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AEROACOUSTIC EFFECTS OF REDUCED AFT TIP SPEED AT CONSTANT THRUST FOR A MODEL COUNTERROTATION TURBOPROP AT TAKEOFF CONDITIONS

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SUMMARY

A model high-speed, advanced counterrotation propeller, F7/A7, was tested in the NASA Lewis Research Center's 9- by 15-Foot Anechoic Wind Tunnel at simulated takeoff and approach conditions of Mach 0.2. The propeller was operated in a baseline configuration with the forward and aft rotor blade setting angles (36.2° and 35.4°) and forward and aft rotational speeds essentially equal. Two additional configurations were tested with the aft rotor at increased blade setting angles and the rotational speed reduced to achieve overall performance similar to that of the baseline configuration. The aft rotor blade angles were adjusted such that the thrust and power absorption for each rotor remained the same as for the baseline configuration. Acoustic data were taken with an axially translating microphone probe that was attached to the tunnel floor. Concurrent aerodynamic data were taken to define propeller operating conditions. The aft rotor fundamental tone was about 6 dB lower with the 36.2° and 38.4° blade setting angles, and about 9 dB lower with the 36.2° and 41.4° blade setting angles. Predicted noise reductions based on tip speed considerations were 5 and 9.5 dB, respectively, for the two altered blade setting angles.

INTRODUCTION

Modern, high-performance turboprop aircraft offer the promise of considerable fuel savings while still allowing for a cruise speed similar to that of current turbofan aircraft. Advanced counterrotation propellers may offer up to 9-percent additional fuel savings over similar single-rotation propellers at cruise conditions (ref. 1). However, there is considerable concern about the potential noise generated by such aircraft, including both inflight cabin noise and community noise during takeoff and landing. One method of reducing this propeller noise may be to reduce the propeller tip speed while increasing the propeller loading, such that the propeller thrust remains constant. Reference 2 considers possible acoustic effects that may be associated with changes in propeller tip speed.

This paper presents results for the F7/A7 model counterrotation propeller (refs. 3 to 5) that was tested in the NASA Lewis 9- by 15-Foot Anechoic Wind Tunnel. Test results are for takeoff conditions of Mach 0.2. The model propeller was tested in a baseline configuration in which the forward and aft rotor rotational speeds were essentially equal, and in two configurations with increases in the aft rotor blade setting angle and reductions in the aft rotor speed such that the rotor aerodynamic performance remained unchanged from that of the baseline configuration. For each forward rotor speed, the stage thrust and power absorption were essentially the same for all three configurations. This test procedure evaluated the acoustic benefits associated with reduced rotor tip speed while maintaining the same propeller thrust and power. Acoustic results are presented for the first-order rotor-alone tones and for second- and third-order interaction tones. These test results were obtained from the model counterrotation propeller as part of a larger test matrix. Clearly, reduced tip speeds would have to be used for both rotors to achieve significant community noise benefits. However, increased forward rotor blade setting angles would generate increased wakes with correspondingly higher interaction tone levels. The acoustic benefits of reduced tip speeds would also apply to single-rotation propellers.

APPARATUS AND PROCEDURE

The NASA Lewis 9- by 15-Foot Anechoic Wind Tunnel is located in the low-speed return leg of the supersonic 8- by 6-Foot Wind Tunnel. The tunnel has a maximum airflow velocity of slightly over Mach 0.2, which provides a takeoff and approach test environment. The acoustic tests presented herein were conducted at Mach 0.2. The tunnel was acoustically treated to provide anechoic conditions down to a frequency of 250 Hz (ref. 6), which is lower than the range of the fundamental tone produced by the F7/A7 propeller. Figure 1 is a photograph of the model propeller installed in the anechoic wind tunnel.

The model counterrotation propeller designated F7/A7 was used in these experiments. The front rotor was nominally 62.2 cm (24.5 in.) in diameter, and the aft rotor was 60.7 cm (23.9 in.) in diameter. Figure 2 is a photograph of the F7/A7 propeller blades. The tests reported herein were for an 8 + 8 blade configuration. The propeller was operated at the "maximum" rotor spacing of 14.99 cm (5.90 in.) axial distance between the forward and aft rotor pitch change axes. See table I for design characteristics at the cruise condition of Mach 0.72. Additional aerodynamic results for the F7/A7 propeller may be found in references 4, 5, and 7. The propeller installation in the 9- by 15-ft tunnel was powered by two independent air turbine drives, allowing the option of independent rotor operation. The model propeller was operated at a 0° angle of attack for these tests.

Table II shows the propeller operating conditions for the three test configurations. The propeller was tested in a baseline configuration with forward and aft blade setting angles of 36.2° and 35.4°, respectively, in which the aft rotor speed was 100 rpm greater than that of the forward rotor. Two additional configurations were tested with the forward rotor blade setting angle kept at 36.2° and the aft rotor blade setting angle increased to 38.4° and 41.4°. The aft rotor speed was adjusted for these two configurations to obtain the same rotor aerodynamic performance (thrust and power) as were recorded for the baseline configuration.

Acoustic data were taken in the 9- by 15-ft tunnel with an axially translating microphone probe that was fixed to the tunnel floor. This probe traversed 6.50 m (21.33 ft) which covered most of the 8.2-m (27-ft) length of the treated test section. The inner microphone on this probe was located 137 cm (54 in.) from the propeller axis, and the second microphone was located 30 cm (1 ft.) ahead and 30 cm further out from the first microphone. The inner microphone of the translating probe surveyed sideline angles from 18° to 150° relative to the propeller axis of rotation (with 90° referenced to the aft propeller plane). The translating microphone probe is partially visible in the installation photograph of figure 1.

A polar microphone probe which was attached to the downstream propeller housing and could take both sideline and circumferential noise surveys (ref. 3) is also shown in figure 1. However, only limited polar probe data were taken for this blade tip speed investigation, and these data are not used in this report.

RESULTS AND DISCUSSION

All tests were performed at a 0.20 tunnel Mach number, which represents takeoff and landing operation. Aerodynamic results are presented to establish the propeller operating conditions. Acoustic results are presented in terms of maximum tone level along a 137-cm (54-in.) sideline and in terms of tone directivities along that sideline. These results show how tone levels for the aft rotor and overall propeller are affected by reducing the aft rotor speed (while the same rotor thrust and power absorption are maintained by means of increased blade setting angle).

