TURBOPROP DESIGN - NOW AND THE FUTURE

ICAS-82-4.5.2

B. S. Gatzen
Hamilton Standard
Windsor Locks, Connecticut

ABSTRACT

While interest in advanced turboprop aircraft waned after introduction of the turbojet, turboprop production and research continued. Today, the capability to do the turboprop propulsion job is better than ever before. This capability is being applied as turboprop interests rise to new levels. Two specific new turboprop efforts have been initiated in the 1970's. Specifically, they are the commuter turboprop and the high speed turboprop, or Prop-Fan. Commuter turboprop technologies will be discussed along with technical progress being made in the Prop-Fan program. Turboprop configuration trends will be discussed covering the conventional 0.4-0.5 Mach speed range, the high speed Prop-Fan range of 0.7-0.8 Mach, and the in between 0.6-0.7 Mach range.

BACKGROUND

In the 1940's, members of the aviation community were predicting the demise of the propeller industry based upon the promise of an import from Europe, the jet engine. In the mid-1950's the airline operators of the world were faced with a major decision. They could try to meet their growing traffic demands either by expanding their fleet of about to be outmoded reciprocating-engined aircraft, while waiting for the military to perfect the highspeed jet transport, or by opting for the newly developed turboprops. The turboprop was chosen by several of the major airlines. Accordingly, first the Viscount in England and shortly thereafter the Electra in the U.S. were introduced into full scheduled service. This represented a major step toward more effective commercial air transportation. The Electra, for example, resulted in an increase in cruise speed from the postwar Mach 0.4 level to Mach 0.6 and with much improved maintainability and reliability over the reciprocating-engined aircraft. Also, much faster thrust control and other new powerplant features were introduced to improve flight safety and passenger comfort.

The most critical decision for the propeller industry came in the late 1950's. Turbo-prop power had been selected for the next Air Force strategic transport, the 0.7 Mach Douglas C-132. In 1957 the Air Force cancelled this program, restudied the mission and equipment needs, and started the activity which ultimately culminated 10 years later in the C-5. By 1958, research on propellers for high subsonic speed aircraft had been brought effectively to a halt. The major thrust of development activity, both for counterrotating designs (subsequently brought to production status by the Russians) and single rotation, thin-bladed supersonic tip speed propellers was terminated. In the early 1960's, development of the turboprop began to wane except for such specialized applications as V/STOL and long-range, long-endurance patrol aircraft. The technology efforts of the 60's and early 70's set the stage for the two most recent propeller advances shown in the center of Figure 1, the Prop-Fan and the commuter propeller. Before discussing these in more detail, lets review the technologies which formed the foundation for today's advances.

TECHNOLOGY DEVELOPMENT

During the 1960's a strong move developed in V/STOL transports and it appeared that they might catalyze a resurgence of the turboprop. The experimental, tilt-wing XC-142 had four main propellers and one tail propeller, all driven through a crosshaft system by four turboshaft engines. For vertical takeoff, the main propellers had to provide exceptionally high thrust/weight, had to have adequate structure to handle the severe nonuniform blade loadings during transition from hover to forward flight, and had to give good cruise efficiency. V/STOL propeller performance requirements were found to be quite stringent and even led to the invention of a new type-the variable camber propeller.

Another R&D activity stimulated by V/STOL was the effort to reduce propulsion system weight. In propeller design, the blade constitutes the greatest weight driver, and so attention was drawn to this component. By this time, high strength fiberglass materials had evolved to sufficient levels of material strength properties backed by a wealth of field operational data to allow serious consideration for major structural applications. Two basic fiberglass designs were developed, one an all fiberglass monocoque hollow construction, and the other a spar-shell type of configuration, where the fiberglass forms the airfoil and is bonded to a metal backbone of either hollow or solid construction. Both types of fiberglass blades provide weight reductions of 30 to 60% versus their more conventional all metal predecessors, and it was this development more than any other that allowed significant propulsion system specific weight reductions.

Of the two types of designs, it was the metal spar/fiberglass shell type that was placed into volume production. Since its introduction in the early 1960's, more than 5000 of these blades have been produced and over 4 million blade hours of successful operation have been accumulated. Today, this blade is in production for the DHC-7 commercial STOL transport, the E2 Hawkeye

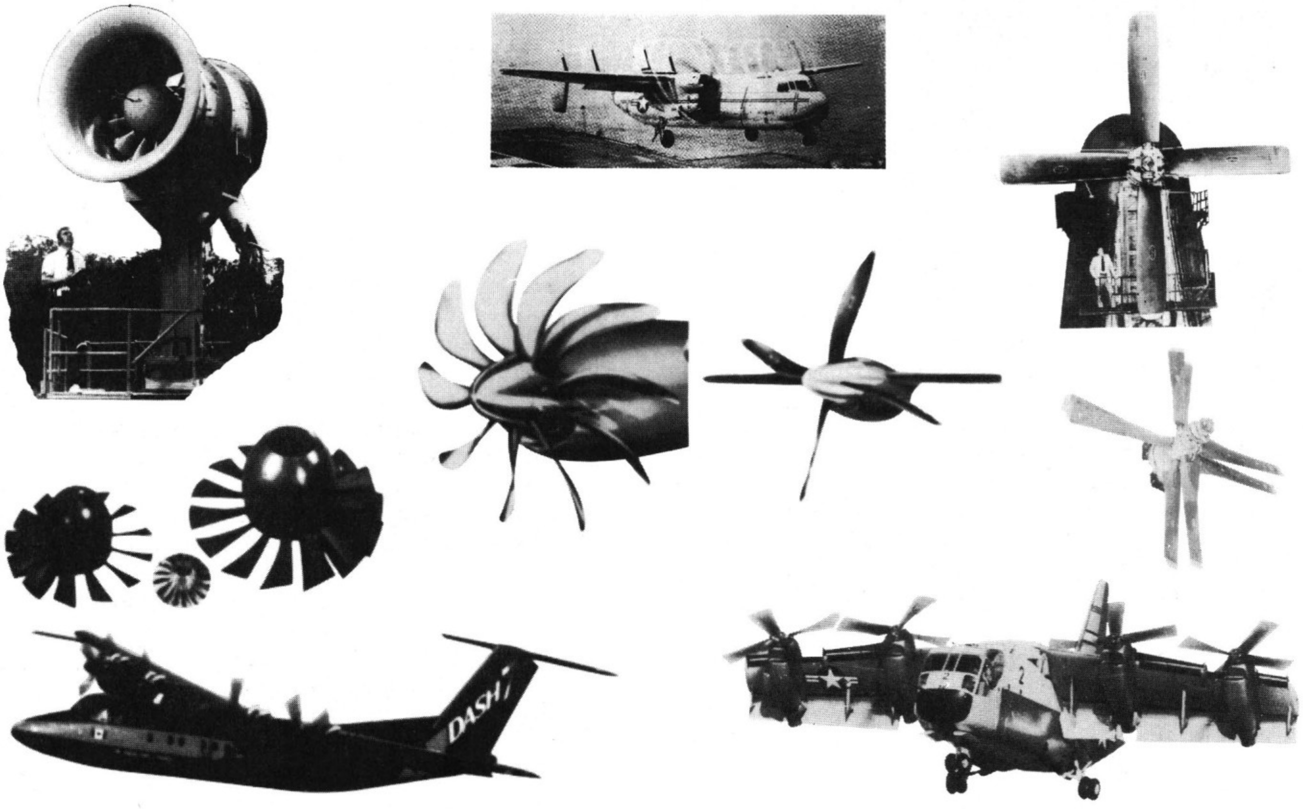


Figure 1. Technology Base

carrier-based AEW and its sister aircraft designated the C2, and the OV-10D surveillance aircraft, where it continues the perfect safety records of earlier turboprop powered aircraft depicted in Figure 2.

New control features had to be incorporated in the V/STOL propellers to provide safe and effective primary aircraft control during hover and transition. Such features as fail-safe pitch control and actuation, pitch lock, self-contained hydraulics, beta feedback, and differential pitch control were also successfully demonstrated on the various V/STOL experimental aircraft.

As a result of the V/STOL propeller development, there was a highly sophisticated propeller technology available in the early 1970's when two more major advances in propulsion development were undertaken. These were the quiet propeller and the variable pitch fan.

The quiet propeller was developed for the de Havilland DHC-7 STOL aircraft. The DHC-7 has demonstrated a remarkable 15 PNdB less noise than other existing STOL aircraft such as the DHC-5 Buffalo and the Brequet 941. An important contribution to the attainment of this goal came from the spar-shell blade with its greater design flexibility. This design flexibility allowed the blade shape characteristics to be optimized for minimum noise with maximum performance. Although the quiet propeller seems to be a good match for the propulsion of moderate-speed, short-haul transports, there also seems to be a need for more compact propulsors with high thrust/weight and fast thrust response. To satisfy these needs, programs were initiated in the early 1970's to develop high bypass, variable pitch (VP) fans.

In summary, this period of activity produced a long list of technical advancements in the area of low speed aerodynamics, acoustics, blade structures, and pitch change mechanisms, much of which was to find application in commuter, propeller and Prop-Fan designs which will now be discussed.

RETURN OF THE PROPELLER

Each of these new type propellers has attributes particular to certain aircraft speeds and missions. Figure 3 shows the commuter and Prop-Fan type rotors with their respective speed range and appropriate missions. You can see that there is a speed range up to about 0.65 Mach where more conventional technology is still appropriate. At higher flight Mach numbers Prop-Fan technology provides necessary relief from compressibility losses. In either event, new propellers for the commercial/military marketplaces, especially com-

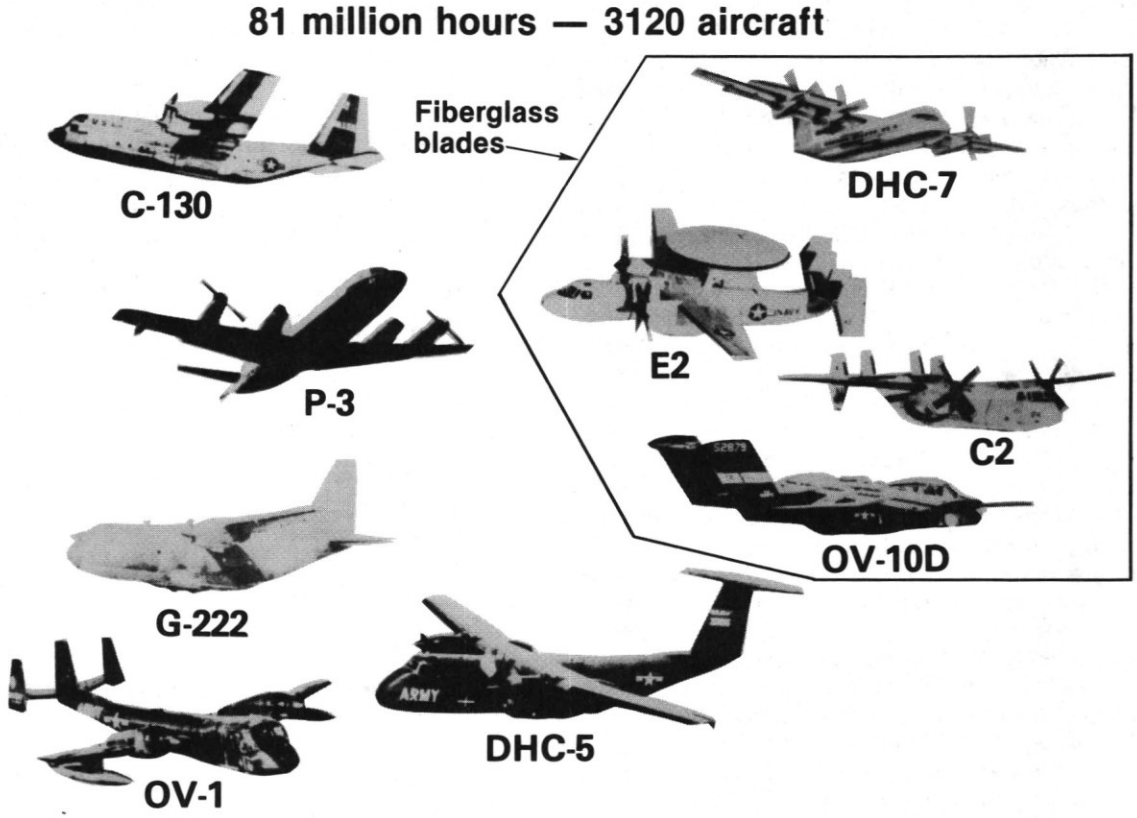


Figure 2. Current Production Turboprops

Near Term Technology	Advanced Technology
0.4Mn → 0.65Mn	0.65Mn → 0.8Mn
Commuters New and repowered	Commercial transports 80 → 160 PAX
Execs	Military ASW Cargo
Military P3 repowering C130 derivatives	

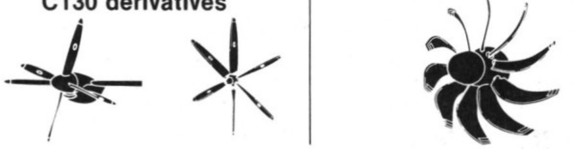


Figure 3. Hamilton Standard is Responding to the Renewed Interest in Turboprops

mercial, must offer a broad range of characteristics compared to 20 years ago. In today's competitive marketplace, new propulsion systems clearly must be efficient; but they must also be quiet, lightweight, and reliable in addition to having controlled costs.

The new generation twin engine commuter aircraft expected to enter airline service in the mid 1980's are aimed at providing comfortable, reliable, economical shorthaul transportation. To meet these goals, most of the new commuter aircraft are using advanced turboprop propulsion systems. The new propellers incorporate advancements in all technology areas, i.e., aerodynamics, acoustics, structure, weight, maintainability and safety as indicated in Figure 4.

• Blade airfoils →	Equal or higher performance 25% less wt
• Blade construction →	Reduced cost & wt, higher strength, precise airfoils, lower noise
• Barrel and retention →	Lower wt
• Control system, actuator & pitchlock →	Safer, simpler, lighter
• Acoustics and synchrophasing →	Lower cabin noise & vibration
• M&R features →	High dispatchability, lower maintenance burden
• System integration →	Systems approach, total propulsion system asset

Figure 4. New Technology in Commuter Turboprop - Now!

