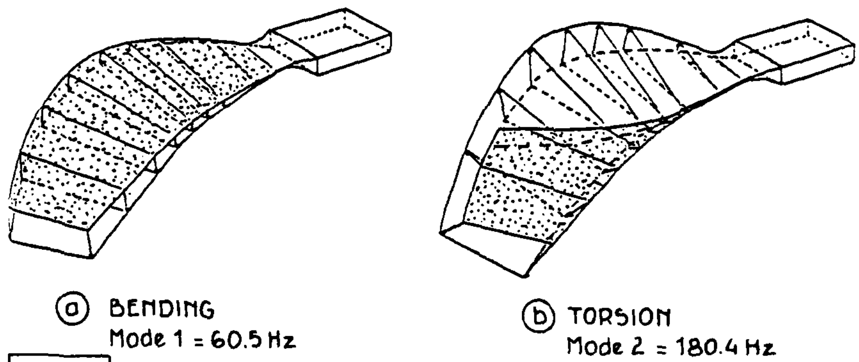


Fig. 20 NATURAL STRUCTURAL MODES measured on an ONERA HT-3 PROP-FAN BLADE fixed at its root, and excited at various frequencies.

IV - PROPELLER/AIRFRAME INTEGRATION

Up to now theoretical prediction methods are not yet available to optimize propeller airframe installations; and even the experimental data base is not sufficient to cover the various possible configurations, illustrated on Figure 40; furthermore, for each specific project, it will be mandatory to test a complete motorized model for obtaining the stability and control data at various flight regimes.

Six different papers were given on this subject, but only relative to "classical low-speed" Aircraft configurations.

IV.1 - About propeller/wing interference at low speed, two complementary experimental studies and one theoretical approach were presented:

a) A parametric analysis of the interference between a wing and a "pusher" propeller, for various locations behind the wing trailing-edge [20] has been made in the University of Southampton 7 x 5 ft tunnel with a combination of a half-wing plus half-fuselage and a propeller nacelle (Fig. 21); the upstream flow from the propeller induces a local lift increase on the adjacent wing which is quite large at take-off regime mainly when the propeller is close and above the trailing-edge as shown on the figure; this interaction is much smaller at cruise regime. In the same paper [20], a theoretical approach is in progress, based on linearized potential flow using panel methods; taking account of the propeller slipstream, with an extension to rotational effects, but problem arise due to the deflected slipstream which rolls up like a jet in a cross-flow.

b) The other paper, by Lockheed-Georgia [21], gives very detailed measurements of the flow behind "tractor" propeller to study the slipstream interaction with nacelle wing flap combination; this experimental analysis was already described in the previous III,3,b section and illustrated on Figure 22; there is a good agreement between the wake analysis and direct thrust force measurement.

c) An asymptotic method for the analysis of the interference of multiple "tractor" propeller slipstream with large Aspect Ratio swept wings was presented by the Old Dominion University NASA Langley [22]. It is assumed that height of the slipstream is of the order of the following wing chord and its width about that of the wing span; asymptotic expansions are made in each of the three regions: the propeller slipstream behind the wing reduces to a thin sheet of jet carrying the momentum gain; in the outer limit, the wing shrinks to a swept lifting line: the governing equations are solved by discretization. Present results of this simple method are compared with numerical solution of 3Dim. Euler Equations (requiring extensive computing effort) and with NASA experiments; very good qualitative agreement is obtained, including at Mach 0.8 (compressibility effects is introduced by the Prandtl-Glanert factor).

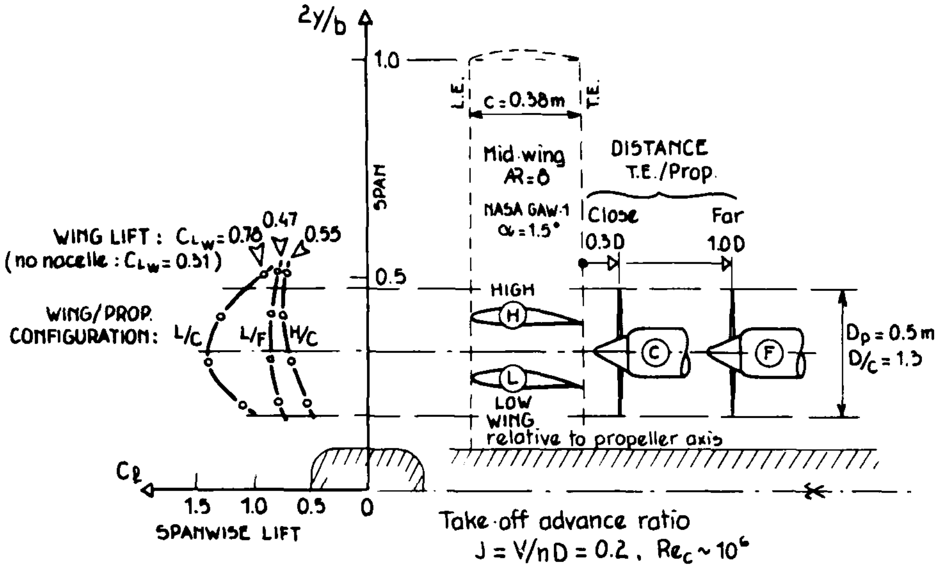


Fig. 21 **WING/PUSHER PROPELLER INTERFERENCE TESTS at low speed . Southampton U. Tunnel (20)**

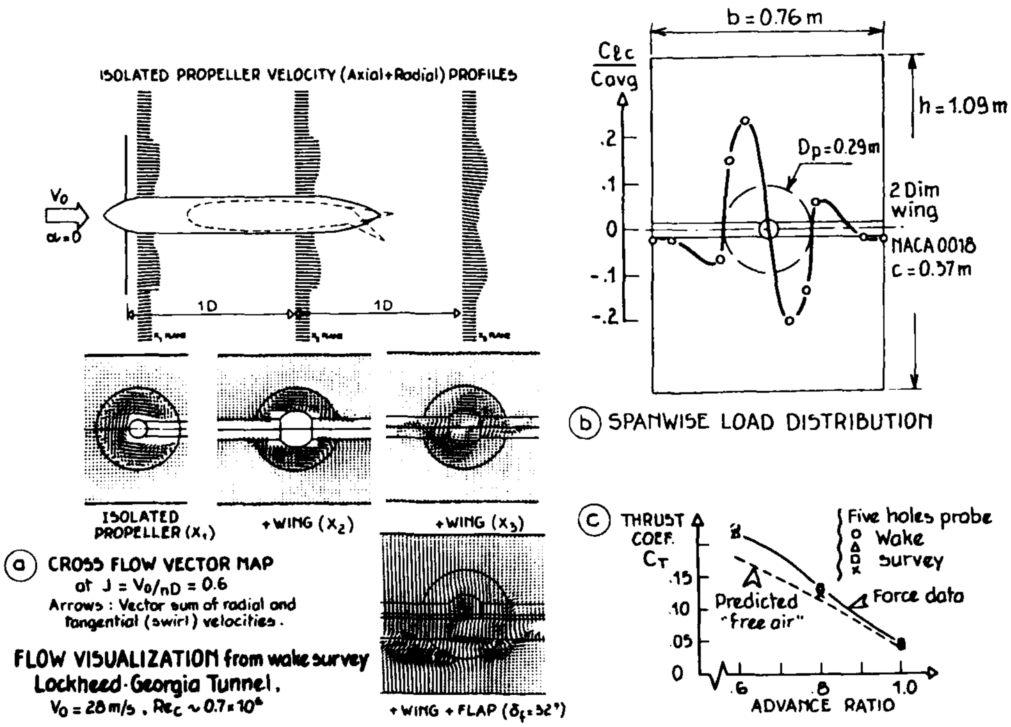


Fig. 22 PROPELLER SLIPSTREAM INTERACTION with NACELLE/WING/FLAP (21)

IV.2 - The De Havilland-Canada presentation on some *considerations in propeller and* <u>*Airframe integration*</u> [18] was given in two parts: the first one deals with the interesting development of a new family of propeller sections for the DHC "Dash-8", already discussed in section III,1.d; the second part describes the wind tunnel testing of a motorized half-model in a 6 x 9 ft low speed tunnel to optimize the wing-fuselage-nacelle respective locations: a high-wing with long nacelles is the best configuration for both the $C_{L_{max}}$ and the drag with flap-up and down, particularly in the case of one engine failure (twin-propeller Dash-8 Commuter Aircraft configuration).

IV.3 - This <u>propeller/Airframe interaction</u> is most sensitive for twin-propellers Aircraft <u>with very powerful turbo-props</u>, like the Breguet-ASW "Atlantic" Aircraft 19 equipped with two 6000 SHP R.R. *Tyne gas-turbines.*

In such a configuration, the propeller slipstream interaction on wing and tail is very important, both for the aerodynamic derivatives, and for the determination of the minimum control speed (which depends upon the rotation direction of the propeller still working, in case of engine failure).

Another paper on the same subject was given by the Cranfield Institute of Technology [8] which analyses the two sources of the propeller/Airframe interaction and gives a method of estimation of the direct forces and moments arising from the installed propeller:

- Firstly, as the Aircraft incidence changes with forward speed, the angle of attack on propeller also changes, giving rise to forces and moments other than thrust and torque;
- Secondly, the high energy slipstream passes over the tailplane, inducing a variation on the pitching *moment.*

These two effects are estimated and analysed for their influence on the Aircraft flying qualities.