Aerodynamic Performance

Propeller aerodynamic performance results show that reductions in the aft rotor speed (with increased blade setting angle) had a minimal effect on the overall stage performance. Figure 3 is a propeller operating map of the total power density (based on the forward propeller) PQAT as a function of the forward propeller advance ratio J. PQAT is defined as

$$\frac{\text{power}}{(\rho)\ (\text{rev/sec})^3\ (D^3)\ (\text{annulus area})}$$

where ρ is the local air density and D is the propeller diameter. Figure 3 confirms that there is essentially no change in the operating map with the reductions in aft rotor speed.

The forward/aft rotor torque ratio is shown as a function of the forward rotor advance ratio in figure 4. The baseline configuration (β_f/β_a = 36.2°/35.4°) has a torque ratio close to 1.0. The aft rotor operated nominally 100 rpm greater than the forward rotor for the baseline configuration. The configurations with increased aft rotor blade setting angle and reduced rpm show the expected increase in the aft rotor torque.

The aft rotor speed and blade setting angle were adjusted such that the rotor performance was essentially the same as for the baseline configuration. Figure 5 shows that the rotor absorbed power as a function of the aft rotor percent design speed. The forward rotor power, (fig. 5(a)), was unaffected by the changes in the aft rotor blade setting angle. Changes in blade setting angle and rotational speed for the aft rotor resulted in essentially no overall change in absorbed power for this rotor at each forward rotor speed (fig. 5(b)). Figure 6 shows the rotor thrust as a function of the aft rotor percent design speed. Figure 6(a) shows results for the forward rotor, whereas figure 6(b) shows results for the aft rotor. These thrust results are similar to those for the absorbed power of figure 5. They show that the thrust and power absorption for each rotor and for the overall propeller remained essentially unchanged for the three test configurations - especially at higher rotor speeds which are more typical of takeoff conditions.

Sound Pressure Level Spectra

The acoustic spectra for counterrotation propellers may be quite complex, consisting of both rotor-alone tone orders for each propeller and an array of interaction tones. Figure 7 presents a typical sound pressure level (SPL) spectra for the F7/A7 propeller. This spectrum, which has a bandwidth of 13 Hz, is for a 72° sideline angle. The propeller was operated with blade setting angles of 36.2° and 38.4° and with reduced aft rotor speed. The first-order rotor-alone tones, B_f and B_a, are clearly seen in the spectra. Higher-order rotor-alone tones are essentially below broadband levels. The second-order interaction tone ($B_f + B_a$) and the third-order interaction tones ($B_f + 2B_a$ and $2B_f + B_a$) are more prominent in the spectrum. A difference in the forward and aft rotor speeds is required to separate particular rotor tones within a tone order for a turboprop with equal blade numbers. The aft rotor was operated at about 100 rpm above that of the forward rotor in the baseline configuration which allowed some tone definition with sufficiently fine narrow bandwidth spectral analysis.

First-Order Tone Levels

The first-order tones consist of the forward and aft rotor-alone tones. Figure 8 shows the maximum first-order tone along a 137-cm (54-in.) sideline as a function of total corrected stage thrust. The forward rotor-alone tone level (fig. 8(a)) shows no change for the three test configurations. This was expected since the forward rotor blade setting angle and rotational speed were the same for all three configurations.

The aft rotor-alone tone shows a significant acoustic benefit associated with operation at a higher blade setting angle and reduced speed (fig. 8(b)). Although the amount of tone reduction varies at different thrust (or percent design speed) levels, tone reductions up to 6 dB from the baseline configuration were obtained for the 38.4° aft blade angle configuration, and up to 9 dB for the 41.4° configuration.

Reference 2 presents a discussion on the acoustic effect of the propeller tip speed and number of blades. This reference gives the following Gutin-type analysis for an estimate of the strength of the "m" harmonic for a propeller as

$$mBJ_{mn}\ (0.8M_t mn \sin \Theta)$$

where m is the order of the harmonic, n is the number of blades, M_t is the blade tip rotational Mach number, Θ is the sideline angle relative to the upstream axis of rotation, and $J_n(x)$ is a Bessel function of the first kind of order n and argument x. This expression of the harmonic strength for the rotor-alone tones may be used to give a rough estimate of the expected tone level reduction with reduced rotor tip speed. Applying this expression to the present test configurations gives an estimated reduction for the aft rotor fundamental tone of about 5 dB for the 38.4° blade setting angle configuration and of 9.5 dB for the 41.4° configuration. The results in figure 8(b) for stage thrust levels above 1500 N are reasonably close to this prediction.

The overall fundamental tone level for the F7/A7 propeller includes contributions from both rotors, with much of the tone reduction for the aft rotor with reduced rpm masked by the higher tone levels for the forward rotor. Figure 9 shows the maximum overall fundamental tone level (BPF) observed along the 137-cm sideline. The tone reductions for the reduced aft rotor speed were on the order of 2 dB because of the forward rotor contribution.

Figure 10 shows the SPL directivity for the forward rotor at 90 percent of the design speed along the 137-cm sideline. The directivities for the three test configurations are nearly identical, again showing that the tone level for the forward rotor (which was operated at the same conditions for the three configurations) was not affected by changes in the aft rotor operation.

Figure 11 shows the corresponding SPL sideline directivities for the aft rotor. The aft rotor SPL directivity with the forward rotor at 90 percent of the design speed (fig. 11(a)) shows the reduction in peak tone level that was plotted in figure 8(b). In addition, the tonal energy for the reduced speed, increased blade-setting-angle configurations is significantly reduced from that for the baseline configuration. That is, the angular region of high tone level is much less when the rotor is operated at a reduced rpm and higher blade setting angle. This observation suggests that lower propeller tip speed operation could affect the fly-over signature of an advanced turboprop aircraft, lowering time-weighted noise measurements. Similar results are seen for the forward rotor at 85, 80, and 75 percent of the design speed (fig. 11(b) to (d)).

Second-Order Tone Levels

The second-order and higher rotor-alone tones are much lower than the fundamental tones at takeoff conditions (fig. 7). The rotor-alone tone prediction method of reference 2 predicts that the second-order rotor-alone tone for the 38.4° aft rotor blade angle would be reduced by about 10 dB, whereas that for the higher blade setting angle would be reduced by about 19 dB from that of the baseline configuration based on rotor tip speed considerations. These higher tone orders are controlled by the interaction tone levels. This level is the $B_f + B_a$ tone at 2BPF. Figure 12 shows the maximum second-order tone level along the 137-cm sideline as a function of total corrected stage thrust. The maximum tone level is slightly lower with reduced tip speed, increased blade-setting-angle operation.