At Hamilton Standard, advanced technology is being applied to the development of a new commuter aircraft propeller line. These propellers will incorporate composite shell and aluminum spar blades with a double-acting pitch change system and a pitch-lock feature for significant weight reduction, greater safety, and improved dependability and durability. Moreover, these propellers must provide near-ideal performance, low cabin noise levels, and meet far field noise certification requirements. In view of the stringent aerodynamic performance and noise requirements, coupled with the need for minimum weight, a comprehensive research program was undertaken by Hamilton Standard to provide aerodynamic criteria needed to design the propellers required for the next generation twin engine commuter aircraft. The objective of this program was to establish aerodynamic performance and noise levels equal or superior to conventional propellers at reduced blade solidity in order to reduce weight per pound of thrust. This effort included the development of a new airfoil family to achieve the low weight objective, and wind tunnel tests on two-dimensional (2-D) airfoils and model propellers to confirm the predicted benefits of the new airfoil family to be incorporated into propeller blades.

The Prop-Fan is a logical extension of propeller technology aimed at lower fuel consumption, lower operating costs, and lower noise levels for high subsonic Mach transports. It is a multiblade, shroudless fan incorporating swept blade tips. This represents a unique potential for a shroudless propulsor but its attainment requires the application of highly advanced aerodynamics, blade structural design, and materials technologies. It also requires carefully integrated design with the engine nacelle and airframe to ensure that there will be no serious interactive losses.

In essence, the Prop-Fan has evolved by taking advantage of an attractive combination of features from both the free air propeller and the high bypass turbo-fan. Initially, it was established that it was possible to reduce the diameter of the free air propeller by about 50% without significantly increasing momentum losses, a fact essential to the maintenance of a high overall level of propulsive efficiency. So it evolved that a diameter of about one-half and a power loading about four times the conventional propeller became the Prop-Fan baseline. While this reflected a departure from high speed propeller research in previous years, this was not breaking entirely new ground. Extrapolation of old wind tunnel data to the blade power loadings of interest indicated that levels of propulsive efficiency in the low 70 percents were attainable. This was not sufficient, however, to provide a clear advantage over turbo-fan equipment, and a goal was established to raise this level of efficiency to 80% or above. The resulting benefits are projected to include:

- For commercial transport aircraft, the lowering of fuel consumption, when compared to comparable turbo-fan aircraft, by approximately 20% and lowering direct operating cost by approximately 10%.
- For military transport type aircraft, lowering fuel consumption by up to 40% and aircraft gross weight by some 10 to 20%, depending on the particular mission.

The above benefits are very substantial and are projected to have as great, or greater impact on the costs of aircraft operation (including the fuel consumed) than any other single technology advancement in subsonic aircraft/engine design now being pursued. Clearly the increasing fuel cost along with the thrust of deregulation has created a place for the modern propeller in today's commercial and military aircraft transport system. Renewed interest as indicated in Figure 5 is justified. The rest of this technical paper will deal with the following specific technology areas: aerodynamics, acoustics, blade structures, and controls. Finally, propeller reliability and maintenance will be discussed before summarizing.

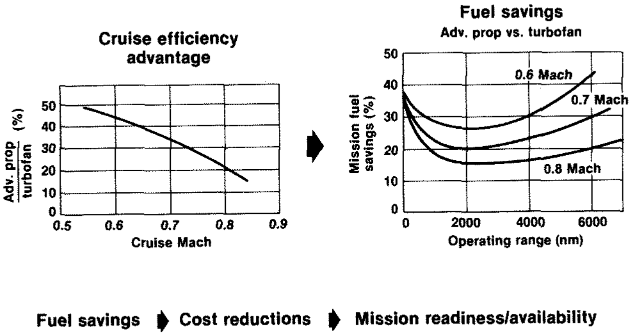


Figure 5. Renewed Interest Justified

AERODYNAMICS

Aerodynamic Methodology

The basic aerodynamic design and performance prediction method utilized by Hamilton Standard over the past forty years is a blade element analysis based on the vortex theory of S. Goldstein. This method has been continually improved and refined over the years and has been correlated with wind tunnel test data on many different propeller configurations ranging from small models to full scale propellers tested in wind tunnels of various sizes and types. Several portions of the formulation have been modified to extend the method capabilities to low advance ratios. Although an incompressible theory, further modifications have been included to extend this method into the compressible range. Generally, at conditions near the design point, the method is within 1% of test data.

The design of Prop-Fans has required the development of aerodynamic methods to handle the differences from conventional turboprops. However, in most instances the design methodology has evolved from existing turboprop and turbofan design techniques. The Prop-Fan blades differ from the turboprop in that they are highly swept and highly loaded and operate at tip helical Mach numbers exceeding the speed of sound in cruise. The transonic outboard blade sections still operate much like a turboprop, but the subsonic inboard blade sections operate like a turbofan because of high root solidities.

Figure 6 shows the areas of aerodynamic analytical efforts that have been applied in Prop-Fan design work. The traditional high cruise propulsive efficiency of the turboprop is maintained into the high Mach number regime through the use of thinner blade airfoil sections and sweep to maximize the effective critical Mach number of each airfoil section and thereby minimize losses due to compressibility. Increased number of blades reduces loading on individual blades until more nearly optimum lift to drag ratios are attained. The inboard blade sections of the Prop-Fan have high solidities and the geometry selection and performance assessment are made using two dimensional cascade airfoil data in a turbofan cascade program, rather than isolated propeller type airfoil data. The mid and outboard blade areas are designed with a lifting line vortex method. This compressible method, developed specifically for Prop-Fan, accounts for the effects of sweep and the operation at transonic tip Mach number on the induced flow at the outer portions of the blade. The method uses two-dimensional, isolated, compressible airfoil test data which are corrected for cascade, sweep, and tip effects. Further improvement in analytical accuracy is expected with the application of a linearized compressible lifting surface method now being developed at Hamilton Standard.

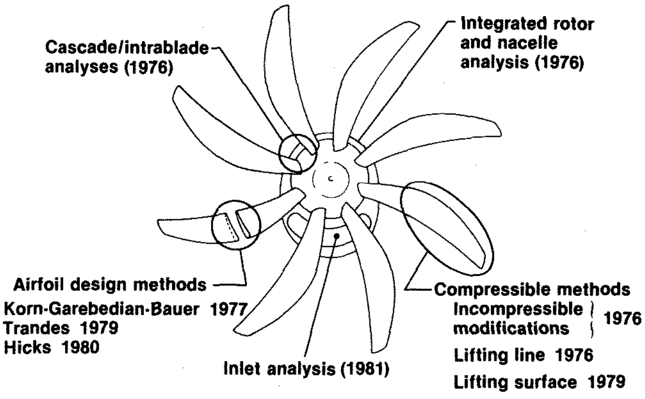


Figure 6. Prop-Fan Aero Analyses

These compressible methods are used in conjunction with existing propeller aero programs which define the input flow field and the optimum camber and twist. Both the inboard and outboard blade analyses take account of the body shape behind the rotor. The nacelle shape must be integrated into the rotor performance analysis since it acts as a blockage which slows the air down and changes the streamline shapes. These analyses are also important in defining the air quality which enters the inlet.

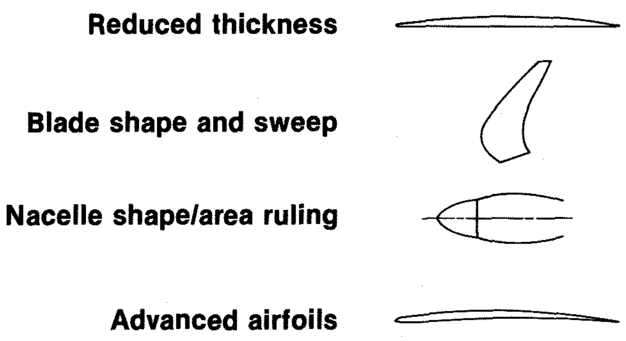


Figure 7. Advanced Aerodynamic Concepts

Figure 7 presents several concepts which have been applied to both commuter propellers and Prop-Fans. Use of these concepts is influenced mostly by aerodynamic and acoustic requirements in the context of blade structural requirements. Blade thickness ratio is usually chosen as the minimum allowed by stress limitation, aeroelastic considerations, and the fabrication state-of-the-art. Blade sweep and nacelle shaping are incorporated to eliminate compressibility losses and root choke. So far, all of the Prop-Fan model designs have used standard airfoil sections. Airfoil design procedures in use at Hamilton Standard have been used in Prop-Fan studies. It is believed that little gain can be made in aerodynamics through the use of advanced airfoil sections if the blades are swept such that each airfoil section operates below its critical Mach number. Advanced airfoils might help to reduce sweep but, as will be seen, acoustic requirements for Prop-Fan will call for maximum sweep. For the commuter, new airfoil sections have been designed, developed and applied.

Advanced Airfoils for Commuters

Advanced propellers for commuter aircraft must meet stringent performance and low cabin and far-field noise requirements with minimum weight and cost. These requirements and constraints led to the selection of high design lift airfoils for this class of propellers. These airfoils must exhibit high lift-to-drag ratios over a wide range of lift coefficients, high critical Mach numbers at lift coefficients both well above and below the design value, and high maximum lift coefficients. In addition, the airfoil profiles should be favorable to structural, manufacturing, erosion and FOD requirements. The dual and diverse requirements of very high operating lift coefficients in take-off/climb and low operating lift coefficients in cruise at relatively high Mach numbers, both with high lift-to-drag ratios, cannot be achieved with existing airfoil families.

Hamilton Standard has completed an advanced airfoil development program to design and wind tunnel test a new airfoil family specifically to meet the airfoil performance requirements of propellers for advanced commuter aircraft. Test results have confirmed the design objectives as shown in Figure 8. On the basis of the 2-D wind tunnel test results, it was concluded that the new HS-1 airfoil family will provide the improved performance predicted for new commuter propellers. As a final step to demonstrate the predicted performance of the propellers incorporating the HS-1 airfoils, a three

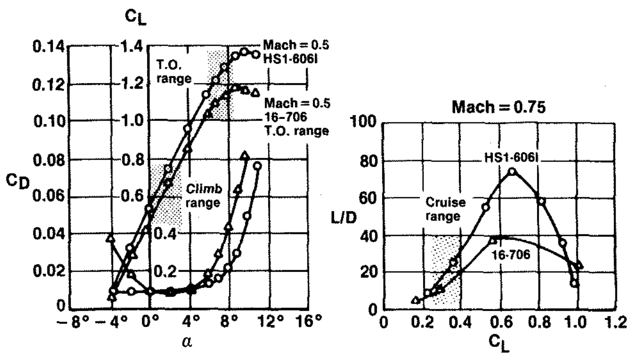


Figure 8. Objectives Achieved

dimensional program was undertaken in the wind tunnel on 3.25 ft. diameter model propellers. The results of this test program completely confirm the predicted performance of the propeller over the full operating spectrum from takeoff to high-speed cruise velocities.

Turboprop Performance Estimates

Having discussed the development of the HS1 airfoil family and the confirmatory model propeller tests, it is now appropriate to show by example how the propeller configuration performs on representative twin engine commuter aircraft relative to predicted performance and to a similar propeller utilizing conventional NACA Series 16 airfoils. Tabulated in Figure 9 are the operating conditions for two representative commuter aircraft; one aircraft incorporates a highly-loaded propeller and the other incorporates a lightly-loaded propeller. For both examples, the predicted performance of two propellers geometrically similar to the test propellers is presented along with the corresponding performance derived from the test data discussed above.

Lightly Loaded Propeller

Condition	Power Coefficient C_p	Advance Ratio, J	Flight Mach No. Mn	Net Efficiency (%)				$\Delta\eta$ HS1-16 Test
				HS1 Propeller		Series 16 Propeller		
				Calculation	Test	Calculation	Test	
Takeoff	0.1600	0.325	0.076	47.1	47.2	45.2	43.0	+4.2
Takeoff	0.1600	0.552	0.129	67.0	67.7	66.3	65.5	+2.2
Climb	0.1600	0.780	0.181	78.4	78.5	77.9	78.3	+0.2
Cruise	0.2305	1.300	0.326	86.4	86.9	86.2	86.8	+0.1
Cruise	0.2250	1.610	0.391	89.1	88.8	88.8	87.9	+0.9
V-max	0.2553	1.658	0.415	88.9	89.0	88.1	88.1	+0.9

Heavily Loaded Propeller

Condition	Power Coefficient C_p	Advance Ratio, J	Flight Mach No. Mn	Net Efficiency (%)				$\Delta\eta$ HS1-16 Test
				HS1 Propeller		Series 16 Propeller		
				Calculation	Test	Calculation	Test	
Takeoff	0.2605	0.360	0.076	36.4	36.2	34.0	31.7	+4.5
Takeoff	0.2605	0.721	0.151	68.6	68.2	66.2	62.0	+6.2
Climb	0.2605	1.081	0.227	81.3	80.7	80.5	80.5	+0.2
Climb	0.3100	1.112	0.229	79.8	80.0	78.3	77.0	+3.0
Cruise	0.2751	1.946	0.440	89.8	89.5	89.3	89.0	+0.5
Cruise	0.4468	2.287	0.440	88.5	89.5	88.3	89.5	+0.0
V-max	0.3363	2.090	0.472	89.4	89.1	89.0	88.6	+0.5

Figure 9. Representative Commuter Aircraft

From a study of these tables it is apparent that the predicted performance of both propellers shows excellent correlation with the test data. For both of the representative commuter aircraft, the predicted propeller performance is generally within 1 percentage point of the test data at all operating conditions with the HS1 propeller. The correlation is equally good for the cruise conditions with the Series 16 propeller. However, for this latter propeller, in several cases the takeoff and climb performance is overpredicted by as much as 2 percentage points, and in one case a ground run takeoff operation, the prediction is high by almost 5 percentage points. Moreover, the predicted advantages of takeoff, climb, and cruise operation of the HS1 propeller relative to the Series 16 propeller are confirmed or exceeded by the test data. With the HS1 propeller, the tables show improvements of 2-6 percentage points in takeoff, 0.2-3 percentage points in climb, and up to one percentage point better in cruise depending upon the power loading. Thus, the lightweight, advanced technology propellers with special airfoils provide excellent aerodynamic performance for the new technology commuter aircraft of the 1980's.

Figure 10 shows the general trends of uninstalled turboprop net efficiency as a function of Mach number. You can see that efficiency is maintained in the high 80 percent area at Mach numbers at or below 0.6. Above 0.6, the technology of the Prop-Fan begins to payoff and its advantages increase as Mach number increases. The Prop-Fan efficiency advantage over an equally advanced technology high bypass turbofan is estimated to be 15% and 22% at 0.8 Mach and 0.7 Mach, respectively.