IV.4 - The absence of contributions -or comments- on <u>Prop-fan/Airframe interference at high speed</u> was quite disappointing; in fact very few experimental results have been published on high speed tests made by NASA in the 14 foot-Ames tunnel with the Prop-fan models (D = 2 foot) of the SR series, mounted in front of various high aspect-ratio swept wings [12]. Some interesting theoretical approaches have been recently published by Grumman at ICAS [42]: a numerical method was conducted to assess the ability of a relatively high grid density computational scheme to predict pressure details and incremental drag levels; this scheme features an extended *transonic small perturbation equation* coupled with mesh-system embedding and simple planar boundary conditions which provide modeling flexibility comparable to that of panel methods; a high-density grid (100 points chordwise) is implemented to resolve flow details. This theoretical approach is compared to preliminary NASA pressure measurements on a swept wing behind the SR-2 prop-fan model on <u>Figure 23</u>: the propeller slipstream has a very strong effect on the inboard wing pressures due to swirl and super velocity in the slipstream and the above theoretical approach gives a quite good picture of the local flow including the strong shock-wave and the boundary-layer separation; this separated flow region behind the spanwise shock-wave (<u>Fig. 24</u>) gives an important parasitic drag at cruise with this crude wing configuration [43]; further tests with small local contouring around the nacelle and the wing leading-edge have shown an important parasitic drag reduction (ΔC_D = -0.0018 at M = 0.8 on <u>Figure 24b</u>.

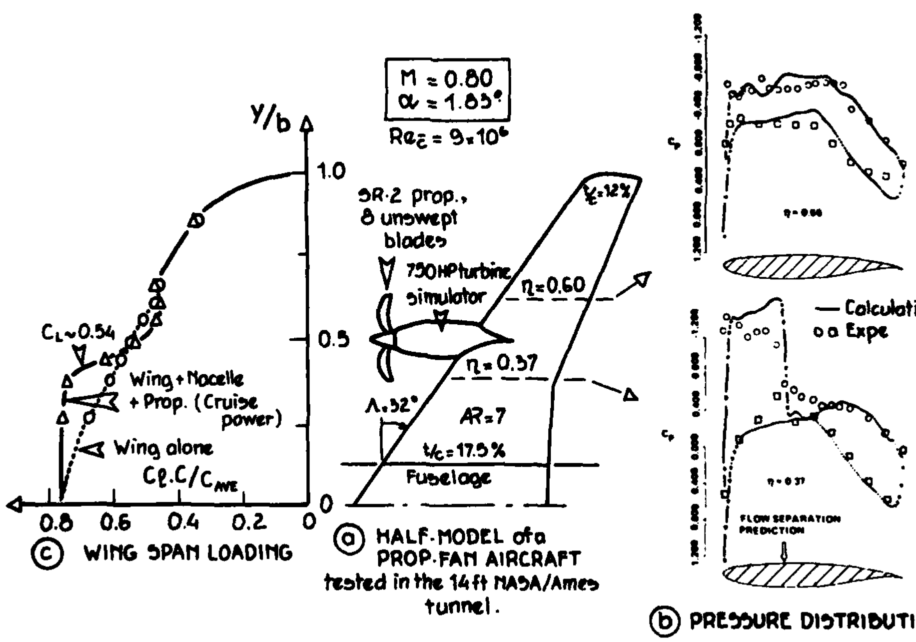
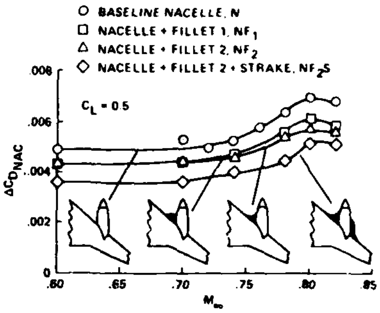


Fig.23 PROP-FAN SLIPSTREAM EFFECT on a SWEPT-WING at CRUISE M=0.8.

Fig. 24 POWERED NACELLE/ SWEPT WING INTERACTION.

(a) UPPER-SURFACE FLOW SEPARATION behind the shock-wave at M=0.8, inducing parasitic drag.

(b) SOLUTIONS :
- Contoured nacelle.
- Leading-edge extension.
- L.E. fillets/strake.



V - PROPELLER ACOUSTICS

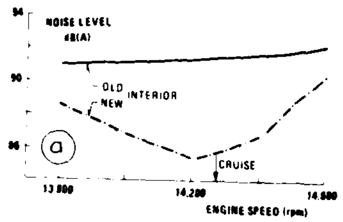
To conclude on noise problems during the RTD, Pr. Lilley said that "it is quite clear that if for any reason we wish to introduce a new form of power plant, we have still got to clearly keep the progress going (in acoustic technology) not providing any deterioration in comfort and noise inside the cabin or any increase in external noise level in relation to community noise; our generation of transport Aircraft have set a level of standard extremely challenging for any development in Aircraft propulsion. We must also mention the success of the smaller commuter-type turbo-prop A/C of the DHC- DASH-7 type, able to be used on STOL-ports inside a city, thanks to its very low noise level; it will be very challenging to reach such standards with a future larger Prop-fan transport; due to a type of noise source quite different than a Turbo-fan, one has to be aware of the certification problems for a Prop-fan Aircraft for both the cabin and external noise."

V.1 - Progress in propeller noise understanding

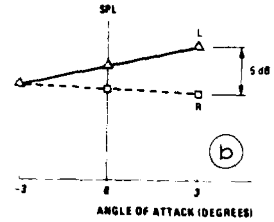
V.1.1 - Dr. Metzger (Hamilton Standard) presented an outstanding review on the state of the art in Prop-fan and Turbo-prop noise [30]. The implementation of the Aircraft noise certification requirements (FAR-36 in 1969), gave a new impetus to the scientific study of noise control in the 70's: successively, it was shown that unsteady loading effects must be added to the well known components: steady loading, thickness and broadband noise; then precise Flight experiments on a DHC-6 showed important differences between Turbo-prop noise under static versus flight conditions because the tone like noise components (which dominate the static spectrum) are dramatically reduced at flight conditions. During this time period the development of the quiet Turbo-prop for the De Havilland Dash-7 was very successful, meeting an extremely low noise goal of 95 PNdB at a distance of 500 ft during take-off (i.e. 13 dB below the certification limit).

At the present time, all the new Turbo-props for new commuter Airplanes incorporate blades with new airfoil sections, with reduced blade chord, narrow thin elliptical blade tips and twist distribution to unload the tip for reducing noise; the general trend is also to increase the number of blades to maintain performance with a smaller diameter, i.e. a tip-speed reduction (less noise) for a given RPM.

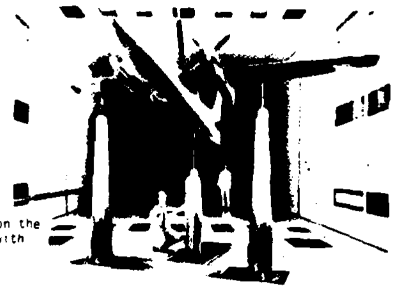
V.1.2 - A major problem for Turbo-prop transport remains the cabin noise particularly due to the strong low frequency tones of the propeller; in general, the noise in a multi-engine Turbo-prop peaks in the passenger cabin near the plane of rotation; but the acoustic treatment of the fuselage wall is not so easy because conventional trim panels are only effective at frequencies higher than the dominant tones of Turbo-props; a solution consists of dynamic absorbers (spring mass systems) attached to the fuselage frames tuned to blade passage frequency: a considerable success to reduce the cabin noise level on the F-27 was obtained recently 40 by the application of a double wall and three differently tuned sets of dynamics absorbers on the backside of the sidewall panels; as shown on Figure 25a, the maximum sound pressure levels on the 4 forward seat rows have been reduced by 7 dBA to the present level of about 85 dBA. During wind-tunnel testing for the new Fokker 50, acoustic measurements have shown that the acoustic excitation of the fuselage wall by port propeller was higher than by the starboard propeller; this difference increases with angle of attack (Fig. 25b) and is attributed to non-axial/non-uniform inflow of the propellers; to reach the target of 80 dBA for the F-50, Fokker has decided to use advanced 6-bladed Dowty-Rotol propellers instead of 4-bladed ones.



F27 interior noise on the 4 forward seat rows



Variation of propeller noise on the fuselage of the F27 RE model with angle of attack



Model of F27 RE scale 1:5 with powered propellers in the DNW

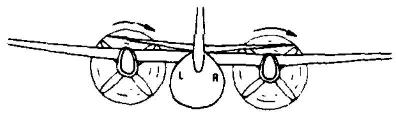


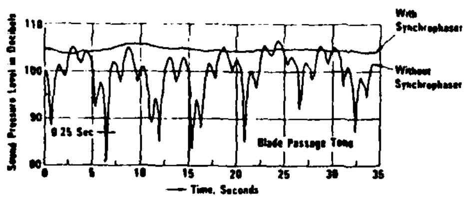
Fig. 25

CABIN NOISE LEVEL for the F-27 turbo prop. A/C

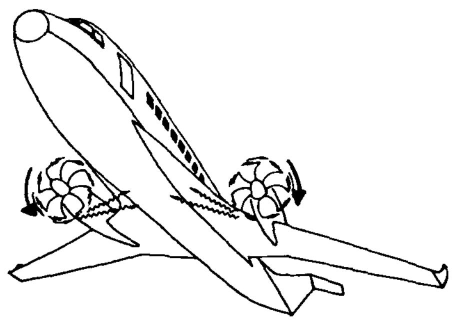
Recently, NASA has developed new experimental techniques such as computerized modal analysis for a more fundamental understanding of the noise transmission through A/C fuselages; and the application of new materials such as composites is very effective for reducing transmission of low frequency noise. Two other concepts contribute to interior noise reduction:

- the synchrophasing system which locks the phase relationship of the propellers to each other by an automatic control system (very effective for eliminating the highly annoying "beats" caused by slightly different propeller speeds (see Fig. 26a).
- The use of opposite rotation for the propellers: with a direction of rotation such that the blades move up as they approach the fuselage in a low wing configuration, the noise generated passes through the fuselage area below the floor before reaching the passengers cabin (see Fig. 26b).

