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Predicted and Measured Boundary Layer Refraction for Advanced Turboprop Propeller Noise

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PREDICTED AND MEASURED BOUNDARY LAYER REFRACTION
FOR ADVANCED TURBOPROP PROPELLER NOISE

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SUMMARY

Currently, boundary layer refraction presents a limitation to the measurement of forward arc propeller noise measured on an acoustic plate in the NASA Lewis 8- by 6-Foot Supersonic Wind Tunnel. The use of a validated boundary layer refraction model to adjust the data could remove this limitation. In this paper an existing boundary layer refraction model is used to predict the refraction for cases where boundary layer refraction had been measured. In general, the model exhibits the same qualitative behavior as the measured refraction. However, the prediction method does not show quantitative agreement with the data. In general, it overpredicts the amount of refraction for the far forward angles at axial Mach numbers of 0.85 and 0.80 and underpredicts the refraction at axial Mach numbers of 0.75 and 0.70. A more complete propeller source description is suggested as a way to improve the prediction method.

INTRODUCTION

The noise of high tip-speed turboprops at cruise speed has been identified as a possible cabin noise problem for advanced turboprop airplanes. Scale models of single and counterrotation propellers have been tested for acoustics in the NASA Lewis 8- by 6-Foot Supersonic Wind Tunnel using pressure transducers embedded flush in the wind tunnel walls or in a plate suspended from the tunnel ceiling (refs. 1 to 6). A picture and an illustration of a single rotation propeller in the wind tunnel with transducers in the ceiling is shown in figure 1(a). Figure 2 illustrates transducers in the acoustic plate.

Both the tunnel ceiling and the plate have a boundary layer built up on the surface. The boundary layer refracts some of the propeller noise away from the measurement transducers. A previous experiment was performed in reference 7 to measure the amount of refraction observed in the NASA Lewis 8- by 6-Foot Supersonic Wind Tunnel. In that experiment the amount of the refraction depended on the ratio of sound wavelength to boundary layer thickness and became progressively larger as the angle forward of the propeller was increased. Currently, the boundary layer refraction presents a limitation to the measurement of forward arc propeller noise in the NASA Lewis 8- by 6-Foot Supersonic Wind Tunnel. This is particularly true at the higher Mach numbers and higher harmonics of the propeller blade passing frequency (ref. 8).

The use of a validated boundary layer refraction model to adjust the data could remove this limitation. This adjustment is similar in concept to the shear layer corrections that are applied to noise measured outside of an open

jet wind tunnel (ref. 9). In this paper an existing boundary layer refraction model (ref. 10) is used to predict the refraction for data contained in references 7 and 8. Comparisons between the predicted and measured boundary layer refraction are presented.

THEORETICAL PREDICTION METHOD

The boundary layer refraction predictions were made by using a theoretical model and computer code developed by Hanson and Magliozzi as described in reference 10. This is a three-dimensional model which solves the problem in the boundary layer and outer shear-free regions, and matches the solution at the boundary between the two regions. The prediction method starts with a simplified noise source in the outer region. It approximates the propeller as a rotating point source and calculates the monopole (thickness) noise only. This yields a typical directivity of the noise striking the boundary layer. The output of the computer code includes the contributions from the boundary layer refraction and the diffraction by a cylindrical fuselage. The code allows the use of different boundary layer velocity distributions; a one-seventh power velocity distribution was used for the calculations in this paper. The computer code was used to predict boundary layer refraction for the experiments described in the following sections.

EXPERIMENTS

Wind Tunnel Ceiling and Plate

Boundary layer refraction was measured in the NASA Lewis 8- by 6-Foot Supersonic Wind Tunnel and reported in reference 7. Advanced propeller tone levels were measured with transducers mounted on the tunnel ceiling (fig. 1) and on a plate suspended from the tunnel ceiling just outside of the tunnel ceiling boundary layer (fig. 3). Noise was measured at four positions on the tunnel ceiling and at eight positions (numbers 2, 4, 7, 8, 10, 11, 13, and 15) on the plate. Four of the positions (numbers 2, 8, 11, and 15) on the plate were directly below the locations on the ceiling and the other four (4, 7, 10, and 13) were at positions where a ray from the propeller would strike the plate on its path to the ceiling transducers. (See ref. 7 for details.) The boundary layer profiles on the ceiling and plate were measured at positions near the transducer positions. Acoustic data were taken at tunnel axial Mach numbers ranging from 0.7 to 0.85 with the propeller operating at an advance ratio of 3.06. Differences were observed between the ceiling and plate noise data and are attributed to boundary layer refraction.

Wind Tunnel Plate and Propfan Test Assessment Airplane

The noise of the model SR-7A propeller was measured in the wind tunnel on a plate suspended from the tunnel ceiling 0.3 diameters above the propeller tip (fig. 2). The noise data at the design condition of the propeller (axial Mach number 0.8 advance ratio = 3.06), were compared with data from the full scale propeller measured on the fuselage of the Propfan Test Assessment (PTA) airplane (fig. 4) in reference 8. Differences between the scaled wind tunnel

and full scale flight data were assumed to be due to boundary layer refraction. These differences will be used to make comparisons with the predicted differences.

Plate in NASA Lewis 8- by 6-Foot Supersonic Wind Tunnel and Free-Field in Boeing Transonic Wind Tunnel

Noise of a counterrotation propeller model, F7-A7, was measured with the transducers mounted on the plate in the NASA Lewis 8- by 6-Foot Supersonic Wind Tunnel (fig. 5). The data at an axial Mach number of 0.72 were compared with data taken on the same propeller by a free-field traversing microphone in the Boeing Transonic Wind Tunnel (fig. 6). Differences assumed to be due to boundary layer refraction were observed at the higher harmonics and attributed to the boundary layer on the plate in the NASA Lewis wind tunnel (ref. 8).

RESULTS AND DISCUSSION

Wind Tunnel Ceiling and Plate

Since boundary layers exist on both the NASA Lewis 8- by 6-Foot Supersonic Wind Tunnel ceiling and on the acoustic plate, predictions were made for both of these boundary layers. The boundary layer thicknesses were measured (ref. 8) for both of these surfaces and these thicknesses were used in the calculations. The predictions were made for plate and ceiling transducers at 0.7, 0.75, 0.80, and 0.85 tunnel axial Mach numbers. The prediction program is designed for a cylindrical fuselage so a large diameter fuselage was chosen to approximate the flat surface of the wind tunnel ceiling and plate. Calculations were made for various fuselage diameter to propeller diameter ratios to determine when the fuselage was large enough not to have an effect on the answers, and a fuselage to propeller diameter ratio of 4.5 was used.

