JOURNAL OF AIRCRAFT
Vol. 30, No. 5, Sept.–Oct. 1993

Rotor Wake/Stator Interaction Noise—Predictions vs Data

D. A. Topol*
Pratt & Whitney, East Hartford, Connecticut 06108

A rotor wake/stator interaction noise prediction method is presented and evaluated with fan rig and full-scale engine data. The noise prediction method uses a two-dimensional semiempirical wake model and an analytical stator response function and noise calculation. The stator response function is a two-dimensional strip theory which is linked to a noise calculation formulated in a constant area annular duct with mean axial flow. Comparisons are made with data from an advanced ducted propeller (ADP) fan rig which is a next-generation turbofan engine design. A calibration of the prediction model is attempted using these rig data. The calibrated method is subsequently utilized to calculate and compare with noise test data from a 4.1-in.-diam fan rig and from a full-scale turbofan engine configuration. Results indicate that the method has promise, but that further improvement is desirable.

Introduction

FAN wakes impinging on a downstream stator row have long been known as important contributors to fan tone noise from turbofan engines. Much has been done to model this noise source. Typically, a rotor wake/stator interaction noise model contains a wake model and a vane response function, which is then coupled to some kind of a duct acoustic calculation. Authors have often concentrated on the vane response function and noise calculation methods,[1–4] utilizing either measured wake harmonic magnitudes from a spatial Fourier decomposition of the wake or magnitudes predicted from a wake model.[5–8]

In the evaluation of these various models, most investigators have concentrated on comparing either the vane response function and noise predictions with data, or a wake model with data.[1–3,6] However, only a few investigators have reported on how the two models together compared with data. One such data-prediction evaluation was found in Ref. 1 for inlet propagating noise. This method is a two-dimensional acoustic and aerodynamic strip theory which combines the cascade wake model of Mugridge and Morfey[5] with the low-frequency (compact) flat plate vane cascade response function of Osborn[9] and the high-frequency (noncompact) isolated flat plate airfoil response function of Amiet.[10] These are then coupled to the two-dimensional thin annulus noise calculation method of Mani.[11] Results of this evaluation were limited and showed varying degrees of agreement with rig data.

Kobayashi,[2] for the case of flow distortion into a fan, compared three different blade response functions and acoustic calculation methods. They were 1) a two-dimensional aerodynamic and acoustic "strip theory" method[1]; 2) a quasi-three-dimensional (i.e., two-dimensional aerodynamics, three-dimensional acoustics) thin airfoil cascade theory[4]; and 3) a three-dimensional (in acoustics and aerodynamics) thin airfoil lifting surface cascade theory.[12] In his comparisons, he found that the differences between the two-dimensional strip theory and the quasi-three-dimensional and three-dimensional theories can be important. However, he indicated that the quasi-three-dimensional theory was adequate for obtaining accurate radial mode decomposition. He later compared the three-dimensional formulation with noise data,[3] using distortion experimental aerodynamic data as input to the blade response and noise calculations. Results showed remarkable noise agreement for the configuration and harmonic compared. However, comparisons with data were limited to one configuration for one inlet noise harmonic.

A wake model comparison with wake data was done by Majjigi and Gliebe[6] for their empirical wake model formulation. Their model utilized lightly loaded fan rig data from Refs. 7 and 8 to develop semiwake width and velocity deficit correlations for the fan wakes. The comparison was made with data independent of their formulation. Results were mixed, but showed the potential for use in combination with a stator response function and noise calculation.

The purpose of this study is to evaluate and calibrate a quasi-three-dimensional fan wake/stator interaction tone noise prediction model with fan rig and full-scale engine tone noise data. The model is a modified combination of the two-dimensional wake model of Majjigi and Gliebe[6] with the quasi-three-dimensional stator response function and noise theory of Ventres et al.[4] Both of these models were developed under funding from NASA Lewis Research Center. Predictions are compared with and calibrated against ADP 17-in.-diam rig data. Using this calibration, predictions and data are compared for 4.1-in. fan rig and full-scale engine configurations.

Rotor Wake/Stator Interaction Tone Noise Theory

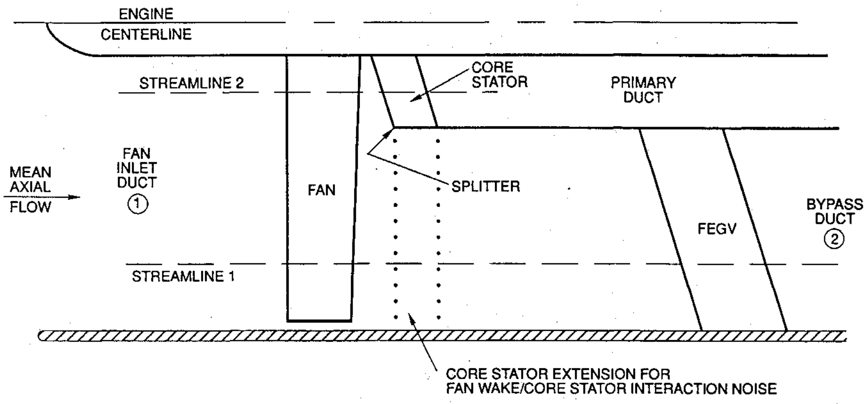
The noise calculation program, which combines the models from Refs. 4 and 6, was originally designed to calculate rotor wake/stator interaction tone noise from a stator row in a constant area annular duct. The present analysis is extended to allow tone noise to be calculated from the rotor wakes impinging on the fan exit guide vanes (FEGV) and core stators, both shown schematically in Fig. 1.

The program is divided into a rotor wake model calculation, the stator response, and noise calculations. The geometry used in the program (Fig. 1) consists of rotor, FEGV, and core stator cascades. The program first predicts the fan wake profile at the leading edge of stator rows along many streamlines. Then, the tone noise emanating from the core stators and from the FEGVs are predicted separately with separate duct definitions for each noise source.