Fig. 26 CONCEPTS for REDUCING PROP-FAN A/C INTERIOR NOISE



(a) Typical effect of current synchrophasers on cabin noise



(b) Opposite rotation cabin noise reduction concept

V.1.3 - A considerable Research effort was recently devoted to the Prop-fan source noise prediction; the NASA-Lewis paper [12] and the Hamilton Standard review [30] give a good summary of the exploratory program around a family of Prop-fan models (SR-1 to SR-6, see Fig. 9) already tested in wind tunnels or in anechoic tunnels:

a) The first acoustic objective of the SR-1 design was to reduce the blade thickness to minimize the related (monopole) noise and to incorporate a moderate tip sweep to lower the effective helical tip Mach number; but at that time (1975), no theoretical analysis was available; the SR-2 was designed *with the same thin* blade sections, but without sweep: the wind tunnel comparisons were quite conclusive, both on efficiency gain and on noise reduction for the swept blades configuration, as shown on Figure 27.

b) The SR-3 Prop-fan model design has taken advantage of a new theoretical approach developed in 1976 by Hanson and Farassat (based on the Ffocks-Williams/Hawkings acoustic analogy) which allowed prediction of near field noise; in this theory two components of the noise are evaluated:

  . the monopole (thickness) noise, a function of the thickness distribution,

  . and the dipole (loading) noise, a function of the loading distribution on the surface of the blade.

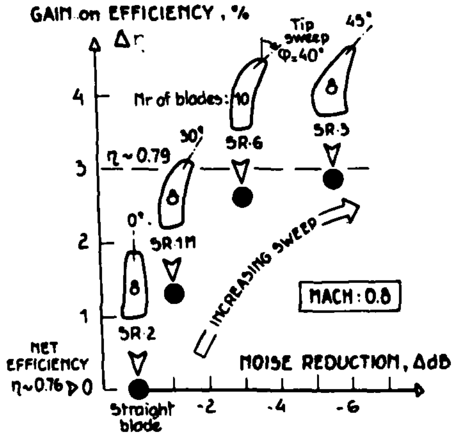


Fig. 27 Blade tip sweep effect on near-field noise from NASA SR prop-fans

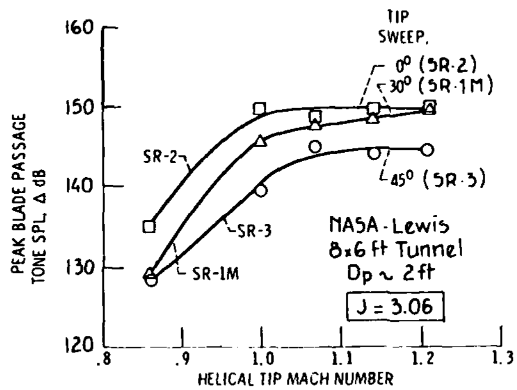


Fig. 28 - Maximum blade passage tone variation with helical tip Mach number for 8-bladed propellers.

This method is of "time domain" type (the acoustic pressure wave form generated by a blade is calculated and then the frequency spectrum of the noise is given by Fourier Analysis); in such case, the effect of sweeping the tip back gives a spanwise favourable interference and reduces the net noise.

This new approach for the SR-3 design was higly effective for noise reduction (ΔdB = 6dB compared to SR-2) and the larger tip sweep (Λ = 45°) gave also a very large gain on efficiency ($\Delta\eta$ = 6%), as shown on Figure 27.

The acoustic measurements (maximum blade passage tone) made at the wall of the 8 x 6 ft NASA-Lewis transonic tunnel are given on Figure 28 as a function of the helical tip Mach number for these 3 first Prop-fan configurations [12]: *in general, the noise of all the propellers increases* rapidly when M_H approached Mach 1, but above this limit, the noise of the 3 propellers tended to level off; the SR-1 (Λ = 30°) swept blade prop was much quieter than the SR-2 (Λ = 0°) at low M_H, but this advantage is lost for $M_H \sim 1.2$; however the advanced SR-3 configuration is much more quiet at supersonic M_H, due to larger sweep and acoustic phase cancellation.

c) The SR-5 model was designed in 1978 with a new "Frequency Domain Noise Prediction Program" initiated by Hanson, which calculates monopole, dipole, quadrupole and total noise; this quadrupole component addition was a sensible step for more precise noise predictions. A block diagram of this method is presented on Figure 29.

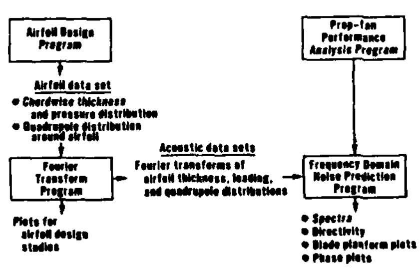


Figure 29 Prop-Fan frequency domain noise prediction method

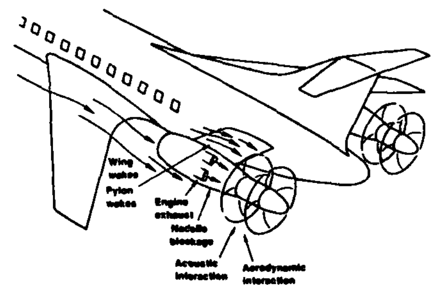


Figure 31 Factors affecting counter rotation Prop-Fan noise

Other approaches in Prop-fan noise theory for predicting performance and noise are the application of the Euler Equations, initiated by Bober (NASA-Lewis [12]), and the application of the compressible lifting surface theory; this unified theory is applicable to acoustics, unstalled flutter and steady performances, and accounts for effects of blade interference, thickness and three-dimensionality.

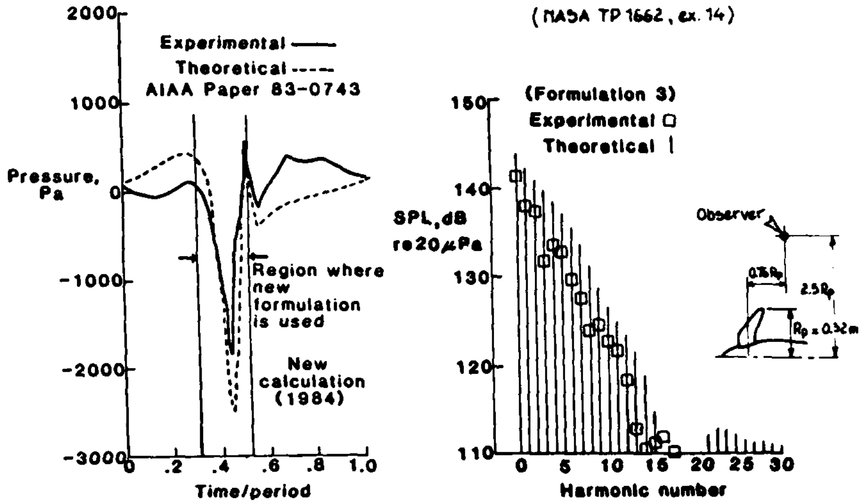
Two other papers on general aeroacoustic approaches, by F. Farassat [10] (NASA-Langley) and L. Long et al. [11] (Lockheed-California) have been already commented in section II,2.

Figure 30 gives a good correlation on pressure signature between the calculation by Farassat [10] and measurements in the near field of a SR-3 prop-fan model with a supersonic blade tip speed.