The predictions for the transducers located in front of and in the plane of rotation are presented in table I. The effect of boundary layer refraction was less than 1 dB behind the plane of rotation, and predictions for these locations are not included in the table. The predictions in this table show the difference between sound pressure levels with and without the large fuselage and boundary layer. As indicated before, the values include effects of both the diffraction from the hard surface (pressure doubling for a flat plate) and the boundary layer refraction. Theoretically, if no boundary layer refraction were present, the pressure amplification on a hard surface would be 6 dB. In table I the variations from 6 dB indicate the effects of boundary layer refraction at this position. As a result of the bending of the sound wave as it passes through the boundary layer, noise from a high sound level portion of the directivity may impact the fuselage surface at a point where the sound in the free-field case was from a low sound level portion of the directivity. This apparent change in source directivity was illustrated in reference 10 and makes it possible to have values greater than 6 dB. For example see table I for twice blade passing frequency at $M = 0.7$, plate positions 2 and 4. Values above 6 dB were also observed for twice blade passing

frequency at $M = 0.8$, plate positions 7 and 8. These values are very local in nature and do not appear to be from the apparent change in source directivity. The reason for these locally high values is not known at this time.

As can be observed in table I, much more boundary layer refraction occurs on the ceiling than on the plate because of the thicker ceiling boundary layer. Also it can be seen that more refraction occurs at the more forward transducer positions and at twice blade passing frequency where the sound wavelength is smaller. Larger amounts of refraction are predicted for higher tunnel axial Mach numbers; little refraction is seen at the lower Mach numbers. As mentioned before, the predictions behind the plane of rotation are not included since they showed little or no refraction.

The noise data reported in reference 8 are the tone levels measured on the ceiling and the plate. The prediction method is evaluated by adjusting the measured ceiling data by the predicted difference in refraction effects between the plate and ceiling. This adjustment is done with the predictions presented in table I and with a 1 dB additional adjustment for spherical spreading (based on 20 times the log of distance from the propeller centerline to the plate and ceiling sidelines).

The measured curves for the ceiling and plate data are presented in figure 7 for the tone at blade passing frequency and in figure 8 for the tone at twice blade passing frequency. Since the results were essentially the same for both the "directly below" and "ray" plate transducer positions, only the ray data are shown. These plots are taken from reference 8. In general, the unadjusted data show differences between the ceiling and plate data at higher Mach numbers in front of the propeller but show little differences at low Mach number and behind the plane of rotation. The data trends are qualitatively the same as the predictions. The ceiling data adjusted with the boundary layer refraction predictions have also been plotted in figures 7 and 8.

For the blade passing frequency at the higher tunnel axial Mach numbers (0.8 and 0.85), the ceiling adjusted data at the farthest forward position are significantly above the measured plate data (figs. 7(a) and (b)). Since the largest part of each adjustment arises from the ceiling boundary layer refraction prediction, it appears that the prediction method is overpredicting the boundary layer refraction at the far forward angles at the high Mach numbers. At the next position aft, the method is, in general, underpredicting for the blade passing frequency at $M = 0.8$ and is approximately correct at $M = 0.85$. At twice blade passing frequency, the method is overpredicting at the most forward positions at $M = 0.8$ (fig. 8(b)) and overpredicting at the "in plane" position at $M = 0.85$ (fig. 8(a)).

At the lower Mach numbers tested, $M = 0.75$ and 0.7 , the predicted adjustments do not bring the ceiling data up to the plate data. Here it appears that the prediction method is underestimating the boundary layer refraction at low Mach numbers. In reference 10 better agreement was found between prediction and data at $M = 0.8$ than in this paper, but the same discrepancy appears at the low Mach numbers.

The general result here seems to indicate that the prediction method is showing qualitatively the same trends as the data. However, the prediction method is not showing quantitative agreement with the data. It overpredicts

at the far forward angles at high Mach numbers (0.8 and 0.85) and underpredicts at low Mach numbers (0.75 and 0.7).

Wind Tunnel Plate and Propfan Test Assessment Airplane

In reference 8 a comparison was made between the noise measured on the plate in the wind tunnel for a model propeller and the noise measured in flight for a full size propeller on the propfan test assessment airplane. At the forward angles for the higher harmonics the difference between wind tunnel and flight data were attributed to boundary layer refraction. The tests were both done at an axial Mach number of 0.8. In order to compare with the data, refraction predictions were made for the plate in the wind tunnel and for the PTA airplane fuselage at the same annular positions as the wind tunnel data. The boundary layer thicknesses for the plate are taken from reference 8 but no thicknesses were measured on the airplane. Therefore an estimate was made of the fuselage boundary layer thickness by using

$$\delta = 0.37 \left(\frac{\nu}{U_0} \right)^{1/5} x^{4/5}$$

from reference 11 for a flat plate, where δ is the boundary layer thickness (ft), ν is the kinematic viscosity (ft²/sec), U_0 is the free stream velocity (ft/sec), and x is the distance from leading edge (ft). As a check, this boundary layer equation was used to calculate the thickness of the Jetstar airplane boundary layer (ref. 12). The calculated thickness and the measured thickness compared well for the Jetstar case, so the equation is assumed to be equally valid here for the PTA airplane fuselage. Using the calculated PTA boundary layer thickness, boundary layer refractions were predicted for the PTA airplane. The predictions for both the plate and the PTA fuselage are contained in table II for the first four propeller harmonics.

The airplane and plate data, normalized to the airplane fuselage condition, are shown in figure 9 taken directly from reference 8. The plate predictions show larger refraction than the fuselage predictions because the plate boundary layer thickness to source wavelength ratio is larger. The plate data are adjusted by the difference in predicted boundary layer refraction and are also plotted for comparison. As with the previous plate and ceiling comparison at $M = 0.8$, the adjusted data at the forward angles for the blade passing tone fall above the PTA data. Again, since most of the predicted adjustment is contributed by only one of the predictions (plate), it appears that the boundary layer refraction is overpredicted. This is the same result as observed for the plate and ceiling comparison and supports the conclusion that the method is overpredicting at the far forward angles for the higher axial Mach numbers.

At other angles, nearer to the plane of rotation, the method more closely predicts the refraction. For example, at the third harmonic, just in front of the plane of rotation (fig. 9(c)), the method is just slightly underpredicting the observed refraction. Slight underpredictions are also seen close to the plane of rotation at the other harmonics, which is consistent with the previous plate and ceiling comparisons.

NASA Lewis 8- by 6-Foot Supersonic Wind Tunnel Plate and
Boeing Transonic Wind Tunnel

Comparisons were also made in reference 8 between model propeller noise taken in the NASA Lewis 8- by 6-Foot Supersonic Wind Tunnel and in the Boeing Transonic Wind Tunnel. The data were taken on the plate in the Lewis tunnel and free-field in the Boeing tunnel. The propeller model was the F7-A7 counterrotation propeller. Even though the prediction has a single point source rotating in one direction for the propeller simulation, the predictions were performed for the counterrotating case to see if the trends were the same as observed previously.

