Benefits of Blade Sweep for Advanced Turboprops

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Blade sweep is one of the features incorporated in advanced turboprop (prop-fan) designs. Sweep is incorporated to enhance efficiency and reduce noise. This paper discusses the theoretical basis for performance enhancement and noise reduction and discusses the experimental evidence demonstrating the value of this feature in current prop-fan designs. The emphasis is on single-rotation prop-fans, but the benefits to counterrotation prop-fan designs are discussed briefly.

Nomenclature

AF = blade activity factor $100{,}000/16\int_{0.15}^{1.0}(b/D)(x^3\mathrm{d}x)$
b = blade section width, ft
C_P = power coefficient $= P/\rho n^3D^5$ $= \mathrm{shp}(\rho_0/\rho)/[2000(N/1000)^3(D/10)^5]$
CR = counterrotation
D = prop-fan installed diameter, ft
J = prop-fan advance ratio $= 101.4V_K/ND$
M_{th} = tip helical Mach number
Mn = airplane Mach number
N = propeller speed, rpm
n = propeller speed, rev/s
P = power, ft-lb/s
shp = shaft horsepower
SR = single rotation
V_K = flight velocity, knots (true air speed)
η = propeller efficiency
ρ = mass density of air, slugs/ft^3
ρ_0/ρ = ratio of density at sea level to density at operating condition

Introduction

FUEL efficiency is a major objective of new transport airplane designs. At present, all large commercial transports use high-bypass-ratio turbofans as propulsors. However, the limits to the efficiency of these propulsors are being approached, since the drag associated with the duct surrounding the fan becomes greater as the bypass ratio is increased to improve efficiency. Prop-fans avoid this duct loss, so they are attractive propulsors for future transports. Since 1975, prop-fan research has been underway to establish the optimum configuration for use on future airplanes. Early work concentrated on configurations with a single-blade row (SR configurations). Because of the added efficiency of configurations with two opposite rotating blade rows (CR configurations), they are the subject of current aerodynamic and acoustic research.

Figure 1 shows the characteristics of the 8 and 10 blade SR prop-fans that have been fabricated to date in NASA programs. Aeordynamic and acoustic tests have been conducted on most of these models. However, testing of the SR-5 was limited to aerodynamics and this testing was restricted by the presence of high-speed flutter. Aerodynamic tests were conducted at the United Technologies Research Center (UTRC) by Hamilton Standard (HS) under NASA funding and also at the NASA Lewis Research Center. Acoustic tests have been conducted 1) at the UTRC Acoustic Research Tunnel by HS under NASA funding, 2) in flight on a Lockheed Jetstar in a joint NASA/HS program, 3) in the NASA Lewis 8×6 wind tunnel, and 4) in the Boeing low-speed and transonic wind tunnels.

Work is currently underway on the SR-7 shown to the far right of Fig. 1. An aeroelastic model has been constructed and currently is being structurally and aerodynamically tested. A large scale 9 ft diameter version of this design is also being manufactured as part of the NASA Large-Scale Advanced Prop-Fan Program. Structural and aerodynamic testing of this large-scale prop-fan is currently being conducted. In 1987, it will be structurally and acoustically tested in flight as part of a complete propulsion system during the NASA Prop-Fan Test Assessment Program.

The benefits of blade sweep are increased efficiency and reduced noise. The general magnitude of predicted sweep benefits for SR prop-fans is shown in Fig. 2. It can be seen here that the efficiency and noise benefits increase with design cruise Mach number *Mn*. At 0.7 *Mn*, a 35 deg tip sweep is expected to improve net efficiency (the efficiency of the blades alone with the increase in static pressure associated with propeller/nacelle interaction removed) by about 2 points by alleviating compressibility losses. Greater tip sweep is not expected to provide further benefits. However, at 0.8 *Mn*, a 50 deg tip sweep is expected to provide benefits of over 3 efficiency points. Note also that at 0 deg sweep the efficiency at 0.8 *Mn* is lower than that at 0.7 *Mn* due to compressibility losses. As indicated in Fig. 2, sweep is expected to allow most of this efficiency penalty to be regained.

As shown in Fig. 2, benefits of blade sweep on near-field noise at cruise (which affects fuselage acoustic treatment required to achieve a comfortable cabin) are similar to those for efficiency, i.e., benefits for a given sweep are less at 0.7 *Mn* than at 0.8 *Mn*.

In the following discussion, the methodology used in the design of swept blade prop-fans will be discussed and experimental evidence proving the expected benefits of the sweep described above will be shown. Also, the benefits to counterrotation prop-fan designs will be discussed briefly.

Aerodynamic Benefits of Blade Sweep for SR Prop-Fans

Aerodynamic Design Methodology

The aerodynamic design of the SR prop-fan is accomplished by using several aerodynamic methods that best apply to par-

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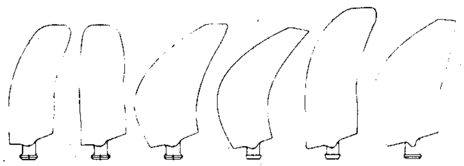

	SR-1&1M	SR-2	SR-3	SR-5	SR-6	SR-7
Design tip speed, ft/sec	800	800	800	600	700	800
Design cruise speed, Mn	0.8	0.8	0.8	0.8	0.8	0.8
Cruise loading, SHP/D2	37.5	37.5	37.5	26.0	30	32
Number of blades	8	8	8	10	10	8
Tip sweep, degrees	23	0	34.5	48	39	36.6
Activity factor	204	203	235	210	204	227

Fig. 1 Characteristic of single-rotation prop-fans.

