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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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- Improving the co-operation among member nations in aerospace research and development;
- Providing scientific and technical advice and assistance to the North Atlantic Military Committee in the field of aerospace research and development;
- Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field;
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I - INTRODUCTION

The propeller has become a focus of attention after being 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 reappraisal 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 bulle 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 NASA 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 0.5, a high by-pass ratio Turbo-fan exhibit only about 85% efficiency compared to about 72% for a "Single Rotation" (SR) Turbo-prop; such SR Prop-fan has a very high power loading (300 kW/m², 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 III Aircraft modified by Lockheed-Georgia and fitted with a Hamilton Standard 9-foot diameter propeller, in front of the left wing (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 "Enhanced Fan" (UDF), with CR Turbine and CR Propeller working together [34]; a NASA-GE contract covers design and around testing of the experimental engine (20,000 HP and 22,000 lb 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 B-747 is scheduled for 1987 (Fig. 1).

About the potential interest of this new type of propulsion, Figure 3 [35] 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 prop-fan, due to 5-10% higher efficiency.
Fig. 1

**PROPELLER RESEARCH in the UNITED STATES**

**PROPELLER TURBOJET** ⇒ **LOW BPR** ⇒ **HIGH BPR TURBOFAN**

<table>
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<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>1955</td>
<td>Mach ≤ 0.6</td>
<td>20 years hiatus in prop. research</td>
<td>Mach = 0.8</td>
<td>F104 core, C.R. U.D.F. D = 2.6m, W = 20000 HP</td>
<td></td>
<td></td>
<td>General Electric nacelle, F404 core, C.R. U.D.F. D = 2.6m, W = 20000 HP</td>
<td></td>
</tr>
</tbody>
</table>

LOCKHEED/Georgia test bed system:
- Hamilton D = 2.75 m prop fan,
- Allison turbo shaft, W = 5000 HP els,
- Gulfstream II Aircraft, M = 0.6.

"CONVENTIONAL/LOW SPEED" ADVANCED L.A.P. "SINGLE ROTATION" ADVANCED C.R. HIGH SPEED TURBOPROP "COUNTER ROTATION" ADVANCED C.R. HIGH SPEED TURBOPROP

- Installed cruise efficiency trends.

**Fig. 2**

"CLIMB AND DESCENT DOMINANT" "CRUISE DOMINANT"

**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 (1), which shows (Fig. 4) a dramatic advantage for the prop-fan configurations on the specific consumption (sfc) 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. & W.

Table:

<table>
<thead>
<tr>
<th></th>
<th>Turbo-Fans</th>
<th>Prop-Fans with Gearbox</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Single Rotation</td>
<td>Counter Rotation</td>
</tr>
<tr>
<td>Engine take-off thrust/Power</td>
<td>7520 kg (16,600 lb)</td>
<td>11,560 HP</td>
</tr>
<tr>
<td>BY-PASS RATIO</td>
<td>7</td>
<td>10,060 HP</td>
</tr>
<tr>
<td>Max Turbine Entry Temp.</td>
<td>1460°C (260°F)</td>
<td>1460°C (260°F)</td>
</tr>
<tr>
<td>Disc Diameter</td>
<td>1.37 m</td>
<td>1426°C (260°F)</td>
</tr>
<tr>
<td>Mach Number Cruise</td>
<td>0.75</td>
<td>(10 BL, 240 m/SEC) (16 + 6, 250 m/SEC)</td>
</tr>
<tr>
<td>Nacelle Location</td>
<td>Underwing Pod</td>
<td>Tractor Prop/Fan in Front/Above Wing</td>
</tr>
<tr>
<td>Prop System Weight</td>
<td>Base + 9%</td>
<td>- 7%</td>
</tr>
<tr>
<td>A/C Operating Empty Weight</td>
<td>Base + 4%</td>
<td>- 0.5%</td>
</tr>
<tr>
<td>A/C 1.0 Gross Weight</td>
<td>Base + 0.5%</td>
<td>- 5%</td>
</tr>
<tr>
<td>(including Acoustic Protection of Fuselage)</td>
<td>Base + 1%</td>
<td>- 2%</td>
</tr>
<tr>
<td>Aircraft Fuel Consumption</td>
<td>SEA-LEVEL/MACH 0.2</td>
<td>35000 FT/MACH 0.75</td>
</tr>
<tr>
<td>1.3 S.F.C.</td>
<td>Base + 39%</td>
<td>- 46%</td>
</tr>
<tr>
<td>400 NM Mission Fuel Burn</td>
<td>Base + 1758 kg</td>
<td>- 21%</td>
</tr>
<tr>
<td>B.O.C. (x 1.5/GALL.)</td>
<td>Base + 11%</td>
<td>- 14%</td>
</tr>
</tbody>
</table>

Fig. 5: Advanced turboprop propulsion system.