Figure 13 shows the 137-cm sideline SPL directivity for the $B_f + B_a$ interaction tone at 90 percent of the forward rotor design speed. Again, there is some indication that reduced tip speed operation will reduce the level of this interaction tone.

Third-Order Tone Levels

The third-order tone level for the F7/A7 propeller is controlled by the two interaction tones, $B_f + 2B_a$ and $2B_f + B_a$. Figure 14 shows the 137-cm sideline directivities for these two tone orders at 90 percent of the forward rotor design speed. Because of the small rotational speed difference and the

8 + 8 blading of the F7/A7 propeller, it was impossible to separate these two tones for the baseline configuration. Figure 14 shows the directivities for the 38.4° and 41.4° aft rotor blade angle configurations, which should still give some indication of the effect of these operational changes. The $2B_f + B_a$ tone (fig. 14(a)) shows a reduction of about 6 dB when the aft rotor blade angle is increased. The $B_f + 2B_a$ tone shows essentially no change in level between these two propeller configurations.

There has been some uncertainty as to the interaction tone generation mechanism for counterrotation propellers, although it is generally thought that these tones are generated at the aft rotor through its interaction with the forward rotor wakes. The results of figure 14 suggest that the two third-order interaction tones may arise from different generation mechanisms. Since only the blade setting angle of the aft rotor was changed in these tests (along with its rotational speed), these results suggest that the $2B_f + B_a$ tone is indeed generated at the aft rotor. However, the relative insensitivity of the $B_f + 2B_a$ tone to these aft rotor changes suggests that its generation mechanism is somehow different from that of the $2B_f + B_a$ tone.

The maximum 137-cm sideline SPL levels for these two interaction tones are plotted as a function of total stage thrust in figure 15. These results are similar to those of figure 14 in that the $2B_f + B_a$ tone level (fig. 15(a)) is lower for the 41.4° aft rotor blade angle configuration at all test speeds, whereas the maximum level for the $B_f + 2B_a$ tone (fig. 14(b)) was insensitive to changes in the aft rotor operating condition.

SUMMARY OF RESULTS

An advanced model counterrotation propeller was operated in a baseline configuration and in two configurations with increased aft rotor blade setting angles and concurrent reduction in aft rotor speeds. These changes were such that the absorbed power and thrust for each rotor remained essentially unchanged for a particular forward rotor speed. These tests were performed in the NASA Lewis 9- by 15-Foot Anechoic Wind Tunnel at takeoff conditions of Mach 0.2. The 8 + 8 blade propeller was tested in a baseline configuration with 36.2° and 35.4° forward and aft blade setting angles, respectively, and with the aft rotor turning 100 rpm faster than the forward rotor. The forward rotor blade setting angle was the same for all three configurations, and the remaining two configurations consisted of increasing the aft rotor blade setting angle to 38.4° and 41.4°. The aft rotor speed was decreased for these two configurations such that the aft rotor thrust, overall propeller thrust, and total power absorption remained essentially the same as those measured for the baseline configuration at each forward rotor test speed. Acoustic data were taken in the wind tunnel with a traversing microphone probe located 137 cm (54 in.) from the propeller axis. All tests were with the propeller at a 0° propeller axis angle of attack.

The following significant results were observed in this study:

1. A significant reduction in the fundamental aft rotor-alone tone was associated with operation at reduced rpm and increased blade setting angles. The maximum sideline tone reduction was up to 6 dB with the 38.4° aft rotor blade angle configuration and to 9 dB with the 41.4° aft rotor blade angle configuration.

2. A Gutin-type analysis based on rotor tip speed predicted a BPF tone reduction of about 5 dB for the 38.4° aft rotor blade angle configuration and of 9.5 dB for the 41.4° configuration.

3. First-order, rotor-alone tone sideline directivities for the aft rotor showed a substantial decrease in tone energy with reduced rpm operation.

4. The $B_f + B_a$ interaction tone showed a modest decrease with reduced aft rotor rpm operation at some thrust levels. (The 2BPF rotor-alone tones were often below broadband levels and thus could not be isolated for analysis.)

5. The third-order $2B_f + B_a$ interaction tone was clearly reduced by lower aft rotor speed, whereas the other third-order interaction tone, $B_f + 2B_a$ was unaffected by these changes. These results suggest that these two interaction tones were generated by different mechanisms.

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TABLE I. - DESIGN CHARACTERISTICS OF F7/A7 COUNTERROTATION PROPELLER

Design characteristic	Forward propeller	Aft propeller
Number of blades	8	8
Design cruise Mach number	0.72	0.72
Nominal diameter, cm (in.)	62.2 (24.5)	60.7 (23.9)
Nominal design cruise tip speed, m/sec (ft/sec)	238 (780)	238 (780)
Nominal design advance ratio	2.82	2.82
Hub-to-tip ratio	0.42	0.42
Geometric tip sweep, deg	34	31
Activity factor	150	150
Design power coefficient based on annulus area	4.16	4.16

TABLE II. - PROPELLER OPERATING CONDITIONS

Blade setting angle for aft rotor,[a] deg	Forward rotor speed, percent of design speed	Speed, rpm		Advance ratio for forward rotor, J
		Forward rotor	Aft rotor	
35.4	65	5515	5615	1.197
	70	5940	6040	1.113
	75	6370	6470	1.041
	80	6800	6900	.972
	85	7200	7300	.914
	90	7640	7740	.863
	95	8080	8180	.818
38.4	65	5520	5170	1.196
	70	5940	5530	1.114
	75	6390	5950	1.038
	80	6810	6380	.974
	85	7200	6690	.915
	90	7610	7120	.862
	95	8041	7520	.820
41.4	70	5950	5140	1.114
	75	6380	5520	1.039
	80	6800	5900	.972
	85	7240	6260	.915
	90	7650	6630	.866

[a]Blade setting angle for forward rotor, 36.2° (for all tests).