Table III contains the predictions for the first four harmonics for the plate in the Lewis tunnel at an axial Mach number of 0.72. The comparisons of Lewis and Boeing data in reference 8 included the 6 dB pressure amplification on the plate surface. These comparisons are shown in figure 10 for the first four harmonics. Also on these plots are data points for the plate adjusted for the predicted boundary layer refraction. Since the plots already contained the 6 dB surface amplification, the plate data are adjusted by the difference between the 6 dB and the amount shown in table III. As can be seen for the first two harmonics, figures 10(a) and (b), little or no boundary layer refraction is seen in the data except possibly at the most forward angles. As seen in table III the predictions show no boundary layer refraction (i.e., differences from the 6 dB pressure amplification are less than or equal to 1 dB). In essence, both the prediction and the data are not indicating any boundary layer refraction at blade passing or twice blade passing frequency. Therefore no adjustments were made to the curves in figures 10(a) and (b).

Boundary layer refraction is present at three and four times blade passing frequency for both the data (figs. 10(c) and (d)) and the predictions (table III). Therefore the predicted boundary layer refraction adjustments were made to the Lewis data and the adjusted points are shown on figures 10(c) and (d). At most of the positions, the adjustment is not enough to bring the Lewis data up to the levels in the Boeing tunnel. This is consistent with the underpredictions observed previously at $M = 0.7$ and 0.75 for the plate and ceiling data. Again it appears that the prediction model is giving the proper qualitative results, indicating refraction when it is observed, but not the proper quantitative answers.

CONCLUDING REMARKS

Currently, boundary layer refraction presents a limitation to the measurement of forward arc propeller noise measured on an acoustic plate in the NASA Lewis 8- by 6-Foot Supersonic Wind Tunnel. This limitation is particularly observed at the higher tunnel Mach numbers and higher harmonics of the propeller blade passing frequency. The use of a validated boundary layer refraction model to adjust the data could remove this limitation. This adjustment is similar in concept to the shear layer corrections that are applied to noise measured outside of an open jet wind tunnel. In this paper an existing model was used to predict the boundary layer refraction for some cases where data strongly suggest boundary layer refraction was present. The prediction method is a three-dimensional formulation and models the propeller as a rotating point source and calculates the monopole (thickness) noise.

In general, the prediction method exhibited the same qualitative behavior as the measured boundary layer refraction. However, the prediction method did not show quantitative agreement with the data. In general it overpredicted the amount of refraction for the far forward angles at high tunnel Mach numbers (0.8 and 0.85) and underpredicted the refraction at the lower tunnel Mach numbers (0.7 and 0.75). In the form used for this paper, the prediction method is not sufficiently accurate to be used to adjust the Lewis data.

The qualitative agreement, which was observed between the predications and the data, indicates that the method might be modified so that it can quantitatively predict the data. The propeller source description appears to be an area where the most improvement can be made to the prediction method. At present the propeller is modeled by a rotating point source for the thickness noise component only. The inclusion of the loading noise component and a distributed source model may both be needed to enable accurate boundary layer refraction predictions.

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TABLE I. - BOUNDARY LAYER REFRACTION PREDICTIONS FOR PLATE AND CEILING IN
NASA LEWIS 8- BY 6-FOOT SUPERSONIC WIND TUNNEL

(a) Blade passing frequency, dB

Mach number	Transducer position					
	Ceiling, A	Plate, 2 (directly below A)	Plate, 4 (on ray to A)	Ceiling, B	Plate, 8 (directly below B)	Plate, 7 (on ray to B)
0.85	-30.2	-7.2	-6.0	1.6	4.0	4.0
.8	-8.2	1.4	2.3	3.8	5.2	5.2
.75	2.8	5.1	5.2	4.3	5.4	5.4
.7	5.3	5.9	6.0	4.6	5.5	5.5

(b) Twice blade passing frequency, dB

Mach number	Transducer position					
	Ceiling, A	Plate, 2 (directly below A)	Plate, 4 (on ray to A)	Ceiling, B	Plate, 8 (directly below B)	Plate, 7 (on ray to B)
0.85	(a)	(a)	(a)	-7.3	1.1	1.0
.8	-24.3	-6.8	-5.0	4.0	10.6	8.8
.75	2.5	2.3	3.8	6.4	6.4	6.4
.7	8.6	7.6	7.0	5.5	5.9	5.9

^aData not available.

TABLE II. - BOUNDARY LAYER REFRACTION PREDICTIONS FOR PLATE IN NASA LEWIS 8- BY 6-FOOT SUPERSONIC WIND TUNNEL AND PROPFAN TEST ASSESSMENT (PTA) AIRPLANE FUSELAGE

Transducer position	Blade passing frequency, dB	Twice blade passing frequency, dB	Three times blade passing frequency, dB	Four times blade passing frequency, dB
Plate position 2 (PTA fuselage at same angular position)	-10.1 (2.2)	-----	-----	-----
Plate positions 3 (PTA fuselage at same angular position)	-8.1 (2.8)	-----	-----	-----
Plate position 4 (PTA fuselage at same angular position)	0.6 (4.2)	-----	-----	-----
Plate position 5 (PTA fuselage at same angular position)	2.7 (4.5)	-5.6 (2.1)	-13.6 (-1.5)	-----
Plate position 6 (PTA fuselage at same angular position)	3.9 (4.9)	-5.4 (-1.7)	1.5 (5.1)	3.9 (6.8)

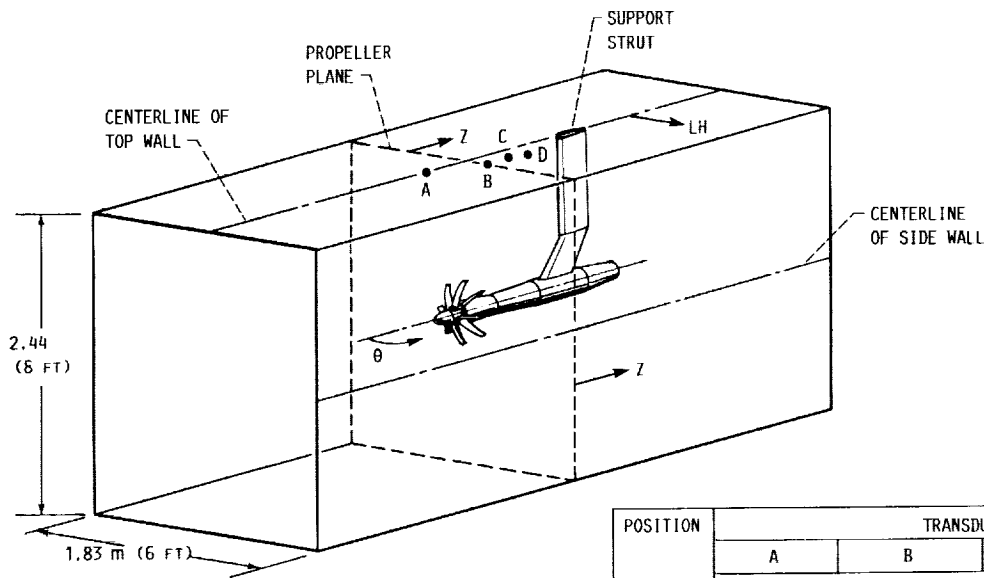
TABLE III. - BOUNDARY LAYER REFRACTION PREDICTIONS OF PLATE POSITIONS AT MACH 0.72 IN NASA LEWIS 8- BY 6-FOOT SUPERSONIC WIND TUNNEL