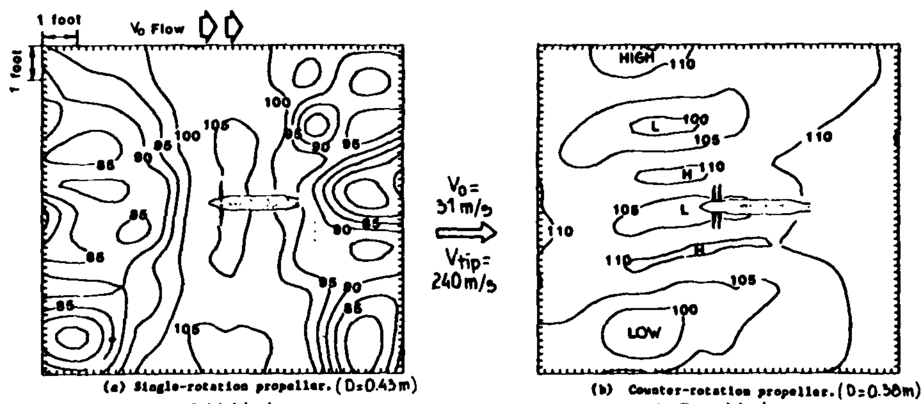
Fig. 30 COMPARISON of PREDICTED and MEASURED PRESSURE SIGNATURE for an ADVANCED SUPERSONIC PROPELLER . NASA-Langley (10)

Four bladed SR-3 prop fan , $M_0 = 0.32$, $M_{tip} = 1.17$

(NASA TP 1662 , ex. 14)



V.1.4 - About Counter-Rotation Prop-fan noise, Metzger [30] has described (Fig. 31) the new mechanisms appearing for this configuration: there is both an acoustic interaction between 2 coherent sources located close together, and an aerodynamic one caused by potential and viscous wake interaction; furthermore, the wing, the pylon and the nacelle influence the flow field and must be introduced in the noise prediction; such a theoretical approach is in progress at Hamilton Standard. Recent *interesting comparative experiments* between two propellers of SR and CR types have been carried out at NASA-Langley [39] in their 4-by7-meter open-jet "anechoic" tunnel: the eight-bladed SR-2 (straight blades) and the CR four-bladed propellers were tested on a sting-mounted motorized nacelle (29 HP); the counter-rotation props were scaled-down by a factor 0.89 viz SR prop. diameter. Figure 32 gives a comparison of the overall noise radiation patterns in contour format (OASPL, decibels) for the two configurations at high-tip- Mach number (V_0 = 31 m/sec.): the SRP has its maximum noise levels in the plane of the propeller disc, and the noise decreases upstream and downstream; the noise patern for the CRP is very different: there are streamwise bands of alternative high (H) and low (L) noise levels repeating every 45° (indicating the directions in which the four blades from each disk are aligned as they rotate 360°); the peak-to-peak levels of these bands are about 10 dB, and 5 dB higher or lower than for the eight-bladed SRP; and the noise levels from the CRP increases upstream and downstream from the disks (by about 30 dB higher than for SRP); analysis of the harmonic contributions to the noise patterns indicates that the second and four harmonics are responsible for the high noise of the CR props in the axial direction, whereas the first and third harmonics contain most of the noise energy in the streamwise bands; in conclusion, it seems that the high level of interaction noise are partly due to the unswept blade shape, and partly to the same 4 blades arrangement on each disk.



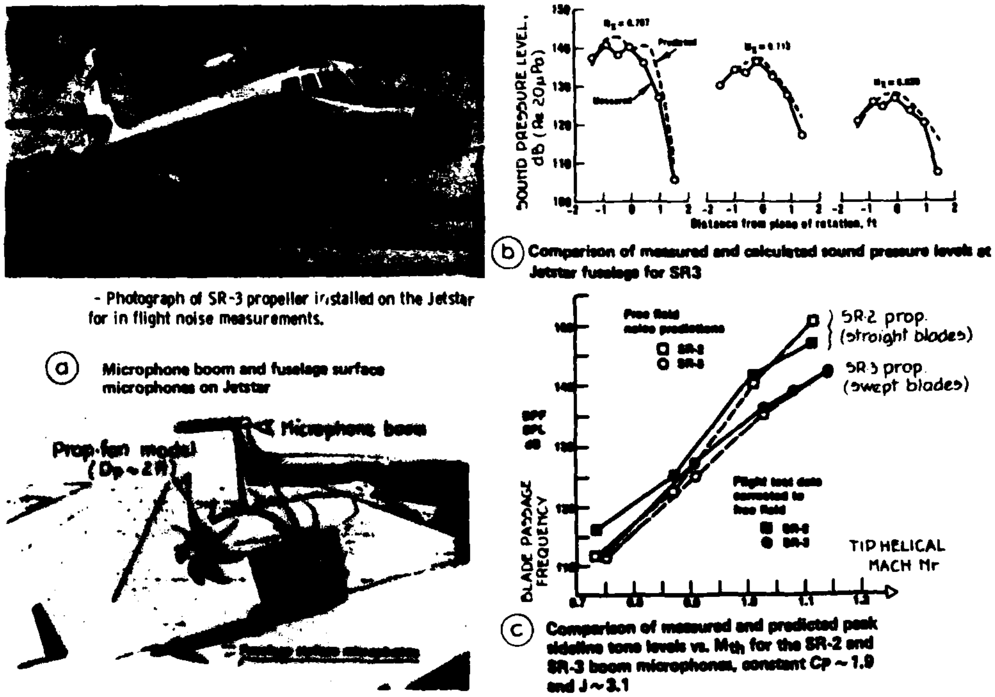
(a) Single-rotation propeller. (D=0.43m) Eight blades

(b) Counter-rotation propeller. (D=0.38m) 2x Four blades

Fig. 32 NOISE RADIATION PATTERNS for PROP-FANS, SR versus CR, with SR-2 STRAIGHT BLADES , TESTED in the NASA-Langley OPEN-JET 4x7m tunnel. Comparison of SRP and CRP configurations with iso-decibels mapping .

In the same report [30], other experiments have shown that for the SR case, the pusher configuration is much noisier than the tractor one, upstream (5 to 15 db), and slightly noisier in the propeller plane; and the pylon wake introduces spikes giving higher noise levels in the higher harmonics.

V.1.5 - Propeller noise measurements in Flight on SR-2 and SR-3 prop-fan models (D ~ 0.6 m) were undertaken in 1981 at NASA-Dryden [30, 12], using an air-turbine drive mounted above the fuselage of a Lockheed Jetstar (Fig. 33a). Initial tests in 1981, using an array of microphones on the fuselage surface for cabin sound-proofing research, have shown that the noise levels were lower than the predicted "free-field" noise, and led to the discovery, by Hanson, that the sound was attenuated by propagation inside the fuselage boundary layer: correction factors were calculated for this flight case which confirms that, at forward locations, the measured level would be much lower than the free-field prediction, due to the boundary layer shielding effect; behind the disk plane, the measured level should exceed the free-field level, due to the pressure amplification associated with the presence of the fuselage; applying this correction, there is a fair agreement between predicted and measured sound pressure levels at the Jetstar fuselage for SR-3 (Fig. 33b). For the second flight testing phase, a microphone boom was mounted above the propeller to obtain the "free-field" noise; Figure 33c shows the comparison of the peak sideline tone levels measured and calculated (Hanson's frequency domain method) for SR-2 (straight blades) and SR-3 (swept blades at 45°): the theory is in good agreement with the experimental results, showing the large benefits of sweep at the high helical Mach numbers corresponding to cruise regime.



- Photograph of SR-3 propeller installed on the Jetstar for in flight noise measurements.

(a) Microphone boom and fuselage surface microphones on Jetstar

(b) Comparison of measured and calculated sound pressure levels at Jetstar fuselage for SR3

(c) Comparison of measured and predicted peak sideline tone levels vs. Mth for the SR-2 and SR-3 boom microphones, constant Cp ~ 1.9 and J ~ 3.1

Fig. 33 NASA-Dryden. FLIGHT RESEARCH on PROP-FAN NEAR-FIELD NOISE.

An interesting Flight Research program was launched in 1982 by Hamilton Standard [30] using an old Fairey Gannet equipped with a conventional Counter-Rotation turbo-prop; although this CR prop. is lightly loaded compared to a prop-fan, the near-field noise measurements have shown that the harmonic levels for the summation of front and rear prop. noise spectra (obtained by operating each separately) is much lower than the spectra of the two CRP operated together (more than 10 dB above the third harmonic); this trend confirms the noise results on CRP models shown previously (Fig. 32).

V.1.6 – The far-field noise of a future Prop-fan Aircraft is an important characteristic for acceptance by civil transport regulation authorities; in his introductory paper, R.M. Lange [1] has commented on the main conclusions of a theoretical study made by Lockheed-Georgia for NASA: the objective was the comparative far-field noise of two twin and four Engine Aircraft (13500 and 60000 lb payload 2300 nM class, Mach 0.75 cruise), with advanced turbo-fans and prop-fans respectively. As shown on Figure 34: all these configurations comply with the FAR-36-stage 3 regulations, the prop-fan schemes having lower noise signature than the turbo-fan Aircraft, mainly at take-off fly-over conditions, because their much larger climb-out slopes at take-off.

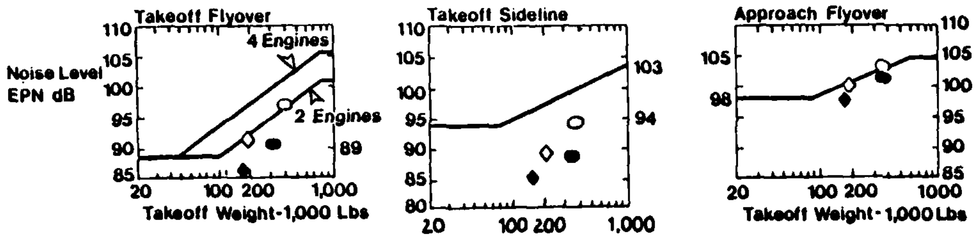


Fig. 34 PREDICTED VALUES of the FAR-FIELD NOISE for PROP-FAN A/C, compared to TURBO-FAN CONFIGURATION viz the FAR-36/Stage 3 Noise Levels Regulation [1].

V.2 – Wind-tunnel and Flight Noise Research on advanced conventional propellers

Four comprehensive contributions on recent studies in Germany, England and Canada were presented in Session IV, all dealing with propeller performance and noise. During the RTD, Pr. Lilley pointed out that "acoustic" wind-tunnels have only been in operation for the last decade, treating this problem of noise measurement and tunnel noise calibration seriously; and all of these tunnels are by no means perfect. The wind-tunnel measurements require a calibration scale; and therefore, it is absolutely essential to have good full-scale Flight data to make that very detailed comparison; as shown by these presentations, a lot of work still needs to be done.

