NASA Technical Memorandum 101329

The Effect of Front-to-Rear Propeller Spacing on the Interaction Noise at Cruise Conditions of a Model Counterrotation Propeller Having a Reduced Diameter Aft Propeller

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E-4340

SUMMARY

The effect of forward-to-aft propeller spacing on the interaction noise of a counterrotation propeller with reduced aft diameter was measured at cruise conditions. In general, the tones at 100 percent speed decreased from close to nominal spacing as expected from a wake decay model. However, when the spacing was further increased to the far position, the noise did not decrease as expected and in some cases increased. The behavior at the far spacing was attributed to changing forward propeller performance, which produced larger wakes. The results of this experiment indicate that a simple wake decay model is sufficient to describe the behavior of the interaction noise only if the aerodynamic coupling of the two propellers does not change with spacing. If significant coupling occurs such that the loading of the forward propeller is altered, the interaction noise does not necessarily decrease with larger forward-to-aft propeller spacing.

INTRODUCTION

The noise generated by advanced fuel-conservative turboprops may create a cabin environment problem under cruise conditions. An extra noise mechanism exists for counterrotation propellers that does not exist for single-rotation propellers: namely, the interactions of the forward and aft propeller flows. As discussed in reference 1, these interaction noise sources can be from the potential field interaction of the two propellers or from the forward propeller wakes and vortexes striking the aft propeller. The wake and vortex interactions are assumed to be stronger noise sources than the potential field interactions for the range of spacings examined in this experiment.

A typical spectrum from a counterrotation propeller, with different forward and aft propeller speeds or blade numbers, may look as in figure 1. Each propeller exhibits a blade passage tone and its harmonics (BPF_1, $2BPF_1$, $3BPF_1$, . . ., and BPF_2, $2BPF_2$, $3BPF_2$,. . .). The noise generated by the interaction mechanisms appears at sums of the blade passage frequencies of the two propellers. The first interaction tone in the spectrum occurs at $BPF_1 + BPF_2$, with others at $2BPF_1 + BPF_2$, $BPF_1 + 2BPF_2$, $3BPF_1 + BPF_2$,. . . .

Reference 1 has indicated that the interaction noise of a counterrotation propeller might be reduced by increasing the spacing between the forward and aft propellers. The theoretical reductions in noise level for two of the mechanisms, wake and vortex interactions, are presented in reference 1 and shown here in figure 2. Both mechanisms show decay with spacing, with the wake decay being more rapid.

The curves in figure 2 were drawn from equations describing the decay of the wakes and vortexes behind isolated airfoils. For example, the wake decay was indicated as

$$\frac{V}{V_F} = \frac{2.42\sqrt{C_D}}{\frac{X}{C_R} + 0.3} \qquad (1)$$

where V is the maximum velocity defect in the wakes, V_F is the free-stream velocity, C_D is the drag coefficient, X is the distance downstream, and C_R is the airfoil chord.

A model counterrotation propeller, F7-A7, was previously tested for spacing effects at the cruise condition. These results are reported in reference 2. (Some spacing noise results at the takeoff condition can be found in references 3 and 4.) Reference 2 indicates wake decay noise reductions with spacing at an axial Mach number of 0.8, but the data do not behave as expected at Mach numbers 0.76 and 0.72. The data trends at these lower Mach numbers are explained by various amounts of the tip vortex hitting the downstream blade at different spacings.

In an attempt to remove this vortex interaction as a noise source, the F7 forward blades were tested in this experiment with a set of reduced-diameter aft blades, A3, so that the tip vortexes from the forward blades would pass outboard of the reduced-diameter aft blades. This counterrotation propeller, with a reduced-diameter aft rotor, was tested with three forward-to-aft propeller spacings in the NASA Lewis Research Center 8- by 6-ft wind tunnel. This paper presents the effect of these spacing variations on the propeller noise.

APPARATUS AND PROCEDURE

Propeller

A counterrotation propeller model, designated F7-A3, was used for these spacing experiments. The counterrotation test rig in the NASA Lewis 8- by

6-ft wind tunnel is shown in figure 3(a), and the F7-A3 blades are shown in figure 3(b). The forward propeller, F7, is nominally 62.2 cm (24.5 in.) in diameter, and the aft propeller, A3, is nominally 53.1 cm (20.9 in.) in diameter. The design characteristics of the propeller are listed in table I. The propeller was tested here with nine forward propeller blades and eight aft propeller blades. For these experiments, the propeller blade angles measured with respect to the plane of rotation at the three-quarter radius location were set at 59° for the forward propeller and 58° for the aft propeller. The design rotational tip speed (100 percent speed) is 283 m/sec (780 ft/ sec) for the front rotor, and 241 m/sec (665 ft/sec) for the aft rotor.

Acoustic Measurements

The noise of the F7-A3 propeller was measured in the NASA Lewis 8- by 6-ft wind tunnel by using pressure transducers embedded in a plate suspended from the ceiling. The plate is able to translate up and down from the tunnel ceiling and was positioned 0.3 diameters (front propeller) or 18.7 cm (7.35 in.) above the forward propeller tips for these experiments. Figure 4(a) shows a sketch of the wind tunnel and translating plate. Figure 4(b) shows a photograph of this ceiling plate above the counterrotation propeller test rig (F7-A7 propeller).

Seventeen transducers were embedded along the centerline of the plate at the positions shown in figure 5. At the plate location tested, 11 transducers were active (1, 2, 4, 6, 8, 9, 10, 12, 14, 16, and 17 in fig. 5.) The plate was located for all of these spacing tests with transducer 9 directly above the pitch change axis of the aft propeller. The front-to-rear spacing is changed by moving the forward propeller so that the plate remained fixed with respect to both the aft propeller pitch change axis and the tunnel. The transducer angles, measured from upstream, ranged from 47° for transducer 1 to 133° for transducer 17, with transducer 9 in the aft propeller plane at 90°.

The propeller had nine blades on the front rotor and eight blades on the aft rotor. The different blade numbers, with the propellers operating at approximately equal revolutions per minute, enable the tones from the two propellers to be separated by using narrowband analysis. The noise data were reduced on a narrowband analyzer by using 0 to 5000 Hz spectra with a 16-Hz bandwidth.

Operating Conditions and Spacing Variations

The tunnel was operated at four axial Mach numbers (0.80, 0.76, 0.72, and 0.67). The propeller was operated at 100 percent and 90 percent speed for 0.80, 0.76, and 0.72 Mach numbers and at 95 percent and 90 percent speed for 0.67 Mach number. Detailed aerodynamic data at the conditions tested are presented in table II.

The propeller was tested at three forward-to-aft propeller spacings for each tunnel operating condition. At the closest position the pitch change axes were 8.57 cm (3.38 in.) apart, at the nominal position 10.64 cm (4.19 in.) apart, and at the far position 14.92 cm (5.88 in.) apart. Figure 6 shows the dimensions for the three spacings and includes some axial measurements from the trailing edge of the forward propeller to the leading edge of the aft propeller.

RESULTS AND DISCUSSIONS

Noise data were obtained for the propeller at three forward-to-aft propeller spacings at two speed settings with four tunnel axial Mach numbers. The interaction tone data for the first three tones (tones at $BPF_{F7} + BPF_{A3}$,

$2BPF_{F7} + BPF_{A3}$, and $BPF_{F7} + 2BPF_{A3}$) are presented in tables III to V. The interaction tone noise variations at the higher speed setting are presented first.