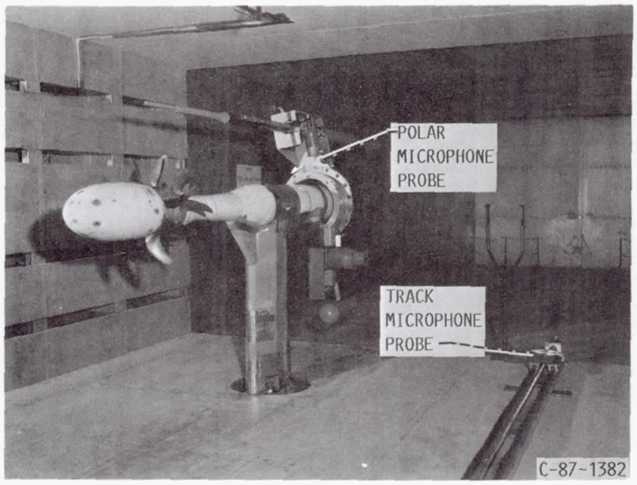

FIGURE 1. - F7/A7 MODEL COUNTERROTATION PROPELLER INSTALLED IN THE NASA LEWIS 9- BY 15-FOOT ANECHOIC WIND TUNNEL.

FIGURE 2. - F7 AND A7 PROPELLER BLADES.

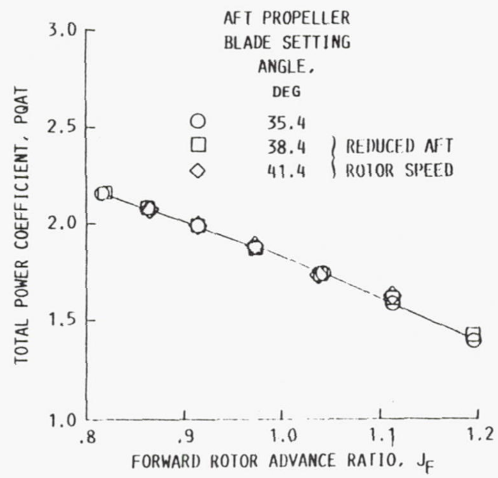

FIGURE 3. - PROPELLER OPERATING MAP. F7/A7 PROPELLER; 8+8 BLADES; MACH 0.2; BLADE SETTING ANGLE FOR FORWARD PROPELLER, 36.2°; ANGLE OF ATTACK, 0°.

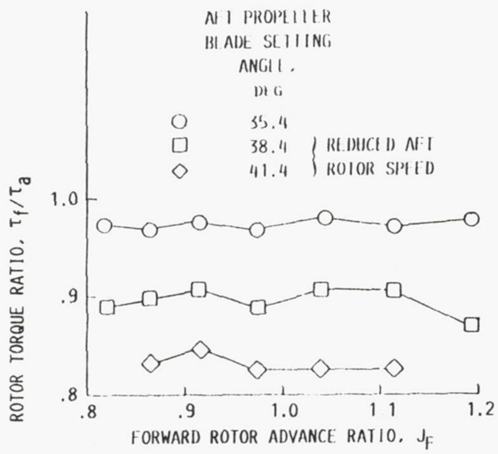

FIGURE 4. - FORWARD/AFT ROTOR TORQUE RATIO AS FUNCTION OF ADVANCE RATIO. F7/A7 PROPELLER; 8+8 BLADES; MACH 0.2; BLADE SETTING ANGLE FOR FORWARD PROPELLER, 36.2°; ANGLE OF ATTACK, 0°.

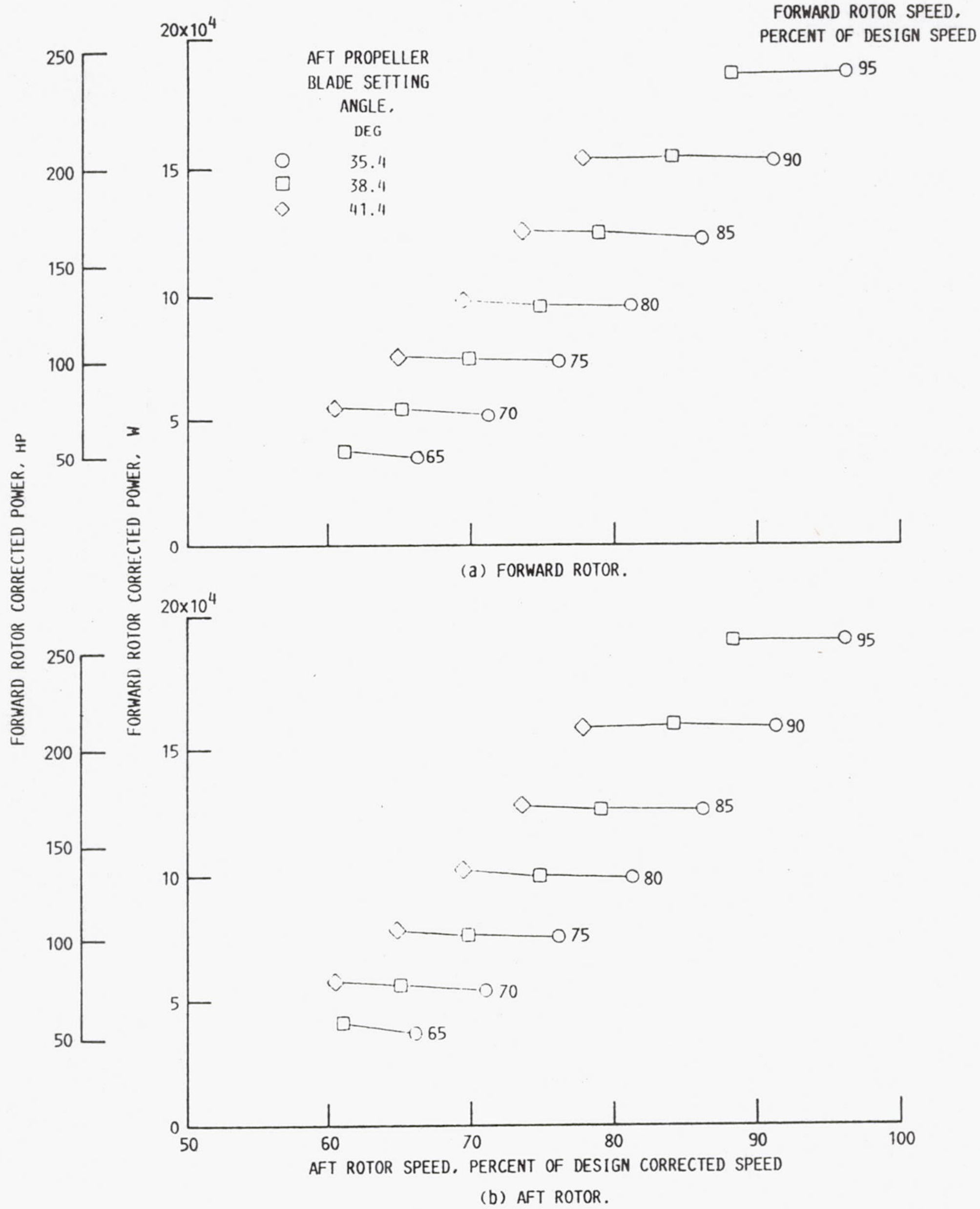

FIGURE 5. - ROTOR POWER AS FUNCTION OF AFT ROTOR PERCENT OF DESIGN SPEED. BLADE SETTING ANGLE FOR FORWARD PROPELLER, 36.2°.