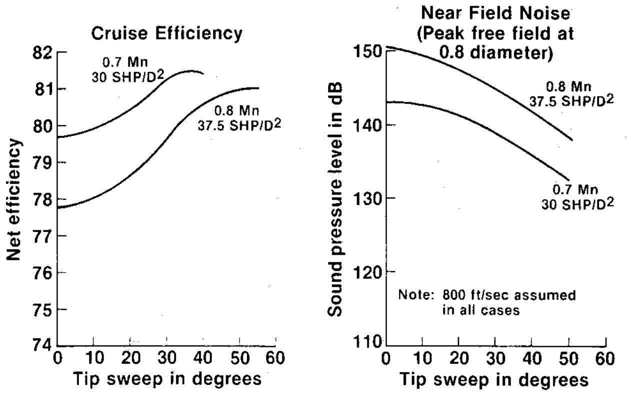

Fig. 2 Magnitude of expected sweep benefits.

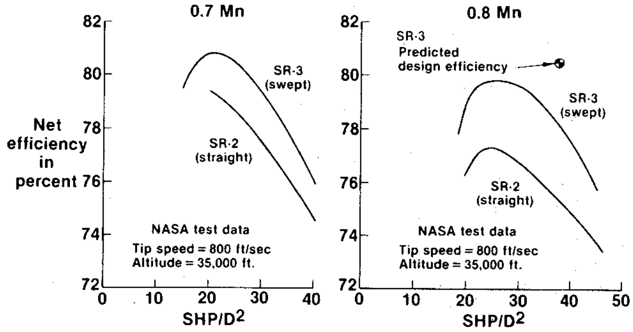

Fig. 3 Effect of sweep on prop-fan efficiency.

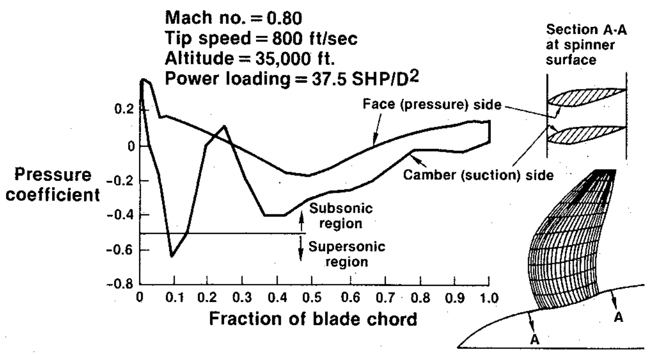

Fig. 4 NASPROP-E code potential blade root choke with SR-3 prop-fan model (NASA Lewis calculations).

ticular portions of the prop-fan and nacelle combination. During the design, the prop-fan is modeled as a turbofan in the root sections where the gap-to-chord ratios are below 1.0, as a turboprop over the outer portions, and as a swept wing for those sections incorporating sweep. To this end, conventional turbofan aerodynamics have been modified to represent the prop-fan root blading and nacelle combination with the usual influence of the turbofan duct removed. For prop-fan designs, the HS basic performance prediction method, based on the early work of Goldstein, was modified to incorporate two-dimensional compressible airfoil data with a cascade correction for the midblade portion. For the tip section, this same method has been further modified to account for the three-dimensional flow effect on compressibility losses. In addition, sweep effects on airfoil performance have been added to the prediction program, which reduce the relative Mach number at a given spanwise location as a function of sweep angle.

Since the design of the SR-1, SR-1M, and SR-2, a new compressible induction method, which utilizes the Biot-Savart equations, has been developed which accounts for the effects of sweep and operation at transonic Mach number on the induced flow at the outer portions of the blade. This method incorporates the same compressible airfoil data, cascade correction and tip sweep correction included in the HS performance prediction method.

While this methodology has been quite successful for design of swept blade prop-fans, work is underway to further improve the design techniques by use of Euler codes and lifting surface theory.[1] These new methodologies are expected to provide guidance for refinements in prop-fan designs.

Aerodynamic Benefits of Blade Sweep

Substantial performance testing of prop-fan models has taken place at UTRC and NASA. Experimental results have been compared with predictions by both Hamilton Standard and NASA in order to provide guidance for understanding test results and to support the development of new configurations.

Early experimental results at UTRC on the straight-blade SR-2 and the swept-blade SR-3 (see Fig. 3) demonstrated that sweep provided significant efficiency benefits. In Fig. 3, at the design point, 0.8 *Mn*, 37.5 shp/D^2 35,000 ft altitude, and 800 ft/s tip speed, the measured benefit is 2.8% as compared with the expected benefit of 2.4% for a sweep of 34.5 deg shown in Fig. 2. At 0.7 *Mn* and 30 shp/D^2 at the same altitude and tip speed as the SR-3 design point, the measured benefit shown in Fig. 3 is 1.9% as compared with the expected benefit of 1.8% in Fig. 2. Thus, the sweep benefits measured in these early tests generally confirmed expectations. However, as Fig. 3 shows, the level of measured efficiency was lower than expected for both SR-3 and SR-2 at 0.8 cruise *Mn*. As a point of reference, the predicted efficiency of the SR-3 at 0.8 *Mn*, 37.5 shp/D^2 was 80.5% as compared with a measured 78.2%. The reason for these lower measured efficiencies has been the subject of HS and NASA research for several years. This work has focused on the blade root flow near the spinner and is discussed further below.

