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Further Comparison of Wind Tunnel and Airplane Acoustic Data for Advanced Design High Speed Propeller Models

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FURTHER COMPARISON OF WIND TUNNEL AND AIRPLANE ACOUSTIC DATA

FOR ADVANCED DESIGN HIGH SPEED PROPELLER MODELS

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SUMMARY

Comparisons were made between the SR-2 and SR-3 model propeller noise data taken in the NASA 8-by-6 wind tunnel, in the United Technologies Research Center (UTRC) anechoic tunnel, and with boom and fuselage microphones on the NASA Jetstar airplane. Plots of peak blade passage tone noise versus helical tip Mach number generally showed good agreement. The levels of the airplane fuselage data were somewhat lower than the boom data by an approximately uniform value. The curve shapes were similar except for the UTRC data which was flatter than the other sets. This was attributed to the UTRC data being taken at constant power while the other data were taken at constant advance ratio. General curves of the peak blade passage tone versus helical tip Mach number fit through all the data are also presented.

Directivity shape comparisons at the cruise condition were similar for the airplane and 8-by-6 tunnel data. The UTRC data peaked farther forward but, when an angle correction was made for the different axial mach number used in the UTRC tests, the shape was similar to the others. The general agreement of the data from the four configurations enables the formation of a good consensus of the noise from these propellers.

INTRODUCTION

The noise of high-tip-speed propellers at cruise has been identified as a possible cabin noise problem for advanced turboprop airplanes. Scale models of this type of propeller have been previously tested for acoustics in the NASA Lewis 8-by-6 wind tunnel using pressure transducers in the tunnel wall (refs. 1 to 7). Some of these propeller models were also flown on the NASA Dryden Jetstar airplane and noise measurements made by microphones installed flush in the airplane fuselage. Comparisons of the wind tunnel and airplane data were made in references 8 to 10.

A subsequent experiment in the NASA Lewis wind tunnel revealed that the previous tunnel instrumentation was apparently miscalibrated and that 6 dB should be added to the previous tunnel data (ref. 11). In addition data have been taken on the Jetstar airplane using a boom microphone mounted above the model propeller which has yielded data different from the data measured on the fuselage (ref. 12). The intent of this report is to make comparisons between these different airplane and tunnel data sets and an additional set of data taken in the UTRC free jet facility (ref. 13).

APPARATUS AND PROCEDURES

Data taken on two propeller models tested in three facilities are used in this comparison. The propeller models, SR-2 and SR-3, are nominally 0.622 m (24.5 in) in diameter; table I indicates some of their design features. More information on these propellers is available in references 14 and 15. The three facilities are the NASA Lewis 8-by-6 wind tunnel, the NASA Dryden Jetstar airplane, and the acoustic research tunnel at the United Technologies Research Center (UTRC). Descriptions and testing methods for these facilities are as follows.

NASA Lewis 8-by-6 Wind Tunnel

Noise measurements were made in the wind tunnel by pressure transducers installed flush with the tunnel ceiling. A photograph of the SR-3 propeller in the wind tunnel is shown in figure 1. The locations of the transducers for the SR-2 test are shown in figure 2(a) and for the SR-3 test in figure 2(b). The experiments were performed at a nominally constant advance ratio of 3.06 at tunnel axial Mach numbers of 0.85, 0.80, 0.75, 0.70, and 0.60. The wind tunnel data for the SR-2 and SR-3 propellers can be found in references 2 and 3.

NASA Dryden Jetstar Airplane

A photograph of the SR-3 propeller being tested on the airplane is shown in figure 3. Part A shows the plane during the fuselage microphone experiments and part B shows the boom installation. The measurement locations on the airplane are shown in figure 4. Figure 4(a) shows fuselage locations and the relationship of the microphone boom to the propeller is shown in figure 4(b). Four microphones were installed in the boom corresponding in position to locations 3, 4, 5, and 7 on the fuselage. The airplane experiments were performed with roughly a constant advance ratio of 3.06 except at the higher axial Mach numbers where power limitations forced a slightly higher advance ratio. The airplane data used in these comparisons are found in references 12, 16, and 17 and were taken with the windshield wipers removed from the airplane.