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, etc.). The 31 papers were given inside four Sessions:

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

which are briefly analyzed 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 (2), including installation problems (mechanical gearbox and gearless concepts, inlet and exhaust locations, etc.).
The ten papers given in this first session will be reviewed in section 11.2.1, prior to this review a summary of the calculation methods is given, which is based on the excellent contribution of Pr. Tijdeman to the Round Table Discussion [12]. Comments on some tests results, on some aerodynamic interference or acoustic aspects will be discussed later on in chapters III, IV and V.

11.1 - 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 and 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 occurred 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 [4, 6, 14, 15, 10], 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 following Tables A to D.

**Fig. 6** SOME ASPECTS OF COMPUTATIONAL FLUID DYNAMICS

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

LIFTING LINE ANALYSES
- STRIP ANALYSIS -SR
- CURVED LIFTING LINE -SR, CR
- PROPELLER/LINCELL -SR, CR

LIFTING SURFACE ANALYSES
- TRANSONIC POTENTIAL -SR
- BLASIUS EQUATIONS -SR, CR
- NAVIER-STOKES -SR

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

**TABLE A**

3 Dim. METHODS FOR ASYMMETRIC FLOW

<table>
<thead>
<tr>
<th>PURPOSES: DESIGN, ANALYSIS; INPUT FOR NOISE COMPUTATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>METHODS: PART A</td>
</tr>
<tr>
<td>NAVIER-STOKES EQUATIONS</td>
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<tr>
<td>FULL EULER EQUATIONS</td>
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<tr>
<td>FULL POTENTIAL EQUATIONS</td>
</tr>
<tr>
<td>LINEARIZED EULER EQUATIONS</td>
</tr>
<tr>
<td>CURVED LIFTING LINE</td>
</tr>
<tr>
<td>2 Dim. APPROXIMATION</td>
</tr>
<tr>
<td>SIMPLIFIED METHODS</td>
</tr>
<tr>
<td>EFFECT OF WAKE ON A/C COMPONENTS IN</td>
</tr>
</tbody>
</table>

(*) EFFECT OF WAKE ON A/C COMPONENTS IN:
- TRANSPORT S.T. (transport and the wake structure) [12]
- Old Rom. U. (wake behind propeller, lift) [12]

ESTIMATE: NON-LINEAR METHODS INCLUDING VISCOUS EFFECTS ARE ESSENTIAL FOR AERODYNAMIC 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 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 LIMI飘羽院. [1]; 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].

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 propellers) requires a time-dependent computation for obtaining the loads on the propeller (I-P and multiple P-loads), the time-dependent content 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".

| PURPOSE: TIME DEPENDENT LOADS ON PROPELLER A.昏8, 1-P LOADS, EXCITATION OF THE AIRCRAFT, INPUT FOR NOISE COMPUTATION |
| METHODS: NAVIER-STOKES EQUATIONS | FULL EULER EQUATIONS | FULL POTENTIAL EQUATIONS | LINEARIZED EULER EQU. | ACCELERATION POTENTIAL |
| ESTIMATE: PROBABLY NON-LINEAR APPROACH REQUIRED FOR PROP-FAN. |

The dynamic (i.e., motion-induced) loads are important for whirl-flutter studies (a quasi-steady way is assumed) 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. 10. 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.

| PURPOSE: MOTION INDUCED |
| METHODS FOR DYNAMIC LOADS |
| WHYRTITLMT: LOW-FREQUENCY (QUASI-STEADY) |
| BLADE FLUTTER: HIGHER FREQ. (UNSTEADY) |
| 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 input, the "steady" aerodynamic loads on the propeller, and the "time-dependent" loads due to flow asymmetry, which give the noise field. A complicated additional step in 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>
<thead>
<tr>
<th>TABLE D</th>
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<tr>
<td><strong>NOISE COMPUTATIONS</strong></td>
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<tr>
<td><strong>&quot;STEADY&quot; LOADS</strong></td>
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<tr>
<td>ON PROPELLER</td>
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<tr>
<td><strong>NEAR FIELD</strong></td>
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<tr>
<td><strong>METHODS</strong></td>
</tr>
<tr>
<td>LINEARIZED EULER EQUATIONS</td>
</tr>
<tr>
<td>ACCEL. POTENTIAL EQ.</td>
</tr>
<tr>
<td>ESTIMATE</td>
</tr>
<tr>
<td>LINEARIZED METHODS WILL SUFFICE</td>
</tr>
</tbody>
</table>