Although originally designed to avoid root choke, the SR-3 design analysis indicated a minimal acceptable choke margin and traversing probe data[2] indicated choke at 0.85 tunnel *Mn* and possible choke at 0.8 tunnel *Mn*. More recently, analytical studies by NASA utilizing their NASPROP E Euler code have indicated the presence of a shock on the blading in the root region near the spinner/blade juncture. This can be seen in Fig. 4 where the calculated pressure distribution at the 0.8 *Mn* design condition on the SR-3 blade surface is shown. It can be seen here that supersonic conditions exist near the 0.1 chord location on the camber (suction) side of the blade. Thus, in an effort to shed more light on the aerodynamic characteristics of prop-fans, further tests were conducted in the UTRC 8 ft wind tunnel using SR-2 and SR-3 eight- and four-blade prop-fan models. This testing included an investigation of variation in spinner/blade juncture configuration and blade root gap-to-chord ratio on the performance of the SR-2 prop-fan model. The SR-3 model tests investigated the effect of blade root gap-to-chord ratio on performance. The prime results of these tests are discussed below.

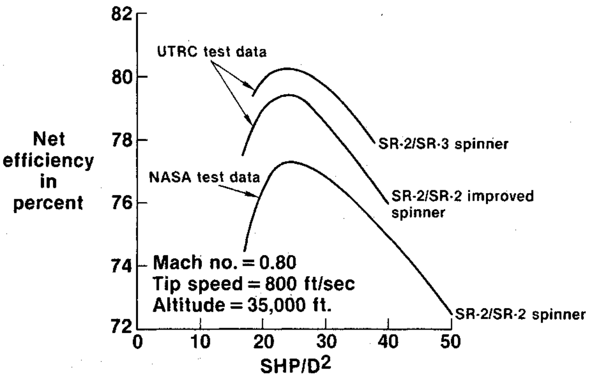

Fig. 5 Effect of spinner/blade junction configuration on performance of SR-2 prop-fan model.

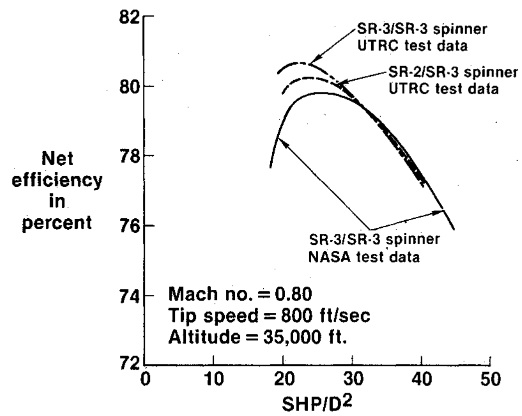

Fig. 6 Component SR-2 and SR-3 measured performance with the SR-3 spinner.

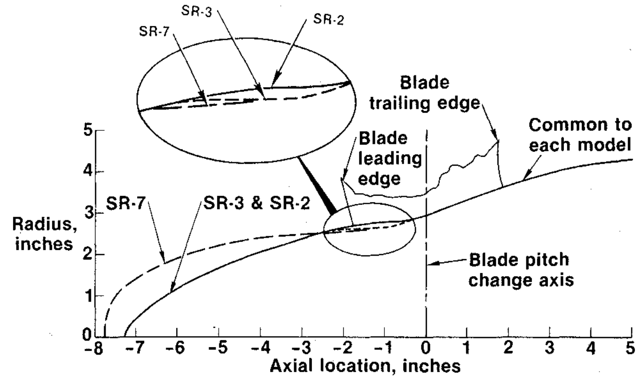

Fig. 7 Prop-fan spinner configuration.

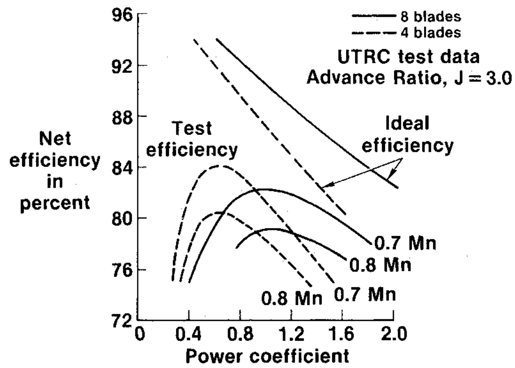

Fig. 8 Comparison of test and ideal efficiencies for eight- and four-blade SR-2 prop-fans.

Figure 5 shows the effect of spinner/blade juncture configuration on the performance of the SR-2 eight-blade prop-fan at 0.8 *Mn*. The lower curve is for the SR-2 model with the original SR-2 spinner tested in the NASA 8×6 wind tunnel. The top curve shows the performance of the same SR-2 model with the area-ruled SR-3 spinner and gaps plugged between the blade roots and spinner surface. An improved version of the original SR-2 spinner with minimum root gaps shows performance levels between those measured for previous configurations. Note that a 1.5–3.0% improvement in performance is achieved with refined spinner/blade juncture designs. In fact, as shown in Fig. 6, at 0.80 *Mn* the straight-blade SR-2 with the SR-3 spinner performed about the same as the swept-blade SR-3 with the SR-3 spinner. For comparison, this plot includes the SR-3 performance from both the NASA and UTRC wind tunnels and shows the generally good correlation between the tunnels, particularly at the 37.5 shp/D^2 design power loading. These results, showing the importance of spinner/blade juncture design for achieving high performance, were unexpected. In fact, the implication from these results is that spinner/blade juncture design may be the prime difference between the eight-blade SR-2 and SR-3 models and not blade sweep. Unfortunately, no spinner/blade juncture modification could be investigated with the eight-blade SR-3 model because suitable hardware was not available.

The apparent sensitivity of prop-fan performance to spinner/blade juncture design is surprising, considering the relatively small difference between the SR-2 and SR-3 spinners shown in Fig. 7. Evidently, the flow between the blades near the spinner and leakage around the blade shanks and under the blade roots at the spinner surface become significant at the higher Mach numbers. As indicated earlier, this effect could be associated with choke. However, while the calculated choke margin of the eight-blade SR-3 was very small, similar calculations on the eight-blade SR-2 model showed significantly more margin. Thus, while these effects may not be entirely due to choke, particularly in the SR-2 design, there definitely appear to be significant spinner/blade interference losses that could be worth as much as 3 efficiency points.