United Technologies Acoustic Research Tunnel

A top view of the acoustic research tunnel is shown in figure 5(a) and the locations of the microphones at 0.8 diameter tip clearance are shown in figure 5(b). The microphones were located axially in the plane of rotation and symmetrically fore and aft of the plane of rotation at ±0.25, ±0.5, and ±1.0 propeller diameters. For these experiments the free jet was operated at a nominal through flow Mach number of 0.32. Therefore in order to obtain helical tip Mach numbers equivalent to those obtained in flight or in the wind tunnel, the propeller was oversped. In addition the propeller was tested using only two blades because of a power limitation and the experiments were conducted at fixed power which means varying the advance ratio for the various test conditions. The power level was nominally 28 kW (37 hp) per blade with some variation at the higher helical tip Mach numbers where the power was as high as 36.4 kW (48 hp) for SR-3 at a helical tip Mach number of 1.21. The data from the experiments is found in reference 13.

RESULTS AND DISCUSSION

In order to compare the data taken in different facilities it is first necessary to adjust the data to the same condition. This condition was chosen as the airplane fuselage condition at 9.1 km (30 000 ft) altitude. In order to do this the various data were adjusted as indicated below.

The NASA 8-by-6 wind tunnel data was adjusted, as in reference 8, by reducing the data by 6.4 dB at a tunnel Mach number of 0.60, 5.9 dB at 0.70, 5.5 dB at 0.75, 4.9 dB at 0.80 and 4.4 dB at 0.85. These corrections are a combination of a distance correction and a correction for the altitude of the wind tunnel with respect to the airplane. Twenty times the log of the pressure ratio was used for the altitude correction and 15 log of the distance ratio for a distance correction. It should be noted here that the distance ratio is so close to one that the use of 20 log of the distance would result in less than 1 dB difference from the 15 log number. In addition 6 dB was added to account for the miscalibration mentioned earlier.

The boom data taken on the NASA Dryden Jetstar airplane has a 4 dB pressure amplification at the surface of the probe, see reference 12, as opposed to an assumed 6 dB amplification on the airplane fuselage. Therefore 2 dB has been added to the boom data to compare them with fuselage data. The combination of boundary layer refraction and pressure amplification may result in different amplification levels as suggested by Hanson (ref. 18). However the 6 and 4 dB amplifications were used consistently in this report and no correction for boundary layer refraction was applied to the airplane or 8-by-6 wind tunnel data.

The data taken in the UTRC anechoic tunnel has a number of corrections applied to it. This data was taken with free field microphones outside the shear layer of an open jet. The first correction to the data is then a 6 dB addition to account for the pressure doubling of the airplane fuselage. During the experiments the propeller was run with two blades in an axial flow of $M = 0.32$. To approximate the cruise condition, the blade is oversped to obtain a simulated cruise helical tip Mach number. To account for the eight blades of the flight propeller the 8P harmonic of the two bladed propeller was used and 12.04 dB was added to the tunnel data.

Corrections to the data to account for the passage of the noise through the jet shear layer are described in reference 13 and those corrections were applied and are included in the data as published in reference 13. The UTRC data were also taken at roughly a constant power setting whereas the other sets of data were taken at a constant advance ratio. No correction was applied for this but a discussion of the possible effect of this is included in the section "Variation with Helical Tip Mach Number" which follows. In addition a 9.88 dB reduction to the UTRC data was applied to account for the difference in the altitude that the tunnel operates with respect to the airplane. The net effect then was to add 8.16 dB to the data taken in the UTRC tunnel.

Variation with Helical Tip Mach Number

SR-2. - Comparisons of the maximum blade passage tone plotted versus helical tip Mach number, M_{Ht}, are shown for the SR-2 propeller in figure 6. The maximum blade passage tone is plotted regardless of its axial location.

Figure 6(a) is the data comparison for the SR-2 propeller. The 8-by-6 wind tunnel data were taken from reference 2. The Jetstar boom data were taken from figure 19 of reference 12. Six decibels were added to the data from this figure since this data had been previously adjusted to free field conditions. The fuselage Jetstar data were taken from figure 14 of reference 16 and were taken with the airplane windshield wipers removed. The UTRC data were taken from figure numbers 3-16(a) of reference 13.