V.2.1 – At the DFVLR-Göttingen, Acoustic wind-tunnel measurements on propeller noise [24] were undertaken on a series of advanced propellers (in close cooperation with Dornier and Hofmann) in the open test section (3 x 3 m) of the Göttingen low speed tunnel equipped with sound absorbing material; five propeller models were tested at 1:3 scale (D = 0.9 m, constant M_{tip} = 0.67); three types of acoustic measurements were carried out: noise near-field at 0.14 D from prop. tips and far-field at 3 D from prop. axis, and investigation of local sound radiation/source distribution in propeller plane by means of an acoustic mirror telescope.

The main conclusions are:

- Noise generation of the propellers was determined mainly by thickness and profile of the blades; modifications of the blade tips had no significant effect on noise,
- Near-field measurements agree well with theory; near-field SPL decreases rapidly with axial distance from propeller plane, particularly the higher harmonics,
- The prop. blades radiate high frequency noise mainly in their direction of motion, due to the convective amplification effect (the sound intensity received from the approaching blade is stronger than the sound received from the receding blade, by a factor of hundred).

V.2.2 – At the DFVLR-Braunschweig, full-scale Flight and model-scale tunnel tests on near-field noise characteristics of A/C propellers [27] were undertaken by the Acoustic Institute:

- The Flight noise tests were made with a single-engined CESSNA T-207 (212 kW) Aircraft, equipped with an array of 8 wing-mounted microphones to investigate near-field noise of a 3-bladed variable pitch McCanley propeller (D_p = 2 m, 2600 RPM); a special electronic technique had been developed to minimize the engine exhaust influence on the propeller signature,
- The wind-tunnel tests were performed in the DFVLR-one meter Acoustic tunnel on tenth-scale propellers (D = 0.27 m) with two to six blades; the free-jet velocity was up to 65 m/sec., with a very low level of turbulence. A similar four-blade-propeller at 1/3 scale was also tested in the DFVLR-Braunschweig 3 m. tunnel for comparison, see [24].

The model tests allowed an exact quantification of the effect of various parameters (Helical blade tip Mach number, blade pitch angle, temperature, etc.) on the harmonic and sub-harmonic propeller noise spectra.

The main conclusions are:

- Helical blade-tip Mach number (HTM) has the largest effect on the near-field signature, i.e. sound pressure level spectrum (a growing number of discrete components at high HTM),
- The tenth-scale propeller tests revealed certain characteristics of the sub-harmonic spectra; harmonic levels are independant of blade number,
- Blade loading distinctly changes the harmonic spectrum,
- Ambient temperature caused fairly pronounced effects on the harmonic levels (a change from 15°C to 30°C raised levels by 3 to 6 dB for the first few harmonics, at HTM = 0.7),
- It is too early to quantify a scale (Reynolds number) effect with these one-tenth-scale tests and it is still difficult to find quantitatively scalable results.

V.2.3 - An integrated Research program on subsonic Aircraft propeller noise has been carried out jointly by the RAE and Dowty-Rotol, with the active participation of Short, and with support from UK Dpt. of Industry. The paper given by Pr. Williams covered some Aeroacoustic wind-tunnel measurements, theoretical predictions, and Flight-test correlations on subsonic Aircraft propellers [25]. The Research work combined acoustic tunnel experiments on propellers at model-scale (1/4 scale, in the 1.5 m Farnborough acoustic tunnel) and full-scale (D_p = 2.8 m in the 24 ft Farnborough tunnel) with Aircraft Flight tests (Short-330 commuter Aircraft), and theoretical predictions; moreover, a 1/4 scale complete model of the Short-330 was aeroacoustically tested in the 24 ft tunnel with the same R-292 four bladed propellers already analysed in the 1.5 m tunnel to investigate installation effects. The Dowty 4-bladed R-292, standard tip, propeller had modern ARA-D sections.

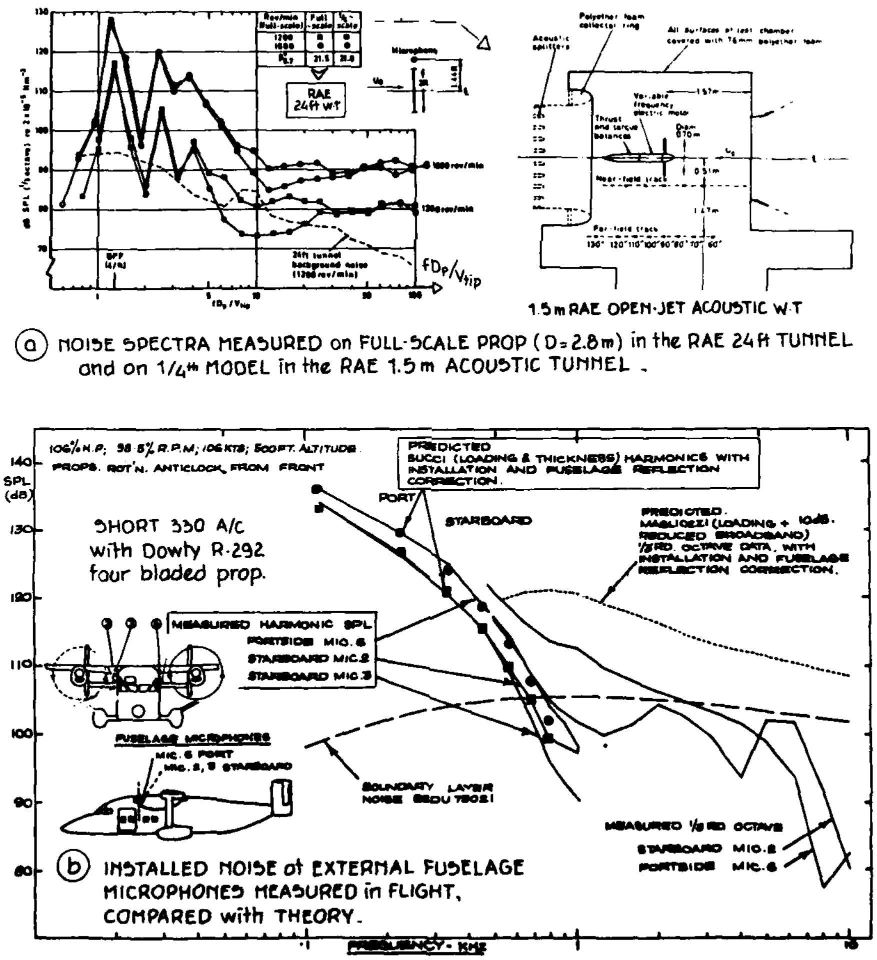


Fig. 35 RAE ACOUSTIC RESEARCH on PROPELLERS .

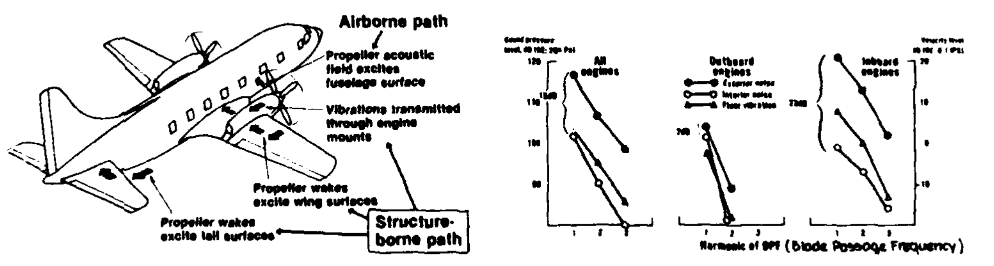
Lastly, the Research Program included the test of another Dowty 4-bladed R-212 propeller with classical NACA-16 series sections both in the 24 foot tunnel and on the BAe HS-748 Aircraft in flight. Analysis of the results led to the following technical gains and scientific clarification for subsonic propeller design and airframe installations:

- The aeroacoustic advantages to be gained from the 1/4 scaled propeller model tested in the 1.5 m acoustic tunnel rather than at full-scale in the quite turbulent 24 ft tunnel (large background noise) are clearly demonstrated, as shown on Figure 35a where are compared the noise spectra as a function of the Strouhal numbers; here the blade-passing frequency for this four bladed propeller occurs at $S = 4/\pi$; the discrepancy between the two tests in the range $5 < S < 20$ is attributable to the intrusion of the background noise in the 24 ft tunnel and to its higher turbulence level (0.5% instead of 0.25% for the 1.5 m tunnel).
- Model propellers at 1/4 scale have aerodynamic performance quite close to full-scale with a good agreement on noise spectra for the same Strouhal number.
- Empirical parametric formulae confirm the reduction in noise level (both discrete-frequency and broadband) with increasing mainstream speed away from near-static conditions.
- It is recommended to duplicate the flight conditions for the mainstream Mach numbers; blade Reynolds numbers do not appear significant here, with a blade chord Reynolds number: $Re \simeq 0.5 \times 10^6$ at the 0.7 radius.
- Much higher aerodynamic performance was obtained with the new ARA-D sections compared to conventional ones without noise increase.
- Differences in blade tip geometry have not led to noise reductions; more theoretical work is need on this subject.
- Increasing the number of blades (from 3 to 8) gives appreciable reductions in the SPL of the BPF tone for the same C_p and M_H, with some gain on aerodynamic efficiency.
- The available theoretical prediction methods for predicting discrete-frequency noise of isolated subsonic propellers have been successfully applied by Dowty and Southampton University for correlation with full-scale and model-scale results: in particular the Succi-DR method and planform-mesh distributions of steady loading and thickness-volume elements, while the simpler Hawkings-SU method involves mainly spanwise distributions.
- The current broadband noise predictions in the far-field by the Magliozzi empirical formula (1/3 octave) can be of the order of 10 dB higher than the measured values, and are questionable for near-field application.
- About Propeller Installation effects, some consistent correlations were obtained between installed and isolated propeller measurements. Encouraging predictions of the near-field tone levels at fuselage-mounted microphones near the propeller discplane have been obtained using the Succi-Dowty method (including simple treatments for prop. rotational sense, airframe upwash incidence and fuselage reflection) as shown on Figure 35b with Flight results.