To investigate these effects, both models were tested as four-blade configurations where the large gap-to-chord ratios are sufficient to preclude blade choke. By comparing the measured performance of the four-blade SR-2 and SR-3 models over a range of *Mn* and power loading, the effect of sweep may be established without being confused by the possible blade root choke/interference loss effects. Then, with similar data on the eight-blade models to compare with corresponding four-blade data, the root loss effects may be identified. For example, Fig. 8 presents plots of net efficiency vs power coefficient *Cp* for an advance ratio *J* of 3.0 and *Mn* of 0.7 for the four- and eight-blade SR-2 models. Similar curves were plotted for the SR-3 model. The SR-2 model incorporated the improved SR-2 spinner with minimum root gaps. The curves show that the four-blade model peak efficiencies occur at about half the power coefficient as those of the eight-blade model. This is consistent with the total solidity of the four-blade model being half that of the eight-blade model for both the SR-2 and SR-3 designs. The upper two curves on this figure show the ideal efficiencies calculated for the four- and eight-blade prop-fans. Ideal efficiencies do not include profile losses and are, therefore, a measure of induced losses only. Then, by comparing the difference between ideal efficiency and the measured efficiency ($\eta_{\text{ideal}} - \eta_{\text{meas}} = \Delta\eta$), a quantitative indication of the profile losses may be identified. These profile losses may include, in addition to skin-friction drags, spinner/blade juncture interference losses and compressibility losses caused by root choke and shock separation where the blades are operating above their section critical Mach numbers. The measured curves peak up when the total profile losses from all causes are minimal and the blades are then operating at maximum lift-to-drag (L/D) ratios. This condition will occur at blade loadings (power coefficient) where the prop-fan solidity allows operation at lift coefficients corresponding to maximum L/D for a given Mach number and tip speed. The ideal curves represent the maximum induced efficiencies for any prop-fan design incorporating the indicated number of blades.

Plots of the difference between the ideal and measured efficiencies $\Delta\eta$ are shown in Figs. 9 and 10 for the four- and eight-blade SR-2 and SR-3 models, respectively, at both 0.7 and 0.8 *Mn*. As discussed previously, $\Delta\eta$ is a measure of the aerodynamic profile losses on the prop-fan blading. Figure 9 for the SR-2 prop-fan shows the minimum profile losses to be about the same for the four- and eight-blade models, except that the minimums occur at different power coefficients, as explained above. The $\Delta\eta$ are noted to be in the 5.5–6.0% range at 0.7 *Mn* and in the 8–8.5% range at 0.8 *Mn*. For a well-designed prop-fan, where the profile losses are primarily skin-friction drags and minimal compressibility effects, the net efficiencies can be expected to come within four or five percentage points of the ideal efficiencies (ignoring a small increment of induced loss due to nonoptimum loading). Thus, the data in Fig. 9 show increasing compressibility loss with increased Mach number, as would be expected with the straight-bladed SR-2 model. The data also indicate that the eight-blade SR-2 model apparently did not lose performance at either 0.7 or 0.80 *Mn* due to blade row choke. This conclusion is reached because the four-blade SR-2, which certainly was not choked, did not perform any closer to the ideal level than the eight-blade model.

Now consider the similar $\Delta\eta$ plot for the SR-3 prop-fan in Fig. 10. In this case, at 0.7 *Mn*, both the four- and eight-blade models show about the same minimum value of $\Delta\eta$ in the range of 4.5–5.5%. Moreover, the four-bladed model shows a $\Delta\eta$ in the range of 5.5–6% at 0.8 *Mn*. Compared to the SR-2 models, these losses are much reduced, being about 1 percentage point less at 0.7 *Mn* and about 2.5 percentage points less at 0.8 *Mn*. Thus, it would appear that the effect of sweep on high-speed performance is essentially as shown by the predictions discussed previously. However, when considering the eight-blade SR-3 model, the effect of sweep at 0.7 *Mn* appears to be the same as for the four-blade SR-3; however, the 0.8 *Mn* performance is quite different. The $\Delta\eta$ for the eight-blade SR-3 is eight percentage points, indicating the same profile loss as for both the four- and eight-blade SR-2 models. Yet, the four-blade SR-3, as indicated above, shows a $\Delta\eta$ of only 5.5%. This comparison indicates strongly that the SR-3 eight-blade model was indeed choked, as implied in Fig. 7. Moreover, the effect of such a choke is to apparently mask completely the benefits of sweep shown by the four-blade SR-3 data and as originally predicted. Thus, the eight-blade SR-8 prop-fan performance at 0.8 *Mn* was limited by the blade root choke, which apparently accounts for the failure of this model to meet its design efficiency of 80.5% at 0.8 *Mn*, 35,000 ft altitude, 800 ft/s, and 37.5 shp/D^2. However, on the basis of these test data, it may be projected that by providing an improved spinner contour and blade/spinner juncture similar to the SR-7 design shown in Fig. 7 to increase the choke margin, the design efficiency of the eight-blade SR-3 prop-fan could be increased about 2.5 percentage points, as indicated in Fig. 11. In fact, later prop-fan designs including the SR-7 have incorporated improved spinner shapes to significantly increase the calculated choke margins.

In summary, these new data indicate 1) that there is a strong effect of spinner/blade juncture design on performance, 2) that choke is of major concern in the design of high-solidity prop-fans designed for cruise above 0.7 *Mn*, and 3) that the benefits of sweep on aerodynamic performance are shown to be as predicted by theory.