Noise Variation with Spacing at 100 Percent Speed

Tone at $BPF_{F7} + BPF_{A3}$. - The interaction noise directivities for the first interaction tone are shown in figure 7 at 100 percent speed except at the lowest Mach number tested (0.67) where speed was 95 percent. Parts (a) to (d) are for 0.8, 0.76, 0.72, and 0.67, Mach numbers respectively. At some of the angles, particularly toward the front, the noise was not plotted because the level of the tone was below the tunnel background level. In general the noise decreased in going from the close spacing to the nominal spacing. However, the noise did not decrease at the far spacing, and in some cases it increased, unexpectedly. Figure 8 shows a plot of the maximum sideline level for the $BPF_{F7} + BPF_{A3}$ tone versus spacing. In general, with the exception of the 0.72 Mach number test, the maximum noise decreased approximately 3 dB in going from close to nominal and then increased or stayed the same at the far position. This figure plots noise versus spacing by using the axial spacing at the tip (dimension C of fig. 6) and the projected tip chord of the F7 propeller in the axial direction. When these dimensions are used in the wake decay model of reference 1 (shown in this report as eq. (1)), the noise is predicted to decrease 3 dB when the spacing is increased from close to nominal position. If the dimensions at the hub are used (dimension B), the noise is predicted to decrease approximately 4 dB from close to nominal position. It appears from this that the propeller is showing the noise reduction expected from wake decay when the spacing is increased from close to nominal. The distance measured along the flow direction may be a better indication of wake or vortex decay than the axial spacing used here. This would yield approximately the same spacing parameter values at each spacing by using the actual aerodynamic chord and would not significantly change the expected noise reductions with each spacing increase.

The wake decay noise reduction model indicates a further noise reduction of 4 dB (5 dB using hub dimensions) when going from nominal to far spacing. As shown in figure 8, this further reduction does not occur. An explanation for this lack of decay may be seen in the aerodynamic data presented in figure 9. Power coefficient based on annulus area, PQA, is plotted versus advance ratio for the front rotor at 0.76 Mach number for the three spacings tested. These data were taken during aerodynamic testing where the propeller was run at many advance ratios. As can be seen, the front propeller operates approximately the same at both the close and nominal spacings, but the power coefficient is significantly higher at the far spacing. Inherent in using equation (1) for the decay of the wake with spacing is that the initial wake is the same. Since the forward propeller loading has increased significantly at the widest spacing, the wakes have undoubtedly charged also. This may yield a larger initial wake, so that the wake impacting the downstream blade at the far spacing is as large or larger than that which came from a smaller initial wake and struck the blade at the close spacing.

The potential aerodynamic interaction between the forward and aft blade rows is composed of both steady and unsteady parts. The unsteady part directly generates interaction noise. This potential interaction noise would decay as the spacing increases and does not explain the lack of reduction at the widest spacing. The steady potential aerodynamic interaction indirectly affects the interaction noise. The steady potential interaction also decreases with spacing. Here the effect of the downstream propeller on the upstream propeller decreases as spacing is increased. In other words, as the spacing is increased the downstream blade does not induce as much velocity through the upstream blade. This results in increased blade angles of attack on the upstream propeller and therefore larger upstream blade loadings at the far spacing. These larger loadings result in increased power coefficients, as shown in figure 9. The higher loading would also have higher drag at the far spacing and possibly larger shock losses, which would result in larger wakes. The larger wakes could then explain the lack of noise decrease at the far spacing. At the takeoff condition for this F7-A3 propeller (ref. 4) the noise decreased with spacing when there was only a minimal change in front propeller loading. This is a further indication that the increase in front propeller loading is probably the cause of the lack of noise reduction at the far spacing in the present investigation.

The increase in the forward propeller wake is probably not uniform from hub to tip but larger at some portions of the span than at others. If it were assumed that the increase is uniform from hub to tip and that, for approximation purposes, the drag coefficient increases in the same proportion as the increase in the power coefficient, an estimate for the noise effect of this uniform wake increase could be made. Near the design condition, the advance ratio $J = 3.0$, the power coefficient goes from 1.8 to 2.0. Using this ratio as the uniform drag coefficient ratio, the wake equation (eq. (1)) can be used to calculate the expected increase in wake strength and noise. This calculation indicates less than 1 dB of noise increase expected from a uniform wake increase. When compared with the expected 4 dB wake decay noise reduction with spacing, this does not appear to be enough to counterbalance the spacing effect. Thus it is likely that the loading increase is localized on the front blade. The wake size increase is then also localized and would be much larger than for the uniform hub-to-tip case. If this localized wake increase hit the downstream blade in a high noise producing region, such as near the tip, it could produce enough extra noise to counterbalance the wake decay noise reduction.

Reference 2, for the F7 front blade tested with the full size aft blade A7, indicated that at some conditions a lack of noise reduction was the result of the tip vortex hitting the downstream blades. This is not the case here at high axial Mach number and high speed. In reference 2 (F7-A7), at the 0.8 Mach number, 100 percent speed condition the data showed wake decay at all spacings; that is, the tip vortex was passing outboard of the A7 tip at these conditions which included the far spacing position. Therefore, with the short aft blades A3, the tip vortex would be passing outboard here also. So the tip vortex is not the cause of the lack of noise decrease at the far spacing for F7-A3 at 0.8 Mach number, 100 percent speed. The increased wake size from the higher loading is the likely cause at the high Mach number, high speed cases. It is possible that the vortex does contact the downstream blade at the lower Mach number, lower speed cases.

The data of reference 2 for F7-A7 at 0.8 Mach number, 100 percent speed and the data here for close to nominal spacing show noise decay with spacing that fits the decay obtained with the wake model (eq. (1)). This indicates that the wake model can be used to predict the decay with spacing in those cases where it can be applied. Inherent in the use of this wake model in predicting the noise reduction with spacing is that the upstream propeller aerodynamic operation is constant. The model is not applicable here with F7-A3 from the nominal to far position because the upsteam propeller conditions have changed.

Tones at $2BPF_{F7} + BPF_{A3}$ and $BFP_{F7} - 2BPF_{A3}$. - In general, the tones at the higher interaction harmonics behaved similarly to the first interaction tone. Figure 10 shows the effect of spacing on the higher interaction harmonics for the 0.76 Mach number, 100 percent speed case. As can be seen, the noise is reduced when going from close to nominal spacing (80° being an exception in fig. 10(a)), but it increases or remains the same when the spacing is increased to the far position. As with the first interaction tone, the reduction of the interaction harmonic from the close to the nominal position is explained by wake decay, while the increase at the far position is attributed to the changed front rotor performance.

Noise Variation with Spacing at 90 Percent Speed

Tone at BPF_{F7} + BPF_{A3}. - The noise directivities for the first interaction tone at 90 percent speed are shown in figure 11 at 0.80, 0.76, 0.72, and 0.67 Mach numbers. For this 90 percent speed data the noise reduction from wake decay is not as apparent as it was at 100 percent speed. In general, the noise remains the same when going from close to nominal spacing and then increases or stays the same at the far spacing. (Again, Mach 0.72 is the exception around 80°). Figure 12 shows the maximum tone level versus spacing. Here the noise remains the same when going from close to nominal spacing, but the noise at far spacing increases for two cases and decreases for two cases. In general, the maximum noise does not decrease with spacing as would be expected. Noise increases at the far spacing are probably the result of increased front propeller loading, which yields larger wakes as explained for the 100 percent speed case. The lack of noise reduction from close to nominal position is not as easily explained since the overall performance of the front rotor is approximately the same at these positions (fig. 9).