11.2 - Progress on Propeller Design

In recent years, major progress on propeller design have been obtained in various countries. 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. Hober 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 = 0.92 to 1.14 for hub to tip) than the corresponding to the drag rise Mach numbers (MD) of each blade airfoil section (from 15% to 25% 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 9 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 5 from NASA-Lewis tests [12] and ONERA theoretical approach [2].
Fig. 7  EFFECTS of ADVANCED AERODYNAMIC CONCEPTS on BLADE SECTION MACH NUMBER DISTRIBUTIONS [12]

©NASA/Lewis, 5R6/77, 0.8
10 BLADES PROP FAN
Tip sweep angle : 40° [12]

©OMERA, HT/77, 0.75
12 BLADES HIGH SPEED PROPELLER PROJECT [2]
2 Dim. "Concave" computation
r/D = 0.3  Merge = 0.65

Fig. 8  INTERBLADE FLOW PROBLEMS near the hub, for multiblaide 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 18 x 6 foot section (see section III.4 on structural testing of these models, illustrated on Figure 11). The objectives of the NASA program (LAP-PTA) on a full-scale demonstrator (Hamiltont. SR-7 propeller, 0.9 ft. to be tested on a static rig, in wind-tunnel, and then in Fig. 12, on a Gulfstream III, see Fig. 11). On the performance prediction side, the NASA prop-fan program has included an experimental research activity with the US Manufacturer and parallel with the development of the experimental propeller models, illustrated on Figure 12; these analysis methods range from simple lifting line [strip analysis for single-rotation prop Goldstein approach, to more sophisticated-computer-consumption 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 axisymmetric nacelle. The results of these calculations [12] compared to the experimental W-T results on the SR-3 propeller model are shown on Figure 12 for a Mach 0.84 cruise; for both efficiency and power coefficients, as a function of the axial ratio. The curved lifting line analysis gives a quite good predictions 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 Figures 12b, with the experimental data obtained (0.21 diameters downstream) with a single instrumented probe mounted on a translating probe in the 8 x 6 foot NASA-Lewis tunnel: the predicted results are much higher than the experimental (A swirl < 30°), this large discrepancy is presumed due to the viscous flow shock wave effects which reduce the blade loading and then the swirl angles as expected the power coefficients are also over-predicted.
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 advantage of the CR aircraft versus SR aircraft (Fig. 4: Fuel burn = -10%, A DC = -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 \( J = 3.06 \), the calculated efficiency at Mach 0.8 cruise increases from 0.79 to 0.85 at 35% greater thrust, but at constant power loading \( \frac{W}{D} = 381 \text{kW/m} \), 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 \( (Z = 35 \text{ Kft}, V = 220 \text{ m/sec}) \) has given a much better cruise efficiency for the CRP: 84% instead of 76%; moreover, the calculated take-off thrust was \( T = 15500 \text{ daN} \) 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-Hawkins 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.I and illustrated in Figure 10.
A general theory of arbitrary motion Aerodynamics using an Aeroacoustic approach was given by L.N. Long and G.A. Watts, Lockheed-California. 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:

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**Figure 11**  
PRELIMINARY COUNTER ROTATION PROPELLER  
PERFORMANCE PREDICTION  
Boeing/G.E. [58]

---

**Figure 12**  
PRELIMINARY PREDICTION for COUNTER ROTATION PROPELLER  
with 5+5 blades similar to SR3 blades,  
$\Lambda = 45^\circ$, SR3 Prop. fan [12].