Acoustic Benefits of Blade Sweep for SR Prop-Fans

Acoustic Design Methodology

The SR-1, SR-1M, and SR-2 were designed using the theoretically based propeller noise methodology available in 1975 with an empirical adjustment for the effect of blade sweep. The SR-3 was designed using a time domain method developed by Hanson,[3] i.e., the acoustic pressure wave form generated by a blade is calculated and then the frequency spectrum of the noise is obtained by Fourier analysis.

This work was based on the Ffowcs-Williams/Hawkings "acoustic analogy"[4] in which the equations of fluid motion are cast into a wave equation for acoustic pressure. Two components of noise were calculated in this theory: 1) monopole (thickness) noise, which is determined by the blade airfoil section thickness distribution and 2) dipole (loading) noise, which is determined by the pressure loading distribution on the surface of the blade. With this method, the sweep distribution of a blade can be optimized. Sweep optimization utilizes the concept of destructive interference of noise from different spanwise stations of the prop-fan blade. This concept is based on

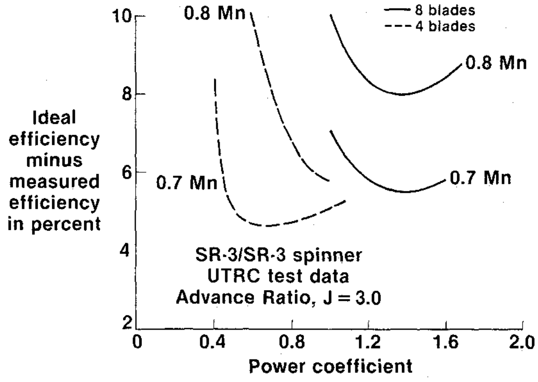

Fig. 10 Profile efficiency loss increment for SR-3.

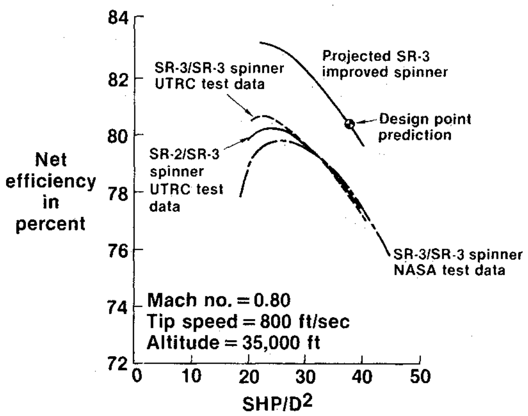

Fig. 11 Projected SR-3 performance with improved spinner.

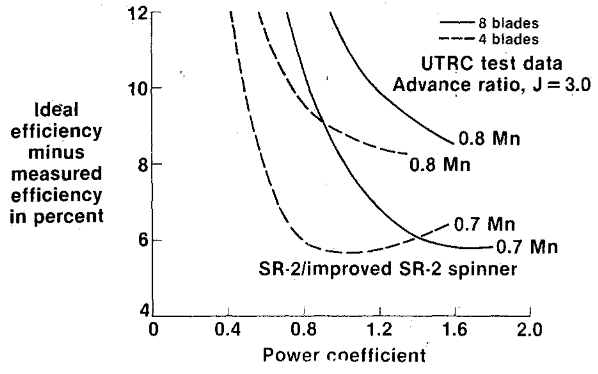

Fig. 9 Profile efficiency loss increment for SR-2.

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. To be done correctly, the summation (or integration) process must account for the amplitude and phase of the elemental contributions.

The phase interference concept is most clearly illustrated with reference to the effect of sweeping a blade planform, as suggested by Fig. 12. At blade passing frequency, the noise from any strip of the blade is simply a sinusoidal wave with an amplitude and phase angle. The noise from one blade is simply the vector sum of the contribution from each strip and the noise of the total prop-fan is the product of the vector sum and the number of blades. The effect of sweeping the tip back is to cause the signal from the tip to lag (increased phase angle) the signal from the mid-blade region, thus causing partial interference and a reduction in net noise. As can be seen in Fig. 12, the outer sections of the blade contribute the most to noise at Mach 0.8. The inboard sections of the blade below 70% radius contribute very little to the noise. Therefore, it is important to increase the magnitude of sweep at the blade tip.

By 1978, a frequency domain method had been developed by Hanson[5] that included a second-order term in the Ffowcs-Williams/Hawkings equation (the quadrupole source term). This term had been ignored in earlier theoretical development because it was believed to be small relative to the monopole thickness term at high *Mn* cruise conditions. However, in 1977, Hanson was able to show that quadrupole noise was an important source in cruise noise of unswept or slightly swept prop-fan configurations. This methodology has been used in recent prop-fan designs and for evaluations of prop-fan noise data.

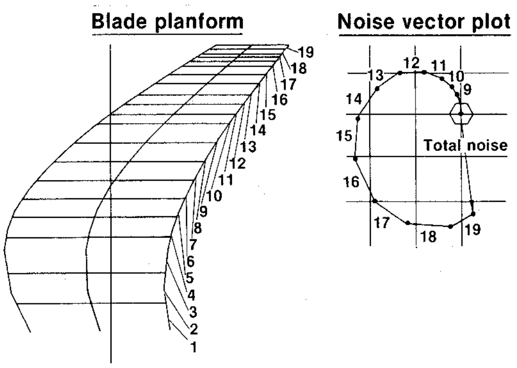

Fig. 12 Concept of noise reduction by blade sweep, 0.8 *Mn*.