Transducer position on plate	Blade passing frequency, dB	Twice blade passing frequency, dB	Three times blade passing frequency, dB	Four times blade passing frequency, dB
1	6.9	5.5	5.1	-----
2	7.0	5.5	4.6	-1.7
3	7.0	6.4	3.3	5.2
4	6.5	6.5	7.0	4.0

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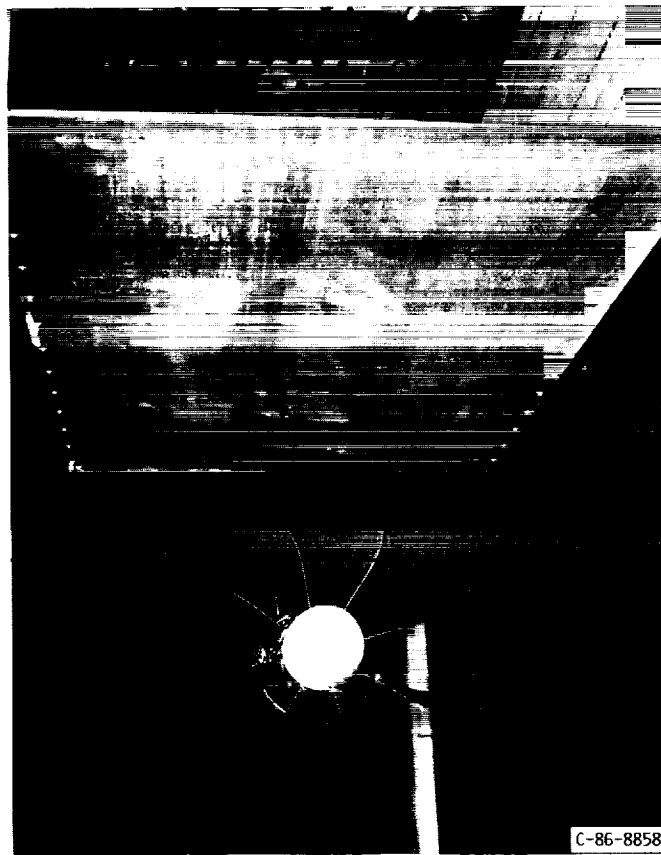
(a) SINGLE ROTATION SR-3 PROPELLER IN TEST SECTION.



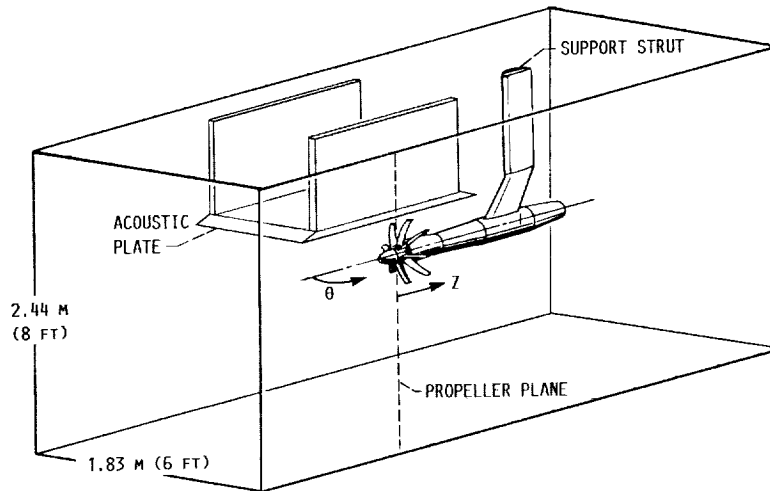
POSITION	TRANSDUCER			
	A	B	C	D
	TRANSDUCER POSITION, CM (IN.)			
Z	-33.0(13.0)	0.953(0.375)	25.7(10.1)	45.2(17.8)
LH	4.83(1.9)	10.2(4.0)	-2.54(1.0)	7.62(3.0)
NOMINAL ANGLE, θ, DEG	75	90.5	102	110

(b) PRESSURE TRANSDUCER LOCATIONS.
FIGURE 1. - CEILING MOUNTED TRANSDUCERS.

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(a) ACOUSTIC PLATE MOUNTED OVER SR-7A PROPELLER.



TRANSDUCER (PLATE 0.3 DIAMETER FROM TIP)											
1	2	3	4	5	6	7	8	9	10	11	12
TRANSDUCER DISTANCE FROM PROPELLER PLANE, Z, CM (IN.)											
-46.7 (-18.4)	-41.7 (-16.4)	-30.5 (-12.0)	-16.0 (-6.3)	-8.9 (-3.5)	0.8 (0.3)	8.9 (3.5)	12.4 (4.9)	18.0 (7.1)	25.0 (9.9)	28.7 (11.3)	42.4 (16.7)
ANGLE FROM UPSTREAM, θ, DEG											
46.8	50.0	58.5	72.2	80	90.9	100	104	110	116.8	120	130.4

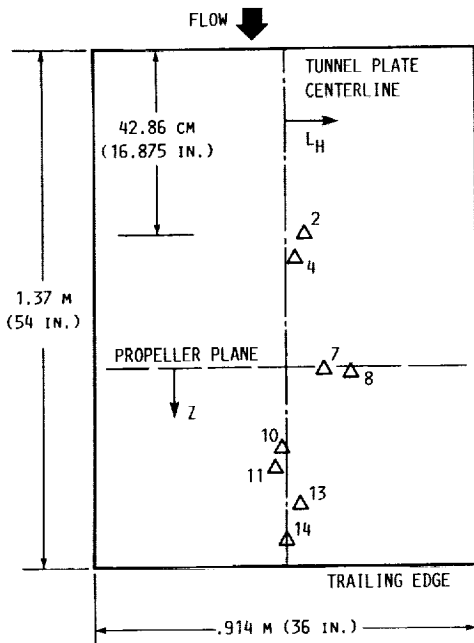
(b) TRANSDUCER LOCATIONS.

FIGURE 2. - ACOUSTIC PLATE MOUNTED TRANSDUCERS WITH PLATE CLOSE TO SINGLE-ROTATION PROPELLER.

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(a) ACOUSTIC PLATE MOUNTED OVER SR-3 PROPELLER.



		TRANSDUCER							
		2	4	7	8	10	11	13	14
		TRANSDUCER POSITION cm (IN.)							
Z		-33.0 (-13.0)	-28.5 (-11.24)	.81 (.32)	.95 (.375)	20.7 (8.14)	25.7 (10.1)	39.1 (15.38)	42.4 (16.7)
L _H		4.83 (1.9)	.15 (.06)	4.78 (1.88)	10.2 (4.0)	-1.83 (-.72)	-2.54 (-1.0)	2.56 (1.01)	0
θ*	PLATE CLOSE	72.8	75.0	90.4	90.5	101.0	103.5	110.1	111.7

* NOMINAL ANGLE FROM PROPELLER AXIS USING Z ONLY.