The fan wake model is a semiempirical two-dimensional streamline calculation which utilizes rotor wake data from Refs. 7 and 8. The fans used in these experiments were lightly loaded rotors, running at relatively low tip speeds (approximately 95–168 ft/s). Majjigi and Gliebe[6] then utilized these data to create empirical expressions for the fan semiwake

Presented as Paper 90-3951 at the AIAA 13th Aeroacoustics Conference, Tallahassee, FL, Oct. 22–24, 1990; received Dec. 10, 1990; revision received July 31, 1992; accepted for publication Aug. 1, 1992.

*Senior Engineer, Acoustics Engineering, Commercial Products Division. Member AIAA.



① FAN INLET DUCT USED TO CALCULATE ROTOR WAKE/CORE STATOR INTERACTION NOISE. CORE STATOR EXTENSION LOADING IS ZERO.

② BYPASS DUCT USED TO CALCULATE ROTOR WAKE/FEGV INTERACTION NOISE.

Fig. 1 Rotor wake/stator interaction geometry for tone noise theory.

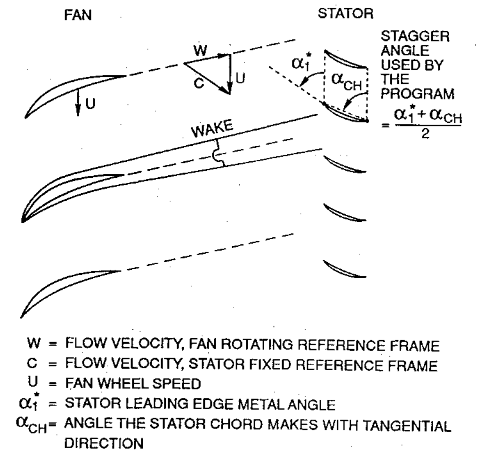


Fig. 2 Rotor wake/stator interaction aerodynamics.

width and velocity deficit. Correlations are based on the fan blade incompressible section drag coefficient and fan trailing edge to stator leading edge streamwise spacing, nondimensionalized by the fan aerodynamic chord. The wake profile shapes are calculated using either a Gaussian or a hyperbolic secant profile. Merged wakes are handled by simply combining the wake profiles for the two neighboring wakes.[6]

To calculate the wake, the duct is unwrapped and divided into streamlines (or strips), see Figs. 1 and 2. The two-dimensional steady flow is then calculated along each streamline. The wake profile for each strip at the vane leading edge is calculated along with a simple tip vortex, if desired, which may be used to modify the tip wake profiles. The wake/vortex flow is then superimposed on the steady flow, and the wake upwash velocities at the vane leading edge are calculated along each streamline. A Fourier decomposition is used to obtain the upwash wake harmonic magnitudes for each harmonic. These values are transferred to the vane response function calculation. Details of the development of the program equations may be found in Ref. 6.

The analytical stator response and noise calculation was developed by Ventres et al.[4] The program, as modified, uses the wake upwash harmonic magnitudes as input to a cascade dipole distribution calculation and duct noise calculation. The cascade dipole distribution calculation is a strip theory calculation based on work done by Goldstein[13] and extended by Ventres et al.[4] The method's assumptions are similar to other strip theory methods such as Kaji[14] and Smith.[15] Along each streamline, the stators are represented by an unwrapped cascade of unloaded flat plates at zero incidence to a compressible, subsonic, steady flow. The flow is then subjected to a small perturbation, periodic upwash velocity for a given rotor rotational frequency and vane/blade ratio (i.e., given wake reduced frequency and interblade phase angle). An unsteady dipole distribution is calculated on a reference vane in the frequency domain. Assuming vanes are an equal distance apart, the vane unsteady dipole distributions are separated by a constant phasing and are, therefore, known on all vanes in the cascade. Unlike the methods of Osborn[9] and Amiet,[10] this method is not limited by the acoustic reduced frequency of the tone noise.

After this calculation, the duct is rewrapped and the vanes are replaced by a series of dipoles in an infinite length, constant area annular duct. A Green's function approach for a mean axial flow through this duct is then used to calculate the mode amplitudes, phases, and power levels for each upstream and downstream propagating (cuton) radial and circumferential mode in the duct. The mode power levels are added together to obtain inlet and aft power levels for each fan tone harmonic. During the calculation, the program preserves all vane dipole amplitudes and phases in the chordwise and radial directions. In addition, the program accounts for the phasing of the wake due to the varying streamwise distances each wake must travel to reach the stator, thus preventing wake "slapping" at the vane leading edge. The program also allows the vane geometry to be "leaned" or swept in both the axial and tangential directions (see Fig. 1). Because the analytical formulation is done in the frequency domain, the program calculates the noise on a mode-by-mode, harmonic-by-harmonic basis. Details of this approach may be found in Ref. 4.

This procedure has been adapted to predict noise from both fan wake/FEGV and fan wake/core stator interactions (see Fig. 1). Predictions from these noise sources are calculated separately using separate constant area ducts for the core stators and FEGVs. This allows for the correct calculation of the cuton mode amplitudes for each noise source.

The fan wake/FEGV interaction noise predictions are done using the bypass duct to represent the constant area annular duct (Fig. 1). The fan inlet duct is used as the constant area annular duct for the fan wake/core stator interaction predictions.

These assumptions had the greatest impact on the rotor/core stator calculation. Because the prediction is done in the fan inlet duct, the core stator needs to be extended past the splitter to the outer duct diameter. Then, during the unsteady dipole calculation, unsteady stator loading is only permitted and is only calculated on the actual core stator span. Consequently, the finite duct characteristics of the primary duct are neglected. In addition, the splitter is assumed to be unloaded and infinitely thin. Note too that the radial mode decomposition is done in the inlet duct. Since the core stator is normally at or close to the leading edge of the splitter, these assumptions are considered reasonable.