It is possible at these part-speed conditions and higher advance ratios that there are some localized changes in the front propeller performance when the spacing is increased from close to nominal. A few sections of the front blade may be operating at a higher loading (higher section power coefficient), but the power coefficient for the entire front blade may not be significantly changed. If this is the case, then the increased wake size from these few sections could counterbalance the general wake decay with distance. As a result, the net noise might remain roughly the same at the close and nominal positions. At the far spacing the affected area on the front blade might be larger or more strongly affected such that the power coefficient for the entire blade is increased and the noise is increased at the far spacing. As mentioned previously in this section it is also possible that the aft blade is being hit by the tip vortex of the forward blade. These results at 90 percent speed further indicate that the interaction noise does not necessarily decrease with spacing. This is apparently due to changes in the disturbance flow field produced by the upstream rotor as the spacing is increased.

Tones at $2BPF_{F7} + BPF_{A3}$ and $BPF_{F7} + 2BPF_{A3}$. - The second and third interaction tones also did not exhibit the expected reductions with spacing. As shown in figure 13(a), the tone at $2BPF_{F7} + BPF_{A3}$ at 90 percent speed behaved similarly to the same tone at 100 percent speed. The noise decreased from close to nominal position, and then remained the same or increased slightly at the far position. The tone at $BPF_{F7} + 2BPF_{A3}$ (fig. 13(b)) goes down at some positions when the spacing increases but goes up at other positions, with the peak noise not changing with spacing. The behavior of the interaction tone harmonics further points out that the noise does not necessarily decrease with larger propeller-to-propeller distances. This is apparently due to changes in forward propeller aerodynamics.

CONCLUDING REMARKS

The effect of forward-to-aft propeller spacing on the interaction noise of a counterrotation propeller having a reduced aft diameter, designated

F7-A3, was measured in the NASA Lewis 8- by 6-ft wind tunnel. Three forward-to-aft spacings were tested at 100 and 90 percent speed for four tunnel axial Mach numbers. The first three interaction tones were measured, that is, those tones at frequencies equal to $BPF_{F7} + BPF_{A3}$, $2BPF_{F7} + BPF_{A3}$, and $BPF_{F7} + 2BPF_{A3}$.

With the reduced-diameter aft blade, the tip vortex from the forward blade was envisioned as not hitting the downstream blade. The interaction tones would then be expected to decrease in the manner of wake decay as the spacing was increased. In general, the tones at 100 percent speed decreased from the close to nominal spacing approximately the amount expected from a wake decay model. This was also shown in reference 2 for the F7-A7 blade at 0.8 Mach number, 100 percent speed. These results indicate that, where the wake model is applicable, the model can be used to predict the noise reduction with increased spacing. However, when the spacing was increased from nominal to far, the noise did not decrease as expected and in some cases increased. An examination of the propeller performance indicated that the front propeller behaved similarly for the close and nominal positions but changed significantly at the far position. This indicated that a larger initial wake may be generated with the propellers at the far spacing. The downstream propeller does not induce as much flow through the front propeller at the far spacing. The result is increased loading of the front propeller, which produces larger wakes. It then becomes necessary to evaluate this aerodynamic coupling of the two propellers before being able to determine the effect of spacing on the interaction noise.

The results at 90 percent speed showed even less decay with spacing. In general, the first interaction tone, $BPF_{F7} + BPF_{A3}$, remained approximately the same from close to nominal position and then increased at the far position.

The results of this experiment indicate that a simple wake decay model is sufficient to describe the behavior of the interaction noise only if aerodynamic coupling of the two propellers does not change with spacing. If significant coupling occurs such that the loading of the forward propeller is altered, the interaction noise does not necessarily decrease with larger forward-to-aft propeller spacing.

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TABLE I. - DESIGN CHARACTERISTICS OF COUNTERROTATION PROPELLER F7-A3

Number of blades	9 by 8
Design cruise Mach number	0.72
Nominal diameter, cm (in.)	
Forward	62.2(24.5)
Aft	53.1 (20.9)
Design advance ratio[a]	
Forward	2.82
Aft	3.29
Tip sweep, deg	
Forward	34
Aft	22
Activity factor[a]	
Forward	150
Aft	243

[a]Based on tip diameter.

TABLE II. EXPERIMENTAL CONDITIONS

Axial Mach Number	Nominal speed percent of design	Forward propeller					Aft propeller					Total power coeffi-cient[a]
		Speed		Advance ratio	Helical tip Mach number	Power coeffi-cient[a]	Speed		Advance ratio[b]	Helical tip Mach number	Power coeffi-cient[c]	
		rpm	Percent of design				rpm	Percent of design				
Close spacing												
0.80	100	8202	100.0	3.11	1.133	1.39	8242	100.4	3.63	1.053	2.64	2.52
.80	90	7400	90.2	3.44	1.079	.97	7447	90.8	4.02	1.011	.77	1.30
.76	100	8200	99.4	2.97	1.102	1.73	8245	100.0	3.47	1.021	3.60	3.27
.76	90	7401	89.8	3.29	1.047	1.32	7448	90.3	3.84	.978	1.94	2.16
.72	100	8249	99.6	2.81	1.077	2.05	8292	100.1	3.28	.993	4.47	3.97
.72	90	7451	89.9	3.10	1.018	1.75	7499	90.5	3.62	.947	2.97	3.02
.67	95	7849	94.2	2.76	1.010	2.28	7902	94.8	3.22	.931	4.60	4.26
.67	90	7500	90.0	2.88	.984	2.14	7551	90.6	3.36	.910	3.91	3.83
Nominal spacing												
0.80	100	8199	99.4	3.12	1.129	1.41	8236	99.8	3.65	1.049	2.34	2.41
.80	90	7399	89.8	3.46	1.077	.94	7439	90.2	4.05	1.010	.44	1.13
.76	100	8249	99.4	2.96	1.100	1.76	8288	99.9	3.46	1.019	3.49	3.25
.76	90	7499	90.4	3.26	1.050	1.35	7540	90.9	3.81	.980	1.96	2.19
.72	100	8348	100.1	2.79	1.079	2.07	8386	100.6	3.26	.994	4.45	3.97
.72	90	7500	90.0	3.10	1.019	1.69	7540	90.4	3.63	.948	2.82	2.90
.67	95	7949	94.8	2.73	1.013	2.32	7991	95.3	3.20	.933	4.69	4.33
.67	90	7501	89.5	2.90	.982	2.08	7542	90.0	3.39	.909	3.74	3.68
Far spacing												
0.80	100	8252	99.6	3.11	1.130	1.61	8289	100.0	3.64	1.050	1.87	2.41
.80	90	7502	90.5	3.42	1.079	1.11	7545	91.0	4.00	1.010	.08	1.14
.76	100	8351	99.9	2.95	1.104	1.94	8409	100.6	3.44	1.023	3.15	3.29
.76	90	7502	89.7	3.28	1.046	1.44	7564	90.5	3.83	.978	1.50	2.09
.72	100	8332	99.2	2.81	1.072	2.22	8389	99.9	3.28	.990	4.10	3.99
.72	90	7532	89.7	3.11	1.017	1.83	7590	90.4	3.62	.947	2.71	3.00
.67	95	7951	94.4	2.75	1.011	2.42	8011	95.1	3.20	.932	4.51	4.37
.67	90	7552	89.6	2.89	.982	2.23	7614	90.4	3.37	.909	3.76	3.85

[a]Based on forward propeller annulus area.
[b]Based on aft propeller diameter.
[c]Based on aft propeller annulus area.