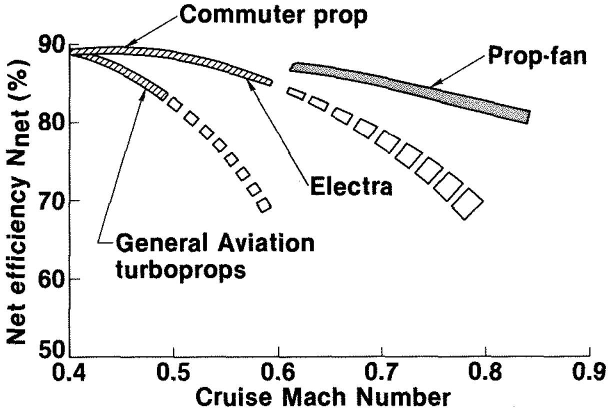


Figure 10. Turboprop Uninstalled Cruise Efficiency Trends

Prop-Fan Experimental Programs

In view of the attractive fuel savings potential of the Prop-Fan propulsion system briefly discussed above, NASA has organized a comprehensive industry-wide research program to demonstrate the predicted performance levels and to provide the technology required to design Prop-Fan propulsion systems appropriate for advanced, energy efficiency aircraft. One phase of this overall program is a wind tunnel program on a series of Prop-Fan models to evaluate the performance potential of this new propulsor concept.

The Prop-Fan aerodynamic program addresses both uninstalled rotor efficiency and installed performance on the wing. Figure 11 depicts the wide spectrum of both model Prop-Fan and wing tests performed since 1976. Three generations of Prop-Fans have been tested, some of them at both NASA-Lewis Research Center and United Technologies Research Center (UTRC) facilities. In general the more recent designs perform best; this is a reflection of the improved design methods discussed earlier. The SR-3 reached a level just under 80% efficiency for its design point at 0.8 Mach. Efficiencies were above 80% for the 0.7 - 0.75 Mach range. Figure 12 shows a comparison of measured and predicted design point performance for the various models. Excepting for the NASA designed SR-6, the predictions very nearly match the test data. It can be seen that the SR-3 model is the best performer of the eight bladed configurations. Both of the 10 blade models built did not demonstrate performance levels higher than SR-3 at the 800 foot per second design case. It appears that the SR-6 model ran into root choke difficulties. The highly swept SR-5 could not be tested at this condition because it exhibited flutter difficulties (this will be discussed later). It does appear, however, that the higher performance expected with 10 blades should be achieved. It is estimated that 81 percent efficiency will be achieved at the SR-3 design point with the use of 10 blades and further technology development.

Figure 11 shows two specific wing aero experimental programs which have already been accomplished. Before discussing these, let's review aircraft study results to date. All the major aircraft manufacturers have evaluated Prop-Fan aircraft for 0.8 Mach design cruise and have made their independent assessment of installation losses. In general the estimates vary from slightly less than high bypass turbofan installation losses to about twice the turbofan levels. Even with the highest losses, significant fuel and DOC savings were shown.

Altitude 35,000 Ft, Mach Number 0.8

Configuration	No. of Blades	SHP/D^2	Tip Speed fps	ηmeas %	ηcalc %	$\Delta\eta$ %
SR-2	8	37.5	800	75.8	76.4	0.6
SR-1	8	37.5	800	76.2	75.9	−0.3
SR-3	8	37.5	800	78.2	78.4	0.2
SR-1M	8	37.5	800	77.7	77.5	−0.2
SR-6(1)	10	30.0	700	77.8	80.6	2.8(2)
SR-5	10	26.0	600	79.0	78.5	−0.5

(1) NASA's aero/acoustic design
(2) Calculation does not reflect root choke evident in test data

Figure 12. Design Point Performance Summary

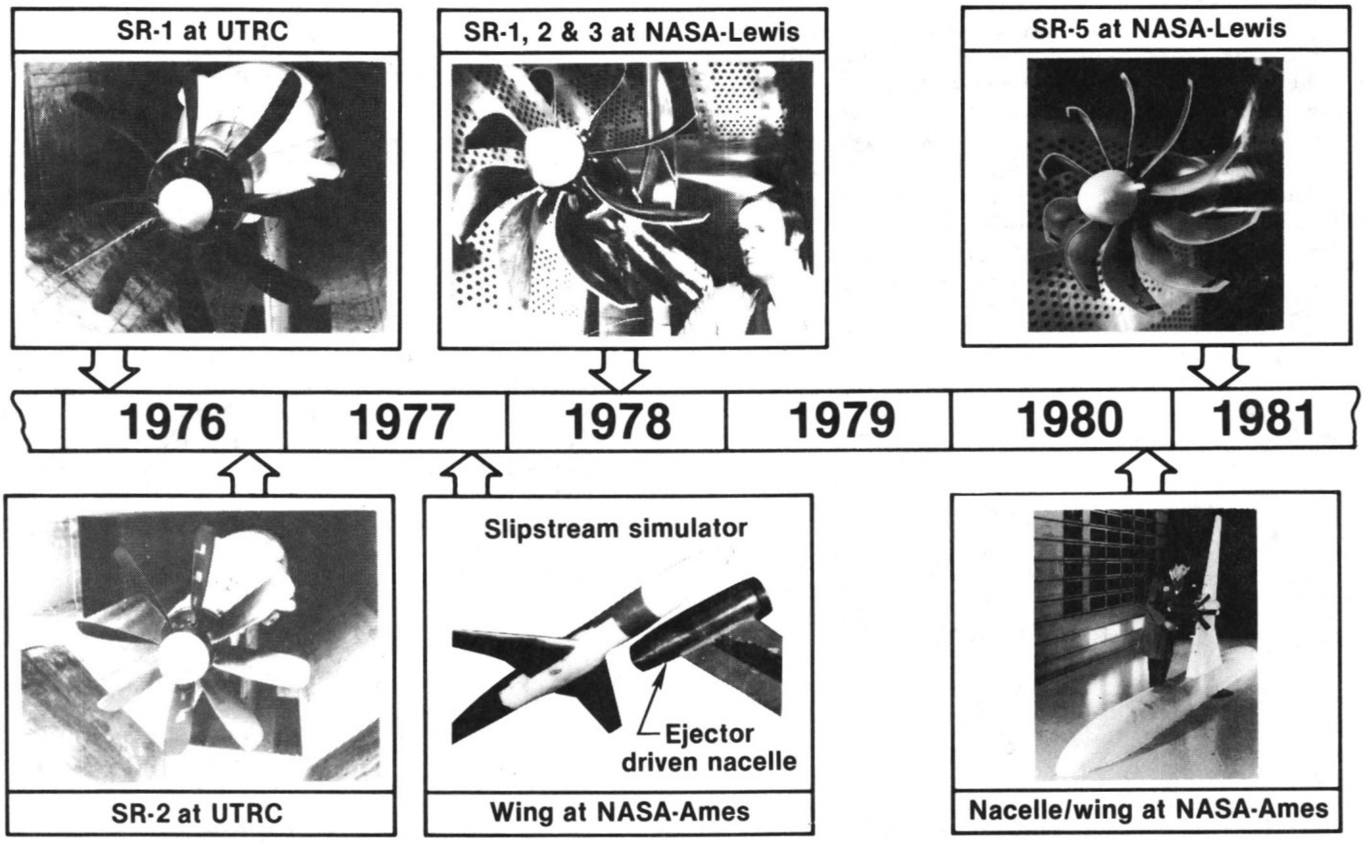


Figure 11. Prop-Fan Aerodynamic Program

In the first test conducted at NASA-Ames, a slipstream simulator was used to direct an airstream on an existing supercritical wing model. The airstream character was varied in velocity and swirl to simulate the Prop-Fan slipstream. The force results indicated that interference drag effects amounted to an increase of about 3% of the aircraft drag for a twin engine configuration at the 0.8 Mach Prop-Fan design operating case. The tests revealed that the wing drag was reduced when the slipstream swirl levels were high, indicating the ability to recover swirl.

In the second wing program shown on Figure 11, the same supercritical wing was adapted to a half-aircraft configuration and an air turbine-powered Prop-Fan was fitted to the wing. The initial powered nacelle tests were completed at NASA-Ames in early 1981. Results of these tests indicates that the nacelle interference drag can be quite large relative to an uninstalled nacelle. However, the losses due to the nacelle were reduced to acceptable levels by changes to the wing leading edge and nacelle intersection. The propeller slipstream causes substantial changes in the wing span load distribution indicating that wing twist modifications are needed to recover a more favorable span load distribution.

Interference drag can be reduced by contouring the wing leading edge or the nacelle or both. This was attempted for the wing and nacelle, but without the Prop-Fan, by installing fillets and strakes between the wing leading edge and the side of the nacelle. The modifications were made on the basis of previous oil-flow pictures and pressure measurements. The first fillet was a straight leading-edge extension with no sweep; it is shown schematically in Figure 13. The drag change due to this fillet is shown in the figure as the distance between the lines faired through the circle and square symbols. A further improvement resulted from reshaping this fillet to have a more curved leading edge, but only at Mach numbers between 0.74 and 0.82. A third modification was the installation of a small strake on the outboard side of the nacelle.

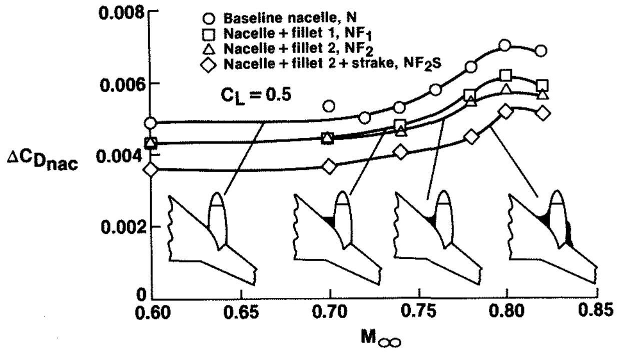


Figure 13. Effect of Fillets and Strake on Nacelle Drag

Further tests were conducted on both powered and unpowered wing and nacelle configurations by NASA Ames in late 1981 and early 1982 as indicated on Figure 14. The latest results from both these tests are unpublished at this time but qualitative comments are indicated on Figure 15. Results appear to be very promising in that installed Prop-Fan drags may be comparable to those of turbofans.

- **Unpowered nacelle contoured on existing Whitcomb wing in 14 ft tunnel late Oct. 1981**
- **Baseline wing/powered nacelle in 11 ft tunnel Jan. 1982 with metric fuselage, with and without lead edge extension and with lead edge extension and fillet**

Figure 14. Recent Tests at NASA-Ames

- **Unpowered contoured nacelle - with wing**
  - **Lift loss recovered with contoured nacelle**
  - **Drag penalty reduced to friction of nacelle**
- **Powered nacelle - with wing**
  - **Test results indicate that the clean wing drag rise Mach number can be achieved**
  - **Tests to date show visibility of 7-10% total installation losses**
  - **Future testing will include an integrated wing/nacelle configuration**

Figure 15. Latest NASA-Ames Results

Figure 16 summarizes the aerodynamic discussion presented in this section. It reflects the very high uninstalled η of turboprops in cruise and the ability to control installed losses. In addition, it provides comments on the very good low speed performance and the yet to be handled inlet configuration selection for Prop-Fans at high Mach.

Uninstalled cruise	**81% η likely at 0.8M** **84% η target at 0.7M** **88-89% η at 0.6M or lower**
Installed cruise	**Expect 0-3% drag penalty at 0.7-0.8M**
Low speed	**Very adequate performance**

Figure 16. Aero Summary

ACOUSTICS

Acoustic Methodology

Takeoff and landing noise control is required to meet the aircraft noise certification requirements and minimize annoyance in the populated areas surrounding the airports. Near field cruise noise control is required to minimize the noise in the passenger cabin. Certain military requirements for audible detection apply to cruise.

Hamilton Standard has for many years conducted research and development programs and developed methodology which addresses all aspects of propeller noise control. In this section, the theoretical prediction methodology used for optimizing the design of a quiet propeller is discussed. There are many noise components which must be included in a prediction methodology to completely describe the noise. Methodology which neglects any of the components will produce misleading low noise predictions that will not be achieved in practice. A propeller design optimized for minimum noise and maximum performance requires the use of theoretical methodology. The components of propeller noise in Hamilton Standard's theoretical prediction method include thickness, loading, quadrupole tone noises; broadband noise; and unsteady loading noise due to atmospheric turbulence and installation effects including skewed inflow. The method also takes into consideration both ground reflection and aircraft shielding effects.

Using a theoretically based computer program and proceeding through a detailed aeroacoustic design will yield a turboprop powered aircraft configuration which can meet far field certification requirements. While turbofan powered aircraft have struggled to reduce noise levels, new turboprop aircraft have had little trouble meeting the requirements. New turboprop powered aircraft are well within requirements as in the case of the Hamilton Standard quiet propellers on the de Havilland DHC-7. The margins under FAR 36 requirements achieved by the DHC-7 are 13.4 EPNdB at takeoff, 19.2 EPNdB at sideline, and 9.6 EPNdB at approach. Projections for new turboprop powered commuters indicate they can easily meet far field standards.

In 1975, there was no acoustic design methodology for handling the high helical tip speed operation of the swept Prop-Fan blades in cruise. An empirical approach was used for the 1st generation model designs. It was not until a year later that a new Hamilton Standard linear method was applied to a 2nd generation design with large effectiveness. The development and application of acoustic analyses for Prop-Fans is shown in Figure 17. The approach is to use thin airfoils and a swept blade shape to reduce noise during cruise where the blade tip helical Mach number exceeds one. This is done by minimizing the linear thickness and loading noise and minimizing the nonlinear quadrupole noise components as well. A powerful effect of blade sweep is to cause the acoustic signal from the blade tip area to lag the signal from the mid-blade region, thus causing partial cancellation and significant reduction in noise levels. The phase interference concept is illustrated by Figure 18. The concept of phase cancellation is based on the fundamental assumption of linear acoustics that the acoustic pressure at any observer position can be calculated as the sum of contributions from each element of the source volume and surface area. The inclusion of sufficient sweep to eliminate the nonlinear source terms from the signature allows the phase cancellation concept to play a significant role in achieving Prop-Fan noise reductions during cruise.