Advanced Ducted Propeller Noise Experiment

To evaluate and calibrate this noise prediction method, data from a fan rig noise test program were utilized. The ADP 17-in. fan rig was designed and built to simulate a variable pitch, high bypass ratio next-generation turbofan (Fig. 3). It includes a 17.3-in.-diam fan capable of developing a pressure ratio of 1.26 at a top speed of 12,000 rpm at the takeoff fan pitch angle. The fan is driven by a six-stage, 7-in.-diam, air-driven turbine which develops 730 hp at 8400 rpm, requiring 10 lb/s of air at 320 psi and 130°F. The fan was tested at various fan pitch angles, fan-to-FEGV axial spacings, and vane/blade ratios. Two vane/blade ratios were used including one cuton (1.4 vane/blade ratio) and the other cutoff (2.5 vane/blade ratio) at blade passing frequency (BPF). Three fan-to-FEGV axial spacings were tested.

The tests were conducted in the United Technologies Research Center's Acoustic Research Tunnel (ART). The tunnel is an open circuit, open jet tunnel which is considered anechoic above 200 Hz. Figure 4 illustrates the test configuration. The facility uses an open jet where the jet shear layer was found to clear the rig nacelle outer diameter by at least 10 in. at the highest running condition. The tunnel was run at 0.25 simulated flight Mach number. An axial array of microphones was located above the model covering a range of 16–150 deg, relative to the inlet axis. Microphone levels and angles were corrected for tunnel shear-layer effects using a correction procedure developed by Amiet.[16]

Signals for each microphone were analyzed in real time using the Pratt & Whitney multiple analyzer portable system (MAPS) for a frequency range of 0–25 kHz. Data were then corrected for shear-layer effects and were adjusted to a constant distance from the model. Tone levels were defined at each angle, and sound power levels were calculated (inlet and aft) by integrating over the proper angle ranges.

Data—Prediction Comparisons

Predictions require various geometry and performance parameters such as chords, radii, flow Mach numbers, and vane stagger angles. In addition, a fan wake shape and tip vortex prediction input, if desired, must be chosen. The vane stagger angle, fan wake shape, and tip vortex input may be chosen at the discretion of the user and will now be discussed.

The theory's cascade response function predicts the dipole distribution on a staggered cascade of flat plates. The stagger angle affects the vane dipole distribution and alignment (coupling) of the dipoles with a given propagating mode. Two common stagger angle alternatives are the vane leading-edge metal angle, and the angle the stator chord makes with the circumferential direction (sometimes called alpha chord). Both of these stagger angle definitions were tried and are shown in Fig. 2.

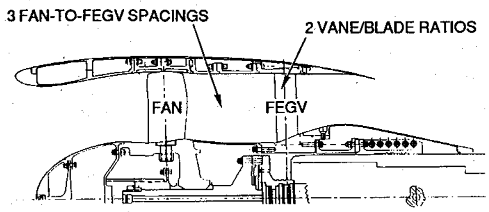


Fig. 3 Advanced ducted propeller rig.

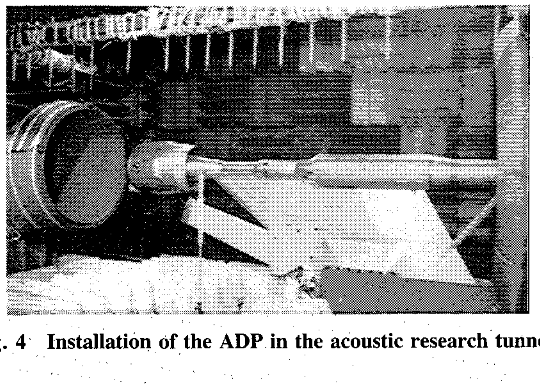


Fig. 4 Installation of the ADP in the acoustic research tunnel.

The average of these two angles was also tried (see Fig. 2). For a circular arc airfoil, this average angle approximates the angle of the vane camber line at the quarter-chord point. Compact noise theories have commonly found the unsteady lift to be concentrated at this point. Thus, this angle definition is used for all data-prediction comparisons. The ADP sound power level data-prediction comparisons were made for all three stagger angle options. These comparisons further confirmed this stagger angle choice.

The fan wake profile shape also needed to be defined for these comparisons. Reference 6 defines two wake profiles: 1) the Gaussian wake profile, and 2) a hyperbolic secant profile. The Gaussian profile is the same as used in Refs. 5, 7, and 8, and is commonly used to represent the wake. The hyperbolic secant profile is given in Ref. 6 as an alternative. In Ref. 6 these two profiles are statistically compared with wake data. The results of this comparison find that either profile may be used. However, a further look at these profiles indicates that there is a slight difference in the way that each profile handles the wake edges. The edges of the wake are often found to greatly affect the wake higher harmonics (i.e., 2 × blade passing frequency, 3 × blade passing frequency). Further evaluation of these profiles found that the hyperbolic secant profile causes the higher harmonics to decay at a slower rate with increased spacing, and is also more consistent with data. Thus, the hyperbolic secant profile was used for the comparisons that follow.