(b) TRANSDUCER LOCATIONS.

FIGURE 3. - PLATE MOUNTED TRANSDUCERS WITH PLATE CLOSE TO WIND TUNNEL CEILING.

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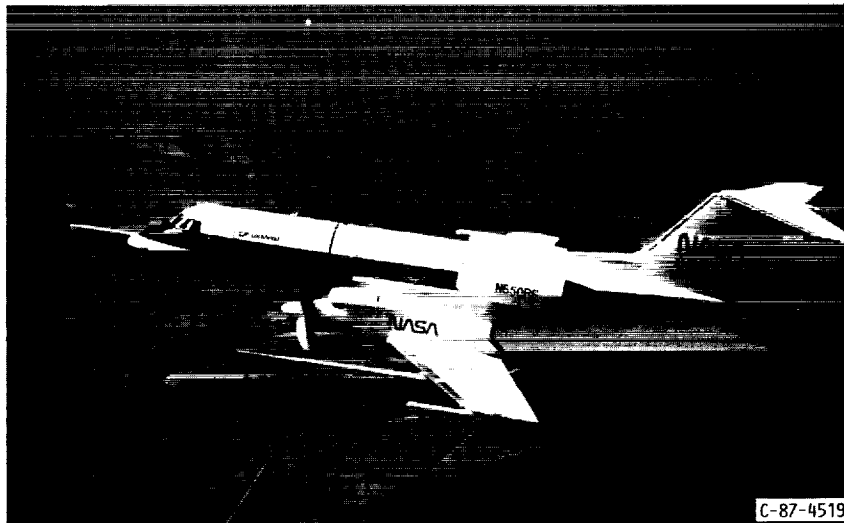
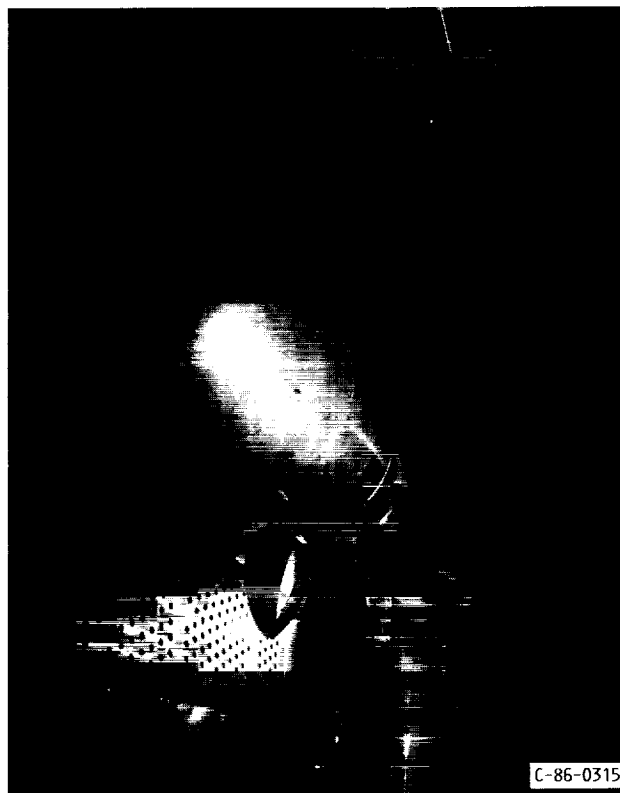
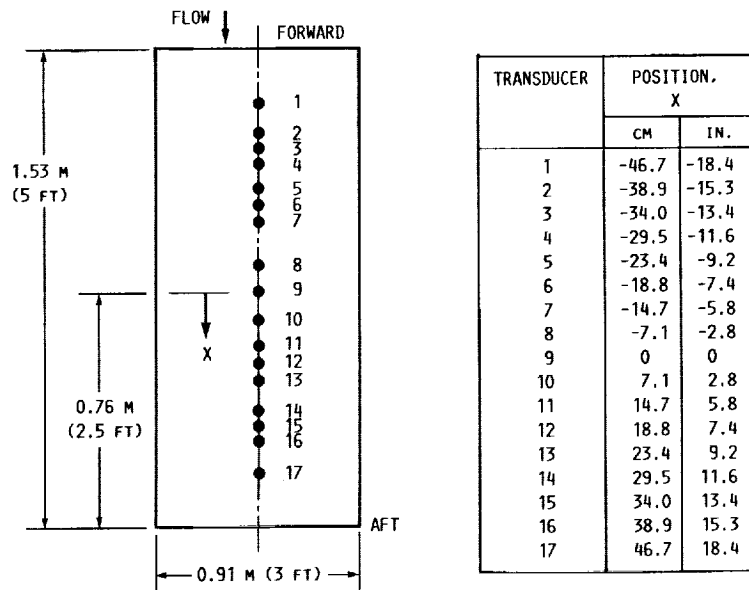
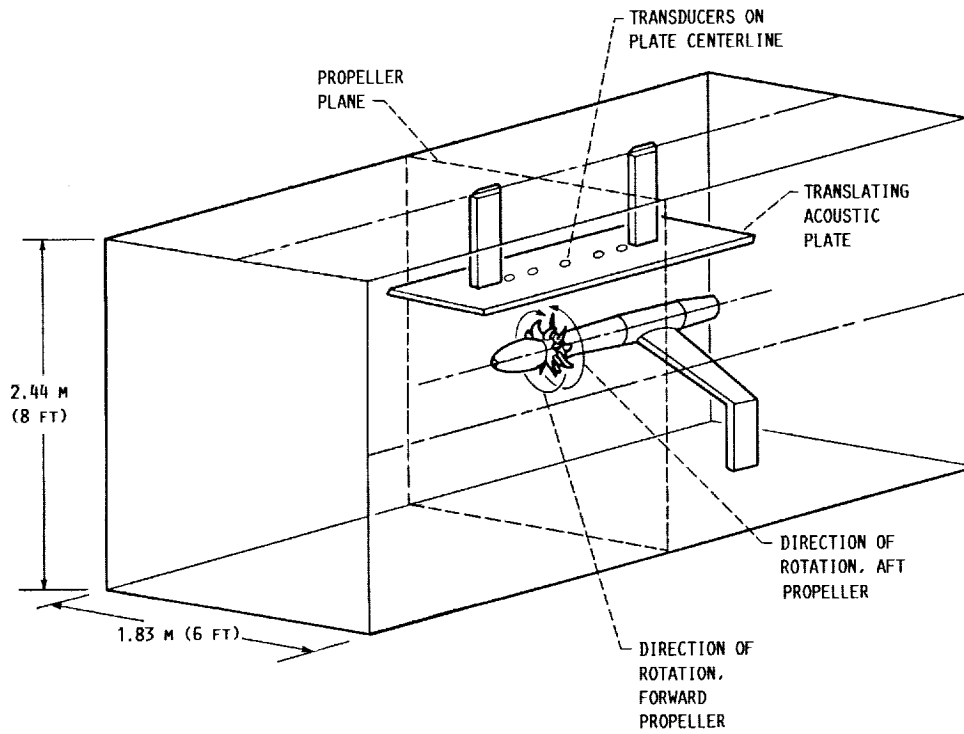


FIGURE 4. - LARGE-SCALE ADVANCED PROPFAN ON TEST BED AIRCRAFT.