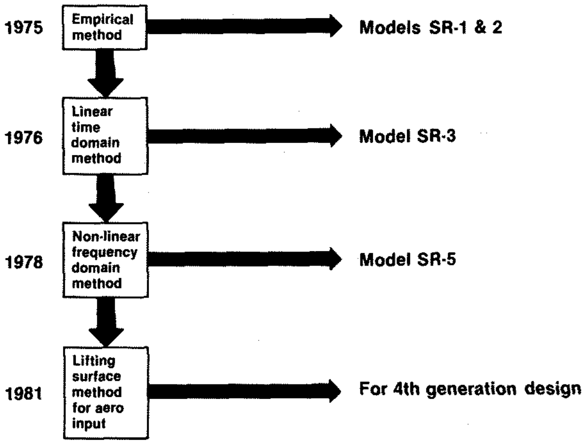


Figure 17. Prop-Fan Noise Analyses

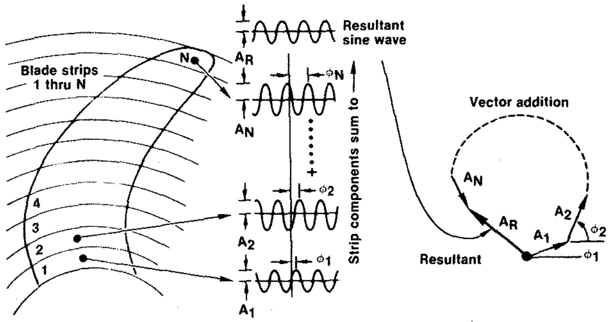


Figure 18. Acoustic Radial Cancellation Technique

Prop-Fan Experimental Program

The Prop-Fan acoustic program addresses source noise and aircraft interior comfort levels. The overall experimental program content is shown in Figure 19. The models have been tested in the United Technologies Research Center (UTRC) Acoustic Research Tunnel and NASA's aerodynamic wind tunnel. The UTRC tunnel allows for accurate source noise measurements for far field cases representative for FAR 36, but the high tip speed cruise cases are simulated with higher rpm at the 0.3 Mach tunnel limit. The NASA-Lewis tunnel does allow measurements at 0.8 Mach but the tunnel is not acoustically treated. For these reasons, NASA has proceeded with the Jetstar program where Prop-Fan models are flight tested at the speeds and altitudes of interest. The JetStar testing is primarily intended to provide confirmation of the cruise source noise levels.

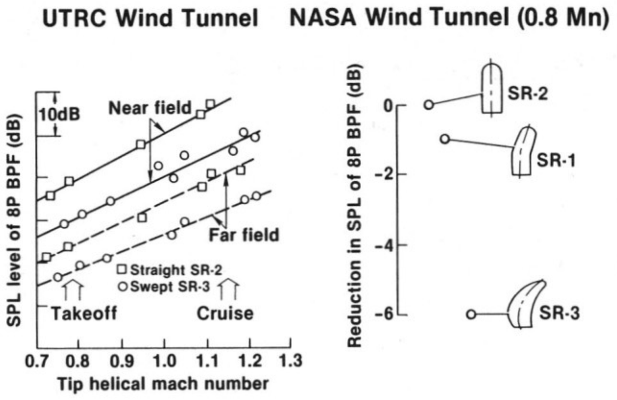


Figure 20. Prop-Fan Model Acoustic Test Results

Test results from the wind tunnel programs are summarized on Figure 20. Both clearly show the 2nd generation swept blade design to be significantly quieter than the 1st generation designs. In the UTRC acoustic tunnel the fundamental tone of the swept SR-3 configuration is significantly quieter at both cruise and takeoff operating cases both in the near and far field. While the cruise case is a simulation by overspeed, the takeoff cases are properly represented and can be scaled for comparison with FAR 36 requirements. It can also be seen that there is no dramatic shift in data trend as the blade enters the transonic regime; the trend is linear. These UTRC tests have been used to confirm airport noise projections and to verify methods for predicting cruise noise levels. The data from the NASA-Lewis

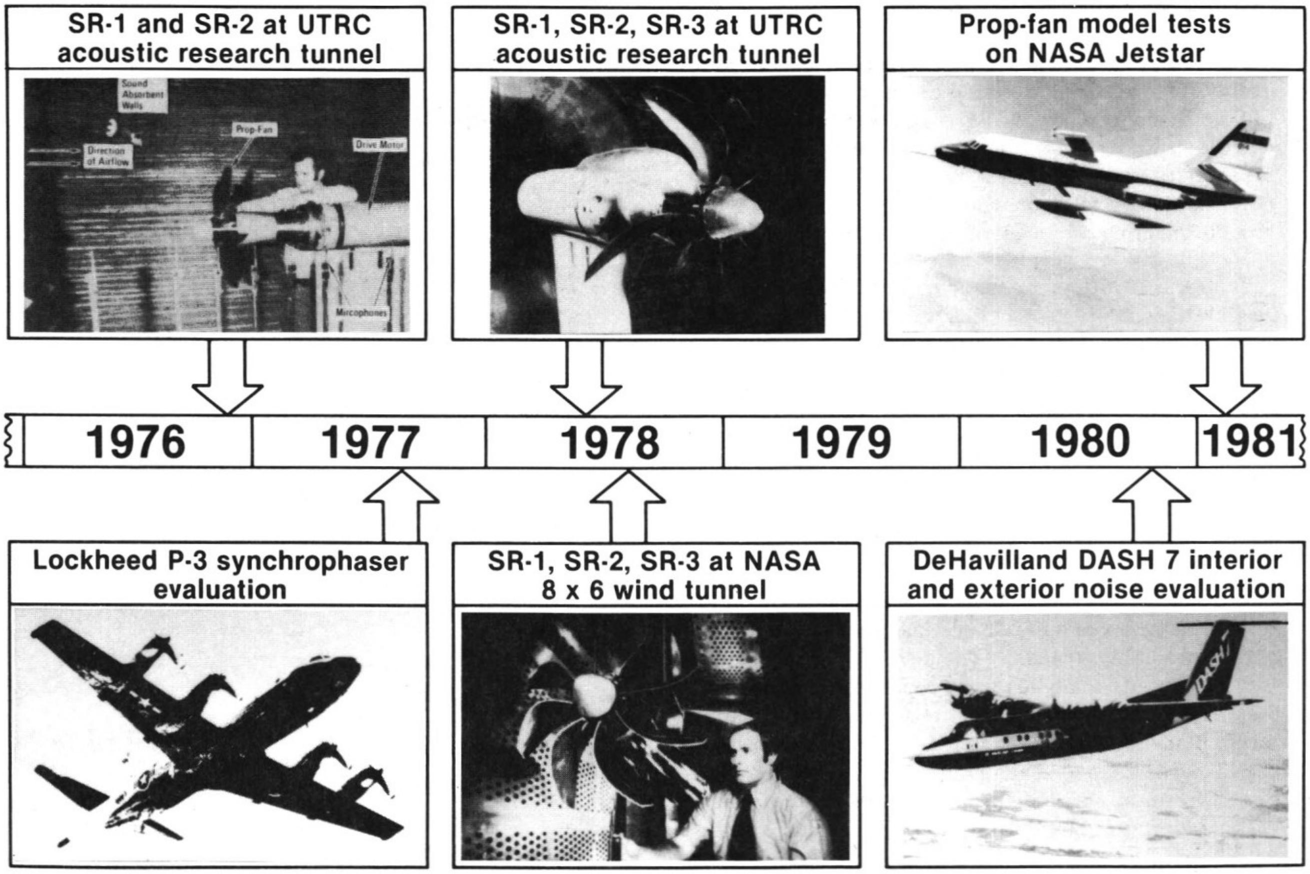


Figure 19. Prop-Fan Acoustic Tests

tunnel shows the swept SR-3 to be 6dB quieter than straight SR-2 at the fundamental blade passing frequency (BPF). The model test program in the UTRC tunnel has provided verification of the acoustic design method. Predictions match test data fairly well for all the models tested. Errors are within two dB.

Recent flight tests of a Prop-Fan model mounted on a JetStar aircraft revealed fuselage surface noise levels to be substantially lower than expected. This is shown in Figure 21. Hamilton Standard has been investigating the cause of the differences and has concluded that the shear flow in the fuselage boundary layer shields the surface by reflecting some of the incident acoustic energy. This revelation also casts doubt on being able to interpret data measured in the NASA 0.8 Mach untreated tunnel. The boundary layer in this tunnel is expected to alter to source noise measurements. Analysis at Hamilton Standard using a fairly crude boundary layer model resulted in the following conclusions:

1. At 0.8 cruise Mach number, the boundary layer does provide shielding over a substantial portion of the JetStar fuselage.
2. The benefit diminishes rapidly with reductions in flight speed.
3. The sheilding also diminishes with increased Prop-Fan scale. Some of the benefit observed in model scale will be lost in full scale installations.

We can conclude that the test data on the Jetstar is influenced by the aircraft boundary layer. NASA has continued Jetstar tests in order to investigate the boundary layer influence further using a free field microphone and fewer blades in the rotor.

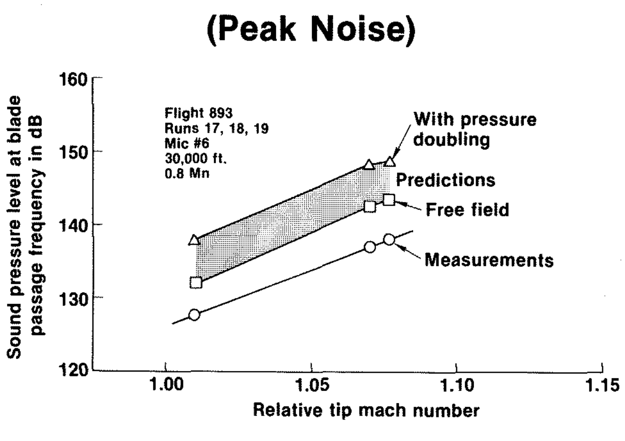


Figure 21. Preliminary Jetstar SR3 Data vs Hamilton Standard Predictions

<u>Interior Noise Control</u>

Propeller driven aircraft have historically been considered less comfortable from an interior noise standpoint than turbofan and turbojet aircraft. At the present time, there is considerable effort underway to (1) develop better noise criteria for propeller aircraft cabins, (2) understand and control propeller source noise, (3) develop a better understanding of the noise transmission path, (4) improve the noise reduction with lightweight fuselage wall treatment, and (5) establish the potential of other novel noise control concepts. This multiple path approach is indicated in Figure 22.

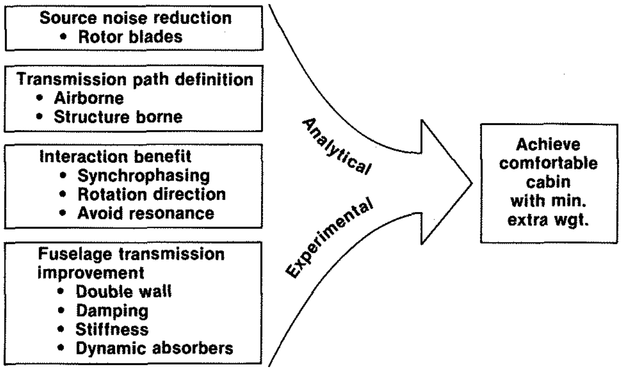


Figure 22. Multiple Path Approach for Interior Comfort

The noise of a propeller consists of tones at harmonics of propeller blade passage frequency (rpm x no. blades/60). This noise signature differs from that which occurs for a turbofan aircraft where the dominant exterior noise component is broadband in nature and is generated by the exterior boundary layer on the surface of the fuselage. The noise signature inside a typical turboprop aircraft is dominated by low frequency tones. Recent psychoacoustic tests conducted by NASA have indicated there are very significant benefits to be achieved by tone noise reduction. These tests indicated that a noise spectrum dominated by tones could be less comfortable than one without tones, but at the same dB level.

The reduction of propeller noise at the source by modification of the propeller configuration or operating condition is an obvious strategy for reducing aircraft interior noise. There are many ways of achieving these reductions but they must be considered in the light of performance and weight impact. It appears that source noise reductions can be achieved by the combination of increasing the number of blades, reducing diameter, and improving blade airfoil performance.

Blade tip modification has also been considered a fruitful area for modification in past propeller noise reduction research. Calculations show that thin narrow elliptical tips are the best with thick, wide square tips being the worst. This is because the noise primarily at higher harmonics of blade passage frequency is a function of the volume of the outer portion of the blade.

Another tip modification now under consideration is the proplet, the equivalent of the winglet now in use on many aircraft. This device has the potential for increasing performance and reducing noise. Performance is increased by alleviation of blade tip induced losses. Noise is reduced by taking advantage of the performance increase to reduce diameter. The noise of the reduced diameter propeller with proplets is reduced by optimizing the proplets such that there is a cancellation of noise associated with the volume of the proplet by noise due to the radial loading on the proplet. Therefore, any reduction in noise with such a device must rely on a maximum enhancement in performance to allow the maximum reduction in diameter coupled with a proplet configuration carefully tailored to cause cancellation of noise sources. The three dimensional aerodynamic and acoustic analysis required to determine the potential of proplets is just now being developed.

Figure 22 indicates that there are both airborne and structureborne transmission paths for the noise found in the cabin of propeller aircraft. The most dominant path for propeller noise is the direct airborne path from the propeller blades through the fuselage sidewall. The importance of other paths is not well understood. The wing may be excited by wakes from the propeller blades with the resulting vibration transmitted by wing structure to the cabin. The tail surfaces may be excited by the propeller wakes or fuselage boundary layer turbulence and the tail surface structure then transmits the vibration to the fuselage where it is radiated as noise.

Hamilton Standard and the Lockheed California Company have been evaluating the P3 interior characteristics over the last few years and quite recently have acquired extensive data on the de Havilland DHC-7 aircraft. In addition, Hamilton Standard has received recent data acquired in Great Britain on the BA-748 and in the Netherlands on the F-27.

The use of opposite rotation of the propellers on either side of the aircraft and the use of synchrophasing have the potential of reducing both the noise and vibration significantly. This is reflected with analysis of P3 and DHC-7 data. Significant noise reductions have been indicated for the P3 if Synchrophasing is used with optimized phase angles between the four turboprops. The potential reduction at BPF in the interior areas near the plane of rotation are shown on Figure 23. Recent analysis of the DHC-7 data with only inboard turboprops operating also indicates a significant reduction in noise is achievable with Synchrophasing. The analysis indicates that 12-15 dB reduction from the maximum is achievable on the fundamental tone, very similar to the P3 results. Taking into account the first three tones and their interior noise sources and switching to dB (A), the improvement is conservatively estimated at about 3 dB(A). The latest aircraft interior data indicate that there are both structure borne and airborne noise paths; the existing fuselage designs provide high attenuation; 1P vibrations levels attributable to rotor unbalance are quite acceptable; and opposite rotation, synchrophasing, the dynamic absorbers do offer large attenuations for both noise and vibration at tonal frequencies.