The tip vortex calculations require that the tip clearance of the fan and the circumferential location of the vortex relative to the rotor wakes be input. For this study, the mean clearance of the fan blade tips for the nonrotating fan was utilized to maximize the vortex effect. The circumferential location of the vortex can have a significant local tip effect on the harmonic content of the incoming gust. This has been studied by many investigators including Majjigi and Gliebe.[6] In this reference, 20 log (wake/vortex harmonic magnitude nondimensionalized by the fan wheel speed) is utilized to study the effect of the vortex on noise. This is consistent with rotor wake/stator interaction theory[4] which shows that sound power level is proportional to 20 log (wake/vortex harmonic magnitude). Reference 6 indicates that if the vortex is placed equidistant circumferentially between the two wakes, then the effect is to significantly increase the amplitudes of the even harmonics of BPF and decrease the amplitudes of the odd harmonics of BPF. On the other hand, placing the vortex circumferentially at the same location as the wake results in a noise increase at all harmonics. For this study, the wake/vortex harmonic magnitude output was utilized to quantify the expected effect of the circumferential location of the vortex. The location where the vortex is centered at the same location as the wake was found to be where the greatest noise effect would be expected. This location is used for a comparison discussed below.

It should be noted that this method predicts forward and aft propagating tone noise from the stator. The forward noise must pass through the fan to reach the far field. The reflections and transmissions that occur at the fan are not accounted for by the model. However, some attempt was made to evaluate the importance of a part of this effect by using the wave reflection prediction method of Topol et al.[17] This method accounts qualitatively for noise generated by forward propagating BPF noise from the stator, reaching the fan, and reflecting off the fan as higher harmonics of BPF. This noise mechanism was found in Ref. 17 to be important in certain engine and rig configurations. The model of Ref. 17 was ap-

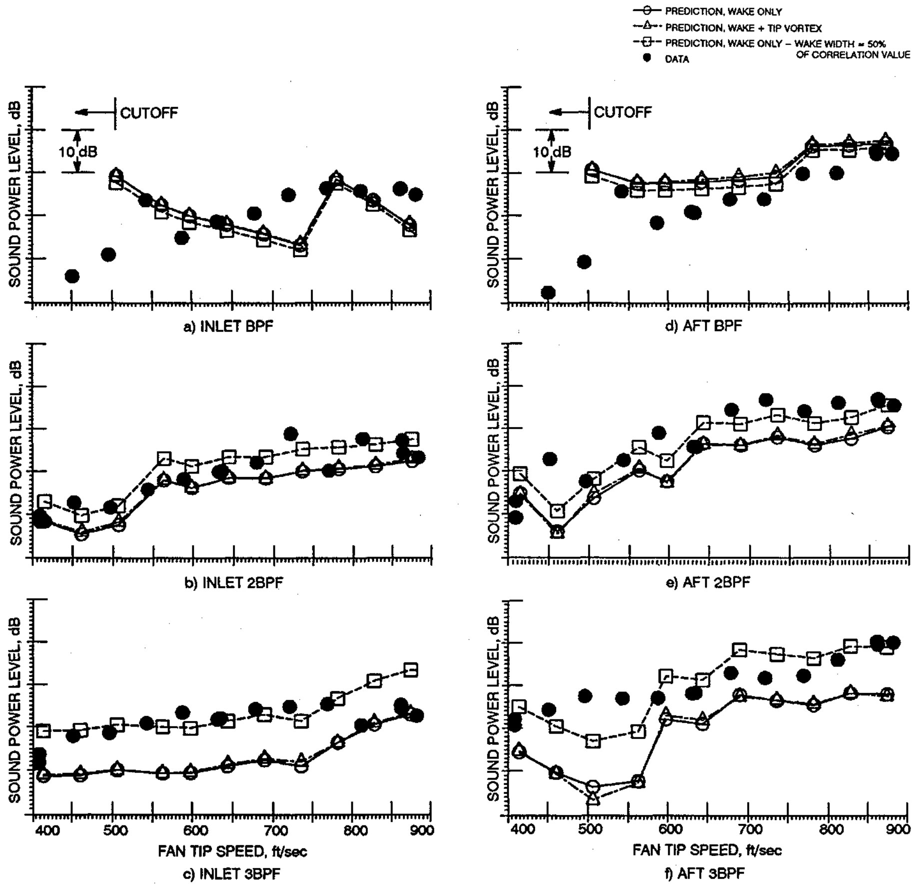


Fig. 5 ADP 17-in. rig prediction calibration 1.4 vane/blade ratio, middle fan-to-FEGV spacing.

plied to both ADP vane/blade ratios and confirmed that the wave reflection mechanism was not a dominant source of noise for these configurations. For all predictions, inlet noise will be shown at all harmonics to illustrate how this rotor wake/stator interaction model compares with data without accounting for the effects of fan blockage through the blade rows.

Using this input, tone sound power level noise predictions were made for two ADP configurations. The ADP is ideal for these comparisons since its most important tone noise source should be fan wake/FEGV interaction noise. The cuton 1.4-vane/blade ratio, middle fan-to-FEGV spacing comparisons are shown for the first three harmonics of BPF in Fig. 5. Predictions are made with and without a tip vortex in order to also evaluate the tip vortex effect on the noise. In addition, the calibrated predictions are shown here, but will be discussed later. Notice that the predicted point of BPF cuton occurs just after the 490 ft/s tip speed data point. This is consistent with the data which does not show a sharp increase in BPF until after the 490 ft/s point, both inlet and aft.

In this figure, it is seen that BPF is slightly overpredicted, while 2 × BPF and 3 × BPF are underpredicted, 3 × BPF being more underpredicted than 2 × BPF. These types of results can be indicative of a predicted wake which is spreading faster than the real wake. As a wake spreads, it tends to have more and more BPF content and less and less higher harmonic content, where 3 × BPF decays faster than 2 × BPF. Inlet BPF shows good agreement over a part of the speed range, but its shape is inconsistent with the data. The reason for this discrepancy is not known at this time, but may be caused by the interaction of this forward propagating tone with the fan.

Notice also that the predictions with a tip vortex caused little change in the results. Thus, even if the tip vortex model is only moderately accurate, the tip vortex would not be expected to yield significant improvements in the predictions as they compare with data.