(a) ACOUSTIC PLATE MOUNTED OVER F7-A7 COUNTERROTATION PROPELLER.
FIGURE 5. - ACOUSTIC PLATE MOUNTED TRANSDUCERS WITH PLATE CLOSE TO
COUNTERROTATIONS PROPELLER.



(b) TRANSDUCER LOCATIONS.
FIGURE 5. - CONCLUDED.

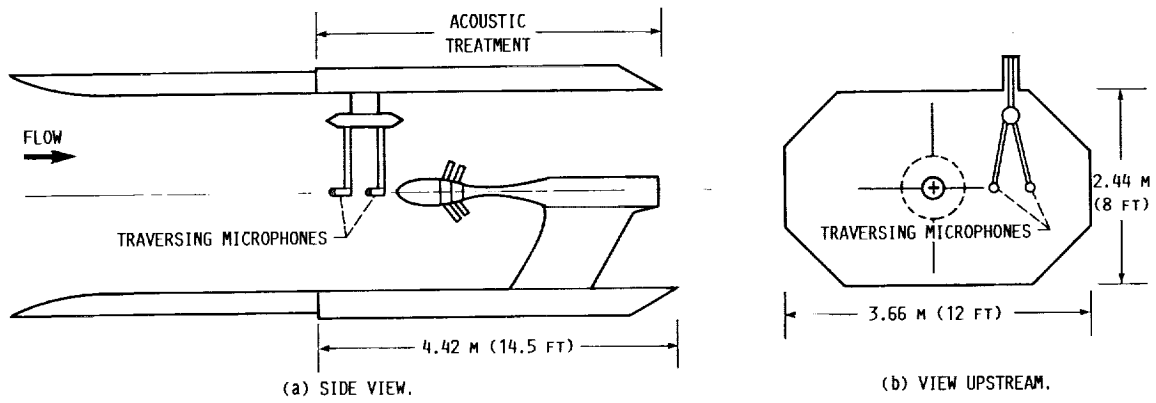


FIGURE 6. - BOEING TRANSONIC WIND TUNNEL ACOUSTIC TEST SECTION.

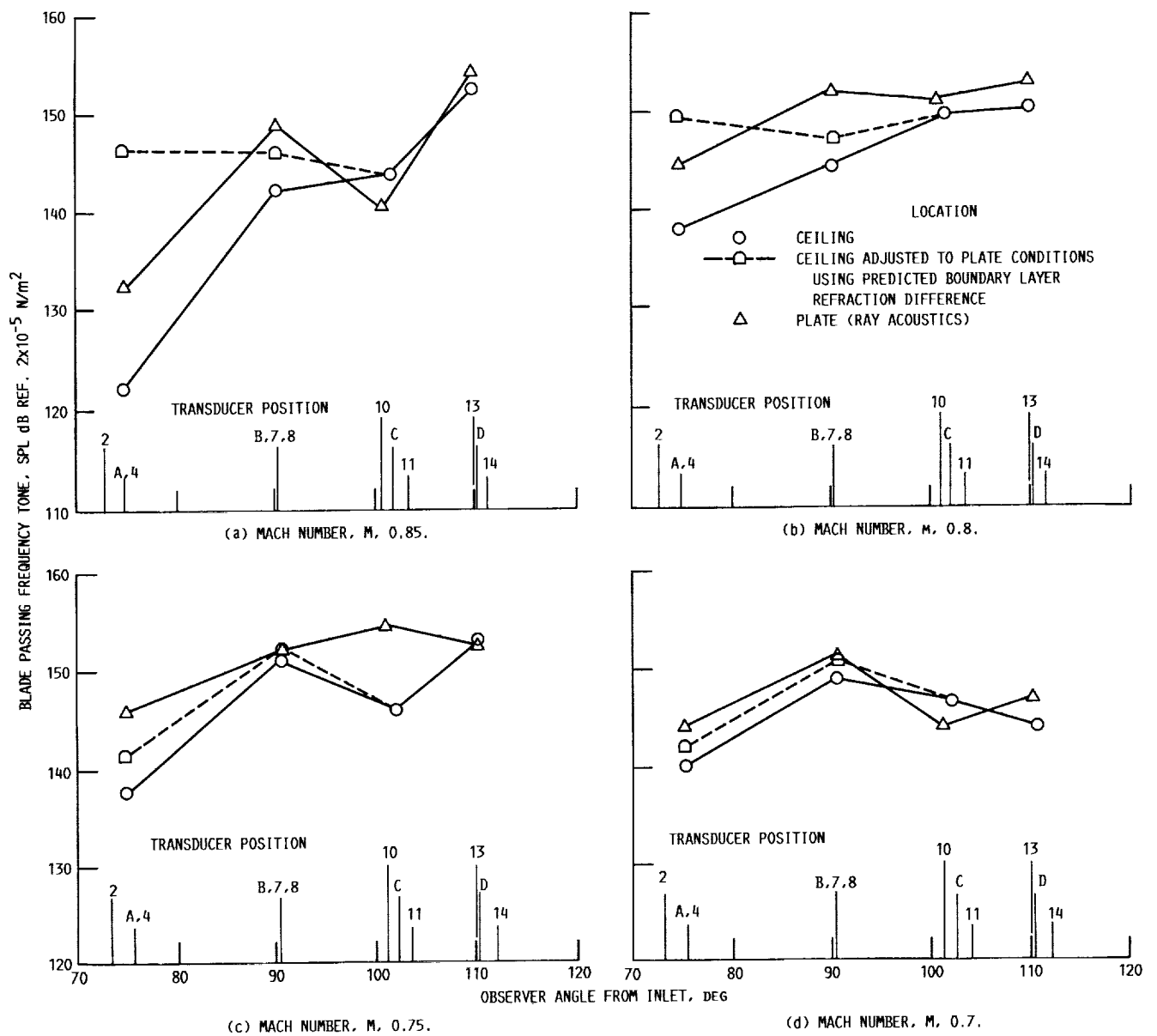


FIGURE 7. - PLATE AND CEILING COMPARISON AT BLADE PASSING FREQUENCY.