As can be seen from figure 6(a) these data compare favorably. Some variation is noted but should be expected considering all of the data scatter possibilities in the four test methods. An attempt to show the different curves drawn by the various authors is also shown in figure 6(a). The individual curve shapes of course were chosen for that particular set of data. With the exception of the UTRC data all of the sets of data are showing a bend over in the data at high helical tip Mach numbers. The difference in curve shapes may be related to the manner in which the UTRC data were taken. The UTRC data were taken at approximately constant power while all the other data was taken at constant advanced ratio. This results in higher power at the low Mach numbers and is the probable cause of the UTRC data being higher at the low Mach numbers than the data taken with a constant advance ratio. The higher loading than the nominal 28 kW (37 hp) per blade at the higher helical tip Mach numbers may also be giving a higher noise here. All of this contributes to the seeming linear shape of the UTRC data. The UTRC data is really only at the same condition as the constant advance ratio data near the design conditions $M_{Ht} = 1.14$ and here it does give similar results.

Although they fall in the same general band of data, the airplane data taken with the boom and with the fuselage microphones are a number of decibels apart at the higher Mach numbers. In reference 12 this lower level of the fuselage data was attributed to boundary layer refraction. However a recent experimental study (ref. 11) has indicated that the boundary layer refraction does not affect the noise at or behind the plane of rotation where the peaks were measured. Even if one were to consider boundary layer refraction as a possibility, the data taken in the 8-by-6 wind tunnel were taken under a boundary layer similar to that on the airplane and they show values similar to the boom except at the $M_{Ht} = 1.11$ condition. More about this subject will be discussed further but it appears that something in addition to boundary layer refraction may be occurring here.

In figure 6(b) an attempt is made to fair a curve through all of the sets of data. The UTRC data point at $M_{Ht} = 0.78$ was not included since it was felt that the loading was too high for comparison with the other sets of data. This data point is left off the plot. The curve is shown bending over at the higher helical tip Mach numbers since the majority of the data indicates that this is occurring. The curve is dotted beyond a Mach number of 1.14 because there is only one 8 by 6 data point. Whether the curve actually becomes flat beyond $M_{Ht} = 1.14$ is not determined as yet and additional points beyond $M_{Ht} = 1.14$ will have to be taken to verify the curve shape.

<u>SR-3</u>. - The comparisons of the data for the SR-3 propeller are shown in figure 7. Part A shows the four sets of data with the various authors' data curves. Again the data comparison is fairly good. In fact the comparison is very good for the UTRC, 8-by-6, and airplane boom data. (Only one point for the UTRC test at $M_{Ht} = 1.03$ is significantly different than the other two data sets.) The airplane fuselage data is however significantly lower than the

other sets of data. This was noticed in the SR-2 comparison but is very prominent in the SR-3 comparison, making this data suspect. Again, even if boundary layer refraction is considered as a possibility, the 8-by-6 wind tunnel data, taken under a similar boundary layer to that of the airplane data does not show this effect and it appears that boundary layer refraction does not explain the lower fuselage noise numbers. The shape of the fuselage data curve is very similar to the other data curves, for both SR-2 and SR-3, appearing to be shifted only in level.

Because of the seemingly low fuselage values, they are not included in the general curve fit to the SR-3 data. This general data curve is presented in figure 7(b). With the exception of the UTRC data point at a helical tip Mach number of 1.03, the curve is a good fit to the UTRC, 8-by-6, and airplane boom data. (The UTRC data point at $M_{Ht} = 0.81$ was left on the plot even though the loading was high.) Again, as with SR-2, the curve bends over at the higher helical tip Mach numbers since the data, here, going to Mach numbers over 1.2, indicate this shape. Considering the different conditions under which the data were taken, in particular the UTRC data which was at a significantly different axial Mach number, the noise comparisons are very good. The airplane fuselage data are lower than the other data but their shape with helical tip Mach number appears correct. In reference 12 this lower level of the fuselage data was attributed to boundary layer refraction but a recent experimental study (ref. 11) has indicated that the boundary layer refraction does not affect the noise at or behind the plane of rotation where the peaks were measured. It may be that there is some factor that can account for the data shift from the other data.

<u>General curve comparisons</u>. - The curves fit through the SR-2 and SR-3 data are shown in figure 8. As has been observed previously from the individual sets of data the SR-3 propeller is quieter than the SR-2. The noise curves exhibit a region of sharp noise increase followed by a region where the noise levels off. The region of sharp noise increase has apparently been delayed to a higher helical tip Mach number by the sweep of SR-3 and the tailoring of this sweep to provide noise cancellation from the spanwise sections has apparently resulted in a lower SR-3 noise level at the higher helical tip Mach numbers.