Similar results were found for the cutoff 2.5 vane/blade ratio, middle fan-to-FEGV spacing comparisons shown in Fig. 6 where, as before, 2 × BPF is less underpredicted than 3 × BPF. In this case, BPF is cutoff and is neither shown nor predicted. The calibrated results shown here will be discussed in the next section.

Therefore, the above predictions did not compare with data as well as one would normally expect, given the capabilities and features of the stator response function and noise prediction models. The results, however, point to a wake model which may be causing the wake to spread too fast. We will now look at this problem in more detail.

Calibration of Predictions with ADP Rig Data

Calibration Method

To effectively calibrate the rotor wake/stator interaction program, various parameters were changed in a physically meaningful fashion, so as to improve sound power level data-prediction agreement. Many different parameters were varied. Three parameters discussed in the previous section were 1) the vane stagger angle definition, 2) wake profile shape, and 3) the tip vortex.

As the previous section pointed out, the data-prediction comparisons found that the predicted wake has spread more than the sound power level data would indicate. This result is consistent with some of the data-prediction comparisons in Ref. 6, where the predicted wake spread more than the data. This caused the wake harmonic magnitudes to be increasingly too low at the higher harmonics. One such example of these results may be found in Fig. 32 of Ref. 6 for the rotor 55 fan rig running at 80% fan design speed. The wake is predicted at 30% span from the tip at 1.23 fan aerodynamic chords downstream of the fan trailing edge. For these predictions it was found that the semiwake width is overpredicted. The wake harmonic magnitudes drop off too quickly for the higher

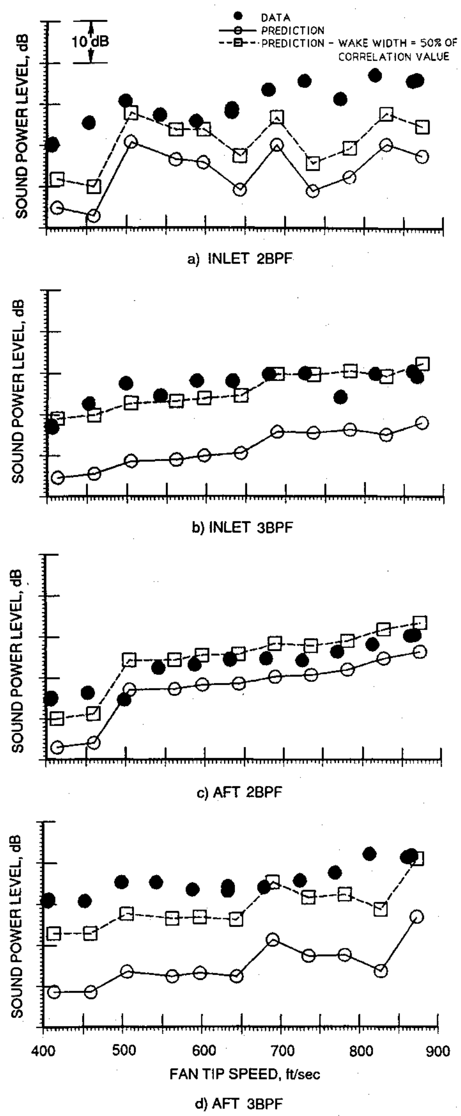


Fig. 6 ADP 17-in. rig prediction calibration 2.5 vane/blade ratio, middle fan-to-FEGV spacing.

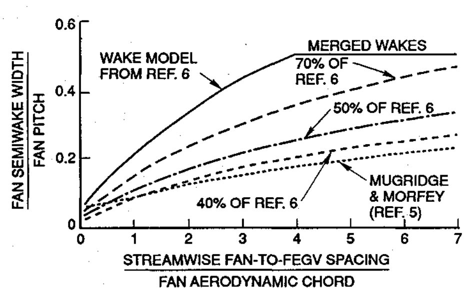


Fig. 7 ADP 17-in. rig semiwake width calculations 77% fan blade span from hub.

harmonics. The use of 20 log (wake harmonic magnitude/fan wheel speed) to illustrate this result is found in Fig. 33 of Ref. 6.

Given these results, it was decided to vary the semiwake width correlation to obtain better agreement with the ADP sound power level data. This was accomplished by using a specified percentage of the correlation's predicted semiwake width. The percentage was varied by trial and error until significant improvement in the agreement was realized. Figure 7 illustrates the semiwake width correlations of Refs. 5 and 6, along with various percentages of the correlation in Ref. 6, as a function of streamwise spacing to fan aerodynamic chord. In this figure the Mugridge and Morfey correlation[5] is shown to spread much more slowly than the wake model used in Ref. 6. Using a percentage of the Ref. 6 correlation, the best agreement with sound power level data was found when the semiwake width was 50% of the predicted correlation value. Thus, these results will be used to compare with sound power level data.

Data-Prediction Comparisons: BPF Cuton

The data-prediction comparisons for the cuton 1.4 vane/blade ratio configuration are shown in Fig. 5 for the middle fan-to-FEGV spacing. Forward fan-to-FEGV spacing results may be found in Ref. 18. Both the calibrated and uncalibrated results are shown. Notice that the BPF and 2BPF data-prediction results improve using a semiwake width, which is 50% of the Ref. 6 value. The predictions are also reasonable for 3BPF, though at the forward spacing, the calibrated wake model somewhat overpredicts this harmonic. Except as noted, the same trends were also found for the forward spacing case. Though wave transmission and reflection through the fan blades are not included in this model, the inlet predicted results look quite promising for both spacings.

The thinner predicted wake for the calibrated case is seen to increase 3BPF noise, while decreasing BPF noise. This is due to the Fourier decomposition of the wake upwash, which contains much more higher harmonic content and much less BPF content for a thin wake than a thick wake.