TABLE III. - PROPELLER INTERACTION TONE NOISE AT CLOSE

AXIAL SPACING

Transducer	Sound pressure level of tone, dB		
	Frequency		
	$BPF_{F7} + BPF_{A3}$	$2BPF_{F7} + BPF_{A3}$	$BPF_{F7} + 2BPF_{A3}$
0.8 Mach number, 100 percent speed			
1	(a)	(a)	(a)
2	↓	↓	↓
4	↓	↓	↓
6	↓	↓	↓
8	139.5	137.0	135.0
9	144.0	136.0	141.5
10	142.0	134.0	140.5
12	135.0	133.5	134.5
14	137.0	137.5	131.0
16	132.0	131.5	131.0
17	133.0	134.0	133.5
0.8 Mach number, 90 percent speed			
1	(a)	(a)	(a)
2	↓	↓	↓
4	↓	↓	↓
6	↓	↓	↓
8	137.0	137.0	133.0
9	137.0	132.0	136.0
10	137.5	138.0	138.0
12	134.0	139.0	134.0
14	136.0	139.0	130.5
16	135.0	135.0	134.0
17	(a)	132.5	137.5
0.76 Mach number, 100 percent speed			
1	(a)	(a)	(a)
2	135.0	↓	↓
4	136.5	↓	↓
6	135.0	↓	↓
8	144.5	141.0	140.0
9	146.5	137.0	140.5
10	138.0	139.5	138.5
12	139.0	139.5	131.5
14	142.0	140.0	130.5
16	134.5	135.0	135.5
17	(a)	128.5	138.0
0.76 Mach number, 90 percent speed			
1	(a)	(a)	(a)
2	(a)	↓	↓
4	(a)	↓	↓
6	133.0	↓	↓
8	135.5	137.0	↓
9	133.0	135.0	135.5
10	133.0	133.0	131.5
12	(a)	140.0	132.5
14	↓	140.0	130.5
16	↓	134.0	128.0
17	↓	137.0	132.5

[a]Tone not measurable above tunnel background.

TABLE III. - Concluded.

Transducer	Sound pressure level of tone, dB		
	Frequency		
	$BPF_{F7} + BPF_{A3}$	$2BPF_{F7} + BPF_{A3}$	$BPF_{F7} + 2BPF_{A3}$
0.72 Mach number, 100 percent speed			
1	135.5	(a)	(a)
2	135.5	(a)	↓
4	138.0	(a)	↓
6	141.0	136.0	↓
8	138.5	140.5	139.5
9	141.5	137.0	134.0
10	136.5	139.0	136.0
12	136.5	139.5	136.0
14	134.0	146.0	135.0
16	137.0	140.5	131.0
17	132.0	131.5	131.0
0.72 Mach number, 90 percent speed			
1	134.0	(a)	(a)
2	134.0	↓	↓
4	133.0	↓	↓
6	136.5	↓	↓
8	139.0	138.5	132.0
9	130.5	133.0	131.5
10	132.0	136.5	134.5
12	132.0	141.0	130.5
14	131.5	141.0	132.0
16	131.0	139.5	133.0
17	134.5	142.0	131.5
0.67 Mach number, 95 percent speed			
1	135.5	131.5	(a)
2	138.0	134.5	↓
4	137.0	132.0	↓
6	135.0	134.0	↓
8	145.0	141.0	134.0
9	143.0	141.5	136.0
10	140.0	142.5	131.5
12	134.5	147.0	132.5
14	134.0	151.0	138.5
16	131.0	146.0	137.5
17	140.0	142.0	130.5
0.67 Mach number, 90 percent speed			
1	133.5	(a)	(a)
2	133.5	(a)	↓
4	134.5	(a)	↓
6	136.0	132.0	↓
8	140.0	140.5	133.0
9	133.5	139.0	135.5
10	129.0	136.5	132.0
12	128.5	145.5	130.5
14	132.0	145.5	135.5
16	137.0	138.5	139.0
17	130.5	138.0	131.0

[a]Tone not measurable above tunnel background.

TABLE IV. - PROPELLER INTERACTION TONE NOISE

AT NOMINAL AXIAL SPACING

Transducer	Sound pressure level of tone, dB		
	Frequency		
	$BPF_{F7} + BPF_{A3}$	$2BPF_{F7} + BPF_{A3}$	$BPF_{F7} + 2BPF_{A3}$
0.80 Mach number, 100 percent speed			
1	(a)	(a)	(a)
2	↓	↓	↓
4	↓	↓	↓
6	↓	↓	↓
8	140.0	138.0	136.0
9	139.0	135.5	137.5
10	139.5	133.0	139.5
12	(a)	(a)	138.5
14	133.0	(a)	132.5
16	(a)	(a)	132.5
17	(a)	130.5	133.5
0.80 Mach number, 100 percent speed			
1	(a)	(a)	(a)
2	↓	↓	↓
4	↓	↓	↓
6	↓	↓	↓
8	140.5	133.5	136.5
9	137.5	132.5	133.0
10	138.0	131.5	137.0
12	135.0	133.5	133.5
14	135.0	133.0	132.0
16	133.0	128.5	129.0
17	132.0	128.5	132.0
0.76 Mach number, 100 percent speed			
1	(a)	(a)	(a)
2	136.0	↓	↓
4	135.5	↓	↓
6	134.0	↓	↓
8	143.5	140.5	139.0
9	143.0	136.0	137.0
10	138.5	135.5	137.5
12	134.5	131.5	134.0
14	134.0	131.0	129.5
16	134.5	127.5	128.5
17	136.0	130.5	127.5
0.76 Mach number, 90 percent speed			
1	(a)	(a)	(a)
2	↓	↓	↓
4	↓	↓	↓
6	↓	↓	↓
8	136.0	132.5	↓
9	133.5	135.0	134.5
10	(a)	129.0	131.5
12	132.5	132.5	130.5
14	(a)	128.0	131.5
16	(a)	132.5	131.0
17	(a)	134.0	130.5

[a]Tone not measurable above tunnel background.

TABLE IV. - Concluded.

Transducer	Sound pressure level of tone, dB		
	Frequency		
	$BPF_{F7} + BPF_{A3}$	$2BPF_{F7} + BPF_{A3}$	$BPF_{F7} + 2BPF_{A3}$
0.72 Mach number, 100 percent speed			
1	136.0	(a)	(a)
2	139.0	(a)	(a)
4	142.5	135.5	(a)
6	138.5	133.5	132.0
8	140.0	135.5	137.5
9	139.0	133.5	137.5
10	137.0	134.0	142.0
12	141.0	139.0	137.0
14	132.0	136.0	133.5
16	133.5	133.0	130.5
17	133.0	131.0	130.0
0.72 Mach number, 90 percent speed			
1	(a)	(a)	(a)
2	(a)	↓	↓
4	134.0	↓	↓
6	132.0	↓	↓
8	139.0	130.5	131.5
9	131.0	131.0	132.5
10	131.0	132.0	128.5
12	133.0	136.0	131.0
14	133.5	134.5	132.0
16	132.5	135.0	134.5
17	131.5	137.5	132.0
0.67 Mach number, 95 percent speed			
1	137.5	(a)	(a)
2	137.0	(a)	(a)
4	139.0	131.5	(a)
6	141.5	132.0	131.5
8	140.0	135.0	132.0
9	135.5	137.5	130.5
10	138.5	133.5	132.5
12	134.5	142.5	130.0
14	137.0	145.0	137.0
16	134.0	143.0	137.5
17	131.5	142.0	136.0
0.67 Mach number, 90 percent speed			
1	132.5	(a)	(a)
2	133.5	(a)	↓
4	134.0	(a)	↓
6	136.5	130.5	↓
8	139.0	131.0	134.5
9	133.5	134.0	128.5
10	135.0	134.0	127.5
12	130.5	141.5	129.0
14	131.0	141.0	134.5
16	132.0	137.0	136.5
17	(a)	134.0	132.5

[a]Tone not measurable above tunnel background.