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11.2.2 - 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 from 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 St 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 ($C_p$, $C_t$, and $\eta$) as a function of the Advance Ratio for two design points requirement (cruise and take-off regimes). The table shown on Figure 13 presents the various theoretical approaches used during this program from the simplest to the more sophisticated 3Dm. 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 is 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 12B, which is limited to the spacing between two consecutive blades, the lower boundary fits the axisymmetrical 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 12A for a cylindrical fairing at \( \hat{M}_d = 0.7 \) \( \hat{J} = 3.0 \); the advantage of an area ruled hub fairing is evident on Figure 12D for the same regime; this optimised hub shape improves the flow over the entire blade; another calculated case was already given on Figure 86 at the cruise regime (\( \hat{M}_d = 0.75 \)), with a subsonic flow along this well streamlined hub.
The three previous methods (Lu, Costes and Euler) give similar results on the radial lift distribution along the blade of the twelve bladed propeller HTI project; the curved lifting line method overestimates the local C\(_\text{l}\) and the simple lifting line method is quite misleading for the shape and the level of the C\(_\text{d}\) 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 \(W/D\) = 250 kW/m\(^2\), and tip speed \(V_T = 220 \text{ m/s}\);
- a specific thin blade section (t/c = 3.5\%) has been calculated and tested, which gives better C\(_\text{l}\) 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 SI Modane are described in Section III.2.a and on Figure 1b.

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 2D inviscid testing of these sections have been made by ONERA and some results are given on Figure 15, which are commented in section III.1.
11.2.3 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 11 data bank is already very comprehensive and is now completed with a relatively limited number of ARA-D airfoils 2Dm. test data; they are used with semi empirical formulae for interpolation and extrapolation purposes. The 2Dm. 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, 3Dm. methods involving solution of the compressible flow have been investigated.

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 3Dm. 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. 9 and 13 obtained by Mrl and ONERA).
11.2.4 - 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 DFWL-Braunschweig [4] 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 developd 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 Pomerl Hofmann DFWL-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 DFWL: 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 Sommer extended to compressible flows; for transonic flow the BOX-IIF 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 15; a very thick section was also developed for the blade root which gives a very high C_{P}_{max} of 2.5. For the calculation of the new propellers, a blade element vortex wake method was used, whereas 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 DFWL tunnel. Then two full-scale propellers were tested in flight on the twin-engine DO-228 commuter aircraft (ZKdp program), compared with well known production propellers, these advanced configurations give much better static thrust (195%), better take-off and climb performance (+ 10% on one-engine case) and cruise speed (+25%). 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 = 0.8 (four blades, D = 1.85 m, AF = 150, M tip = 0.4).

11.2.5 - 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-axisymmetric flow [2]: usually such conditions prevail for propellers installed on aircraft, where upwash being the most common flow asymmetry; 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-helical unsteady lifting surface theory is formulated for propellers in a non-axisymmetric 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 blade tip vortices. The boundary condition of vanishing normal velocity is applied at the actual blade surfaces, i.e. a non-helical 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 [26], both for Dimensional Testing on blade sections, and for 2Dim. 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. III) 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 1%) with enough stiffness and equipped with numerous pressure taps along their chord!
OMERA 2 Dim. TESTS on BLADE SECTIONS: \( t/c \) = 4, 7.12 and 20%.

OMERA/HOR – e – S3 Modane, S10 Toulouse w.t.
NACA-96 – a – S3 Modane w.t.

De HAVILLAND/Canada 2 Dim. TESTS (NAE) on \( t/c \) = 4.6, 15 and 21%.

DFVLR 2 Dim. TESTS (TWB, \( Re = 2.5 \times 10^6 \)) on \( t/c \) = 5.6 % to 19.8 %.

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

For example, OMERA has used the S3 Modane blow-down transonic tunnel for testing several families of blade sections designed either for "Conventional" propeller Aircraft or for Prop-fan development. The blade sections, usually 0.2 m chord, and equipped with up to 90 pressures taps (for a good definition of CL and CD and detailed comparison with computed pressure distributions) are mounted between walls \( b = 0.36 \) 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 CD, 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 \( (1 \times 2 \) m²), using a 0.5 m chord model \( (C_L \) and \( C_D \) from balance and \( C_D \) from wake measurements). Usually, a well known "reference" propeller section \( (\text{from NACA-16 family}) \) is tested in the same conditions to have a direct and fair estimation of some expected gains 5, 2, 18.
y. In England, the ARA Bedford pressurized transonic 2D-3m.-tunnel (0.40 x 0.20 m²) is also used for developing a new family of blade sections (ARA-D, 20' to 45') at variable Reynolds numbers (11.5 to 3.5 x 10⁶) without blockage problems [3].