Data-Prediction Comparisons: BPF Cutoff

Figure 6 shows data-prediction comparisons before and after calibration for the cutoff 2.5 vane/blade ratio configuration at the middle fan-to-FEGV spacings. The forward and aft spacings were also predicted and may be found in Ref. 18. In these cases BPF is cutoff and levels are not shown or predicted. Notice for these predictions that the calibration improves data-prediction agreement. In this case the aft 2BPF and inlet 3BPF noise predictions are more accurately predicted than the inlet 2BPF and aft 3BPF predictions. This may be due to the flat plate cascade approximation of the program. As stated earlier, the flat plate approximation affects both the dipole calculation and acoustic mode-dipole alignment. Perhaps vane camber may be important here.

For the uncalibrated predictions at all fan-to-FEGV spacings (see Ref. 18), 2BPF is less underpredicted than 3BPF, lending further credence to the concept that this wake model's predicted wake spreading was more rapid than the actual wake spreading in the ADP rig.

Thus, this calibration seems to improve these predictions.

Comparisons with Powered Nacelle Rig Data

With the prediction system calibrated, it will now be applied to another rig to see how it performs. To accomplish this task, the "powered nacelle" fan rig was used. Figure 8 shows this model that was designed to operate with interchangeable FEGV vane sets, which allows for testing with different vane/blade ratios and rotor-to-vane spacings. In previous testing it has proven to be a useful tool for assessing fan noise mechanisms.[17]

The powered nacelle was designed and built to simulate typical high bypass ratio turbofan engine/nacelle configurations and operating conditions. It includes a 4.1-in.-diam fan capable of developing a pressure ratio of 1.55 at the top speed of 80,000 rpm. The fan has 18 fan blades and is driven by a single-stage turbine containing 29 blades. The drive turbine develops 87 hp and requires approximately 1.3 lb/s of air or nitrogen at about 400 psi at the maximum speed.

Tests were conducted in the Pratt & Whitney anechoic test facility. The chamber is considered to be anechoic above frequencies of 150 Hz. The facility does not allow for the simulation of flight speeds, but low-speed, filtered airflow is induced over the model to ensure low turbulent flow into the fan. An array of 24 0.25-in. B&K microphones at a radius of 7 ft from the nacelle centerline was used at angles ranging from 15 to 140 deg, relative to the inlet axis. Signals from each microphone were recorded on magnetic tape, with narrow-band spectra (0–100 kHz) obtained by tape playback through a spectrum analyzer. Tone levels were then defined at each angle and sound power levels calculated (inlet and aft) by integrating over the proper angle ranges.

Comparisons are shown in Fig. 9 for the aft fan-to-vane spacing, 1.9 vane/blade ratio configuration before and after calibration. Results in this case show that, for this small model, the wakes seem to correlate differently from the moderately sized ADP rig. Reynolds number differences may explain part or all of this observation. Predictions are seen here to compare best when using the original wake model of Ref. 6. This strongly suggests a need to develop a wake model, which uses the performance and geometry parameters that properly account for more of the important effects, which influence the wake structure.

In these comparisons there is a rise in the data just above 800 ft/s tip speed in the aft 2BPF and 3BPF data that is not accounted for by the predictions. This is the wave reflection mechanism explained in Ref. 17, which causes inlet propagating BPF to reach the fan and reflect off the fan as aft 2BPF

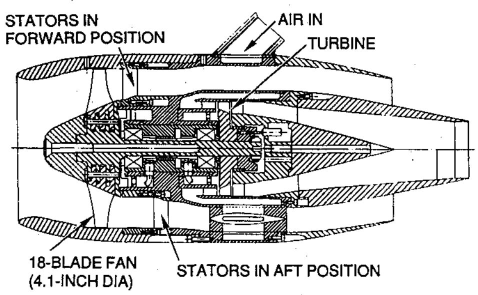


Fig. 8 Advanced powered nacelle rig.

and 3BPF. As mentioned earlier, the current program does not account for this effect, thus explaining the differences between the data and predictions in the speed range between about 850–1100 ft/s.

Full-Scale Engine Noise Predictions vs Data

In this section, the rotor wake/stator interaction prediction model will be compared with full-scale engine noise data. The high bypass ratio turbofan engine was run at an outdoor test stand with an inflow control structure using standard test procedures. The engine has a 1.9 vane/blade ratio and fan trailing edge-to-FEGV leading-edge spacing to aerodynamic fan chord ratio similar to the powered nacelle configuration of the last section.

For this comparison, both fan wake/FEGV and fan wake/core stator interaction noise predictions were made to fully assess the noise prediction system. In addition, the power levels for the two noise sources were logarithmically added together to compare the total power levels from these two noise sources with data. Only the calibrated prediction model was used for these comparisons. For this evaluation, it was assumed that the noise from fan wake/core stator interactions does not contribute to aft radiated noise.

Comparisons are shown in Fig. 10 for the calibrated case. It should be noted that the uncalibrated case would have more wake spreading, thus resulting in more of an underprediction of 2BPF and 3BPF noise.