Directivity Comparisons

<u>SR-3</u>. - The blade passage tone versus angle data for the SR-3 propeller at the design condition referenced to the airplane fuselage are shown in figure 9. Figure 9(a) shows the data as taken from the following references: The NASA 8-by-6 data from reference 3; the UTRC data from figure 10(a) of reference 13; and the Jetstar boom data from figure 10 of reference 12; and the fuselage data from figure 28 of reference 17. Straight lines are drawn to connect the data points to show the curve shapes. The shapes appear similar for the 8-by-6 wind tunnel and both sets of airplane data but the UTRC data peaks further forward. The shapes of the airplane boom and fuselage curves are very similar appearing to be shifted only in level. Reference 11 has indicated that boundary layer refraction affects the forward angles much greater than the rear and thus this almost uniform shift may be further indication that the shift is not caused by boundary layer refraction.

A comparison of the curve shapes normalized at the peak noise level is shown in figure 9(b). The airplane boom and fuselage data are nearly together.

The fuselage data does fall off slightly faster toward the front (60° position) but at 90° and aft is almost the same as the boom data. This slight fall off toward the front is very similar to that found to be caused by boundary layer refraction in reference 11, but the overall shift in level would not be similar to boundary layer refraction. The directivity plots then further indicate that the fuselage data may be shifted in level by some unaccounted for factor.

As mentioned all of the data sets indicate the peak noise occurs in the rear around 110° except the UTRC data which has the peak toward the front. The effect of convection probably explains this angle difference. The 0.8 Mach number flow of the airplane and 8-by-6 tunnel test sweeps the noise further downstream than the 0.32 Mach number flow of the UTRC tests. A simple correction using ray acoustics was developed. This vector diagram method first determined the zero flow emission angle and then calculated the measurement angle at Mach 0.8. This resulted in the UTRC data at 65° being shifted rearward to 100.1°, that at 77° to 108.2°, 87° to 114.9°, and 97° to 121.5°.

Figure 9(c) presents the UTRC data with this convection correction applied to it. Because of the data being taken on a sideline, the shift in angle also results in a different source-receiver distance. A level correction would then also result. The UTRC data at 65° in figure 9(b) were increased by 0.54 dB and the data set at 77°, 87°, and 97° were decreased by 0.34, 0.63, and 0.99 dB, respectively (based on 15 $\log_{10}$). With these adjustments figure 9(c) now shows the various directivity patterns all with their peaks around the same location and all having similar shapes. Toward the front, the 8-by-6 wind tunnel data falls off more quickly than the airplane data and toward the rear, around 130°, the 8-by-6 and UTRC data are not in agreement. The UTRC data taken at 117° and 133° were shifted beyond the range of the other data but they also would appear high. The cause of this discrepancy has not been resolved. Even with these aforementioned discrepancies the convective shift of the UTRC data has resulted in the four data sets now showing very similar directivities particularly near the peak noise angle.

<u>SR-2</u>. - Blade passage tone versus angle data for the SR-2 propeller at roughly the design condition are shown in figure 10. Figure 10(a) shows the data taken from the following references.

The NASA 8-by-6 tunnel data is taken from reference 2. The directivity data presented here is for the propeller operating at a helical tip Mach number of 1.07. This data was used because of apparent anomalies in the M_{Ht} = 1.14 data at off peak angles. Even though this is at a slightly lower Mach number it should yield a reasonable shape for comparison purposes. The UTRC data is from figure A-8(a) of reference 13. The Jetstar boom data is from figure 19 of reference 12 and the fuselage data is from figure 13 of reference 16.

The SR-2 curve shapes in figure 10(a) are similar for the 8-by-6 tunnel and the airplane boom data sets. The UTRC data again peaks further forward and the airplane fuselage data which appears to be shifted in level from the boom data has a somewhat different shape toward the rear.

A comparison of the normalized SR-2 data is shown in figure 10(b). The airplane boom and fuselage data look very close in the front but behind 90° they start to diverge with the fuselage data falling off faster than the boom data. The good shape comparison in the front is encouraging but the reason for the divergence to the aft is not understood. The 8-by-6 tunnel and the boom data are in very good agreement except around the 77° position.

The directivity pattern of the UTRC tunnel data again peaks forward of the other data. In figure 10(c) the UTRC data has the convection correction applied shifting it to the aft and again, as it did with SR-3, this brings the location of the peak level in agreement with the other sets of data. The discrepancies toward the rear, around 130°, were also present with the SR-3 data and are not explained. Again the convective shift applied to the UTRC data has brought the directivities of the four sets of data into fairly good agreement, particularly near the peak noise angle.