TABLE V. - PROPELLER INTERACTION TONE NOISE

AT FAR AXIAL SPACING

Transducer	Sound pressure level of tone, dB		
	Frequency		
	$BPF_{F7} + BPF_{A3}$	$2BPF_{F7} + BPF_{A3}$	$BPF_{F7} + 2BPF_{A3}$
0.80 Mach number, 100 percent speed			
1	(a)	(a)	(a)
2	↓	↓	↓
4	↓	↓	↓
6	↓	↓	↓
8	141.0	135.5	134.0
9	137.0	135.5	137.5
10	141.0	134.5	137.0
12	135.0	132.0	135.5
14	133.0	(a)	(a)
16	132.5	(a)	(a)
17	134.0	(a)	134.5
0.80 Mach number, 90 percent speed			
1	(a)	(a)	(a)
2	↓	↓	↓
4	↓	↓	↓
6	↓	↓	↓
8	139.0	135.0	135.0
9	143.5	135.5	131.0
10	136.0	130.5	134.5
12	(a)	128.5	130.0
14	↓	130.0	130.5
16	↓	(a)	132.0
17	↓	(a)	134.0
0.76 Mach number, 100 percent speed			
1	(a)	(a)	(a)
2	(a)	(a)	↓
4	134.5	(a)	↓
6	137.0	133.0	↓
8	142.0	135.0	138.0
9	141.0	136.5	137.0
10	141.5	137.0	137.0
12	136.0	134.0	133.5
14	138.5	131.5	131.0
16	133.0	130.0	136.5
17	133.0	129.5	137.5
0.76 Mach number, 90 percent speed			
1	(a)	(a)	(a)
2	(a)	↓	↓
4	(a)	↓	↓
6	136.0	↓	↓
8	139.0	133.5	↓
9	132.5	135.5	131.5
10	133.5	131.5	129.5
12	134.0	129.0	127.5
14	(a)	131.5	132.0
16	(a)	133.0	134.5
17	(a)	131.0	134.0

[a]Tone not measurable above tunnel background.

TABLE V. - Concluded.

Transducer	Sound pressure level of tone, dB		
	Frequency		
	$BPF_{F7} + BPF_{A3}$	$2BPF_{F7} + BPF_{A3}$	$BPF_{F7} + 2BPF_{A3}$
0.72 Mach number, 100 percent speed			
1	(a)	(a)	(a)
2	139.0	132.5	(a)
4	139.0	134.0	(a)
6	139.0	135.0	134.0
8	141.5	136.5	139.0
9	141.5	130.5	142.0
10	142.5	132.0	138.5
12	135.5	135.0	131.5
14	(a)	130.5	130.5
16	136.5	(a)	142.0
17	133.5	(a)	142.0
0.72 Mach number, 90 percent speed			
1	135.0	(a)	(a)
2	132.5	↓	↓
4	134.0	↓	↓
6	132.5	↓	↓
8	134.5	129.0	↓
9	134.0	128.0	128.0
10	134.0	130.0	129.0
12	132.5	129.5	(a)
14	131.0	131.0	130.5
16	128.5	132.0	133.5
17	128.0	131.5	133.5
0.67 Mach number, 95 percent speed			
1	(a)	132.0	(a)
2	139.5	134.5	(a)
4	142.5	134.0	132.5
6	134.0	133.5	136.5
8	142.0	130.0	135.0
9	140.5	135.0	134.0
10	139.5	131.5	131.0
12	140.0	139.5	131.0
14	135.5	141.0	134.0
16	(a)	138.0	136.5
17	(a)	135.0	138.0
0.67 Mach number, 90 percent speed			
1	132.5	(a)	(a)
2	134.5	(a)	↓
4	137.0	132.0	↓
6	137.0	136.0	↓
8	135.0	130.5	129.5
9	137.0	(a)	131.5
10	137.0	(a)	134.5
12	134.0	131.5	131.0
14	130.5	130.0	(a)
16	131.5	129.5	131.5
17	129.5	130.0	132.0

[a]Tone not measurable above tunnel background.

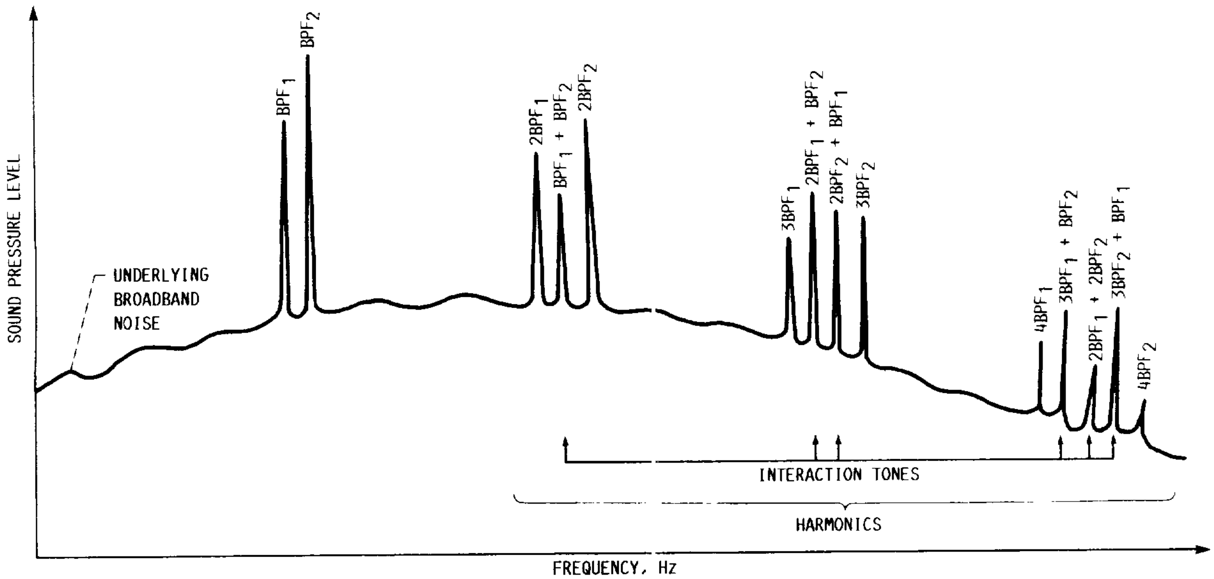


FIGURE 1. - GENERAL COUNTERROTATICN PROPELLER NOISE SPECTRA.