c) The DFVLR Braunschweig 2Dm. tunnel TNK (0.0 x 0.34 m²), with slotted walls, is used for developing also a family of advanced blade sections (c = 0.1 to 0.2 m!) at Re = 2.5 x 10⁶ [10].

d) Lastly, the NAE Transonic tunnel, equipped with a 2Di. insert 16.5 x 1.55 m²) is used for testing one-foot chord of propeller sections, having 45° to 21° thickness chord ratios, and developed for NAE/Canada STOL configurations [19]. 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 Cₙ minimum was measured! Similar penalties were observed on a 2Dm. test propeller with such usual protruberances.

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 NAE Fluid Dynamics Panel has certainly a leading role to play for improving the quality of 2Di. 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 minimise the propeller nacelle interaction, ONERA uses in its St Modane tunnel a "minimum body" rig [2], powered by a twin gas-turbine (500 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 0.5% 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 ANF/Breguet paper for the Breguet-Atlantic propeller development [19].

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

- The Börner/Hoffman presentation [16] describes the DFVRG Göttingen rig in their 3m low-speed tunnel, used for the propeller development on the Börner Bo-105 Experimental Aircraft.

- The de Havilland-Canada paper [14] describes the NAE/Ottawa rig in the 9 x 9 m low-speed tunnel (Fig. 10b), used for the full-scale testing of 5.5 foot propellers (developed by Hartzel and Dowty-Rotol respectively, for a BMC-Twin Otter class of commuter aircraft). This rig is powered with a 340 SHP 2000 RPM modified turbine gearbox P/B 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/DLR/Fokker paper [17] describes two different tunnels used for propeller testing:
  - the low-speed LTK/LST tunnel (2 x 2 m²), with an isolated nacelle on a fairing strut mounted on a floor balance; this rig is used for the calibration of the propellers (Fig. 0.70 m) designed for the complete F-104N model tested in the DNW tunnel.
  - the new low-speed Deutch-German DW tunnel, with several test sections: the 8 x 6 m² is used with a closed section for a complete motorized model (Fokker F-27 BE at 1.5th scale, see Fig. 23d), the propeller drive unit is a single stage turbine working with compressed air, W = 113 kW. This large tunnel is also used with an open-section (8 x 0.2 m²) 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 0 ft) Transonic Tunnel, where almost all the new NASA Hamilton Prop-fan configurations were tested since 1976. This tunnel has a porous wall test section for transonic tests up to Mach 0.95; the isolated nacelle (PTR) is powered by a 740 kW turbine using compressed air routed through the support strut (Fig. 16b). Axial force and torque on the propeller are measured on a rotating balance located inside of an axisymmetric nacelle behind the single-rotation propeller (c = 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 0 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).
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 in 0.02 m2 absorbing 2 x 750 HP (1110 kW) to simulate the GE EDF gearless configuration [13] and Fig. 16a. This CR CATD rig was recently installed in the Boeing transonic tunnel (2.4 x 3.7 m²) with a special acoustic treatment fitted on the test-section wall.

To study the interaction between these same "2 foot" propellers and the airframe nacelle, NASA used the Ames 12 foot transonic tunnel for 0.05 x 0.5 x 0.5 [1, 12].

Furthermore, for both low-speed and transonic testing, the Onera sonic M.6 Modane tunnel seems very well suited for full-scale testing of motorized nacelles in its circular 5 m section, as illustrated on Figure 17a. 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](image)

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. 15a) were discussed:

III.3.1 - 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 NR-3 Prop-fan model.

III.3.2 - 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.3.3 - 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 IIFM low-speed tunnel (Elliptic section 3.1 x 2.2 m, Vmax = 45 m/sec, four blades conventional propeller D = 0.95 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.
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. For the new thin, highly swept and twisted blades used on high-speed prop-fans, 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 - 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 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 10: the Aeroelastic Research deals with three phenomena (Fig. 10a):

- 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 occurring 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): 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 10b, 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 (Aeros 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.
During the NASA Lewis tunnel tests on the SR-5 (90° sweep) prop. model, a classical coupled bending-torsion flutter was encountered inside a large range of Mach numbers (0.6 to 0.75) 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 vibration signals and then an "explosive" growth near the first blade mode, and finally, a large stress hysteresis phenomena [41], as shown on Figure 16c.