CONCLUDING REMARKS

Comparisons were made of the SR-2 and SR-3 propeller noise data taken in the NASA 8-by-6 wind tunnel, the UTRC anechoic tunnel and on the NASA Jetstar airplane with boom and fuselage microphones. These comparisons were made with all of the data corrected to the airplane fuselage conditions.

Plots of the peak blade passage tone noise versus helical tip Mach number showed good agreement among the sets of data. The shapes of the curves were very similar for the 8-by-6, and the Jetstar boom and fuselage microphones. The levels of the fuselage microphones were somewhat lower than the boom data by an approximately uniform shift. However, the UTRC data curve shape was different than the others and was attributed to the fact that the UTRC data was taken at constant power and not at constant advance ratio. General curves of peak blade passage tone noise versus helical tip Mach number were developed for the two propellers and when compared indicated the noise advantages of the swept SR-3 propeller over the straight SR-2 propeller.

Directivity comparisons were performed at the cruise condition for the two propellers. The directivity shapes were similar for the 8-by-6 and airplane boom and fuselage data but the UTRC data peaked further forward. When a convective correction was applied the UTRC directivity, the shape was similar to the others. The airplane fuselage directivities were similar to the boom directivities and the normalized curves further indicate what appears to be a shift in the level of fuselage data. The general agreement of the data from the four configurations enables the formation of a good consensus of the noise signature of these propellers.

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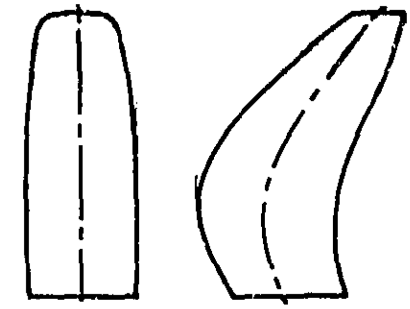
TABLE I. - COMPARISON OF PROPELLERS



	SR-2	SR-3
Design cruise tip speed, m/sec (ft/sec)	244(800)	244(800)
Design cruise power loading, P/D^2, kW/m^2 (shp/ft^2)	301(37.5)	301(37.5)
Number of blades	8	8
Tip sweep angle, degrees	0	45
Design efficiency, %	77	81
Nominal diameter, D, cm (in)	62.2(24.5)	62.2(24.5)