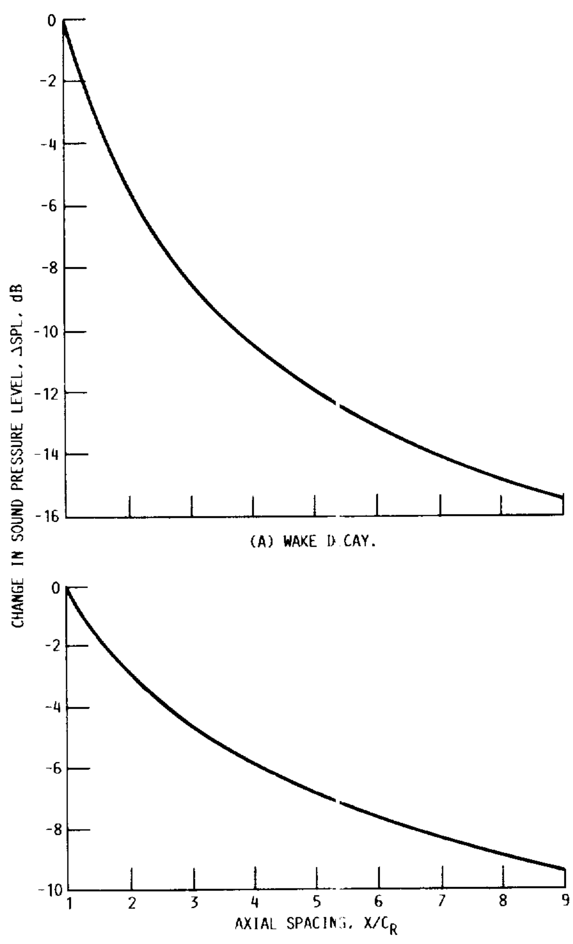
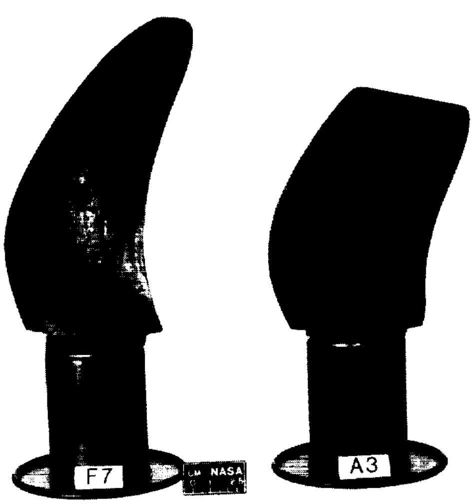


FIGURE 2. - CHANGE IN SOUND PRESSURE LEVEL WITH SPACING.

(a) TEST RIG IN 8- BY 6-FT WIND TUNNEL.



C-88-09811

(b) F7/A3, REDUCED-DIAMETER AFT PROPELLER.

FIGURE 3. - PROPELLERS.

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OF POOR QUALITY

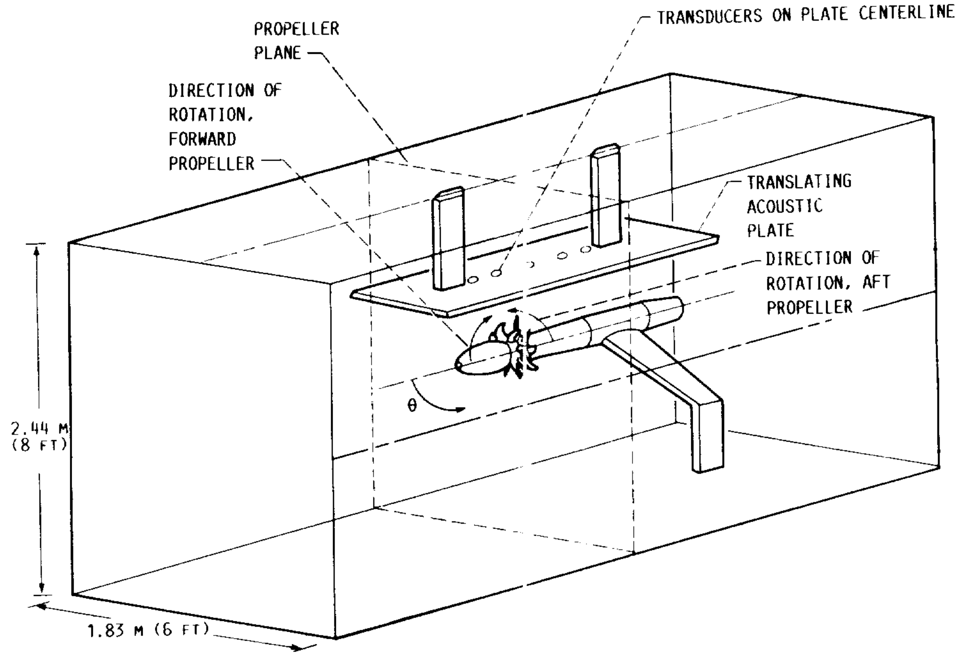
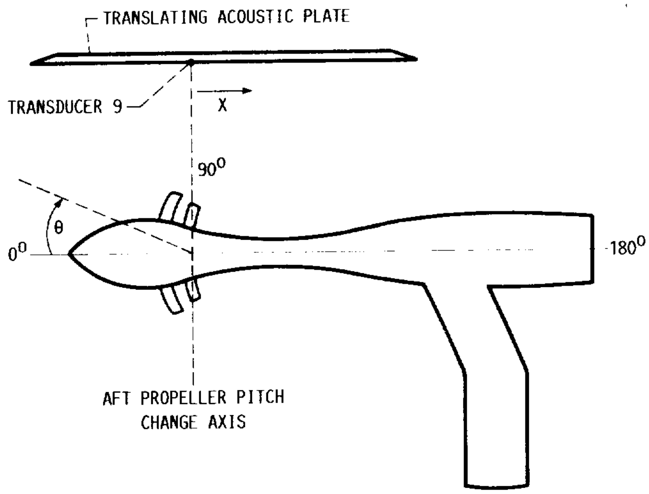
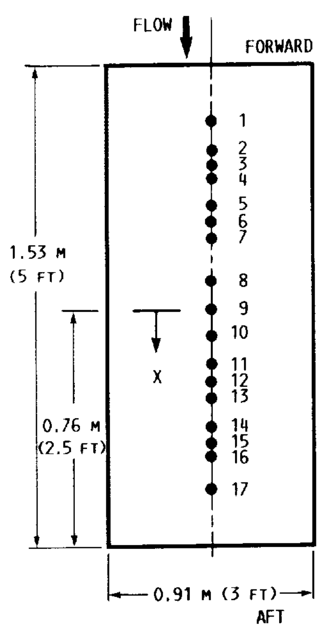


FIGURE 4. - TEST APPARATUS SHOWING TRANSLATING ACOUSTIC PLATE.



(a) ANGLE REFERENCES.

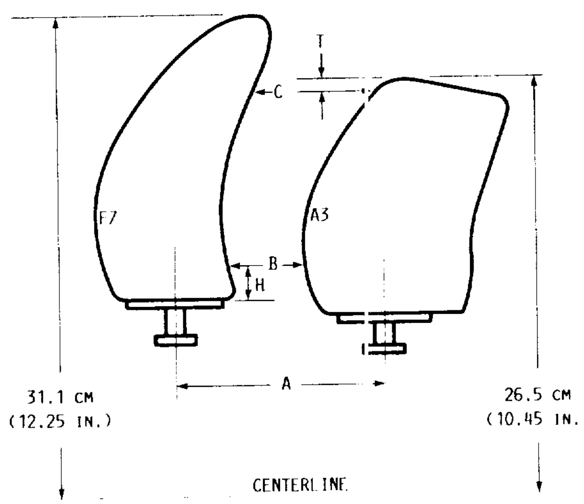


TRANSDUCER	POSITION, X		ANGLE MEASURED FROM FORWARD-PROPELLER AXIS,[a] θ, DEG
	CM	IN.	
1	-46.7	-18.4	47
2	-38.9	-15.3	52
3	-34.0	-13.4	56
4	-29.5	-11.6	59
5	-23.4	-9.2	65
6	-18.8	-7.4	69
7	-14.7	-5.8	73
8	-7.1	-2.8	82
9	0	0	90
10	7.1	2.8	98
11	14.7	5.8	107
12	18.8	7.4	111
13	23.4	9.2	115
14	29.5	11.6	121
15	34.0	13.4	124
16	38.9	15.3	128
17	46.7	18.4	133

[a]TRANSDUCER 9 ALIGNED WITH AFT PROPELLER PITCH CHANGE AXIS.