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 19a where are compared specific experimental flutter boundary obtained for ten-bladed configurations with the other hand, the two theoretical approaches for flutter onset prediction for the 10-bladed prop appeared very conservative compared to the experimental [101] Mach1 boundary.

III.4.2 - The Dynamic behaviour of a prop-fan model was presented by ONERA Aerospatiale [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 (D1 - 1 m) to be tested in the 31 Modane transonic tunnel, and included structural analysis for both the isolated propeller and the propeller fitted on the SI Modane tunnel "minimum body" rig. Furthermore the structural predictions were made for the actual carbon fibre blade structures, the calculations were carried out by finite element method, adapted to the anisotropy of the composite materials the calculations were done with both the SAMEF code used at Aerospatiale and the ASTROFEM 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 carbon 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 SI Modane tunnel testing.

III.4.3 - Another structural aspect of wind-tunnel testing was presented in a joint paper by Dowty NLR and Fokker [17] describing the development of a 1/5th scaled four bladed model propeller (D1 = 0.76 m) to be calibrated, isolated, in the 1.2 x 2 m NLR LST tunnel, and then put on a F-227 "keel" complete model in the DND 1 x 6 m tunnel (see Figure 25d).

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.
In like manner, the elastic properties of a blade can be changed without altering its shape simply by modifying the fibre 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 small size.
Fig. 21  WING/Pusher PROPELLER INTERFERENCE TESTS at low speed - Southampton U. Tunnel [20]

Fig. 22  PROPELLER SLIPSTREAM INTERACTION with NACELLE/WING/FLAP [21]
The De Havilland-Canada presentation on some considerations in propeller and airframe integration [11] was given in two parts: the first one deals with the interesting development of a new family of propeller sections for the DHC "Dash-4", already discussed in section III.4, the second part describes the wind tunnel testing of a motorized half-model in a 0 x 0.5 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 C16 and the drag with flap-up and down, particularly in the case of one engine failure (twin-propeller Dash-4 commuter aircraft configuration).

This propeller-airframe interaction is most sensitive for twin-propellers aircraft with very powerful turbo-props, like the Breguet-ASW "Atlantic" aircraft [14] 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 [5] 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.

The absence of contributions or comments on prop-fan/airframe interference at high speed 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 Figure 23: 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 (Fig. 24) 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 (ΔC₀₉ = -0.0018 at M = 0.8) as shown in Figure 25.

**Figure 23** Prop-Ran slipstream effect on a swept-wing at cruise M = 0.8.
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 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-O 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 double wall and three differently tuned sets of dynamic 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 dB(A) to the present level of about 85 dB(A). 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.
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).

V.1.1 - 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-5, 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 (1974), 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/Hawkins 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.
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 highly effective for noise reduction (dB compared to SR-2) and the larger tip sweep ($\lambda = 45^\circ$) 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 25 as a function of the helical tip Mach number for these three 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 ($\Lambda = 30^\circ$) swept blade prop was much quieter than the SR-2 ($\Lambda = 0^\circ$) 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.

Other approaches in Prop-fan noise theory for predicting performance and noise are the application of the Euler Equation, initiated by Bower (NASA-Lewis [12]), and the application of the compressible lifting surface theory; this unified theory is applicable to acoustics, uninstalled 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 11.2.

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.
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-by-7-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 (\(V_t = 31 \text{ m/sec}\)): the SRP has its maximum noise levels in the plane of the propeller disc, and the noise decreases upstream and downstream; the noise pattern 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.

Fig. 32 NOISE RADIATION PATTERNS for PROP-FAN, 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-decibel mapping.
In the same report [39], 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.

4.1.4 - Propeller noise measurements in flight on SR-2 and SR-3 prop-fan models (1, 2) were undertaken in 1961 at NASA-Dryden [30, 12], using an air-turbine drive mounted above the fuselage of a Lockheed Jetstar (Fig. 14). Initial tests in 1961, 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 noise was attenuated by propagation inside the fuselage boundary layers; correction factors were calculated for this flight case which confirmed 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-2 (Fig. 13b). For the second flight testing phase, a microphone boom was mounted above the propeller to obtain the "free-field" noise; Figure 11 shows the comparison of the predicted sideline tone levels measured and calculated (Hanson's frequency domain method) for SR-2 (straight blades) and SR-3 (swept blades at 15°): 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.