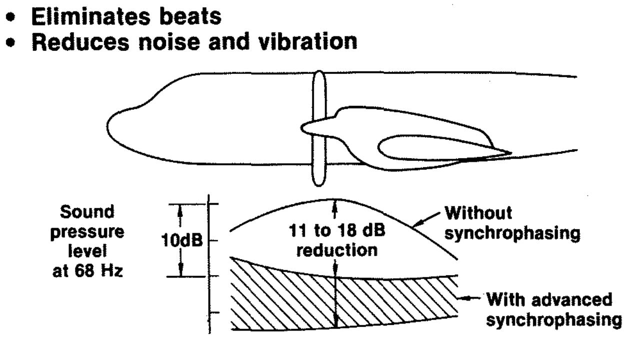


Figure 23. P3C Interior Noise Reduction Potential with Synchrophasing

The problem of interior noise control for Prop-Fan represents the most severe case. As depicted on the left side in Figure 24, Prop-Fan source noise levels on the fuselage are equal or greater than on existing turboprop aircraft. This is primarily a result of the higher aircraft speed. On the right side of the figure, Prop-Fan interior noise levels with a conventional sidewall treatment and reductions due to Synchrophasing and direction of rotation are in the range of existing propeller aircraft. Advancements in fuselage sidewall treatment are one of the likely ways to get further noise reductions.

NASA has funded both analytical and experimental efforts on fuselage wall concepts for improved low frequency tone noise attenuation. Figure 25 shows the experimental test set-up for tests recently completed by the Lockheed California Company. The objective of the program was to experimentally verify prior analytical

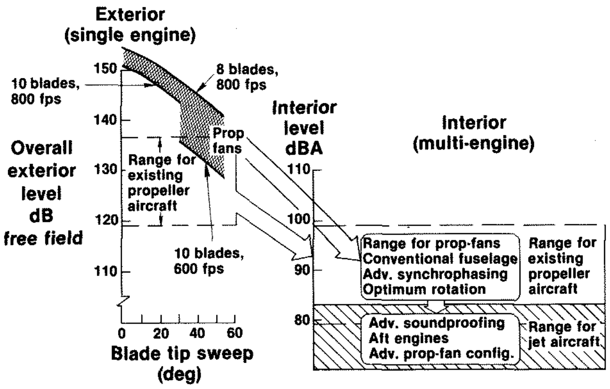


Figure 24. Maximum Exterior and Interior Noise at Cruise (Wing-Mounted Engines)

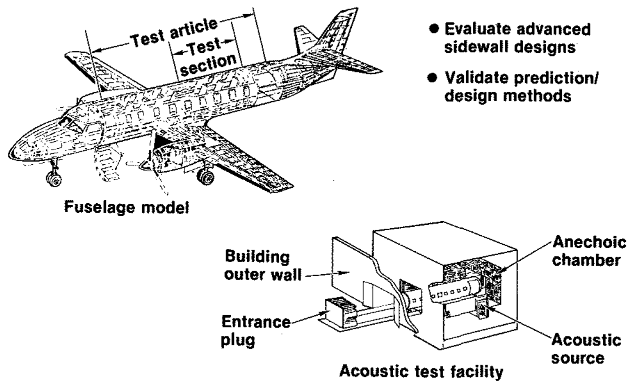


Figure 25. NASA/Lockheed Interior Noise Control Program

studies. The test hardware consisted of a Swearingen Metro fuselage section in which nine different wall and floor arrangements were installed. Both inner and outer walls were varied in both isolated and structurally mounted configurations. Results from this program appear to be positive.

Summary of Noise Control Strategies

A noise control strategy is a combination of noise control concepts which allow a noise reduction goal to be met. The best noise control strategy for reaching an aircraft interior noise goal is the one that has the least impact on weight, cost, and performance of the aircraft. In the following discussion, the noise reduction potential of the various noise control concepts discussed above will be evaluated in broad general terms as they apply to the four hypothetical aircraft shown on Figure 26. It should be noted that much of the work in the development of noise control concepts is not yet complete at this time and, therefore, these strategies are considered preliminary. Also, the practical application of these concepts in many cases has yet to be proven. In some cases (such as blade sweep, reduced tip volume, and proplets, the structural adequacy of such designs must be established. Figure 26 lists the noise reduction concepts and indicates the potential for noise reduction if each are applied to four hypothetical aircraft. Several concepts could not be rated for their noise reduction potential as sufficient research work in these areas has not been conducted. Also it should be noted that the indicated noise reductions for several concepts may not be additive. The optimum noise reduction strategy for any particular aircraft will be the combination of the concepts that provides the largest reduction with minimum cost, weight, and performance penalties.

For the commuter aircraft, there appears to be a large noise reduction potential for added fuselage panel stiffness and synchrophasing. For the large commuter and conventional aircraft, the largest noise reduction appears to be achievable with synchrophasing and dynamic absorbers. For the Prop-Fan aircraft, the largest noise reduction appears to be achievable with reduced tip speed, reduced blade loading, opposite rotation, use of limp mass double fuselage wall, increased cabin sound absorption, synchrophasing and dynamic absorbers.

	Aircraft Class			
Noise Reduction Concept	Commuter	Large Commuter	Large Conventional	Prop-Fan
I. Reduction of noise at the fuselage surface				
a. Reduced tip speed	2	1	1	2
b. Reduced blade loading	1	2	2	3
c. Reduced tip loading	1	1	1	1
d. Proplets	TBD	TBD	TBD	TBD
e. Reduced prop tip volume	2	2	2	1
f. Blade sweep	2	1	1	2
g. Counter rotation	TBD	TBD	TBD	TBD
h. Opposite rotation	1	1	2	3
i. Increased tip clearance	2	2	2	1
II. Reduction of noise transmission through the fuselage wall				
a. Reduction by added panel stiffness	3	2	1	1
b. Reduction by limp mass double wall	1	1	2	3
III. Other noise reduction concepts				
a. Reduction by increased cabin absorption	1	2	2	3
b. Synchrophasing	3	3	3	3
c. Dynamic absorbers	2	3	3	3
d. Isolation of structure borne noise	TBD	TBD	TBD	TBD

Symbols:
1. Indicates 1-2 dB reduction potential
2. Indicates 3-4 dB reduction potential
3. Indicates 5 or more dB reduction potential
TBD is "To Be Determined"

Figure 26. Potential of Various Noise Reduction Concepts

BLADE

Background & Experience

The availability of a technology for the design and fabrication of blades is a major contributing factor to the turboprop's capability. The blade is one of the most important components in the advanced turboprop propulsion system. The blade is critical with regard to meeting performance, noise, weight, and safety goals. It also is the largest contributor to acquisition cost and it is the longest lead-time component.

The simplest blade construction from both design and fabrication standpoints is a solid, homogeneous blade. It has two major disadvantages, the inefficient use of material and the lack of isolation from environmental damage. Damage isolation is a term used to describe the ability of a blade to sustain service inflicted damage from encounters with foreign objects without degrading its structural capacity. Damage isolation is different from damage resistance; the former accepts damage as a natural occurrence and affords survivability, whereas the latter deals with the threshold of damage. In a solid blade, if the normal steady and cyclic stressing is raised above the material strength by the stress intensifying effect of a nick or gouge, the crack can propagate through the blade leading to separation; there is no damage isolation other than that supplied by the material and conservative design practice.

In attempts to minimize the inefficient use of materials, most blade manufacturers tried monocoque or stressed-skin construction. The next step was to introduce added shear load paths into the pure monocoque construction. The basic result was to modify the pure monocoque to overcome as many of its disadvantages as possible.

The spar-shell construction, because of its superior structural efficiency, was originated and developed by Hamilton Standard as an alternate to modified monocoque concepts. The spar-shell concept shown in Figure 27 is particularly easy to fabricate and has demonstrated damage isolation as well as other unique features. Damage isolation is achieved by separating the shell from the isolation spar by a low modulus layer. This approach has been shown to limit service inflicted damage and propagation of that damage to the shell only. This is particularly true with the selected material combination; fiberglass shell and metal spar. The blade shown in Figure 27 combines modern materials and fabrication technology with a design concept having many years of successful flight proven experience. The primary load-carrying member of the spar-shell structure is the solid aluminum or hollow steel spar which is continuous from the integral retention to the tip. The airfoil shape is provided by a lightweight fiberglass shell which is adhesively bonded to the spar. The cavities in the leading and trailing edge areas are filled with a low density urethane foam. Additional features include a nickel leading edge erosion protection strip and an integral deicing heater.

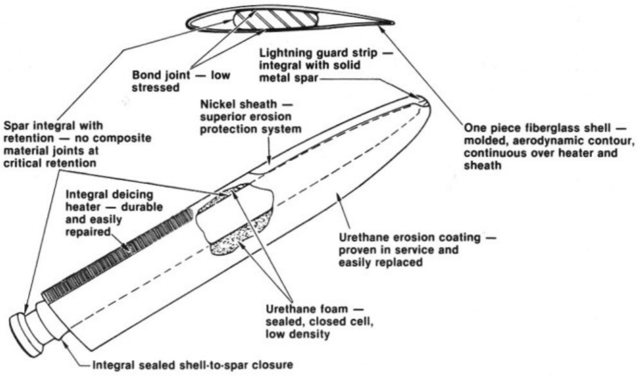
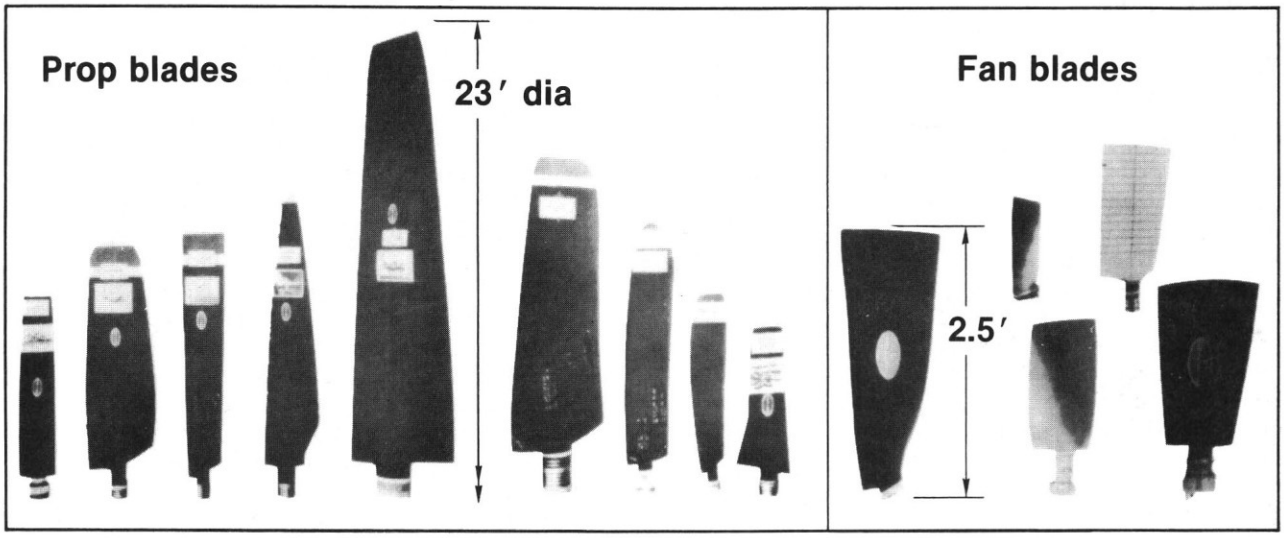


Figure 27. Hamilton Standard Spar/Shell Blade

Hamilton Standard's experience with spar-shell blades is extensive. A representative summary of the metal spar-composite shell blade engineering activity and test/operating experience is shown in Figure 28. Over 5000 blades have been manufactured since 1961 in 25 different designs. In the years since inception of the metal spar-composite shell concept, Hamilton Standard has conducted programs which included systems tests on a static rig or engine, in the Ames low speed wind tunnel, and in flight. Of the 25 blade programs, thirteen achieved flight test status as prototypes, four of these are in production, and three are in production development. Test experience on engines and whirl rigs includes high 1P cyclic stress levels and significant overspeeds and overpower conditions. The estimated total spar-shell blade flight time is 5 million hours. Over 80 blade vibration test programs have been accomplished with rotors on whirl rigs and on engines in test cells, wind tunnels, and in flight. In addition to these systems tests, numerous material tests, structural response tests, and fatigue tests have been accomplished on the spar-shell blade and its components.



- **5000 blades manufactured**
- **25 different designs**
- **5,000,000 flight hours**
- **200,000 engine test hours**
- **6400 hour hi-time blade**
- **375 hours whirl rig**
- **250 hours wind tunnel**
- **80 vibration surveys**
- **240 full scale fatigue samples**
- **Over 3000 specimen fatigue tests**

Figure 28. Blade Highlights - Metal Spar - Composite Shell

The Hamilton Standard experience on aircraft during the last ten years is summarized below. In the early 1970's Hamilton Standard undertook a propeller retrofit program of the Navy's E-2 and C-2 aircraft which originally had been equipped with Aeroproducts propellers. Due to structural requirements that were unique to carrier based aircraft, a propeller possessing very high structural capacity was required. Hamilton Standard proposed its metal spar/fiberglass shell blade and a very successful program resulted in the retrofit of the entire fleet of E-2 and C-2 aircraft and today new aircraft off the Grumman assembly line are fitted with this now well proven propeller. In the middle 1970's another severe structural requirement was adequately met with a Hamilton Standard metal spar/fiberglass shell blade on the Rockwell OV-10D aircraft. This is a high performance night observation aircraft and imposes high aerodynamic and maneuver loads on the propellers. With 15 years of flight proven experience behind it, Hamilton Standard introduced its metal spar/fiberglass shell bladed propeller into commercial service on the de Havilland DHC-7 aircraft. Reports from operators of the DASH 7 have shown the composite blades of the 24PF propeller to be reliable, maintainable, and trouble free.

In more than five million flight hours accumulated to date on fiberglass blades in commercial and military service, there have been many reported and unreported FOD incidents. None have resulted in the loss of a blade or propeller. Impacts with large soft bodied objects such as ducks and geese, to our knowledge, have not even required blade repair. Small hard bodied objects such as gravel and stones rarely do more damage than to scrape the paint. Large hard bodied objects such as 2 and 3 lb. pieces of aircraft carrier catapult systems have caused tears in the fiberglass shells which have required repair.