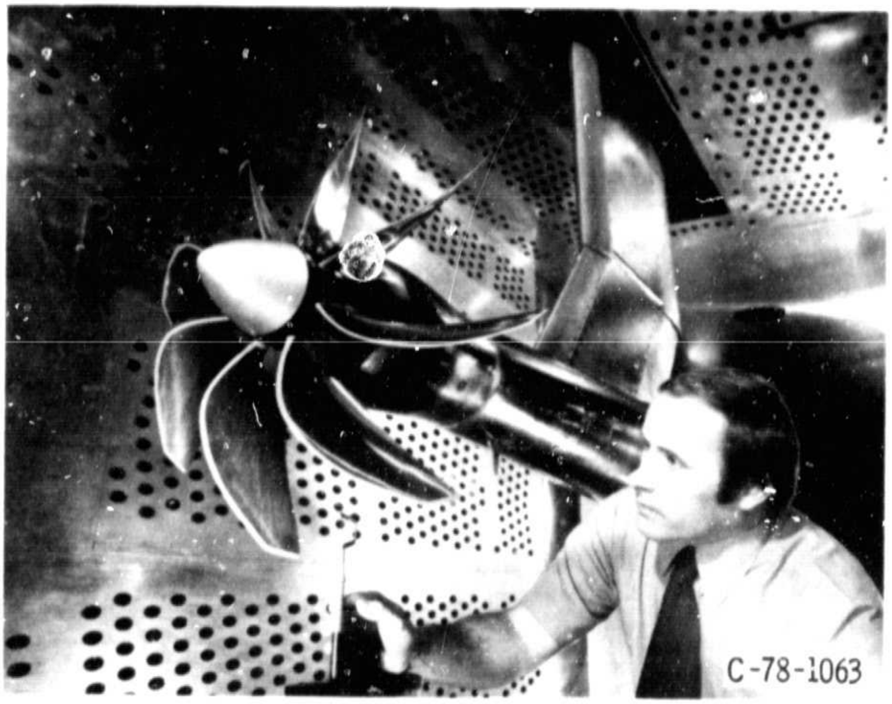
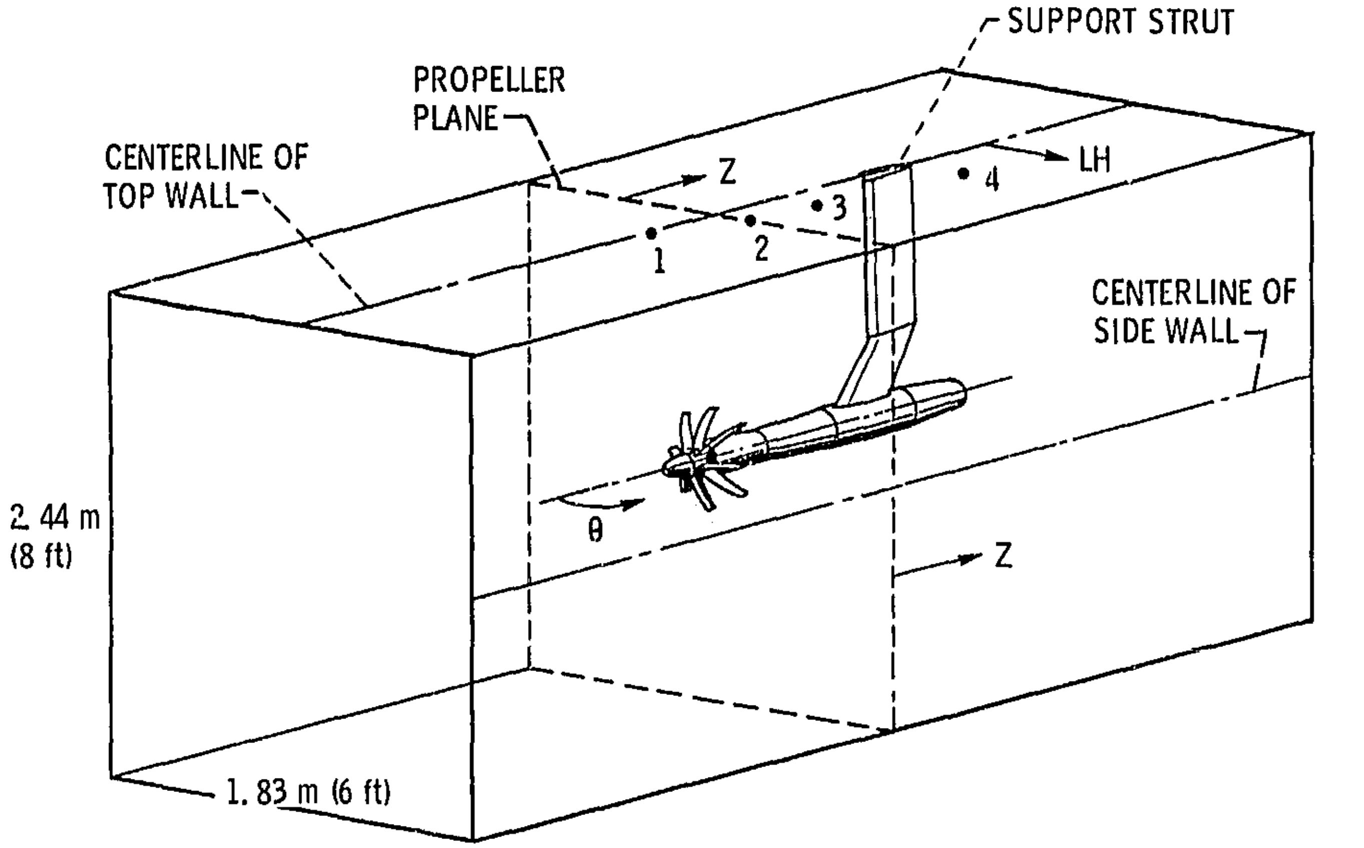