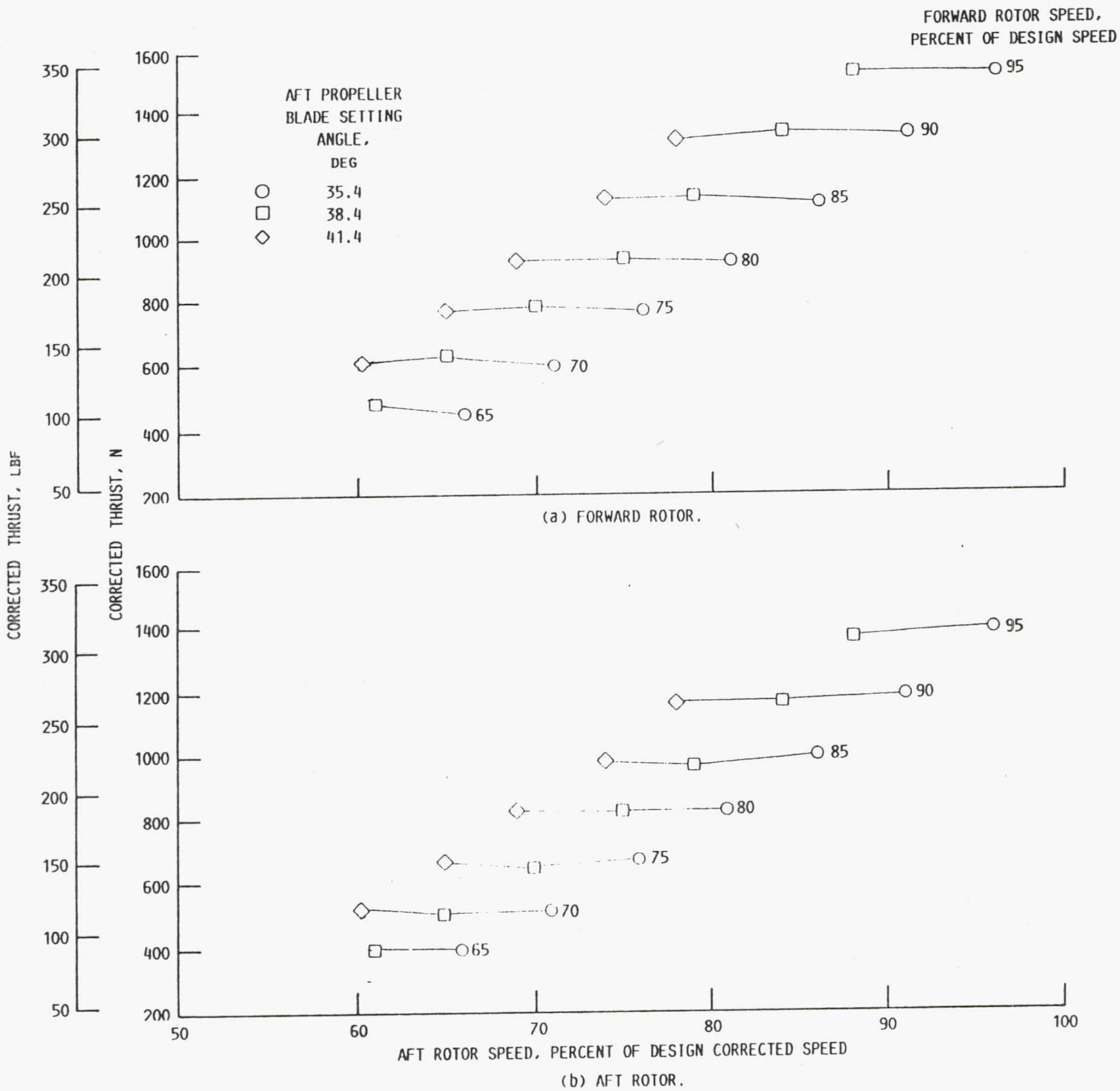

FIGURE 6. - ROTOR THRUST AS FUNCTION OF AFT ROTOR SPEED. BLADE SETTING ANGLE FOR FORWARD PROPELLER, 36.2°.

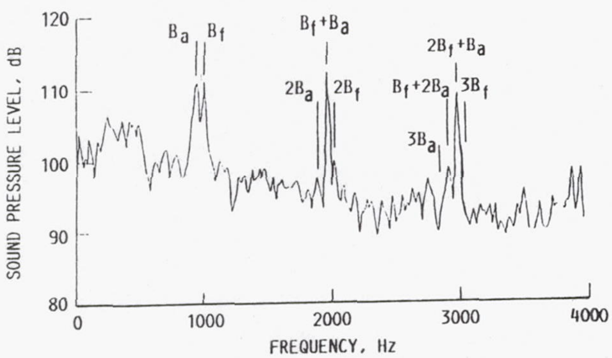

FIGURE 7. - TYPICAL SOUND PRESSURE LEVEL SPECTRUM. F7/A7 PROPELLER; 8+8 BLADES; MACH 0.2; BLADE SETTING ANGLE FOR FORWARD PROPELLER, β_f, 36.2^{o}; BLADE SETTING ANGLE FOR AFT PROPELLER, β_a, 38.4^{o}; SPEED OF FORWARD PROPELLER, 7610 RPM; SPEED OF AFT PROPELLER, 7120 RPM; SIDELINE DISTANCE, 137 CM (54 IN.); SIDELINE ANGLE FROM UPSTREAM PROPELLER AXIS, θ, 72^{o}; ANGLE OF ATTACK, 0^{o}.