(b) TRANSDUCER LOCATIONS (STANDING INSIDE TUNNEL, LOOKING UP).

FIGURE 5. - TRANSDUCER POSITIONS ON TRANSLATING ACOUSTIC PLATE.



AXIAL DISTANCE		AXIAL SPACING, CM (IN.)		
		CLOSE	NOMINAL	FAR
A	DISTANCE BETWEEN F7 AND A3 PITCH CHANGE AXES	8.57 (3.38)	10.64 (4.19)	14.92 (5.88)
B	DISTANCE FROM F7 TRAILING EDGE TO A3 LEADING EDGE MEASURED AT LOCATION H[a]	1.11 (0.44)	3.18 (1.25)	7.46 (2.94)
C	DISTANCE FROM F7 TRAILING EDGE TO A3 LEADING EDGE MEASURED AT LOCATION T[b]	3.33 (1.31)	5.40 (2.13)	9.68 (3.81)

[a]LOCATION H IS 1.27 CM (0.5 IN.) UP FROM ROTOR F7 HUB. MEASUREMENT B WAS THE SAME FOR THIS LOCATION AND ALL LOCATIONS FROM 1.27 TO 6.35 CM (0.5 TO 2.5 IN.) UP FROM THE HUB. THE CHORD OF F7 AT LOCATION H IS 8.26 CM (3.25 IN.), AND THE AXIAL PROJECTION OF THE CHORD IS 7.30 CM (2.88 IN.).

[b]LOCATION T IS 0.32 CM (0.13 IN.) DOWN FROM ROTOR A3 TIP. THE CHORD OF F7 AT LOCATION T IS 5.40 CM (2.13 IN.), AND THE AXIAL PROJECTION OF THE CHORD IS 4.76 CM (1.88 IN.).

FIGURE 6. - PROPELLER SPACING.

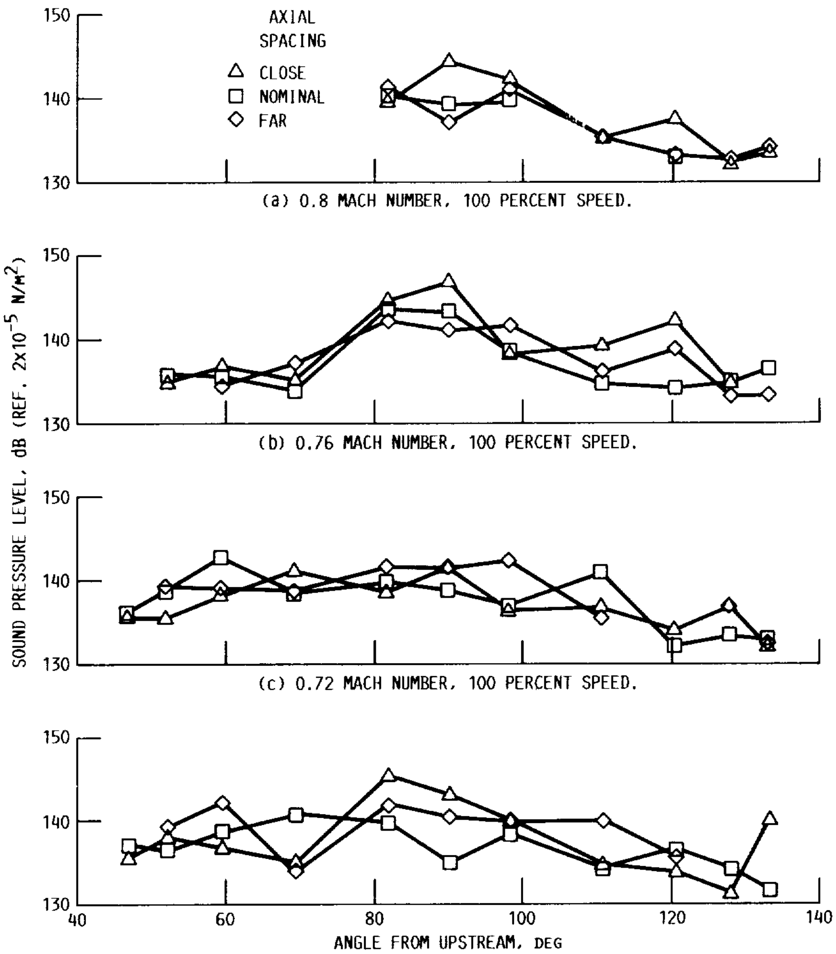


FIGURE 7. - DIRECTIVITY OF FIRST INTERACTION TONE, $BPF_{F7} + BPF_{A3}$.

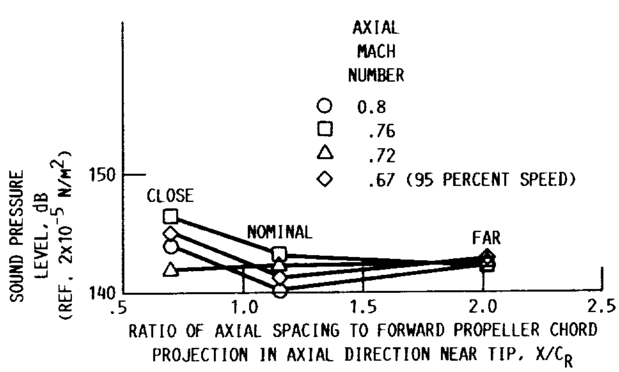


FIGURE 8. - VARIATION OF MAXIMUM TONE AT A FREQUENCY OF $BPF_{F7} + BPF_{A3}$ WITH SPACING AT 100 PERCENT SPEED.

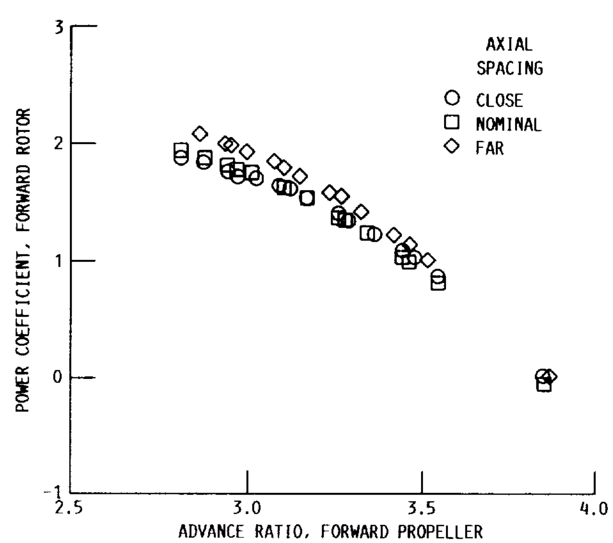


FIGURE 9. - FORWARD PROPELLER POWER COEFFICIENT VARIATION WITH ADVANCE RATIO AT 0.76 MACH NUMBER (POWER COEFFICIENT BASED ON FORWARD PROPELLER ANNULUS AREA).