V.2.4 - An investigation of in-Flight near-field propeller noise generation and transmission is reported by Pratt and Whitney Canada [26]; the measurements were conducted on an experimental twin-engine turbo-prop. Aircraft equipped with a series of microphones installed on a wing mounted boom and flush with the A/C fuselage, as well as inside the cabin. Measured propeller harmonic levels are compared to calculations of the near-field noise, using a modified version of the Farassat computer program, in which the blade surface pressure is described using the known aerodynamic properties of the blade (NACA 16) airfoil sections; the dominant harmonic levels are well predicted, while higher harmonic levels are unpredicted. The "transmission loss" between exterior and interior noise levels is quite independent from the propeller regimes. Finally, it was found that interior noise was not reduced by changing engine mount stiffness.

V.3 - Cabin noise analysis and reduction

One of the ultimate objective of turbo-prop. Aircraft noise Research is to reduce the noise level inside the passenger's cabin, not only by decreasing airborne noise but also by structure borne noise reduction.



(a) Candidate transmission paths for propeller noise

(b) Comparison of exterior and interior noise to floor vibration DHC-7 port side prop-plane 9500 ft 10% RPM

Fig. 36 PROP. NOISE TRANSMISSION through AIRCRAFT STRUCTURE

V.3.1 - Three candidate structural transmission path are pictured on Figure 36a, from Metzger [30]. A Research program was launched by Hamilton/Lockheed/De Havilland-Canada to demonstrate these points, using a four propeller driven DHC Dash-7; measurements in Flight were made with a series of flush mounted microphones on the fuselage surface and in the cabin; Figure 36b gives the sound pressure levels measured outside and inside the fuselage and the floor vibration level for all engines operating, then for outboard engines alone (the fuselage surface noise is reduced by 13 dB, but not the cabin noise), and finally for inboard engines alone (the exterior level is higher due to larger power used to maintain the speed); the noise caused by the propeller wakes interacting with the wing is dominating the cabin noise (blade passage frequency) when the outboard engines are operating alone.

V.3.2 - Propeller Aircraft cabin vibration and noise excitation, source and paths were also the subject of a Lockheed-California contribution [29] which describes the Flight tests conducted on a Navy Lockheed P-3C four propeller patrol A/C; the objective was to measure the structure borne noise transmission and radiation characteristics of the P-3C when the engines, wing, fuselage, and empennage are excited by electrodynamic shakers and impulse hammers that can excite the A/C structure in the frequency range where the cabin noise problem is the greatest; four microphones and 7 accelerometers were installed to measure its structural and acoustical response to the mechanical excitations.

The main results are:

- The nacelle/inlet and wing system can produce non uniform flow fields which results in 4P aerodynamic propeller blade loads inducing important cabin vibration and acoustic levels.
- Wing and tail propeller slipstream excitations can be important to the P-3C.
- The source/paths that influence cabin vibration and noise probably varies considerably between configurations, and the mechanical excitation techniques seem useful in providing some quantification of the relative importance of each source.

V.3.3 - Theoretical and experimental methods for cabin noise reduction of a new development turbo-prop. commuter Aircraft were presented by Aeritalia/Napoli Institute [28]; interior noise control of the new twin turbo-prop. commuter ATR-42 to a level of 78 dBA was the objective of the study.

The experimental program for developing the acoustic configuration of fuselage sidewall structure and add-on insulation/absorber systems have used a full-scale fuselage section including windows and floor structure, and pressurized (3.25 m long); acoustic excitation is obtained through a loudspeaker system driving an acoustic horn and several microphones are mounted inside the chamber. The sidewall treatment acoustic performance was studied theoretically using several procedures: the panel-stringer periodic model was in good agreement with the experiments; the main concern is the prediction of low frequency noise reduction; experimental modal analysis performed on the bare and furnished fuselage section showed the importance of a detailed description of the main structure, that should consider also the attached mass-spring system of the interior furnishing.

V.3.4 - A very new approach to the problem of cabin noise was finally presented by Lockheed-Georgia, dealing with the application of active noise control to model propeller noise [31].

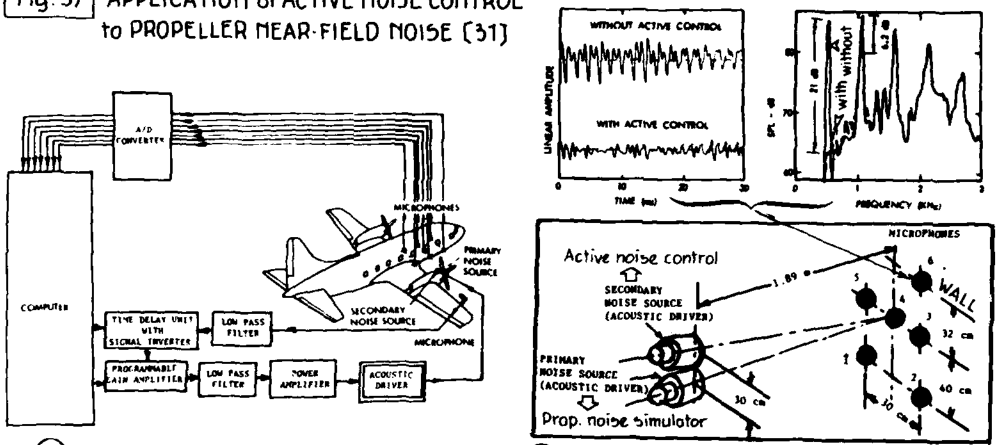
The basic principle of active noise control is to reduce the noise radiated from a primary source (i.e. the propeller or prop-fan) by using a secondary sound source: if the secondary source signal can be made identical in amplitude but opposite in phase to the primary sound signal, then a complete cancellation can be achieved within certain regions of the space surrounding the two sources: on a real Aircraft, a possible application is shown on Figure 37a where the noise generated by the propeller has to be minimized at the fuselage surface using a secondary source installed through the nacelle and facing toward the fuselage surface; the secondary source can be controlled by a signal measured at a remote location, and modified in amplitude and phase so that the secondary source output reaching the fuselage surface would meet the active noise control requirements of reducing the blade passage tone and its harmonics. The feasibility of this active control has been successfully demonstrated by three experiments using:

- discrete-frequency sinusoïdal signal;
- simulated propeller noise;
- noise generated by a 1/10th scale C-130 model propeller with simulated flight as the primary noise source.

On Figure 37b, a pre-recorded time history of propeller noise from a 1/10 scale C-130 is used as input to the primary source (acoustic driver); the tape recorded noise for secondary source input is fed through a number of low and high pass filters to separate each of the four harmonics and each of the harmonics are modified individually for the best attenuation; here the first two blade passage harmonics were successfully reduced in terms of signal time histories and spectral level (21 and 6 dB attenuation).

To conclude, even though these experimental results in the laboratory environment are very encouraging, we are far of the practical implementation of active noise control on a real Aircraft: a lot of hardware planning is clearly needed (secondary source, microphone location on the fuselage, electronic equipment, power supplies,...).

Fig. 37 APPLICATION of ACTIVE NOISE CONTROL to PROPELLER NEAR-FIELD NOISE [31]

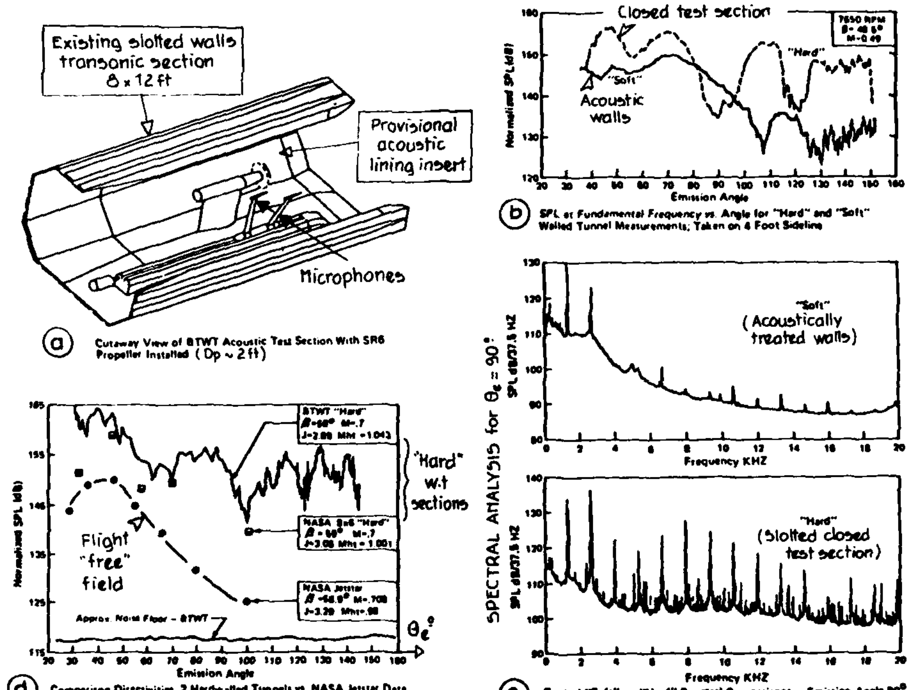


(a) Computer-controlled analog active noise control system with feedback loop for propeller aircraft.