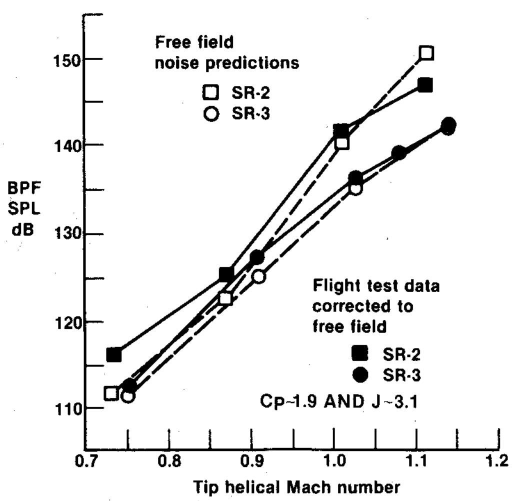

Fig. 13 Comparison of measured and predicted peak sideline tone levels for the SR-2 and SR-3 boom microphones.

Correlation of Noise Predictions and Measurements

Test data show that SR prop-fan noise is dominated by the blade passage frequency (BPF) tone level (rpm × number of blades/60). Therefore, correlations between predictions and measurements have concentrated on this tone. The most difficult regime for the calculation is cruise, where the tip helical *Mn* is transonic. Early tests in the UTRC Acoustic Research Tunnel were conducted to investigate this operating condition; however, the tests were limited by the low through-flow *Mn* of the facility. Flight tests using a Lockheed Jetstar were conducted to acquire data at actual high *Mn* operating conditions. For these tests, prop-fan models were powered by an air turbine drive mounted above the fuselage.

Figure 13 shows how the predictions agree with measurements on the Jetstar for both the swept SR-3 design and the unswept SR-2 design. Agreement over the complete range of tip helical Mach number M_{th} shown is remarkably good and is excellent at the transonic conditions typical of cruise. The SR-2 predicted levels do not agree quite as well with measurements as the SR-3, but the agreement is quite good. It can be seen that the predicted benefits of sweep at high M_{th} shown earlier in Fig. 4 are confirmed by the test data. For SR-3 with a 34.5 deg tip sweep, Fig. 4 indicated that 6.5 dB reduction should be achieved. The measured reduction in Fig. 13 is 7 dB. Also, at low tip helical Mach number, the measurements shown indicate that sweep may provide more benefits than expected.

It is instructive to evaluate the trends shown in Fig. 13 by review of the predicted vs measured directivities. Figure 14 shows predicted and measured directivities for the SR-2 and SR-3 at conditions approximating their cruise design point. These are the highest tip helical Mach number points of Fig. 13. The directivity pattern of the predicted total noise is made up of monopole, dipole, and quadrupole noise components. The overprediction of SR-2 peak noise from Fig. 13 can be seen in the left-hand graph of Fig. 14. The good agreement of SR-3 peak noise from Fig. 13 can be seen in the right-hand graph of Fig. 14. Comparing the noise components for SR-2 and SR-3 in Fig. 14, it is found that the blade sweep has suppressed both monopole and dipole peak noise in SR-3 by about 6 dB, but quadrupole noise has been suppressed by about 10 dB. For the SR-2, quadrupole noise appears to be overpredicted. This is not surprising, since the prediction of nonlinear quadrupole noise as opposed to linear monopole and dipole noise at the transonic tip speed is very difficult for an unswept blade. By sweeping the blade as in the SR-3 design, the local relative velocities can be reduced and it appears that a more reasonable estimate of quadrupole noise can be made. This is reflected in the better agreement of predictions and measurements for SR-3 in Fig. 14.

At the lowest M_{th} conditions of Fig. 14, there appears to be some measured benefit of sweep, since the SR-3 is lower than SR-2. This benefit is not, however, reflected by the predic-

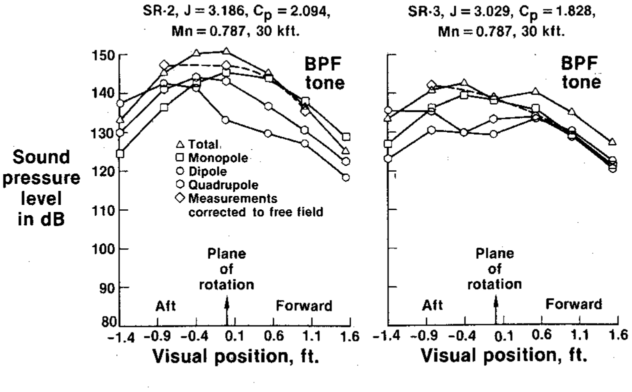

Fig. 14 Comparison of predictions and measurements at high tip helical Mach number.

tions. These data are evaluated in more detail in Fig. 15 relative to predictions. The operating flight speed for these comparisons is about 0.5 *Mn*. It can be seen that predictions of monopole and dipole noise are very similar for the SR-2 and SR-3. Quadrupole noise is somewhat reduced by the SR-3 sweep. However, dipole noise related to the blade loading is dominant by more than 10 dB relative to monopole or quadrupole noise, so any deficiency in predictions is likely to be related to dipole noise. The SR-3 directivity is fairly well predicted. However, the SR-2 is underpredicted. Therefore, it appears that sweep may be more beneficial than predicted at subsonic flight speeds, subsonic M_{th}, and high loadings.

In summary, the experimental evidence confirms the expected magnitude of blade sweep benefits at high M_{th} encountered at 0.8 *Mn* cruise. At lower flight speeds, measurements indicate that benefits may be greater than predicted. However, swept blade data have been found to be better predicted than that from unswept blades.