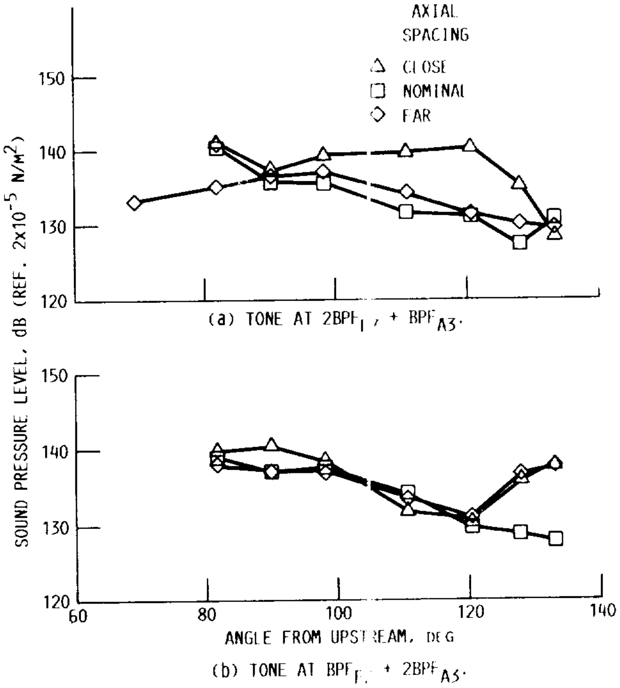


FIGURE 10. - HIGHER ORDER INTERACTION TONES AT 0.76 MACH NUMBER, 100 PERCENT SPEED.

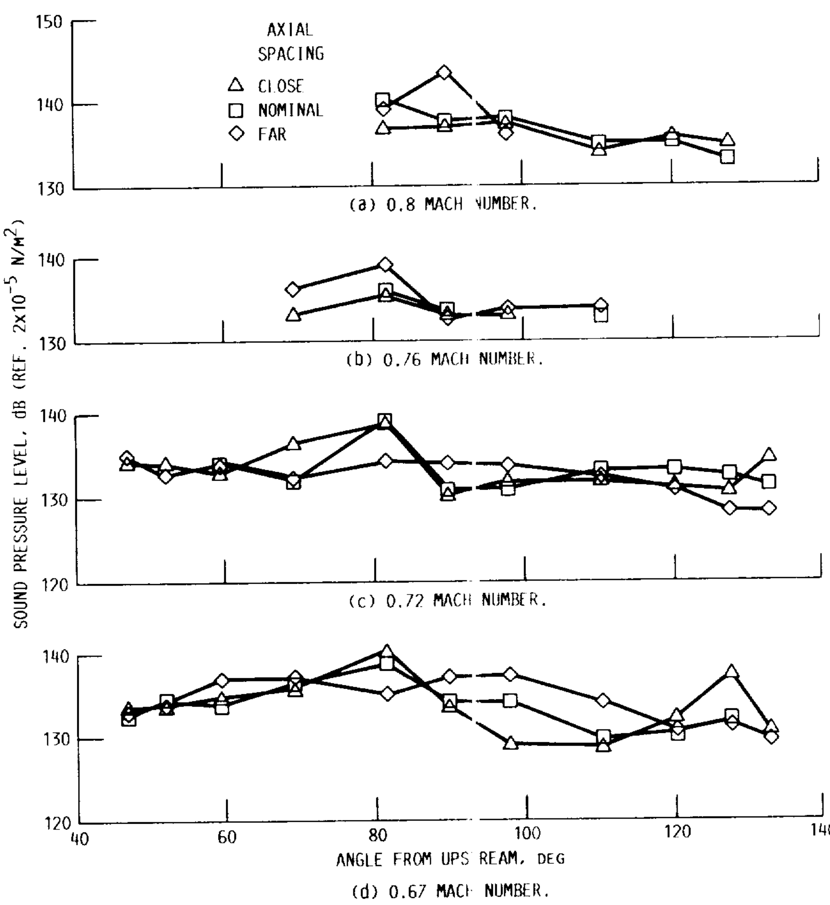


FIGURE 11. - DIRECTIVITY OF FIRST INTERACTION TONE, $BPF_{F7} + BPF_{A3}$, AT 90 PERCENT SPEED.

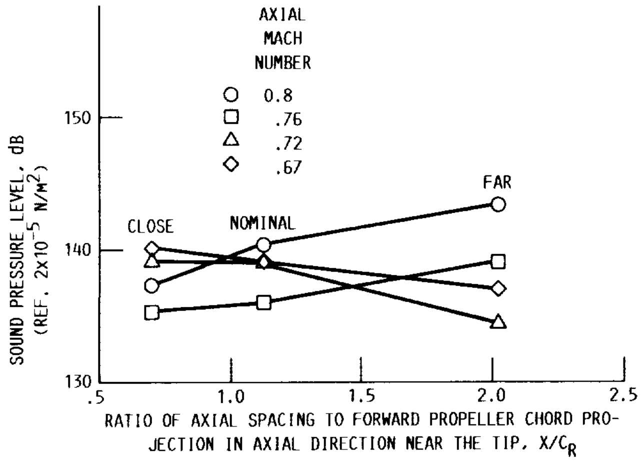


FIGURE 12. - VARIATION OF MAXIMUM TONE AT A FREQUENCY OF $BPF_{F7} + BPF_{A3}$ WITH SPACING AT 90 PERCENT SPEED.

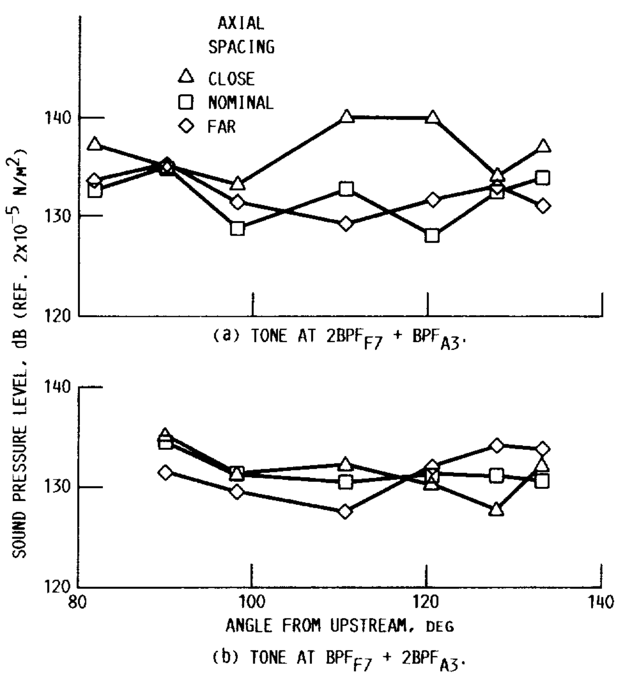


FIGURE 13. - HIGHER ORDER INTERACTION TONES AT 0.76 MACH NUMBER, 90 PERCENT SPEED.

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16. Abstract
The effect of forward-to-aft propeller spacing on the interaction noise of a counterrotation propeller with reduced aft diameter was measured at cruise conditions. In general, the tones at 100 percent speed descreased from close to nominal spacing as expected from a wake decay model. However, when the spacing was further increased to the far position, the noise did not decrease as expected and in some cases increased. The behavior at the far spacing was attributed to changing forward propeller performance, which produced larger wakes. The results of this experiment indicate that simple wake decay model is sufficient to describe the behavior of the interaction noise only if the aerodynamic coupling of the two propellers does not change with spacing. If significant coupling occurs such that the loading of the forward propeller is altered, the interaction noise does not necessarily decrease with larger forward-to-aft propeller spacing.

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