(b) Simulated propeller noise experiment (10200 RPM, $V_0 = 75$ m/s) : Effect of active noise control on noise signature and level reduction (first 2 BPF).

V.4 - Validity of noise measurements in wind-tunnels

Most of the low speed anechoic wind-tunnels have only been in operation for about the last decade, and are by no means perfect, as stated Prof. Lilley during the Round Table discussion; and it is mandatory to have good full-scale measurements in Flight for a detailed calibration (such calibration was recently successfully done on a helicopter rotor model tested in two large European anechoic tunnels with open test sections: the DNW 6 x 8 m and ONERA/CEPr 3 m. tunnels; the data obtained were compared with those measured in Flight by the *US-Army* on a *Bell Helicopter*.



(a) Cutaway View of 8TWT Acoustic Test Section With SR6 Propeller Installed (Dp ~ 2 ft)

(b) SPL at Fundamental Frequency vs. Angle for "Hard" and "Soft" Walled Tunnel Measurements; Taken on 4 Foot Sideline

(c) Typical "Soft" vs. "Hard" Spectral Comparisons – Emission Angle 90°

(d) Comparison Directivities 2 Hardwalled Tunnels vs. NASA Jetstar Data (Fundamental); Mach $M_0 \sim 0.7$, $M_{HT} \sim 1$.

Fig. 38 NOISE TESTING of a SR-6 PROP-FAN MODEL in the BOEING TUNNEL with and without wall acoustic treatment.

If a closed test-section tunnel is used for noise testing, parasitic reflections on the "hard walls" have a substantial effect on the measured noise signature of the propeller; in a recent paper [36], Boeing has published some interesting comparisons on noise directivity measurements from a SR-6 propeller model tested at Mach 0.7 in two closed test-sections of the Lewis 8 x 6 ft and the Boeing 8 x 12 ft transonic tunnels; on Figure 38d, the measured normalized noise as a function of the emission angle, illustrates that the two hardwalled tunnel results are quite similar, but very different from NASA-Dryden *Flight Tests* obtained on the same SR-6 propeller mounted above the Jetstar fuselage (see Fig. 33a); this is a further evidence that a free-field, or non-reflective, test environment is highly desirable for propeller noise testing.

Then, the Boeing Transonic Tunnel was equipped with an acoustically treated test section (25% reduction of the cross sectional area, and max. Mach number reduced to M = 0.49); tests were again conducted with movable microphones (Fig. 38a) for comparing the noise measurements made with these "soft" walls and the original "hard" walls; Figure 38b shows significant differences in the shapes and peak levels of the normalized noise as a function of the emission angle; spectral comparisons for 90° emission angle given on Figure 38c exemplify marked changes between treated and untreated test-section measurements for similar locations and operating conditions.

Since November 1984, Boeing has undertaken a prop-fan noise program on the UDF configuration with a new acoustic lining insert (see Fig. 16d) which is quickly removable, and does not penalize the requested testing velocity (Mach up to 0.85).

VI - PROSPECT FOR NEW TURBO-PROP SYSTEMS

A very good "State of the Art" on engines designed for the new generation of high-speed propellers was given by Prof. SARAVANAMUTTO [23]; the paper begins with a brief historical overview on Turbo-prop Aircraft, from their introduction on Airlines (with the famous British Viscount) to their continuous use since 30 years for military transport, or ASW missions, but also for civil commuter services; special mention was given to the Russian Tu-114 long-range transport, equipped with contra-rotating- 18 foot propellers, driven by 4 Kuznetsov 12000 SHP Turbo-props, and able to cruise at Mach 0.74 500 mph at 33 000 ft; its military version is still in service as the "Bear" Bomber.

VI.1 - Engine cycle and power transmission

At the present time, we see the need for much more powerful engines to drive a Prop-fan (10000 to 20000 HP) than for a conventional propeller (Max Power around 6000 HP for the R.R. Tyne or the GE T-56...); that is why it is expected that the "interim" Prop-fan nacelle chosen to validate the concept will be powered by an engine using the "core" of an existing advanced turbo-jet turbo-fan.

It must be remembered that the Prop-fan operates at extremely high-by-pass ratios ~30 to 60~, and, for a given cruise thrust, the gas generator flow will be much lower than the flow required for the equivalent turbo-fan: thus, it means very small compressor and turbine sizes, with less efficiency.

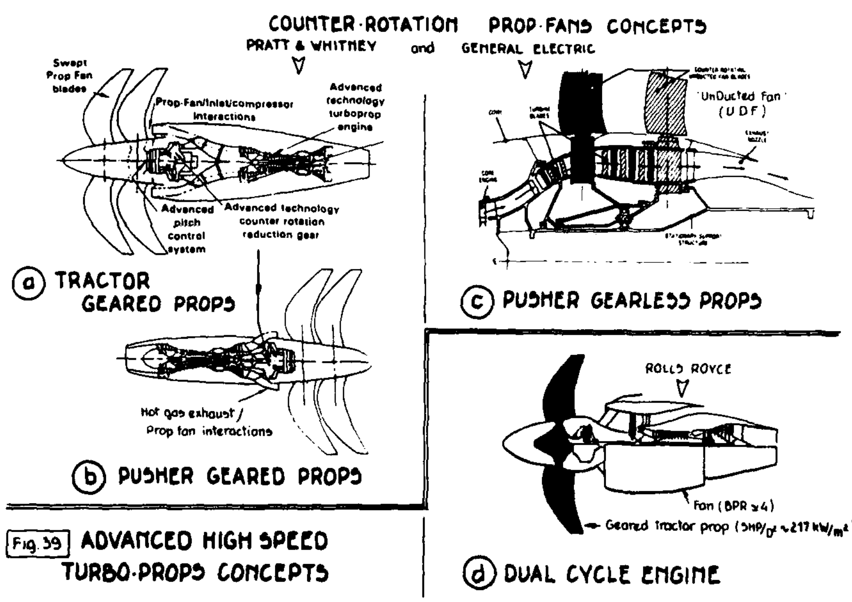


Fig. 39 ADVANCED HIGH SPEED TURBO-PROPS CONCEPTS

Various Turbo-prop configurations (Fig. 39) are described: fixed turbine, free turbine single spool compressor, twin spool compressor propeller driven by L.P. Turbine, and twin spool compressor with free turbine, which are all quite viable; a fifth scheme is proposed by General Electric, with the revolutionary Counter-Rotating turbines, driving directly two C.R. propellers (Un-Ducted Fan, [34], Fig. 39c); this requires considerable technology advances to build such turbines without stators, and several problems are expected [33]: low speed turbines and higher loading Prop-fans mean less overall efficiency than for a geared C.R. propeller configuration.

On the other hand, high power gearbox development is also a challenge with other mechanical and lubrication problems, and extra weight, maintenance cost, etc.; but it is interesting to notice that a contra-rotating differential planetary gearbox seems lighter than a S.R. gearbox [12].

Another possibility, suggested by Rolls Royce [23], is the dual cycle engine which combines a Turbo-fan with a geared Prop-fan; this configuration (Fig. 39d) would lead to some loss on propulsive efficiency, but a substantial gain in gearbox power.

VI .2 - Propulsion System Configurations

We have already seen that many choices are available to Engine and Airframe Designers for future Prop-fan powered Aircraft [33, 34, 30, 12]:

- S.R. or C.R. Prop-fan.
- Geared or gearless engines.
- Tractor or pusher configurations.
- Wing or fuselage mounted installations.

VI.2. a - Both tractor and pusher schemes have advantages and disadvantages:

- For the tractor scheme, (Fig. 39a), the propeller has a "clean" flow approaching, but the engine designer is concerned with the swirl flow from the S.R. propeller on the inlet and with diffuser efficiency distortion problems.

- For the pusher case, (Fig. 39b), management of the hot exhaust gas through the propeller is a concern (addition of a protective coating?).

Both of these disadvantages are overcome with the GE UDF configuration (Fig. 39c).

VI.2.b - When comparing wing and fuselage mounted nacelles, illustrated on Figure 40, both aerodynamic and acoustic impacts must be discussed [33]:

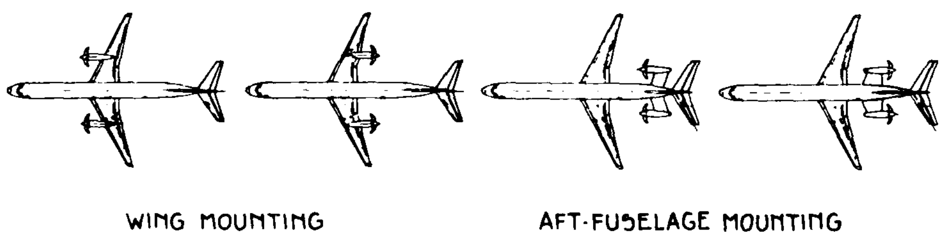


Fig. 40 PROP-FAN PROPULSION SYSTEMS on TRANSPORT AIRCRAFT.