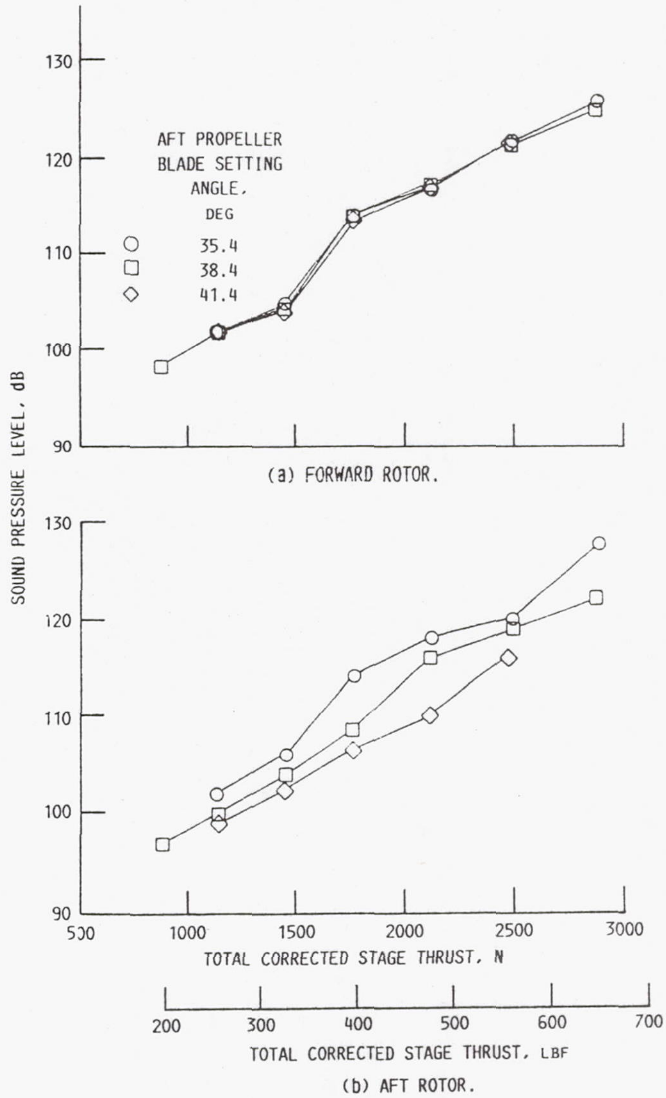

FIGURE 8. - MAXIMUM FIRST-ORDER (BPF) ROTOR-ALONE TONE ALONG 137-CM (54-IN.) SIDELINE. F7/A7 PROPELLER; 8+8 BLADES; MACH 0.2; BLADE SETTING ANGLE FOR FORWARD PROPELLER, 36.2^{o}; ANGLE OF ATTACK, 0^{o}.

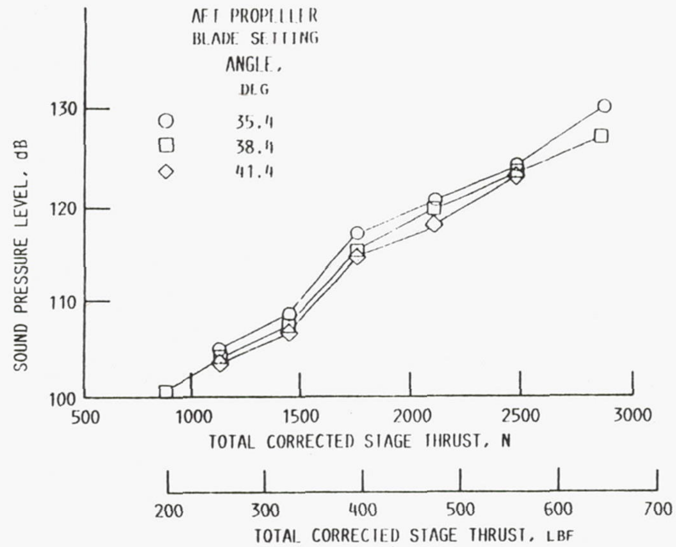

FIGURE 9. - MAXIMUM FIRST-ORDER (BPF) OVERALL TONE LEVEL (SUM OF FORWARD AND AFT TONES) ALONG 137-CM (54-IN.) SIDELINE. F7/A7 PROPELLER; 8+8 BLADES; MACH 0.2; ANGLE OF ATTACK, 0°.

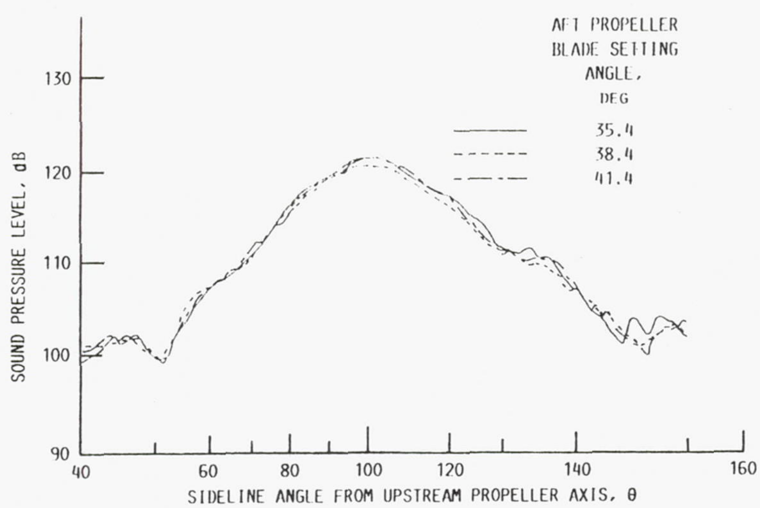

FIGURE 10. - FIRST-ORDER, FORWARD ROTOR (BPF_f) TONE DIRECTIVITY ALONG 137-CM (54-IN.) SIDELINE. 90-PERCENT FORWARD ROTOR DESIGN SPEED; MACH 0.2; BLADE SETTING ANGLE FOR FORWARD PROPELLER, 36.2°.