An interesting Flight Research program was launched in 1962 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. 12).
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 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. Three propeller models were tested at 1/3 scale (D = 0.6 m, constant H = 0.6); three types of acoustic measurements were carried out: noise near-field at 0.14 R from prop. tips and far-field at 5 0 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 were undertaken by the Acoustic Institute.
- The Flight noise tests were made with a single-engined (CESSNA T-207) Aircraft, equipped with an array of wing-mounted microphones to investigate near-field noise of a 3-bladed variable pitch McCanley propeller (D = 2 m, 2000 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 = 0.22 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 1 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 independent 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 = 0.71.

V.2.1 - 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 (0.125 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.
Lastly, the Research Program included the test of another Dowty 4-bladed R-212 propeller with classical NACA-10 series sections both in the 24 feet 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 $S = 4 \cdot r$; the discrepancy between the two tests in the range $S < 20$ is attributable to the intrusion of the background noise in the 24 ft tunnel and to its higher turbulence level ($0.1$ 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: $Re = 0.5 \times 10^6$ 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 needed in 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 $M$ 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 Hawkins-DR 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 $10 \text{ dB}$ 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 turboprop 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.
V.3.1 - Three candidate structural transmission paths 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 DMC 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 wind 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 [28], 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 LP 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 75 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 reductions; 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 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; a typical method 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 sinusoidal 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 1/10th 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,...).
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 CEP 3 m. tunnels; the data obtained were compared with those measured in Flight by the US-Army on a Bell Helicopter.
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 propellers. In a recent paper [36], Boeing has published some interesting comparisons on noise directivity measurements from a SN-0 propeller model tested at Mach 0.7 in two closed test-sections of the Lewis 5 x 5 ft and the Boeing 4 x 12 ft transonic tunnels. Figure 3d, 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-Lewis Flight Test results obtained on the same SN-0 propeller mounted above the Jetstar fuselage (see Fig. 3a); 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 = 0.40); tests were again conducted with movable microphones (Fig. 3e) for comparing the noise measurements made with these "soft" walls and the original "hard" walls. Figure 3b 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 3c, exemplify marked changes between treated and untreated test-section measurements for similar locations and operating conditions.

Since November 1981, Boeing has undertaken a prop-fan noise program on the UPF configuration with a new acoustic lining insert (see Fig. 10d) which is quickly removable, and does not penalize the requested testing velocity (Mach up to 0.75).

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. SARAVANAMUTHU [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-144 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-50...); 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 90-, 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.
Various Turbo-prop configurations (Fig. 29) but are described: fixed turbine, free turbine
single speed compressor, twin speed compressor-propeller driven by P.T. Turbine, and twin speed
compressor with free turbine, which are all quite viable; a fifth scheme is proposed by General
Electric, with the revolutions Counter-Rotating turbines, driving directly two C.R. propellers
inducted fan (Fig. 34). Fig. 29b. this requires considerably technology advances to build such turbines
without damage and several problems are expected: low speed turbines and higher running
Prop-fans mean less overall efficiency than for a geared X 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-rotation differential planetary gearbox seems lighter than a N.R. gearbox [13].

A further possibility, suggested by Rolls Royce [22], is the dual cycle engine which combines
a fan-engine with a geared Prop-fan; this configuration Fig. 34b would lead to some loss in
propulsive efficiency, but a substantial gain in gearbox power.

VI.2 Propulsion System Configurations

VI.2.1 Propellers, power plants and Airframe Designers for future Prop-fan powered Aircraft [23, 34, 50, 12]:
- N.R. or C.R. Prop-fan
- geared or gearless engines
- Tractor or pusher configurations
- wing or fuselage mounted installations

VI.2.2 Both tractor and pusher schemes have advantages and disadvantages:
- For the tractor scheme (Fig. 34a), the propeller has a "clean" flow approaching, but the engine
designer is concerned with the swirl flow from the a.R. propeller on the inlet and with diffuser
efficiency distortion problems.
- For the pusher case (Fig. 34b), 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 C.E.FF configuration (Fig. 34c).

VI.2.3 When comparing wing and fuselage mounted propellers, illustrated on Figure 40, both aerodynamic
and acoustic impacts must be discussed [51].

WING MOUNTING AFT-FUSELAGE MOUNTING

Fig. 40 PROP FAN PROPULSION SYSTEMS on TRANSPORT AIRCRAFT.