Like the powered nacelle data, the full-scale engine aft 2BPF and 3BPF tone data include the effects of wave reflections (see Ref. 17) in the center of the speed range. Notice the similarity between the uncalibrated noise prediction comparisons for the powered nacelle in Fig. 9 and the calibrated full-scale engine results in Fig. 10 for aft 2BPF and 3BPF. These results are quite encouraging since they show good agreement with data at the low speeds and high speeds, where

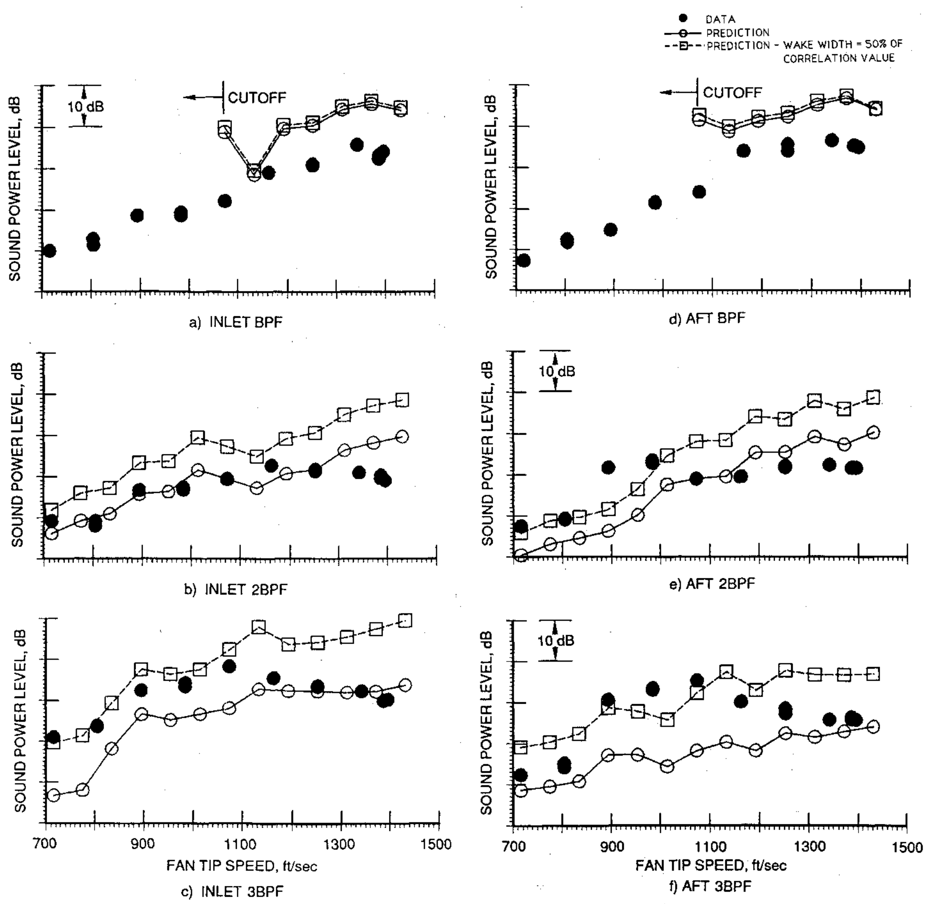


Fig. 9 Powered nacelle 4.1-in. rig calibration comparison 1.9 vane/blade ratio, aft fan-to-FEGV spacing.

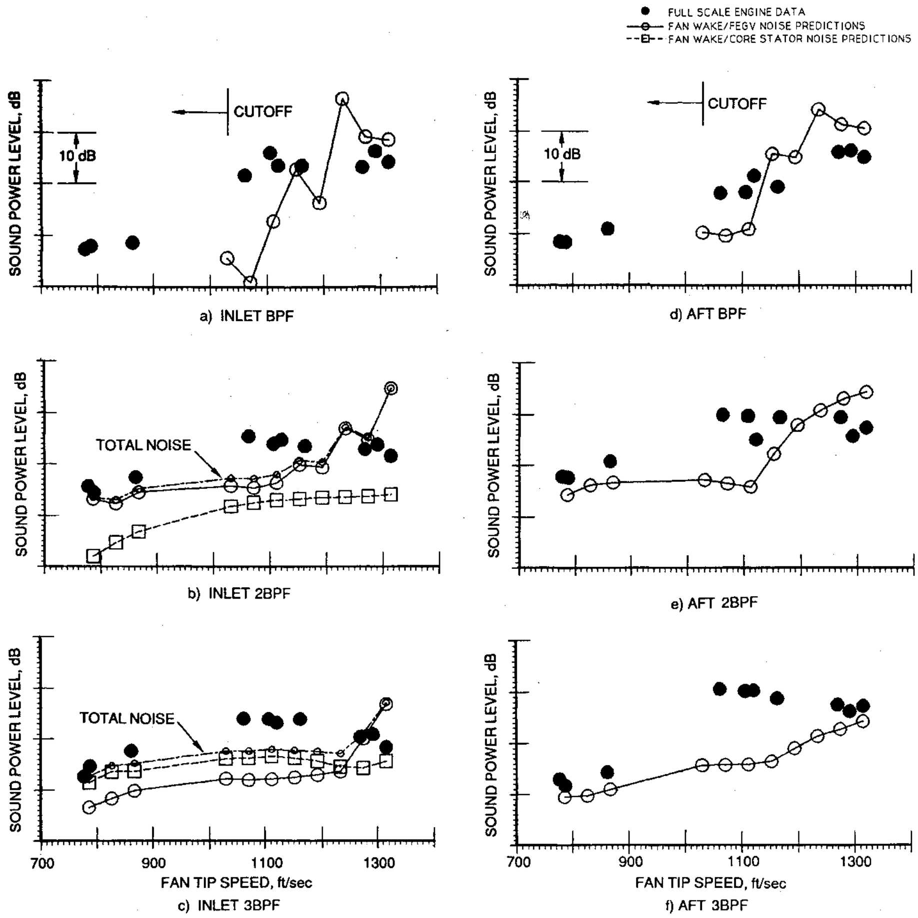


Fig. 10 Full-scale engine prediction vs data calibrated results: wake width is 50% of prediction.

the wave reflection mechanism is not important. In the midspeed range, where the reflection mechanism is important, predictions do not agree with data, as would also be expected.