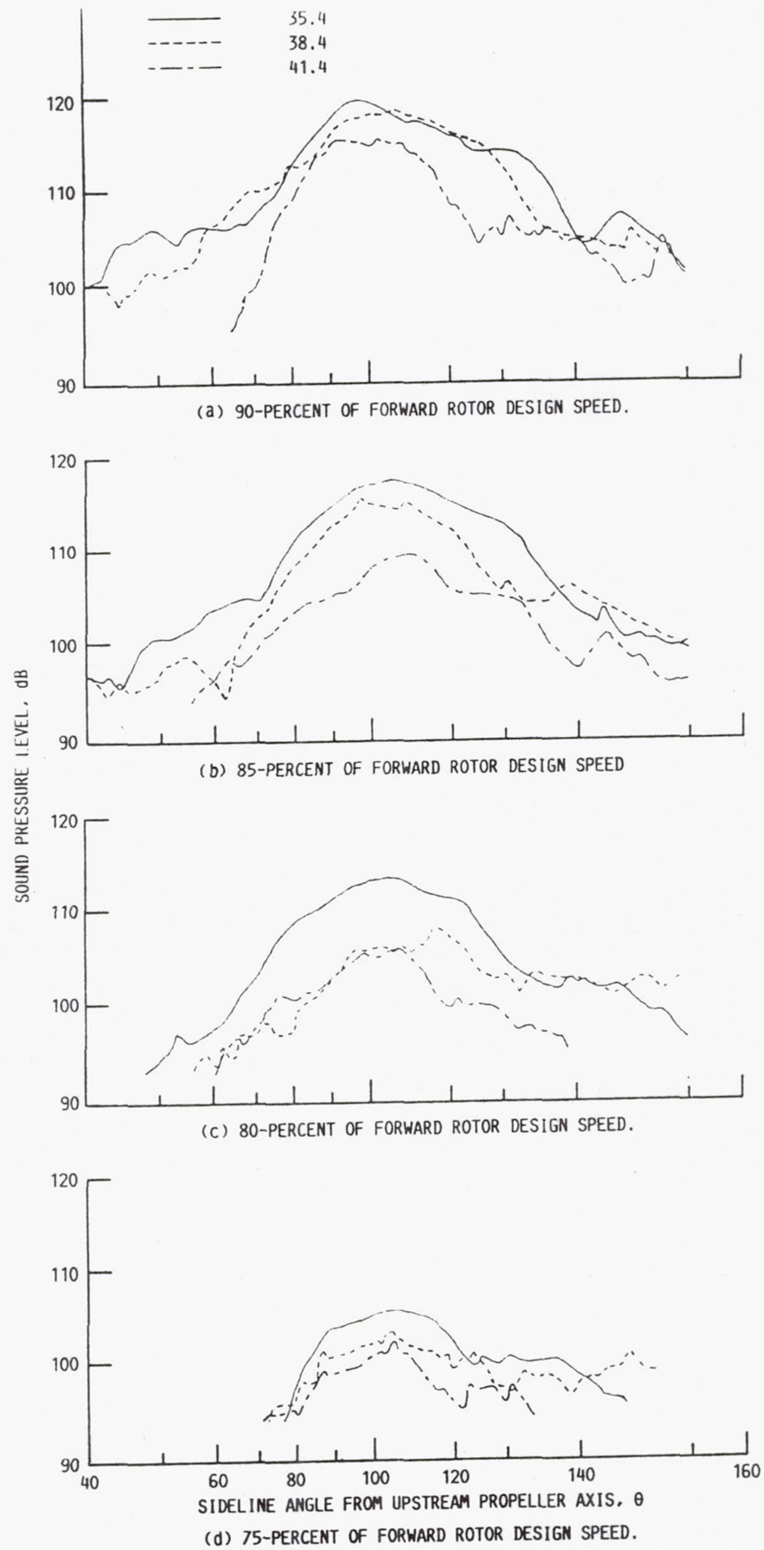

FIGURE 11. - FIRST-ORDER, AFT ROTOR (BPF_a) TONE DIRECTIVITY ALONG 137-CM (54-IN.) SIDELINE.

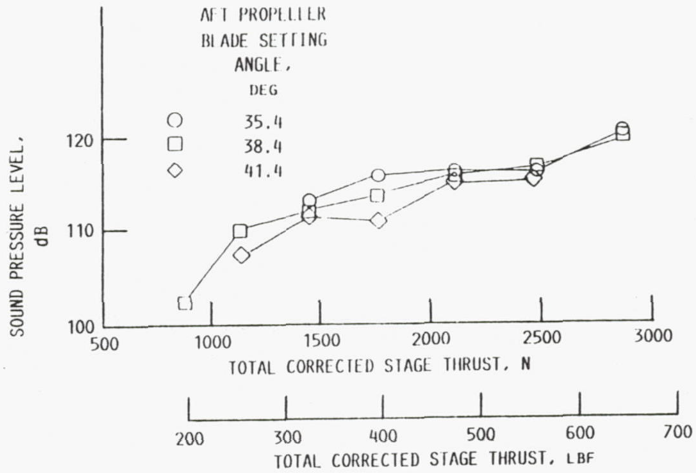

FIGURE 12. - MAXIMUM SECOND-ORDER (2BPF) TONE LEVEL (SUM OF ALL TONES CONTROLLED BY INTERACTION TONE) ALONG 137-CM (54-IN.) SIDELINE. F7/A7 PROPELLER; 8+8 BLADES; MACH 0.2; BLADE SETTING ANGLE FOR FORWARD PROPELLER, 36.2^{0}; ANGLE OF ATTACK, 0^{0}.

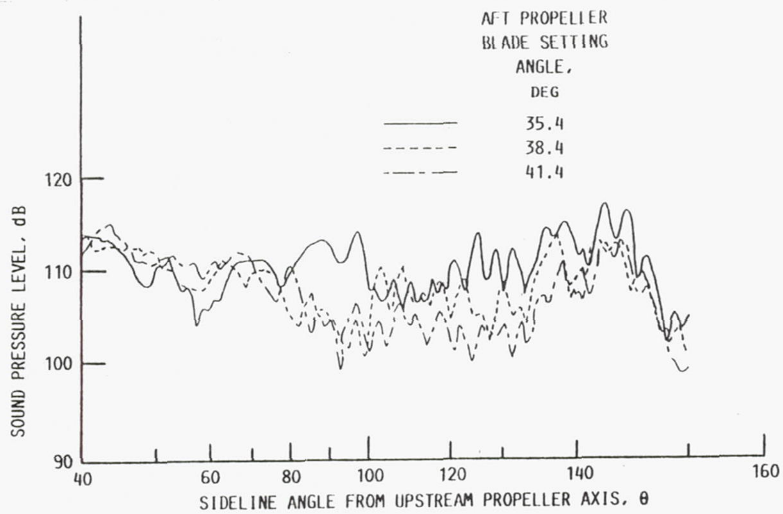

FIGURE 13. - B_f+B_a INTERACTION TONE DIRECTIVITY ALONG 137-CM (54-IN.) SIDELINE. 90-PERCENT OF FORWARD ROTOR DESIGN SPEED; MACH 0.2; BLADE SETTING ANGLE FOR FORWARD PROPELLER, 36.2^{0}.