The introduction of advanced technology into commercial aircraft hardware has always been met with extreme reluctance and skepticism by the airlines. They have not been willing to subject themselves to the rigors, both financial and schedular, of introducing advanced technology hardware. There was even an initial airline reluctance to accept the Hamilton Standard spar/shell blade for the 24PF propeller on the DHC-7 aircraft, despite its extensive successful military service record. It is expected that there would be an even greater airline reluctance to accept an all composite blade construction which is unproven by either commercial or military service. All composite materials are subject to in-service degradation of modulus and strength due to normal fatigue loads, FOD and thermal cycling. If composite materials are used as prime structures, these effects must be evaluated in aircraft service over extended periods of time to assure long term structural integrity. With this background, Hamilton Standard has selected the metal spar-fiberglass shell blade construction for its new commuter turboprops and for the more advanced Prop-Fan propulsion system.

New Spar/Shell Fabrication Process

In order to meet the stringent blade performance, noise and cost targets for a modern turboprop, a new approach to lightweight metal spar/fiberglass shell blade fabrication, illustrated in Figure 29, is being employed by Hamilton Standard. This is a vacuum injection fabrication approach which involves only four major steps instead of the nine used in previous approaches. Since the blade airfoil is formed during final blade assembly by matched dies, blade aerodynamic shape and surface finish are precisely controlled against design requirements and are repetitive from blade to blade. The injection molding process has been proved out using the 24PF propeller blade design (used on the DHC-7 aircraft). A quantity of blades were manufactured and tested with the objective of full certification. The blades have completed the certification fatigue tests and have demonstrated strength margins equivalent to blades fabricated by the previous process. The final certification requirements have been met and full certification was approved in March 1981.

Blade Structural Methodology

Blade structural analysis has traditionally been done with beam-type analyses. The analyses have evolved into computer programs which provide satisfactory results for high aspect ratio blades, such as propeller blades where radial length is large relative to chord width. Accuracy decreases significantly, however, when the beam programs are applied to blades of low aspect ratio or blades having significant sweep, such as the Prop-Fan. In an effort to improve analytical deflection, stress and frequency predictions for advanced blades, developments in three-dimensional finite element analytical (FEA) techniques have been applied to a variety of blades at Hamilton Standard.

The Hamilton Standard blade mechanical design tasks are shown in Figure 30 for both conventional beam type analysis and FEA. Each type analysis investigates the same critical areas for blade design, however foreign object damage analysis is presently handled by beam models. An in-house, computerized, finite element solution program is the analytical tool for Prop-Fan blade studies. It incorporates a unique, variable thickness type of shell element, well suited for three-dimensional representation of each composite shell, as well as the blade spar. Also, a link element is included, specially developed to represent the actual bond joint connecting the individual layers of spar and shell elements. a spring element is used to represent the blade retention stiffness. Finite element techniques are also being used in hub analysis where unusual shapes require more accurate modelling in order to achieve an optimum design.

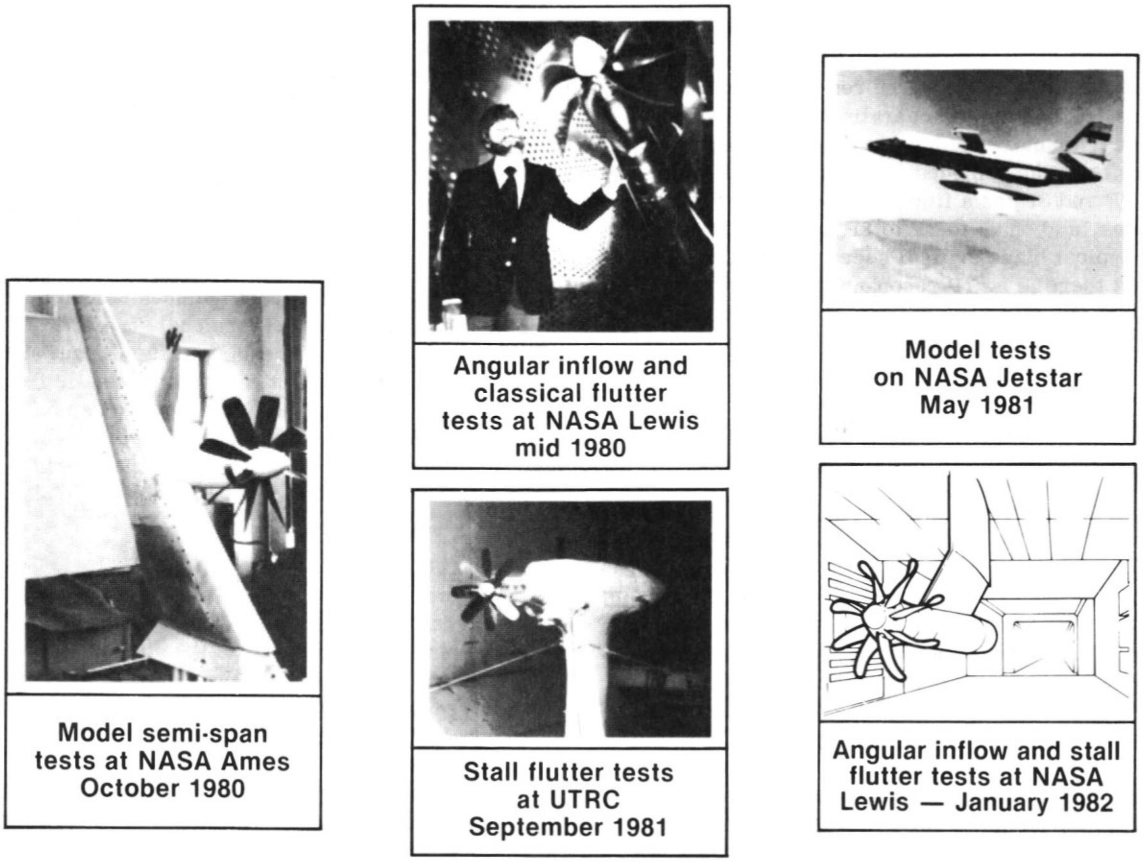
accurate. Installed weights take into account all the nacelle and wing attachment hardware. This type of hardware is usually much heavier on a turbofan installation when compared to a turboprop since it includes the duct, pylon, and reverser. When weight comparisons are done in that fashion, the Prop-Fan is competitive with installed turbofan weights.

Prop-Fan Experimental Program

Prop-Fan blade characteristics are initially dictated by the aerodynamic and acoustic programs discussed earlier. However, the final blade must also be structurally sound. Model programs are being conducted to provide the verification of design prediction methods and a baseline level of confidence for proceeding to a large scale program. Complementing the model work are full scale blade design efforts. The overall intent of the program has been to evolve a blade configuration which provides the desired high aeroacoustic performance while maintaining the high structural reliability of existing turboprops. The result has been basically to keep the tip chord narrow to reduce tip volume and mass, and to keep the mid-blade area wide to provide increased structural capacity and stiffness in the presence of the low thickness ratio.

Figure 33 shows the structural model programs conducted since 1980. There are extensive structural model tests covering the response and stability areas. The model tests will determine the response of Prop-Fan blades to angular inflow both with and without a wing, and the location of stall and classical flutter boundaries and the parameters affecting their location. Model tests in the NASA-Lewis high speed wind tunnel have shown operating critical speeds (the interaction of modes at rotational frequencies) to be in expected locations. The test data from the angular inflow model program shows the predicted increasing stress trends with both increasing velocity and angular inflow parameters. The rotor test data from the NASA semispan program did not reveal any abnormalities with the swept wing. Tests on the JetStar indicated the ability to operate in real atmospheric conditions without limitations.

Test results from angular inflow tests have shown that swept blades have higher vibratory response than straight blades at high operating Mach numbers. In the stability testing, the results show that swept blades are more prone to classical flutter than straight blades, however, straight blades are more prone to stall flutter. An example of this is with the most highly swept model, the ten blade SR-5 configuration. While no stall flutter



Model semi-span tests at NASA Ames October 1980

Angular inflow and classical flutter tests at NASA Lewis mid 1980

Stall flutter tests at UTRC September 1981

Model tests on NASA Jetstar May 1981

Angular inflow and stall flutter tests at NASA Lewis — January 1982

Figure 33. Prop-Fan Structural Programs

was encountered at zero velocity, classical flutter was encountered at high tip helical Mach numbers. Just the opposite was experienced with the straight SR-2 configuration. Here, no high Mach classical flutter was present but stall flutter was encountered at zero velocity.

As stated earlier, the experimental model structural programs are being used to verify the analytical tools. For the SR-5, Figure 34 shows a comparison of measured classical flutter test points compared to the single blade flutter prediction using the latest theoretically based analysis. Correlation with two and five blade test points is excellent. The inclusion of cascade effects in the analysis should improve the correlation with the ten blade test points.

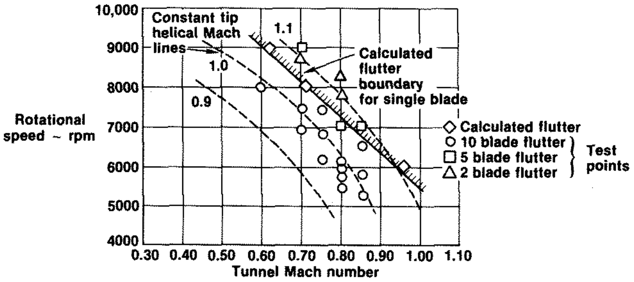


Figure 34. Predicted vs Measured SR-5 Model Prop-Fan Flutter Boundary

Large Scale Prop-Fan Program

The progress to date in the experimental model programs provides the assurance for a successful large scale hardware program. The model test program and blade design analysis efforts have reached the point where the Prop-Fan structural issue cannot be further satisfied with small scale programs. The present plan which initiates large scale blade design is clearly timely. A large scale Prop-Fan rotor flight test program is regarded as necessary to provide final confirmation of structural dynamics and blade construction techniques.

In moving towards the start of a large scale rotor program, significant full scale blade preliminary design effort has taken place. Hamilton Standard has analyzed several Prop-Fan blades, having metal spar, composite shell construction, using the analytical tools discussed in this section. Most of these designs are considered practical. The all composite blade in the study matrix was not considered satisfactory. A summary of the Prop-Fan large scale structure is shown on Figure 35.

VARIABLE PITCH SYSTEMS AND CONTROLS TECHNOLOGY

To provide effective blade angle control for the turboprop, the pitch change mechanism and its controller must be designed to be mutually compatible for fast, accurate pitch change. Moreover, there can be no compromise of safety, reliability or ease of maintenance in the selected design approaches.

Fabrication	**• Metal spar — composite shell**
Frequency	**• No major problem**
Stressing	**• Swept blades have higher vibratory stresses than straight blades at high Mach numbers** **• Test/prediction comparisons in process**
Stall flutter	**• Swept blades have higher flutter boundaries at V = 0** **• Test/prediction comparisons in process**
Classical flutter	**• May limit blade sweep**
FOD	**• Appears satisfactory**

Figure 35. Prop-Fan Structures Summary

Fortunately, there is available a mature technology of propeller pitch change systems which has been developed to a high degree of reliability. A step improvement in the hydromechanical actuator came in the 1950's with the change from using contaminated engine oil to a separate integral oil supply and with the introduction of new fail-safe features such as automatic pitch lock. Further refinements came in the 1960's and 1970's with improved hydraulic fluids, dualized hydraulics and the cleaner environment of the gas turbine.

The key requirements for the pitch change system are as follows:

1. No failure mode will allow undesired overspeeds.
2. High reliability.
3. Modular removal for ease of maintenance.
4. Remotely located power source for ease of maintenance.
5. Feathering, reversing and governing capability.
6. Integrated digital electronic controls for the propeller and gas turbine engine.

An advanced hydromechanical pitch change system has been conceived for new propellers including the Prop-Fan. The new system uses modular design concepts which permit removal of major pitch change components without pulling the complete fan assembly. The system has easily maintainable components and positive blade pitch lock functions. The hydromechanical pitch change system can be made fail-safe and can provide feathering, reversing and speed-governing features, as desired.

The two major components of the variable pitch sys- are the actuator and the regulator. The pitch change actuator is located within the propeller hub and the regulator is mounted on the aft face of the engine gearbox. These two assemblies are interconnected with a torque tube which runs through the center of the propeller and gearbox shaft. This torque tube transmits the pitch change signal and transfers the high pressure hydraulic oil supply from the control to the actuator

An in-place pitch lock is incorporated in the actuator to prevent rotor overspeeds. This type of pitch lock represents a significant advance over earlier pitch lock mechanisms. All pitch lock systems prevent loss of blade angle in the event of a hydraulic system malfunction.

The in-place pitch lock utilizes a screw to convert the rotary signal of the propeller control and to position the actuator servovalve. Should the hydraulic pressure drop to a level that is not sufficient to maintain the blade angle specified by the control, the blade forces tend to move the actuator in a direction to decrease blade angle. In this concept, however, the actuator reacts through the screw and closes the pitch lock "gap". The blades are then mechanically held in position because of the irreversible nature of the screw, automatically pre- the screw and closes the pitch lock "gap". The blades are then mechanically held in position because of the irreversible nature of the screw, automatically preventing serious rotor overspeeds and thrust/drag differentials. The propellers used on C-130's and P3's use the 1950's pitch lock mechanical concept which is reactive. Experience with this production system is good, although the blade angle may drop appreciable before locking. Experimental propellers incorporating the in-place pitchlock concept have been very successful with regard to controlling blade angle with loss of hydraulic pressure. Figure 36 shows the features and failure characteristics of the various pitchlock technologies.

Time Frame	Engine Type	Features		Failure Characteristics
1940-50's	Recip	Reactive system	Hydraulic lock	High rpmΔ High drag
1950-60's	Turbo-prop	Reactive system	Hydraulic-mechanical lock	High rpm Δ Low drag
1970-80's	Turbo-prop	Active system	Mechanical lock	Low rpmΔ Low drag

Figure 36. Pitch Lock Technology Progression

The most widely used control systems for turboprops, as well as turbofans, have been of the hydromechanical type. These have been brought to a high standard of reliability. Much attention is now being focussed on digital electronics. By providing more precise control of the propeller and engine, these controls will provide improved propulsion system life and lower fuel consumption.