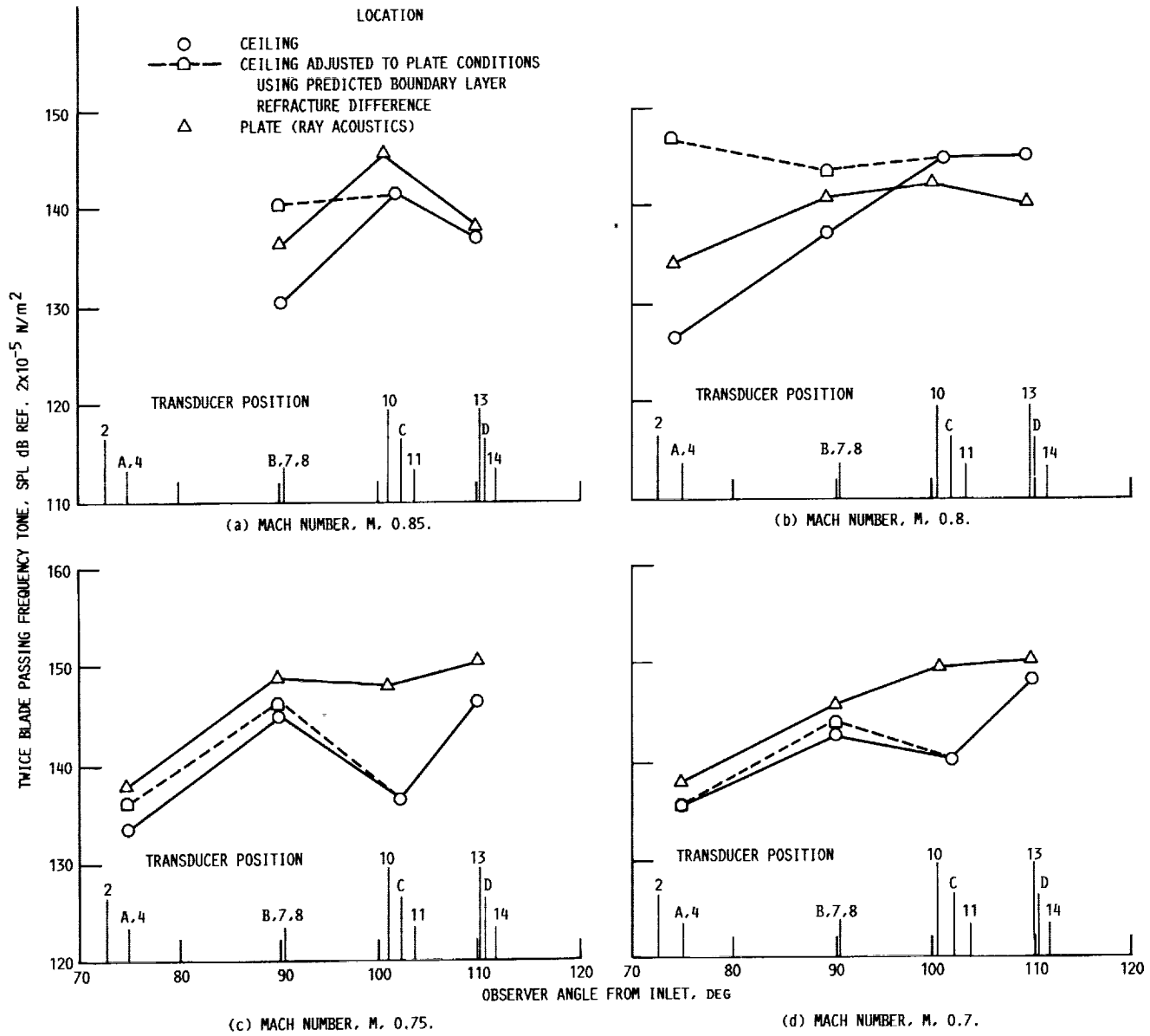


FIGURE 8. - PLATE AND CEILING COMPARISON AT TWICE BLADE PASSING FREQUENCY. (RAY POSITIONS ON PLATE.)

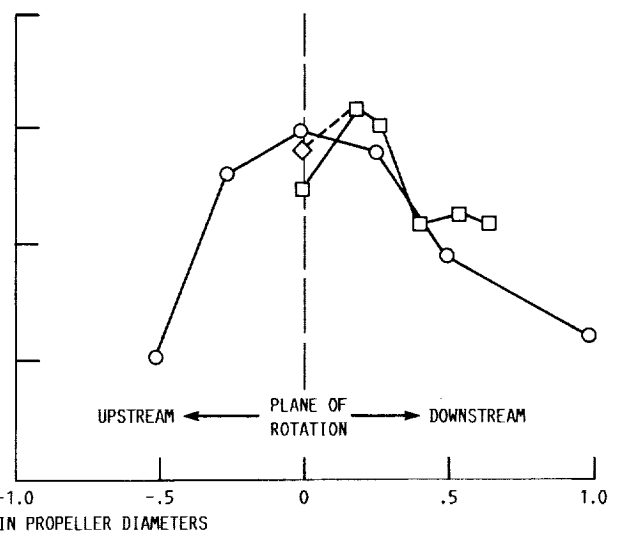
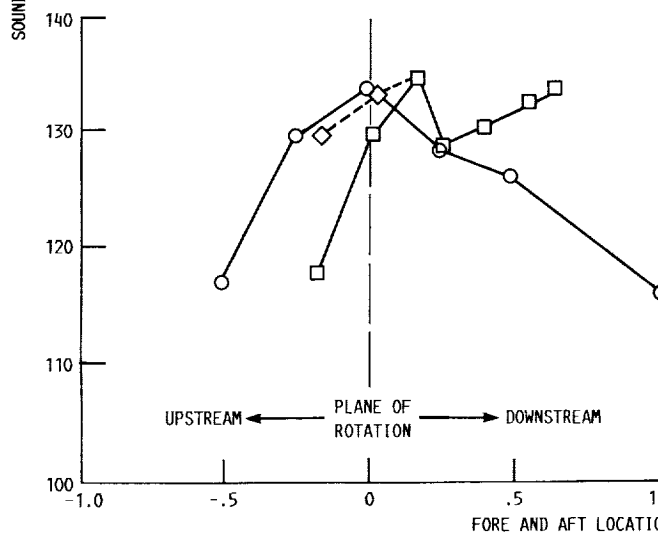
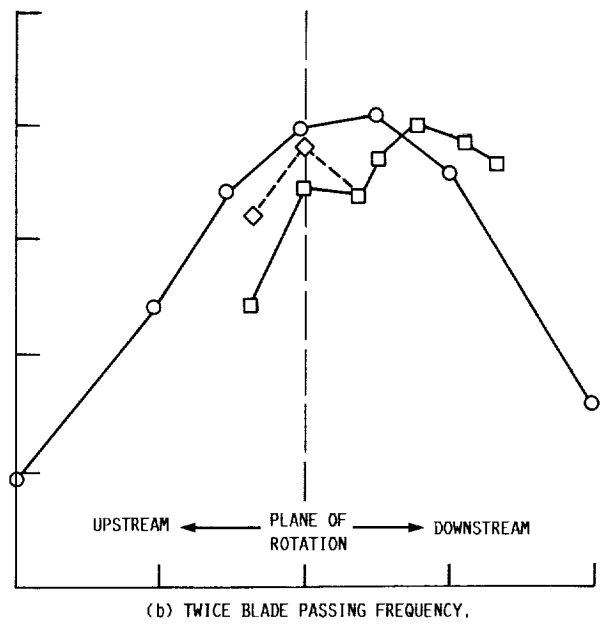
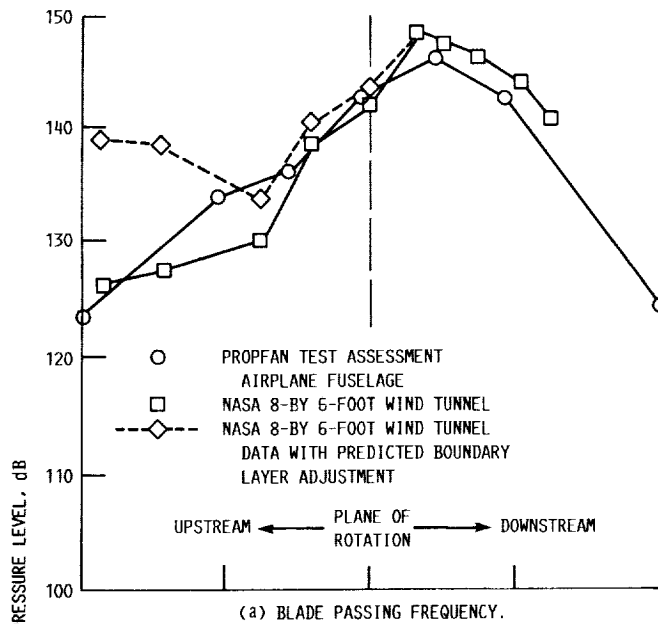