- Tractor configurations mounted on the wing gives a high speed slipstream on the wing (with a strong swirl angle for a SRP), which can induce parasitic shock-waves -and extra drag at high speed cruise regimes; a positive aspect of this slipstream is a "blown wing effect", which gives better low speed (STOL) performance (mainly with flap-down).

  Another negative aspect of this wing mounted configuration is the strong noise in the vicinity of the passenger cabin, which necessitates added fuselage acoustic attenuation treatment.

- Pusher configuration on the wing is probably out of the question because of the strong wing wake inducing unsteady structural loading on such thin blades working just behind the wing trailing-edge.

- Configurations mounted aft on the fuselage are very attractive because the acoustic signature is behind the passager cabin; but the sound pressure levels (about 150 db) are higher because of the closer proximity to the fuselage, and a vibration damping material is still mandatory on aft-fuselage and tails. At this rear location, both tractor and pusher schemes are possible, with negative effect of the pylon wake on the pusher propeller, but a better inlet efficiency is expected for this configuration.

VII – REFERENCES

The papers presented at the AGARD FDP Symposium are listed as references [1] to [31] inside the four sessions; and ref. [32] is the final publication AGARD-CP 366 which contains the Round-Table discussion.

The next complementary references are related to key papers on high speed propellers recently published.

Reference

SESSION I – PROPELLER ANALYSIS AND DESIGN

[1] A REVIEW OF ADVANCED TURBOPROP TRANSPORT ACTIVITIES
by R.H.Lange

[2] METHODES AERODYNAMIQUES UTILISEES EN FRANCE POUR L'ETUDE DES HELICES POUR AVIONS RAPIDES
par J.M.Bousquet

[3] DESIGN CONCEPT AND PERFORMANCE PREDICTION TECHNIQUE FOR POTENTIAL FLOWS AROUND ADVANCED PROPELLERS
by T.S.Luu and R.Collercandy

[4] PAPER WITHDRAWN

[5] REVIEW OF ARA RESEARCH INTO PROPELLER AERODYNAMIC PREDICTION METHODS
by A.J.Bocci and J.I.Morrison

[6] PROFILS MODERNES POUR HELICES
par A.M.Rodde, J.J.Cuny et J.J.Thibert

[7] AERODYNAMICS OF WIDE-CHORD PROPELLERS IN NON-AXISYMMETRIC FLOW
by J.B.H.M.Schulten

[8] ON THE AERODYNAMICS OF INSTALLED PROPELLERS
by M.E.Eshelby

[9] A UNIFIED APPROACH FOR THE AERODYNAMICS AND ACOUSTICS OF PROPELLERS IN FORWARD MOTION
by A.Das

[10] THEORETICAL ANALYSIS OF LINEARIZED ACOUSTICS AND AERODYNAMICS OF ADVANCED SUPERSONIC PROPELLERS
by F.Farassat

[11] COMPRESSIBLE, UNSTEADY AERODYNAMICS USING AN AEROACOUSTIC INTEGRAL EQUATION
by L.N.Long and G.A.Watts

SESSION II – PROPELLER TESTING

[12] SUMMARY OF RECENT NASA PROPELLER RESEARCH
by D.C.Mikkelson and G.A.Mitchell and L.J. Bober

[13] COMPORTEMENT DYNAMIQUE D'UN ROTOR DE PROP-FAN
par J.M.Besson et D.Petot

[14] PERFORMANCE EVALUATION OF FULL SCALE PROPELLERS BY WIND TUNNEL TEST
by D.J.Barber

[15] ETUDE DU SILLAGE 3D D'UNE HELICE AERIENNE
par D.Favier et C.Maresca

[16] INVESTIGATIONS OF MODERN GENERAL AVIATION PROPELLERS
by H.Zimmer, R.Hoffmann and K.H.Horstmann

[17] AERODYNAMIC AND STRUCTURAL ASPECTS OF PROPELLER AND DRIVE FOR A $\frac{1}{5}$ SCALE MODEL WIND TUNNEL PROGRAMME
by R.M.Bass, B.Munniksma and J.van Hengst

SESSION III – PROPELLER AIRFRAME INTEGRATION

[18] SOME CONSIDERATIONS IN PROPELLER AND AIRFRAME INTEGRATION
by B.Eggleston

[19] LES PROBLEMES D'INTEGRATION DES HELICES A LA CELLULE D'UN AVION ET, PLUS PARTICULIEREMENT, D'UN BIMOTEUR DE FORTE PUISSANCE
par R.Taisseire

[20] A FLOW MODEL FOR WINGS/BODY PROPELLER INTERFERENCE
by A.Emerati and G.M.Lilley

Reference

[21] WIND TUNNEL INVESTIGATION OF INTERACTION OF PROPELLER SLIPSTREAM WITH NACELLE/WING/FLAP COMBINATIONS
by A.S.Aljabri and A.C.Hugues

[22] AN ASYMPTOTIC THEORY FOR THE INTERFERENCE OF LARGE ASPECT RATIO SWEPT WINGS AND MULTIPLE PROPELLER SLIPSTREAMS
by R.K.Prabhu, C.H.Liu and S.N.Tiwari

SESSION IV – PROPELLER ACOUSTICS

[23] DEVELOPMENT OF MODERN TURBOPROP ENGINES
by H.I.H.Saravanamuttoo

[24] AEROACOUSTIC WIND TUNNEL MEASUREMENTS ON PROPELLER NOISE
by F.R.Grosche and H.Stiewitt

[25] SOME AEROACOUSTIC WINDTUNNEL MEASUREMENTS, THEORETICAL PREDICTIONS, AND FLIGHT TEST CORRELATIONS ON SUBSONIC AIRCRAFT PROPELLERS
by W.G.Trebble, J.Williams and R.P.Donnelly

[26] AN INVESTIGATION OF IN-FLIGHT NEAR-FIELD PROPELLER NOISE GENERATION AND TRANSMISSION
by H.Bonneau, D.F.Wilford and L.Wood

[27] FULL-SCALE FLIGHT AND MODEL-SCALE WINDTUNNEL TEST ON THE NEARFIELD NOISE CHARACTERISTICS OF AIRCRAFT PROPELLERS
by H.H.Heller and M.Kallergis

[28] CABIN NOISE REDUCTION FOR A NEW DEVELOPMENT TURBOPROP COMMUTER AIRCRAFT
by A.Carbone, A. Paonessa, L.Lecce and F.Marulo

[29] PROPELLER AIRCRAFT CABIN VIBRATION AND NOISE-EXCITATION, SOURCES AND PATHS
by R.E.Donham, F.J.Balena, E.Z.Bochary and O.K.Liehr

[30] THE STATE OF THE ART IN PROP-FAN AND PROPELLER NOISE
by F.B.Metzger

[31] APPLICATION OF ACTIVE NOISE CONTROL TO MODEL PROPELLER NOISE
by M.Salikuddin, H.K.Tanna, R.H.Burrin and W.E.Carter

[32] -ROUND-TABLE DISCUSSION (See AGARD CP-366, March 1985) chaired by MM. Ohman (CA), Tijdeman (NL), Peckham (UK), Sacher (Ge), Lilley (UK), and Roberts (USA)

[33] -Single Rotation and Counter Rotation Prop-Fan Propulsion System Technologies, by B.S. Gatzen (Hamilton Standard) and C.N. Reynolds (Pratt & Whitney). ICAS Paper 84-5.6.2, Sept. 1984

[34] -Unducted Fan for To Morrow's Subsonic Propulsion, by R.C. Hawkins (General Electric). AIAA-Aerospace America, Oct. 1984

[35] -Cold Air Turbine Drives for Model Advanced Design Propellers, by B.M. Glover et at. (Boeing). AIAA Paper Nr 84-2368, Oct. 1984

[36] -Noise Testing of an Advanced Design Propeller in the Boeing Transonic Wind Tunnel with and without Test Section Acoustic Treatment, by B.M. Glover et al (Boeing). AIAA Paper Nr 84-2366, Oct. 1984

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[38] Analysis of Counter-Rotating Propeller Performance, by J.L. Colehour and F.J. Davenport (Boeing) and J.S. Sokhey (G.E.). AIAA Paper Nr 85-0005, Jan. 1985

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[40] Aeroacoustic Research in the Netherlands related to Aircraft Development. ICAS Paper Nr 84-5.8.2, Sept. 1984

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[42] Computation of Prop-Fan Engine Installation Aerodynamics, by C.W. Boppe and B.S. Rosen (Grumman Corp.). ICAS Paper 84-5.5.3, Sept. 1984

[43] Prop-Fan Installation Aerodynamics of a Supercritical Swept Wing Transport Configuration. AIAA Paper Nr 81-1563, July 1981

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The Advisory Report contains a review and evaluation of the material presented at the AGARD Fluid Dynamics Panel Symposium on "Aerodynamics and Acoustics of Propellers" held in Toronto, Canada, 1—4 October 1984. The author has also included related information from other sources and presents an excellent discussion of the state of art of modern propeller design and performance.

This Advisory Report was produced at the request of the Fluid Dynamics Panel of AGARD.

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