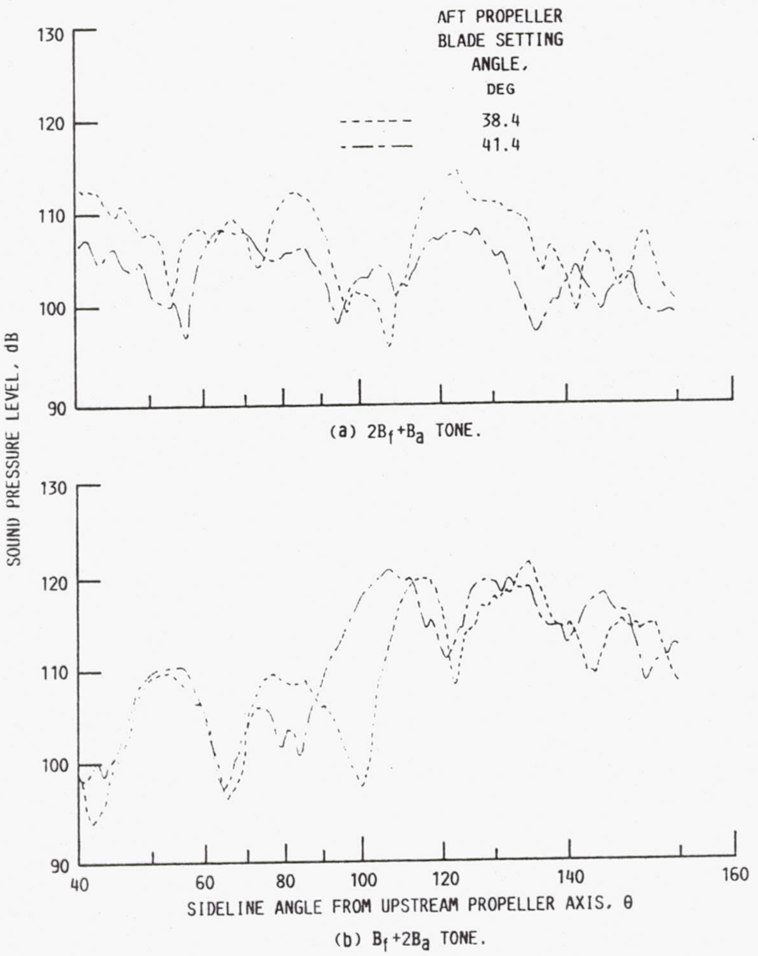

FIGURE 14. - THIRD-ORDER INTERACTION TONE DIRECTIVITY ALONG 137-CM (54-IN.) SIDELINE. 90-PERCENT OF FORWARD ROTOR DESIGN SPEED; MACH 0.2; BLADE SETTING ANGLE FOR FORWARD PROPELLER, 36.2°.

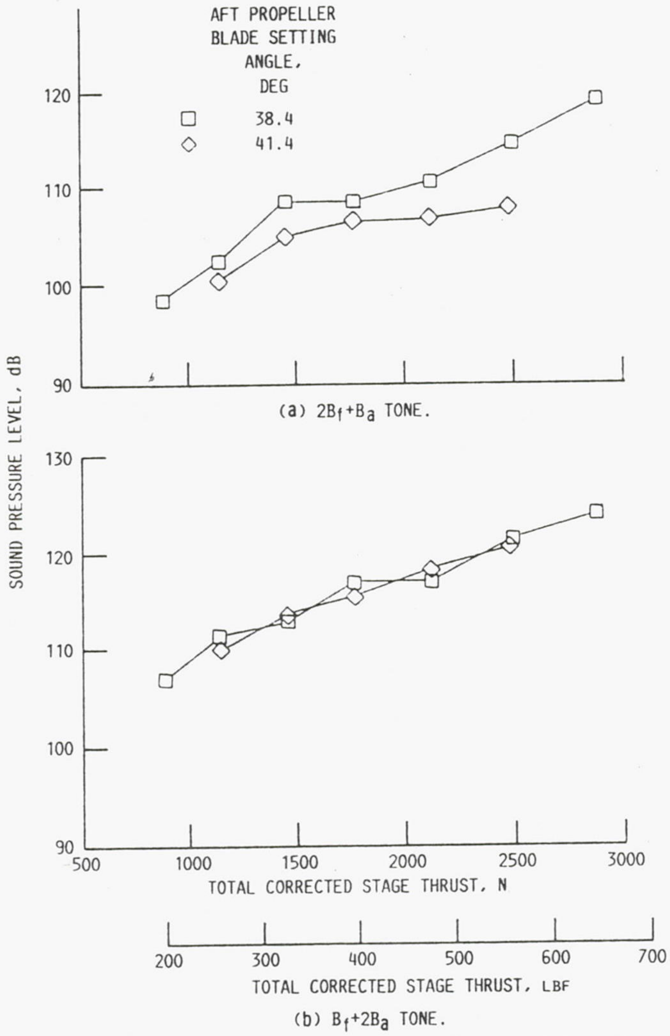

FIGURE 15. - MAXIMUM THIRD-ORDER INTERACTION TONE ALONG 137-CM (54-IN.) SIDELINE. F7/A7 PROPELLER; 8+8 BLADES; MACH 0.2; BLADE SETTING ANGLE FOR FORWARD PROPELLER, 36.2^{o}; ANGLE OF ATTACK, 0^{o}.

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16. Abstract

A model high-speed, advanced counterrotation propeller, F7/A7, was tested in the NASA Lewis Research Center's 9- by 15-Foot Anechoic Wind Tunnel at simulated takeoff and approach conditions of Mach 0.2. The propeller was operated in a baseline configuration with the forward and aft rotor blade setting angles (36.2° and 35.4°) and forward and aft rotational speeds essentially equal. Two additional configurations were tested with the aft rotor at increased blade setting angles and the rotational speed reduced to achieve overall performance similar to that of the baseline configuration. The aft rotor blade angles were adjusted such that the thrust and power absorption for each rotor remained the same as for the baseline configuration. Acoustic data were taken with an axially translating microphone probe that was attached to the tunnel floor. Concurrent aerodynamic data were taken to define propeller operating conditions. The aft rotor fundamental tone was about 6 dB lower with the 36.2° and 38.4° blade setting angles, and about 9 dB lower with the 36.2° and 41.4° blade setting angles. Predicted noise reductions based on tip speed considerations were 5 and 9.5 dB, respectively, for the two altered blade setting angles.

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