Predicted Acoustic Benefits for Blade Sweep at Cruise Conditions

An indication of the sweep benefits in full scale expected for different cruise conditions is discussed in this section. The blade configurations selected for these predictions are the SR-2 with no sweep and the SR-3 with a tip sweep of 34.5 deg. The SR-3 has been found in tests to be acceptable from a structural and performance standpoint as well as noise. Furthermore, within the structural constraints, its spanwise sweep distribution was optimized to minimize noise without penalizing performance. Figure 16 summarizes the peak near field predictions for SR-2 and SR-3 at 0.5, 0.65, and 0.8 cruise *Mn*. For each cruise *Mn*, a loading (shaft horsepower per diameter squared, shp/D^2) and altitude considered appropriate has been assumed: 1) at 0.5 *Mn*, a loading of 22.5 shp/D^2 at 25,000 ft; 2) at 0.65 *Mn* 26, shp/D^2 at 30,000 ft; and at 0.8 *Mn*, a 37.5 shp/D^2 at 35,000 ft. This implies that, for a given engine power, the prop-fan diameter would increase as cruise *Mn* was reduced. However, less power would be needed to cruise at lower *Mn* for a given airplane, so the diameter remains about the same for the configurations considered. Note that the loading assumed for 0.8 *Mn* cruise is the design cruise condition for SR-3. For all predictions, a tip speed of 800 ft/s and a nondimensional tip-to-fuselage clearance of 0.8 prop-fan diameter was assumed. It can be seen that the beneficial effects of sweep are generally as expected in Fig. 2, i.e., lower benefits are achieved as cruise *Mn* is reduced. However, even at 0.5 *Mn*, some sweep benefits are predicted.

Figure 17 shows how the noise components are affected by sweep and operating condition. For the SR-2 at 0.5 *Mn*, the monopole and dipole noise are the dominant contributions. At 0.65 *Mn*, monopole noise dominates, with some contributions from quadrupole noise. At 0.8 *Mn*, monopole noise is even more dominant. For the SR-3 at 0.5 *Mn*, the relative levels of the noise components are very similar to those for the SR-2. At 0.65 *Mn*, the monopole noise is dominant, but has been suppressed by phase cancellation. Some phase cancellation is also achieved for dipole noise. The most reduction is achieved for quadrupole noise. This is due to phase cancellation and to basic reduction in the source strength due to reduction in the relative *Mn* at each spanwise location on the blade. At 0.8 *Mn*, the monopole noise is again dominant. Sweep has minimized the increases in the level with the increased cruise *Mn* seen for the SR-2.

SR Sweep Benefits at Takeoff Conditions

The above discussion has established that important noise reductions are achievable in the near field at high-speed cruise conditions. Early tests in the UTRC Acoustic Research Tunnel showed the benefits of the swept SR-3 relative to the unswept SR-2 of about 3 db at the blade passage frequency. These benefits are similar to predictions showing that phase cancellation is beneficial even at low flight *Mn*. At takeoff cutback conditions, a predicted benefit of about 2 EPNdB is predicted.

Aerodynamic Benefits of Blade Sweep for CR Prop-Fans

The aerodynamic benefits of blade sweep are significantly greater for CR prop-fans than discussed above for SR prop-fans. Whereas sweep benefits on SR prop-fans were shown to be 1.5–2.0 efficiency points at 0.7 *Mn* and 2.5–3.0 points at 0.8 *Mn*, predictions for CR prop-fans show efficiency benefits of sweep to be about double these values. The reason for these increased blade sweep benefits is that the counterrotating blade rows experience significantly greater section relative Mach numbers. This is due to the increased flow induced through the front blade row by the rear blade row and by the addition of the slipstream flow from the front blade row to the flow through the rear row. The effects of the superimposed flowfields are to typically increase spanwise relative Mach numbers at the front row about 2–3% and at the rear row about 8–10%. The precise values are functions of power loading and tip speed. Thus, it is apparent that sweep benefits the rear row of a CR prop-fan significantly more than the front row. Considering aerodynamic efficiency only, the foregoing discussion would imply that blade sweep may need to be greater on the rear row than on the front row for equal blade row efficiency.

To date, only limited data have been published on CR model wind tunnel testing. A tractor CR model is currently being tested in the UTRC 8.0 ft wind tunnel. These experimental data are expected to provide further guidance on the benefits of sweep for CR prop-fans.

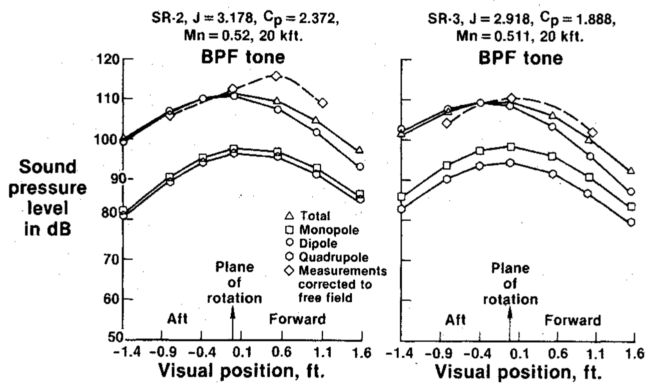

Fig. 15 Comparison of predictions and measurements at low tip helical Mach number.

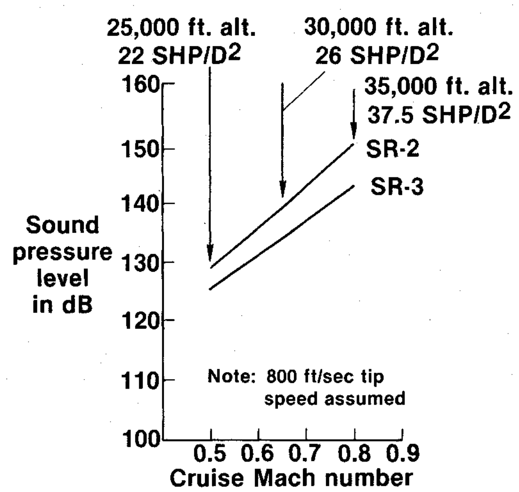

Fig. 16 Predicted near-field blade passage frequency levels at cruise.