FIGURE 9. - COMPARISON OF 8-BY 6-FOOT WIND TUNNEL ACOUSTIC DATA WITH PROPFAN TEST ASSESSMENT AIRPLANE FUSELAGE DATA.

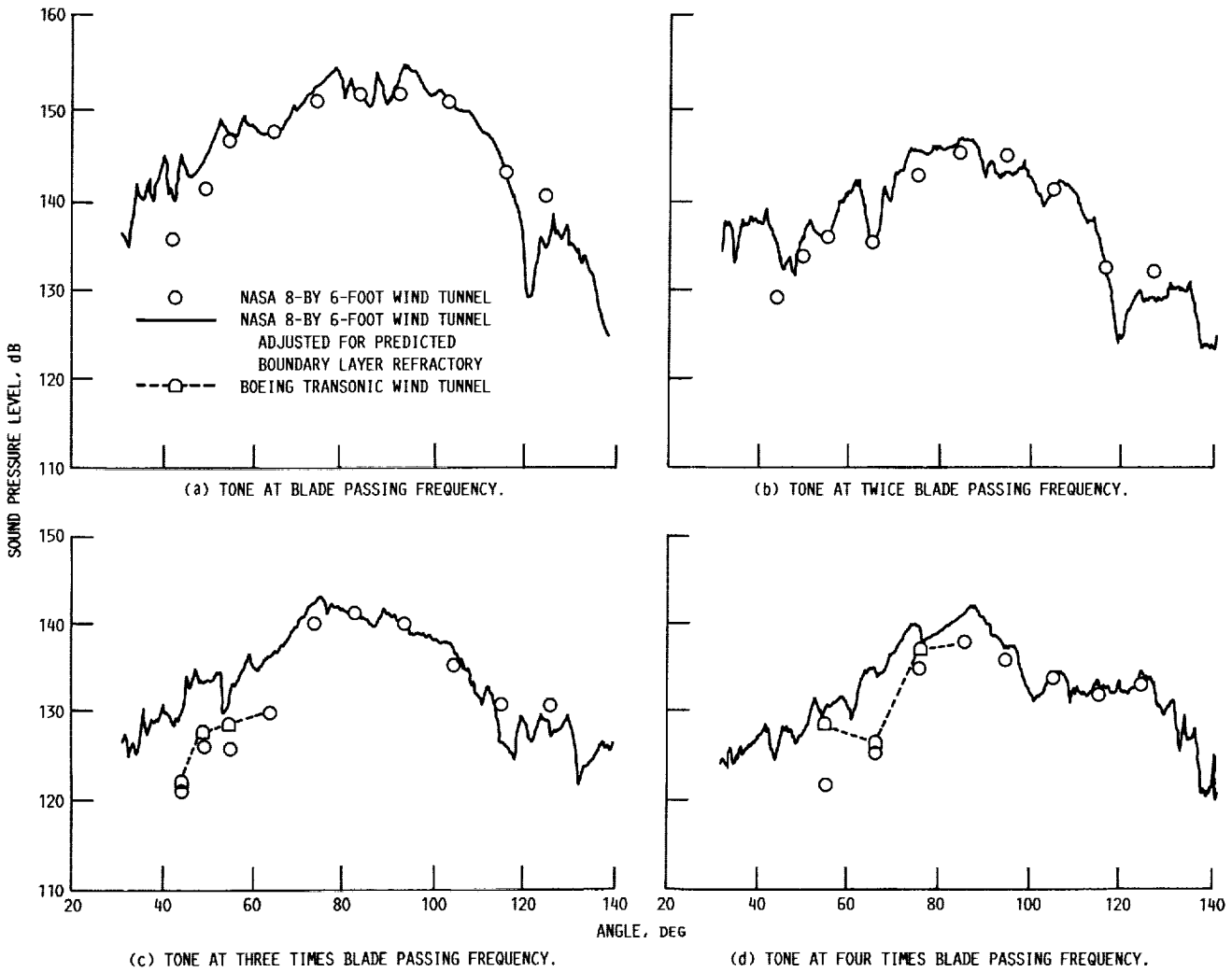


FIGURE 10. - COMPARISON OF NASA 8-BY 6-FOOT WIND TUNNEL ACOUSTIC DATA AND BOEING ACOUSTIC DATA FOR F7-A7 COUNTERROTATION PROPELLER.

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16. Abstract Currently, boundary layer refraction presents a limitation to the measurement of forward arc propeller noise measured on an acoustic plate in the NASA Lewis 8- by 6-Foot Supersonic Wind Tunnel. The use of a validated boundary layer refraction model to adjust the data could remove this limitation. In this paper an existing boundary layer refraction model is used to predict the refraction for cases where boundary layer refraction had been measured. In general, the model exhibits the same qualitative behavior as the measured refraction. However, the prediction method does not show quantitative agreement with the data. In general, it overpredicts the amount of refraction for the far forward angles at axial Mach numbers of 0.85 and 0.80 and underpredicts the refraction at axial Mach numbers of 0.75 and 0.70. A more complete propeller source description is suggested as a way to improve the prediction method.					
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