- Tractor configurations mounted on the wing give a high speed slipstream on the wing (with a strong
swirl angle for a VNP), which can induce parasitic shock-waves and extra drag at high speed cruise
regime. A possible aspect of this slipstream is a "blown wing effect", which gives better low speed
(SAO) 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 passenger 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 expander wake on the pusher propeller, but a better inlet efficiency is expected
for this configuration.
REFERENCES

The papers presented at the AGARD FEP Symposium are listed as references (1) to (11) inside the four sessions; and ref. (12) is the final publication AGARD-CP 396 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
    HECILES POUR AVIONS RAPIDES
   par J.M. Bouquerti

(3) DESIGN CONCEPT AND PERFORMANCE PREDICTION TECHNIQUE FOR POTENTIAL
    FLOWS AROUND ADVANCED PROPELLERS
   by T.S. Lau and R. Cullenrandy

(4) PAPER WITHDRAWN

(5) REVIEW OF NASA RESEARCH INTO PROPELLER AERODYNAMIC PREDICTION METHODS
   by A.J. Bucci and J.L. Morrison

(6) PROFILS MODERNES POUR HELICES
   par A.M. Rodde, J.J. Cony et J.J. Thibert

(7) AERODYNAMICS OF WIDE-CHORD PROPELLERS IN NON-AXISSYMMETRIC FLOW
   by J.B.H. M. Schuler

(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. Forant

(11) COMPRESSIBLE, UNSTEADY AERODYNAMICS USING AN AEROACOUSTIC INTEGRAL EQUATION
    by L.N. Leng 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. Boher

(13) COMPORTEMENT DYNAMIQUE D'UN ROTOR DE PROPFAN
   par J.M. Braun et D. Petit

(14) PERFORMANCE EVALUATION OF FULL SCALE PROPELLERS BY WIND TUNNEL TEST
    by D.J. Boucher

(15) ETUDE DU SILLAGE 3D D'UNE HELICE AERIENNE
    par D. Favier et C. Mareux

(16) INVESTIGATIONS OF MODERN GENERAL AVIATION PROPELLERS
    by H. Zimmer, R. Hoffmann and R.H. Horstmann

(17) AERODYNAMIC AND STRUCTURAL ASPECTS OF PROPELLER AND DRIVE FOR
     A SCALE MODEL WIND TUNNEL PROGRAMME
    by R.M. Barn, R. Mareska and J. van Hengst

SESSION III — PROPELLER AIRFRAME INTEGRATION

(18) SOME CONSIDERATIONS IN PROPELLER AND AIRFRAME INTEGRATION
    by R. Eggerton

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

(20) A FLOW MODEL FOR WINGS/BODY PROPELLER INTERFERENCE
    by A. Emeral and G.M. Liley
SESSION IV - PROPELLER ACOUSTICS

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

[22] AN ASYMPTOTIC THEORY FOR THE INTERFERENCE OF LARGE ASPECT RATIO SWEEP WINGS AND MULTIPLE PROPELLER SLIPSTREAMS

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

[24] AEROACOUSTIC WIND TUNNEL MEASUREMENTS ON PROPELLER NOISE
by F.R. Groschge

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

[26] AN INVESTIGATION OF IN-FLIGHT NEAR-FIELD PROPELLER NOISE GENERATION AND TRANSMISSION
by H. Bennecess, 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.M. Hoffer and M. Kallergis

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

[29] PROPELLER AIRCRAFT CABIN VIBRATION AND NOISE-EXCITATION, SOURCES AND PATHS
by R.E. Dondham, F.J. Balsem, E.Z. Bochery and O.E. Liehr

by F.R. Meager

[31] APPLICATION OF ACTIVE NOISE CONTROL TO MODEL PROPELLER NOISE
by M. Balthadod, H.K. Tsuna, R.H. Burton and W.E. Carter

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


[37] -Advanced Turbo-ProP and Dual Cycle Engine Performance Benefits and Installation Options on a Mach 0.7 Short-haul Transport Aircraft, by H.W. Bennet (Rolls-Royce) and A.P. Layes/C.L. Herstine (Lockheed-Calif.). AIAA Paper Nr 83-1212, June 1983


[40] -Aerodynamic Research in the Netherlands related to Aircraft Development. ICAS Paper Nr 84-5.3.2, Sept. 1984


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