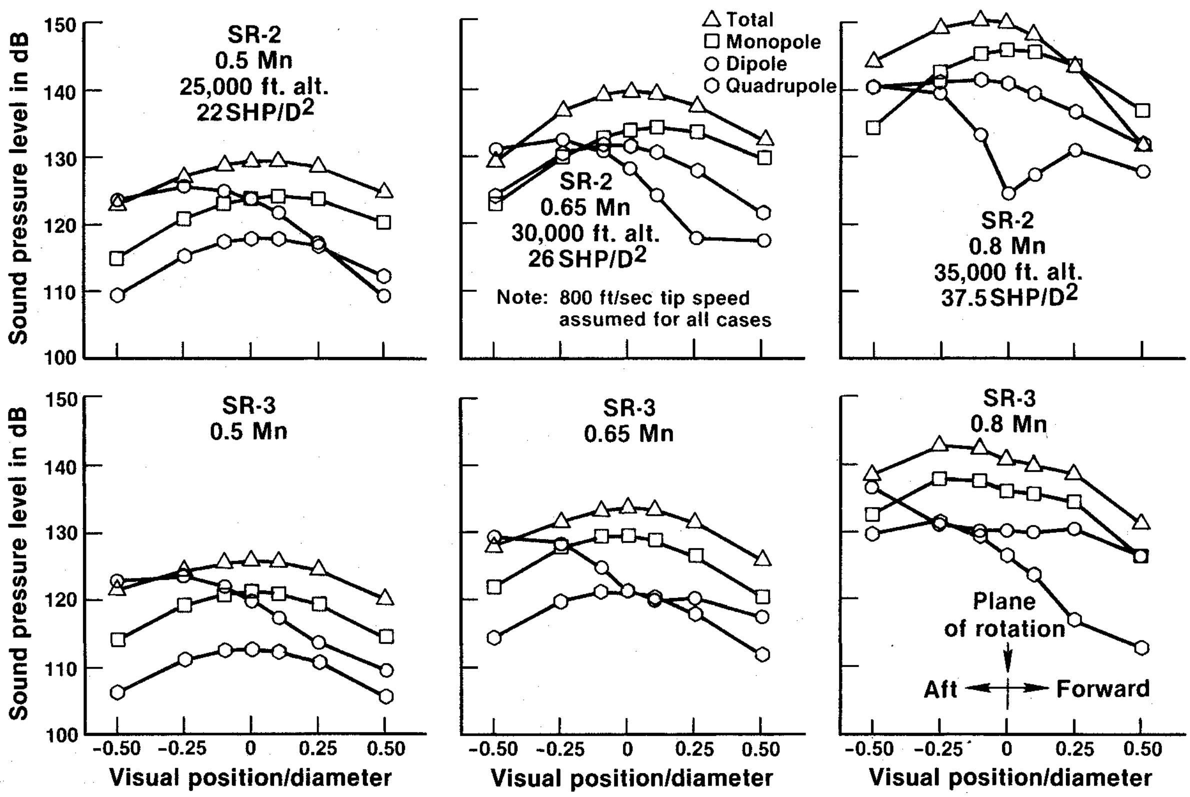

Fig. 17 Predicted blade passage frequency levels at different cruise conditions.

Acoustic Benefits for CR Prop-Fans

In addition to the noise components of SR prop-fans, CR prop-fans have acoustic and aerodynamic interaction components that must be considered. The acoustic interaction component is simply the result of two phased coherent noise sources (the rotors). The aerodynamic interaction component is due to viscous wake and potential field interaction of the two rotors. Experiments on a Fairey Gannet (which has a CR propeller) have demonstrated that interaction noise becomes dominant at the fourth and higher harmonics of the blade passage frequency. This was done by measuring the propeller noise in the near field at a wing-mounted microphone boom. This conclusion was drawn from the sum of noise produced by the front and rear blade rows of the Gannet operated separately (separate engines drive the front and rear rotors so the front or rear rotors can be operated alone) and the two rotors operated together.

At the present time work is still underway to develop methodology for accurate prediction of interaction noise. However, blade sweep may have beneficial effects on interaction noise since sweep becomes more effective as frequency increases and interaction noise appears to dominate the high-frequency part of the CR noise spectra, particularly at takeoff conditions. At cruise, it is not yet clear that aerodynamic interaction noise will be significant relative to isolated rotor levels.

Conclusions

Extensive aerodynamic and acoustic testing of single-rotation prop-fan models has been conducted for the past nine years. Blade sweep has been demonstrated in these tests to improve efficiency and reduce noise of SR prop-fans. At cruise conditions, a benefit of 2 or 3 efficiency points and 6 dB noise reduction appears achievable in practical prop-fan designs. Achieving these benefits requires careful design of the spinner contour and blade root spinner juncture and optimization of spanwise distribution of sweep as part of the aerodynamic and acoustic design process. For counterrotating prop-fans, it is expected that there will be larger aerodynamic benefits for blade sweep. At cruise, sweep is expected to have similar noise reduction benefits in CR prop-fans to those that occur in SR designs. At takeoff, blade sweep is expected to be beneficial for suppressing high-frequency aerodynamic interaction noise. Further experiments and theoretical development are under way to establish blade sweep benefits for CR prop-fans.

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