RELIABILITY AND MAINTENANCE

1950's Turboprop

The ability to attain acceptable R&M levels for the advanced turboprop propulsion system is no less important to its acceptability than its fuel conservation, performance, safety, and passenger comfort features. Let us start off this topic by reviewing the reliability and maintenance for the existing production Electra-type propeller system which resulted from a joint Hamilton Standard Detroit Diesel Allison study conducted for NASA. These turboprop costs were compared with the JT8D low bypass turbofan. Since the JT8D is a considerably larger propulsor (in terms of thrust) than the 501-D13/54H60, a scaling process was applied to the 501-D13/54H60 to determine its maintenance cost if it was sized large enough to have a propulsive capability equal to the JT8D at Mach 0.8 at 35,000 feet altitude. In this comparison of turboprop with turbofan, the turboprop cost exceeded the turbofan by 74.5%. This stemmed largely from the 501-D13 core which was an older technology than the JT8D's and was designed to military rather than airline requirements. However, the propeller and reduction gearbox represented a small portion of the total for the turboprop. The conclusions from the study were that the existing propeller and main reduction gearbox maintenance costs were a small percentage (13%) of the total for the 501-D13/54H60 and that new turboprop or Prop-Fan system maintenance costs can be reduced from that of older turboprops.

Turboprop R&MC Improvements

The study of reliability and maintenance cost data for the 501-D13/54H60 turboprop system shows that an advanced turboprop system should incorporate the following features:

- On-Condition Maintenance - A design objective of a future system must be the achievement of "On-Condition" maintenance whereby scheduled overhauls are eliminated and inspections are minimized.

- Modularization - The entire propulsion system must be designed using modular concepts. Increased modularity permits the on-aircraft replacement of a minimum amount of hardware when a failure occurs. It also reduces line and shop maintenance repair times, spare parts requirements, and the opportunity for maintenance errors.

- Improved Reliability and Durability - All parts must be designed for high durability and long life, with particular attention to historical areas of wear. Means to accomplish this include hardware simplification, use of improved materials, and design criteria that are consistent with airline operational requirements.

Quantification of Benefits

A detailed comparison was made of the maintenance cost per flight hour of the 501-D13/54H60 system versus the Prop-Fan system. The results quantify the benefits of the improvements that are proposed for this system. The maintenance philosophy utilized incorporates repair or replacement of only the module causing the failure. This philosophy is in line with present day turbo-prop field service experience.

The maintenance costs were developed by including scheduled inspections, unscheduled line repairs, and unscheduled removals. A significant factor in the maintenance cost of Prop-Fan hardware is the design philosophy utilized at Hamilton Standard. This philosophy includes designing both the blade and hub for infinite life. Consequently, these items will only require replacement in the event of an accident of significant FOD. Blades are repairable for all FOD except cases where spar damage is evident. Therefore, there will be no life limit on major parts, and accordingly very low maintenance costs associated with scrap.

The adjustments to the original 54H60 propeller maintenance cost are shown on Figure 37. This includes the scale-up to JT8D size, avoidance of scheduled major maintenance (including overhaul), and improved design resulting in better reliability and lower maintenance costs. The conclusion is that maintenance costs can be reduced to about 50% of the 1950's type turboprop now in general use. The benefits of many of the concepts discussed here are already being seen with new turboprops. The turboprop on the DHC-7 is on-condition with over 6000 hours on the high time unit. New turboprops for commuters will likewise have very attractive maintenance characteristics. Similar improvements are projected for new geartrains.

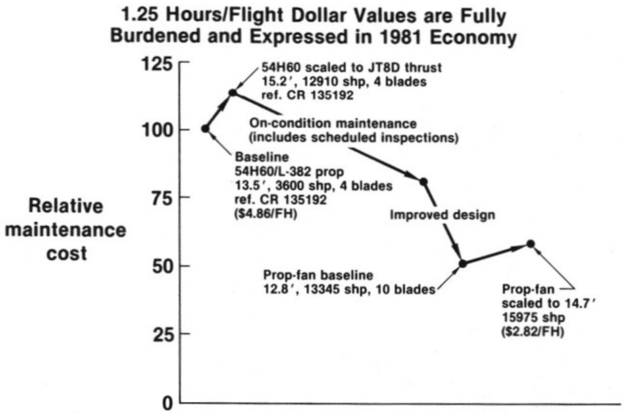


Figure 37. Maintenance Projection Propeller to Prop-Fan

A comparison of the advanced turboprop and the advanced turbofan is shown in Figure 38. Engine core costs are estimated to be comparable for both systems. The reverser and fan costs of the turbofan are based upon historic relations with the core; the Prop-Fan and gearbox are projected to have competitive maintenance costs. The conclusion from this comparison is that advanced turboprops and advanced turbofans, using similar cores, will have very competitive total maintenance costs per flight hour.

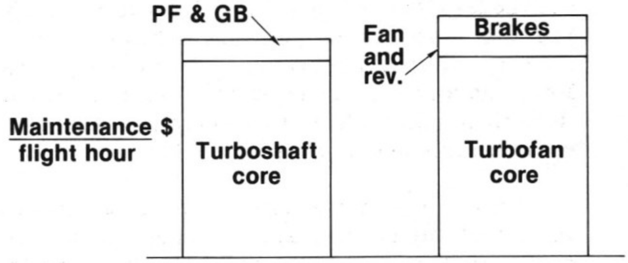


Figure 38. Prop-Fan and Advanced Turbofan Maintenance Cost Comparison

Not reflected is the improved engine access in the Prop-Fan nacelle relative to that of the turbofan with both fan and core nacelle cowls. Also, with the Prop-Fan, thrust reversers typical of turbofans are not required and the level of reverse thrust is greater than attainable with turbofans thus reducing the use of mechanical brakes. When the projected costs of thrust reverser and brake systems are accounted for, the Prop-Fan establishes a significant potential advantage.

TURBOPROP APPLICATION

In the low speed regime, an advanced technology propeller family is being developed for commuter aircraft of the 1980's. It was recognized at the start that successful expansion of the commuter airline market would involve aircraft of more than 30 passengers and require major improvements in safety, passenger comfort, dispatch reliability and operating cost to approach the levels currently being experienced with larger aircraft. Further, commuter aircraft are likely to operate from less developed runways and spend greater time at the more demanding take-off conditions due to high utilization in short flights, therefore, requiring special emphasis on propeller durability. The new propeller system therefore incorporates advancements in all technology areas, i.e., aerodynamics, acoustics, structures, weight, maintainability and safety, which will contribute to these improvements. Figure 39 shows the aircraft which will use the Hamilton Standard commuter propeller.

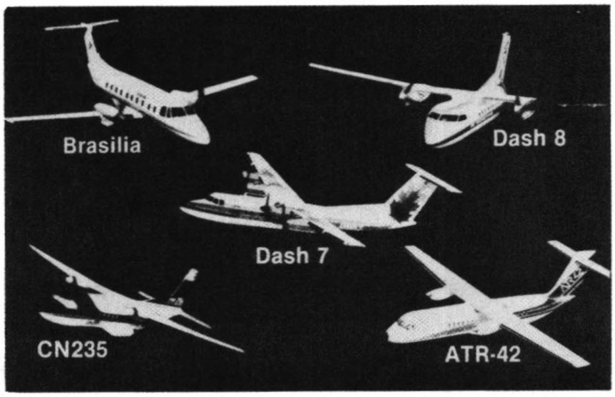


Figure 39. Hamilton Standard Commuter Aircraft

The trend toward higher and higher turbofan bypass ratios to achieve higher propulsive efficiencies may be reaching practical limitations. The turboprop, with the Prop-Fan concept, can achieve the same ultimate objective with practical aircraft configurations at significant improvements in cost and mission effectivity.

It has been suggested that because of the high costs associated with the development and introduction of a new aircraft, a new passenger transport will not be developed unless it offers significant cost savings over competing designs. The advanced turboprop may provide a large fraction of this savings. In fact, the advanced turboprop may be required in order to meet this requirement. Similarly, the advanced turboprop may be required to meet the requirements of certain military missions. Many aircraft systems studies have been accomplished for a variety of subsonic air transport applications and all these studies have shown significant fuel savings available with Prop-Fan propulsion.

The Prop-Fan aircraft applications studies have primarily been of conventional take-off field length designs with cruise speeds of 0.7 - 0.8 Mach number. While this speed range continues to be the specific focus of the NASA technology programs, the technology demonstrated can be applied to propeller or Prop-Fan designs for aircraft that require from 0.6 - 0.85 cruise Mach number.

Hamilton Standard is now in the process of defining some turboprop configurations which are intermediate between the low speed commuter type and the high speed Prop-Fan type. In addition, a NASA funded counter-rotation turboprop study is presently underway. The blade shapes presently being explored are shown on Figure 40. The highly swept version on the right of this figure is aimed at 0.7 - 0.8 Mach flight conditions. The straight version on the left is aimed at the 0.6 - 0.7 Mach flight conditions. The in-between version in the middle is being explored for 0.7 Mach. The performance and noise differences between the unswept and highly swept versions are shown by Figure 41. It can be seen that the aerodynamic advantage of sweep is small at 0.6 Mach and increases to about 3 efficiency points at 0.8 Mach. The acoustic advantage of sweep is significant even at lower Mach numbers because of the acoustic cancellation concept.

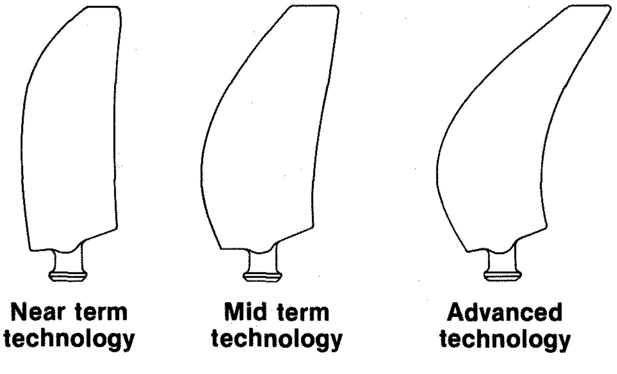


Figure 40. Advanced Turboprop Blade Planforms

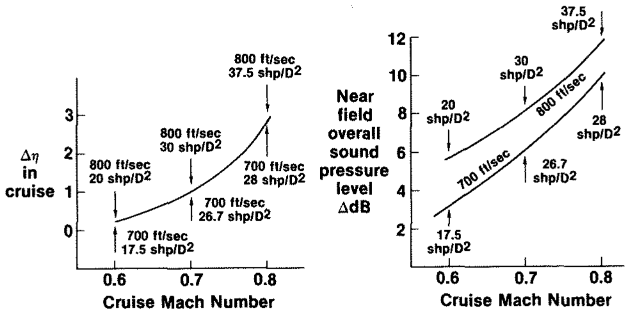


Figure 41. Swept Blade Advantages Over "Straight" Blade

Counter rotation propellers also appear promising. However, there is very little flight test data on this propeller concept and the theoretically based prediction methods have not been brought up to date to allow reliable analytical evaluation of the potential. It is well known, however, that the counter rotation propeller is inherently higher in efficiency than the single blade row because the downstream blade row extracts the swirl introduced by the forward blade row. Hamilton Standard is conducting a NASA funded counter-rotation (CR) propeller study.

Obviously performance is improved with counter rotation, but the noise issue is unclear. It may be possible to operate the counter rotation propeller at a lower tip speed than the single row propeller and therefore expect a lower noise level. The counter rotation propeller however has an additional noise source, the interaction of the viscous wakes from the blades of the forward row with the blades of the downstream row. This additional source must be included in theoretically based propeller noise prediction methods and these methods adapted to consider two blade rows before the noise reduction potential of counter rotation can be established. Weight, reliability, costs, and airframe interactions will also be considered. The intent of this study is to determine if the expected large efficiency gain is significantly eroded by other potential drawbacks associated with counter-rotation. This study will be completed in 1982.

CONCLUSIONS

It is concluded that the continued evolution of the turboprop has brought it to an advanced status where it can have an important place in the realm of commercial subsonic air transportation, and for subsonic, long-range patrol and logistic transport missions required by the military. Advanced turboprops are able to deliver improved aero, acoustic and structural performance and advantages over competitive propulsion equipment are significant.