In the inlet, fan wake/core stator interaction noise does not exist at BPF. This is due to the fact that over most of the speed range this source is cutoff at BPF. At high speeds when it does cuton, however, the propagating radial mode shapes in the inlet duct are of zero amplitude along the core stator span. Thus, these acoustic modes do not couple with the unsteady pressures on the vane for this tone, yielding zero noise from this noise source at BPF.

Observe, however, that for inlet 2BPF and 3BPF, rotor wake/core stator interaction noise is seen to be an increasingly important noise source. This is due to the close fan-to-core stator spacing which causes the higher harmonic wake harmonic magnitudes to become important. In addition, a number of radial modes propagate in the duct which couple efficiently with the unsteady core stator pressures. When the two noise sources (i.e., FEGV and core stator) are added together, some small improvement in the data-prediction comparisons is observed, but inlet noise results are still somewhat underpredicted. This may be due again to wake model deficiencies or possibly to other assumptions in the analysis. In addition, only two of the possible engine noise sources are taken into account. It is not known for sure what other noise sources are important in this situation. Thus, the results from these comparisons show that the calibrated prediction system seems to give some mixed results while predicting engine noise for this engine.

Concluding Remarks

A rotor wake/stator interaction theory was compared and calibrated with two fan rigs and a full-scale engine. Based on these evaluations, the following conclusions can be made:

1) The program shows promise of giving reasonable predicted levels for inlet and aft tone power levels emanating from fan/FEGV and fan/core stator interactions.

2) For an empirical wake model, the choice of wake profile shape can be important in predicting the higher harmonics of the tone noise. The hyperbolic secant profile worked better than the Gaussian profile for these predictions due to its more representative wake harmonic structure.

3) For a flat plate cascade dipole calculation, the choice of vane stagger angle is up to the user. The choice can be important in calculating the tone noise results.

4) Based on the ADP and powered nacelle scaled fan noise predictions, it is apparent that a more accurate wake model is needed which properly accounts for the effects of important geometry and performance variables.

5) A fan cascade transmission/reflection model should be added to this rotor wake/stator interaction model to account for these effects, including the scattering of energy by the fan from one fan tone to another.

6) The differences between the cutoff and cuton ADP vane/blade ratio results indicate the need to further enhance the vane response and/or noise calculations. These enhancements might include 1) to some degree, the effect of swirl flow on noise propagation; 2) real airfoil geometry and camber in the vane response calculation; and 3) creating a three-dimensional lifting surface theory to replace the strip theory vane response calculation.

References

[1]Gliebe, P. R., and Kantola, R. A., "Effects of Vane/Blade Ratio and Spacing on Fan Noise," NASA CR-174664, Dec. 1983.

[2]Kobayashi, H., "Three-Dimensional Effects on Pure Tone Fan Noise Due to Inflow Distortion," AIAA Paper 78-1120, July 1978.

[3]Kobayashi, H., and Groeneweg, J. F., "Effects of Inflow Distortion Profiles on Fan Tone Noise," *AIAA Journal*, Vol. 18, No. 8, 1980, pp. 899–906.

[4]Ventres, C. S., Theobald, M. A., and Mark, W. D., "Turbofan Noise Generation," NASA-CR-167952, Vols. 1 and 2, July 1982.

[5]Mugridge, B. D., and Morfey, C. L., "Sources of Noise in Axial Flow Fans," *Journal of the Acoustical Society of America*, Vol. 51, No. 5 (Pt. 1), 1972, pp. 1411–1426.

[6]Majjigi, R. K., and Gliebe, P. R., "Development of a Rotor Wake/Vortex Model," NASA CR-174849, Vol. 1, June 1984.

[7]Reynolds, B., and Lakshminarayana, B., "Characteristics of Lightly Loaded Fan Rotor Blade Wakes," NASA CR-3188, Oct. 1979.

[8]Ravindranath, A., and Lakshminarayana, B., "3D Mean Flow and Turbulence Characteristics of the Near Wake of a Compressor Rotor Blade," NASA CR-159518, June 1980.

[9]Osborne, C., "Compressible Unsteady Interactions between Blade Rows," *AIAA Journal*, Vol. 11, No. 3, 1973, pp. 340–346.

[10]Amiet, R. K., "High Frequency Thin-Airfoil Theory for Subsonic Flow," *AIAA Journal*, Vol. 14, No. 8, 1976, pp. 1076–1082.

[11]Mani, R., "Discrete Frequency Noise Generation from an Axial Flow Fan Blade Row," *Transactions of the American Society of Mechanical Engineers, Journal of Basic Engineering*, Vol. 92, Series D, No. 1, 1970, pp. 37–43.

[12]Namba, M., "Three-Dimensional Analysis of Blade Force and Sound Generation for an Annular Cascade in Distorted Flows," *Journal of Sound and Vibration*, Vol. 50, Feb. 1977, pp. 479–508.

[13]Goldstein, M. E., *Aeroacoustics*, McGraw-Hill, New York, 1976, pp. 222–232.

[14]Kaji, S., "Noncompact Source Effect on the Prediction of Tone Noise from a Fan Rotor," AIAA Paper 75-446, March 1975.

[15]Smith, S. N., "Discrete Frequency Sound Generation in Axial Flow Turbomachines," Aeronautical Research Council Reports and Memoranda 3709, March 1972.

[16]Amiet, R. A., "Refraction of Sound by a Shear Layer," AIAA Paper 77-54, Jan. 1977.

[17]Topol, D. A., Holhubner, S. C., and Mathews, D. C., "A Reflection Mechanism for Aft Fan Tone Noise from Turbofan Engines," AIAA Paper 87-2699, Oct. 1987.

[18]Topol, D. A., "Rotor Wake/Stator Interaction Noise—Predictions Versus Data," AIAA Paper 90-3951, Oct. 1990.