BIBLIOGRAPHY

1. AIAA Paper No. 76-667, "A Report on the Aerodynamic Design and Wind Tunnel Test of a Prop-Fan Model." C. Rohrbach, Hamilton Standard, July 1976.
2. AIAA Paper No. 75-1208, "The Prop-Fan -- A New Look In Propulsors," C. Rohrback and F.B. Metzger, Hamilton Standard, October 1975.
3. AGARD Paper, "Multi-Mission Uses for Prop-Fan Propulsion," A.H. Jackson, Jr. and B.S. Gatzen, Hamilton Standard, September 1976.
4. SAE Paper 751085, "General Characteristics of Fuel Conservative Prop-Fan Propulsion System," B.S. Gatzen, Hamilton Standard and S.M. Hudson, Detroit Diesel Allison, Noevmber 1975.
5. NASA CR-137923 Final Report Volume I: Technical Analysis, NASA CR-137924 Final Report Volume II: Market and Economic Analyses, and NASA CR-137925 Summary Report, "Cost/Benefit Tradeoffs for Reducing the Energy Consumption of the Commercial Air Transportation System," Douglas Aircraft Co., NASA Ames Contract NAS2-8618, June 1976.
6. SAE Paper 760538, "Aircraft Propulsion, A Key to Fuel Conservation, An Aircraft Manufacturer's View," J.A. Stern, Douglas Aircraft Company, May 18-20, 1976.
7. NASA CR-137926 Final Report and NASA CR-137927 Summary Report, "Study of the Cost/Benefit Tradeoffs for Reducing the Energy Consumption of the Commercial Air Transportation System," Lockheed-California Company, NASA Ames Contract NAS2-8612, August 1976.
8. SAE Paper 760537, "Fuel Conservative Potential for the Use of Turboprop Powerplants," R. L. Foss and J.P. Hopkins, Lockheed-California Company, May 1976.
9. NASA CR-137937 Final Report and NASA CR-137928 Summary Report, "Energy Consumption Characteristics of Transports Using the Prop-Fan Concept," Boeing Commercial Airplane Company, NASA Ames Contract NAS2-9104, October 1976.
10. NASA CR-135065 Final Report, "Study of Unconventional Aircraft Engines Designed for Low Energy Consumption," Pratt & Whitney Aircraft, NASA Lewis Contract NAS3-19465, June 1976.
11. SAE Paper 760535, "Fuel Conservative Propulsion Concepts for Future Air Transports," D.E. Gray and J.W. Witherspoon, Pratt & Whitney Aircraft, May 1976.
12. NASA CR-152138, "Simulated Propeller Slipstream Effects on a Superficial Wing," H.R. Welge and J.P. Crowder, Douglas Aircraft Co., NASA Ames Contract NAS2-9472.
13. Rand Report R-1889-AF, "An Evaluation of Very Large Airplanes and Alternate Fuels," W.T. Mikolowsky, The Rand Corp. Division of the Air Force Systems Command, USAF Contract F49620-77-C-0023, December 1976.
14. USAF Report, "Innovative Aircraft Design Study (IADS), Task II, E.A. Barber, et.al., Boeing Aerospace Co., Aeronautical Systems Division Contract F33615-76-C-0122, June 1977.
15. USN Report, "Prop-Fan Technology Study, Task I Final Report," Hamilton Standard, Naval Air Development Center Contract N62269-77-C-0465, October 1977.
16. AIAA Paper 76-565, "Near Field Noise of High Tip Speed Propellers in Forward Flight," D.B. Hanson, Hamilton Standard, July 1976.
17. Hamilton Standard Document, SP 11A77, "Prop-Fan," October 1977 Status Summary.
18. NASA CR-152186, "An Analysis of Prop-Fan/Airframe Aerodynamic Integration," Boeing Commercial Airplane Co., NASA Ames Contract NAS2-9104, October 1978.
19. Journal of Sound and Vibration, Vol. 61, Number 3, "The Importance of Quadrupole Sources in Prediction of Transonic Tip Speed Propeller Noise," D.B. Hanson, Hamilton Standard and M.R. Fink, United Technologies Research Center, December 8, 1978.
20. CTOL Transport Technology Conference at NASA Langley, NASA Conference Publication 2036, "Status of Advanced Turboprop Technology," J.F. Dugan, B.A. Miller, and D.A. Sagerser, NASA Lewis, February 1978.
21. Air World, Volume 30, No. 2, 1978, "Fuel Efficiency: New Dimension in Aircraft Design," Exxon Corp.
22. USAF Report, "Innovative Aircraft Design Study (IADS), 1977," E.A. Barber, et. al., Boeing Aerospace Co., Aeronautical Systems Division Contract F33615-77-C-0111, July 1978.
23. NASA CR-137891, "Study of Cost/Benefit Tradeoffs for Reducing the Energy Consumption of the Commercial Air Transportation System," United Airlines, NASA Ames Contract NAS2-8625, June 1976.
24. Task Force Report, "Aircraft Fuel Conservation Technology," NASA Office of Aeronautics and Space Technology, September 10, 1975.
25. SAE Paper 760536, "Alternate Concepts for Advanced Energy Conservative Transport Engines," R. Hirschkron and R.E. Neitzel, General Electric Co., May 1976.
26. NASA CR-135136, "Study of Unconventional Aircraft Engines Designed for Low Energy Consumption," General Electric Co., December 1976.
27. NASA CR-152096, "Fuel Conservation Merits of Advanced Turboprop Transport Aircraft," Lockheed-California Co., NASA Ames Contract NAS2-8612, August 1977.
28. SAE Paper 774458, "Design and Performance of Energy Efficient Propellers for Mach 0.8 Cruise," D.C. Mikkelson et al., NASA Lewis, 1977.
29. SAWE Paper 1124, "Air Transportation Energy Efficiency -- Alternatives and Implications," L.J. Williams, NASA Ames, May 1976.
30. AIAA Paper 76-770, "Comparisons of Alternate Energy Efficient Engines for Future Subsonic Transports as Affected by Engine Technology Improvements," R.E. Neitzel, General Electric Co., July 1976.
31. AGARD Paper, "High Efficiency Engine Cycles for Air Transport Fuel Economy," D.E. Gray, Pratt & Whitney Aircraft, September 1976.

32. AIAA Paper 77-1223, "Advanced Turboprop Technology Development," J.F. Dugan, NASA Lewis and D.P. Bencze and L.J. Williams, NASA Ames, August 1977.
33. SAE Paper 771009, "Advanced Turboprop Propulsion System Reliability and Maintenance Cost," P.C. Stolp, Detroit Diesel Allison, and J.A. Baum, Hamilton Standard, November 1977.
34. NASA CR-152141, "Prop-Fan Data Support Study," Hamilton Standard, NASA Ames Contract NAS2-9750, February 1978.
35. ASME Paper 78-GT-201, "Evolution of the Turboprop for High Speed Air Transportation," G.E. Holbrook, Detroit Diesel Allison, And G. Rosen, Consultant to Hamilton Standard, April 1978.
36. SAE Paper 780997, "Propeller Slipstream Wind Interactions at Mach No. 0.8," D.P. Bencze and J.P. Crowder, Ames Research Center, H.R. Welge and J.P. Crowder, Douglas Aircraft Co., November 1978.
37. SAE Paper 750536, "A Second Generation Trubo-Prop Power Plant," J.B. Houston and D.F. Black, de Havilland Aircraft of Canada, Limited, April 1975.
38. NASA TM-78962, "Fuel Conservative Aircraft Engine Technology," D. L. Nored, NASA Lewis, September 1978.
39. NASA TM-79124, "Wind Tunnel Performance of Four Energy Efficient Propellers Designed for Mach 0.8 Cruise," R.J. Jeracki, D.C. Mikkelson, and B.J. Blaha, NASA Lewis, April 1979.
40. Canadian Symposium on Energy Conserving Transport Aircraft, "Improved Efficiency for Small CTOL Transport Aircraft," S. Bernstein, G.A. Adams, and A. Oberti, Canadair, Limited, October 1977.
41. AIAA Paper 78-1487, "Application of Advanced High Speed Turboprop Technology for Future Civil Short-Haul Transport Aircraft Design," J.A. Conlon and J.V. Bowles, NASA Ames, August 1978.
42. SAE Report, "Potential Applicability of Prop-Fan Propulsion to Maritime Patrol Aircraft," Lockheed-California Company, November 1978.
43. NASA CR-135192, "Study of Turboprop Systems Reliability and Maintenance Costs," Detroit Diesel Allison, NASA Lewis Contract NAS3-20057, June 1978.
44. AIAA Paper 80-0225, "Summary of Advanced Methods for Predicting High Speed Propeller Performance," L.J. Bober and G.A. Mitchell, NASA Lewis, January 1980.
45. AIAA Paper 79-1861, "Energy Efficient Aircraft Engines," R. Chamberlin and B. Miller, MASA Lewis, August 1979.
46. NASA Conference Publication 2092, "Aeropropulsion 1979," NASA Lewis, May 1979.
47. Canadian Aeronautics and Space Journal, Vol. 24, Number 4, "Prospects for Energy Conserving STOL Transports Using Prop-Fans," B. Eggleston, de Havilland Aircraft of Canada, Limited, August 1978.
48. SAE Paper 780995, "Prop-Fan Propulsion -- Its Status and Potential," J.F. dugan, Jr. NASA Lewis Research Center, B.S. Gatzen and W.M. Adamson, United Technologies, November 1978.
49. AIAA/SAE/ASME Paper 79-1116, "Structural Design and Analysis of Prop-Fan Blades," R.W. Cornell and E.A. Rothman, Hamilton Standard, June 1979.
50. AIAA Paper 79-0610, "Aeroacoustic Design of the Prop-Fan," F.B. Metzger and C. Rohrbach, Hamilton Standard, March 1979.
51. AIAA Paper 80-0856, "Progress and Trends in Propeller/Prop-Fan Noise Technology," F.B. Metzger, Hamilton Standard, May 1980.
52. AIAA Paper 80-0995, "Acoustic Measurement of Three Prop-Fan Models," B.M. Brooks, Hamilton Standard, June 1980.
53. AIAA Paper 80-1002, "Acoustic Pressures on a Prop-Fan Aircraft Fuselage Surface," B. Magliozzi, Hamilton Standard, June 1980.
54. NASA CR-159668, "Advanced Turbo-Prop Airplane Interior Noise Reduction - Source Definition," B. Magliozzi and B.M. Brody, October 1979.
55. NASA CR-159667, "Acoustic Test and Analysis of Three Advanced Turboprop Models," B.M. Brooks and F.B. Metzger, January 1980.
56. SAE Paper 80-1120, "The NASA High-Speed Turboprop Program," James F. Dugan, Brent A. Miller, Edwin J. Graber and David A. Sagerser, NASA Lewis, October 1980.
57. AIAA Paper 79-0609, "The Influence of Propeller Design Parameters on Far Field Harmonic Noise in Forward Flight," D.B. Hanson, Hamilton Standard, March 1979 (To be Published in AA Journal, November and December 1980 Issues).
58. AIAA Paper 80-1090, "Potential Benefits for Prop-Fan Technology on Derivatives of Future Short-to-Medium-Range Transport Aircraft," L.M. Goldsmith, Douglas Aircraft Co., and J.V. Bowles, NASA Ames Research, June 1980.
59. SAE Paper 80755, "The Future of Short-Haul Transport Aircraft," L.J. Williams, NASA Ames, May 1980.
60. SAE Paper 800733, "Prop-Fan Propulsion for Commercial Air Transports," T.G. Coussens and R.H. Tullis, Lockheed-California Company, May 1980.
61. AIAA Paper 80-1035, "Propeller Signatures and Their Use," J.F. Johnston, R.E. Donham, W.A. Guinn, Lockheed-California Company, June 1980.
62. NASA CR3047, "Aerodynamic Design and Performance Testing of an Advanced 30° Swept, Eight Bladed Propeller at Mach Numbers from 0.2 to 0.85," D.M. Black, R.W. Menthe and H.S. Wainauski, September 1978.
63. NASA CR-159222, "Analytical Study of Interior Noise Control by Fuselage Design Techniques on High-Speed, Propeller-Driven Aircraft," J.D. Revell, F.J. Balena, and L.R. Koval, Lockheed-California Company, July 1978.
64. NASA CR-159200, "Interior Noise Control Prediction Study for High-Speed Propeller-Driven Aircraft," D.C. Rennison, J.F. Wilby, and A.H. Marsh, Bolt, Buranek and Newman, September 1979.

65. NASA TM-79046, "Tone Noise of Three Supersonic Helical Tip Speed Propellers in a Wind Tunnel at 0.8 Mach Number," J.H. Dittmar, B.J. Blaha, and R.J. Jeracki, NASA Lewis, December 1978.
66. NASA TM-79042, "Feasibility of Wing Shielding of the Airplane Interior from the Shock Noise Generated by Supersonic Tip Speed Propellers," J.H. Dittmar, December 1978.
67. NASA TM-78587, "Interface Effects of Aircraft Components on the Local Blade Angle of Attack of a Wing-Mounted Propeller," J.P. Mendoza, June 1979.
68. NASA TM-81482, "High Speed Turboprops for Executive Aircraft-Potential and Recent Test Results," D.C. Mikkelson, and G.A. Mitchell, April 1980.
69. NASA TM-815-9, "A Comparison Between an Existing Propeller Noise Theory and Wind Tunnel Data," J.H. Dittmar, May 1980.
70. AIAA 80-0992, "An Overview of NASA's Propeller and Rotor Noise Research," G.C. Greene, and J.P. Raney, June 1980.
71. NASA TP-1662, "A Numerical Technique for Calculation of the Noise of High-Speed Propellers with Advanced Blade Geometry," P.A. Nystrom, and F. Farassat, July 1980.
72. Astronautics & Aeronautics, June 1980, "Turbine Engines in the '80's," J.P. Frignac, Air Research; F.E. Pickering, General Electric; W.W. Wagner, Naval Air Propulsion Center; and J.W. Witherspoon, Pratt & Whitney Aircraft.
73. AIAA Paper No. 81-0521-CP, "Attenuation of Propeller Related Vibration and Noise," J.F. Johnston and R.E. Donham, Lockheed-California Co., April 1981.
74. ASME Paper 81-GT-216, "The Role of Flight Research Vehicles in Prop-Fan Technology Development," E.S. Bradley and B.H. Little, Jr., Lockheed-Georgia Co., December 1980.
75. AIAA Paper 81-0810, "Prop-Fan Technical Progress Leading to Technology Readiness," B.S. Gatzen and W.M. Adamson, Hamilton Standard, May 1981.
76. AGARD Paper 33, "Prop-Fan Integration at Cruise Speeds," H.R. Welge, Douglas Aircraft Co., May 1981.
77. AIAA-81-1563, "Prop-Fan Installation Aerodynamics of a Supercritical Swept Wing Transport Configuration," R.C. Smith and A.D. Levin, NASA-Ames, July 1981.
78. NASA CR-3505, "Evaluation of Wind Tunnel Performance Testings of an Advanced 45° Swept Sight - Bladed Propeller at Mach Numbers from 0.45 to 0.85," C. Rohrbach, F.B. Metzger, D.M. Black, and R.M. Ladden, March 1982.
79. AIAA-81-1648, "Turboprop Engine Propulsion for the 1990's", H.J. Banach and C.N. Reynolds, Pratt & Whitney Aircraft, August 1981.
80. AIAA-81-1649, "Propulsion System Installation Design for High Speed Prop-Fans," B.H. Little, Jr., Lockheed-Georgia, August 1981.
81. AIAA-82-0020, "Compressible Lifting Surface Theory for Propeller Performance Calculation," D.B. Hanson, Hamilton Standard, January 1982.
82. SP 08A80, "Aircraft Noise Control A Compendium of Reference Material," Hamilton Standard, November 1980.
83. NASA Document, "An Accelerated and Enhanced Advanced Turboprop Program," July 1981.
84. SAE 810560, "Straggegies for Aircraft Interior Noise Reduction in Existing and Future Propeller Aircraft," F.B. Metzger, Hamilton Standard, April 1981.
85. SP 04A80, "Prop-Fan Parametric Data Package, Aerodynamics and Acoustics," Hamilton Standard, October 1980.
86. J.J. Foody and S.C. Colwell, "Role of the Turboprop in the Air Transportation System for the 1980's and Onward," Fairchild Industries, presented at the SAE Engineering Meeting, Los Angeles, California, October 1980.
87. NASA TM 81745, "Low and High Speed Propellers for General Aviation - Performance Potential and Recent Wind Tunnel Test Results," R.J. Jeracki and G.A. Mitchell, NASA Lewis, April 1981.
88. AIAA-81-1565, "Aerodynamic Characteristics of an Advanced Technology Propeller for Commuter Aircraft," C. Rohrbach and H.S. Wainanski, Hamilton Standard, July 1981.
89. SAE 820720, "Advanced Propeller Technology for New Commuter Aircraft," R.G. Daighneault and D.G. Hall, Hamilton Standard, May 1982.
90. SP 02A82, "Commuter Propeller Aerodynamic Estimates," Hamilton Standard, March 1982.
91. NASA CR-145105, "The Influence of Forward Flight on Propeller Noise", B. Magliozzi, Hamilton Standard, February, 1977.
92. NASA TM 81971, "Sources, Control and Effects of Noise from Aircraft Propellers and Rotors", J.S. Mixon, G.C. Greene, and T.K. Dempsey, NASA Langley, April, 1981.