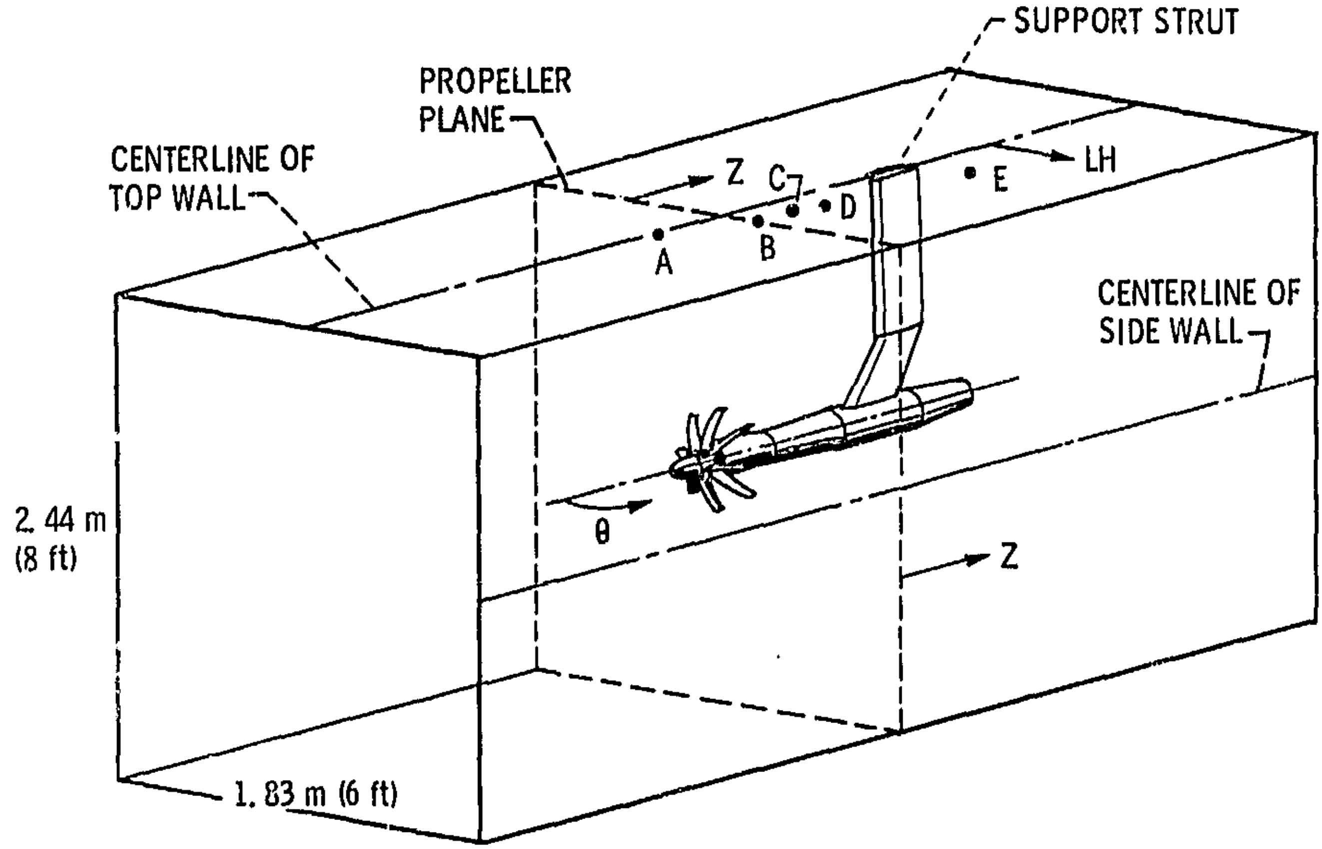
Figure 1. - SR-3 propeller in 8 by 6 foot wind tunnel.



POSITION	TRANSDUCER (1 1/2 DIAMETER FROM TIP)			
	1	2	3	4
	TRANSDUCER POSITION, cm (in.)			
Z LH	-27.7(-10.9) 2.54(1.0)	0.953(0.375) 10.2(4.0)	45.2(17.8) 7.62(3.0)	104.4(41.1) 31.5(12.4)
NOMINAL ANGLE, θ, deg.	77	90	110	130

(a) SR-2 positions.

Figure 2. - Pressure transducer positions.



POSITION	TRANSDUCER (1 1/2 DIAMETER FROM TIP)				
	A	B	C	D	E
	TRANSDUCER POSITION, cm (in.)				
Z LH	-33.0(13.0) 4.83(1.9)	0.953(0.375) 10.2(4.0)	23.9(9.4) 2.54(1.0)	45.2(17.8) 7.62(3.0)	107.4(42.3) 31.5(12.4)
NOMINAL ANGLE, θ, deg.	75	90	101	110	131

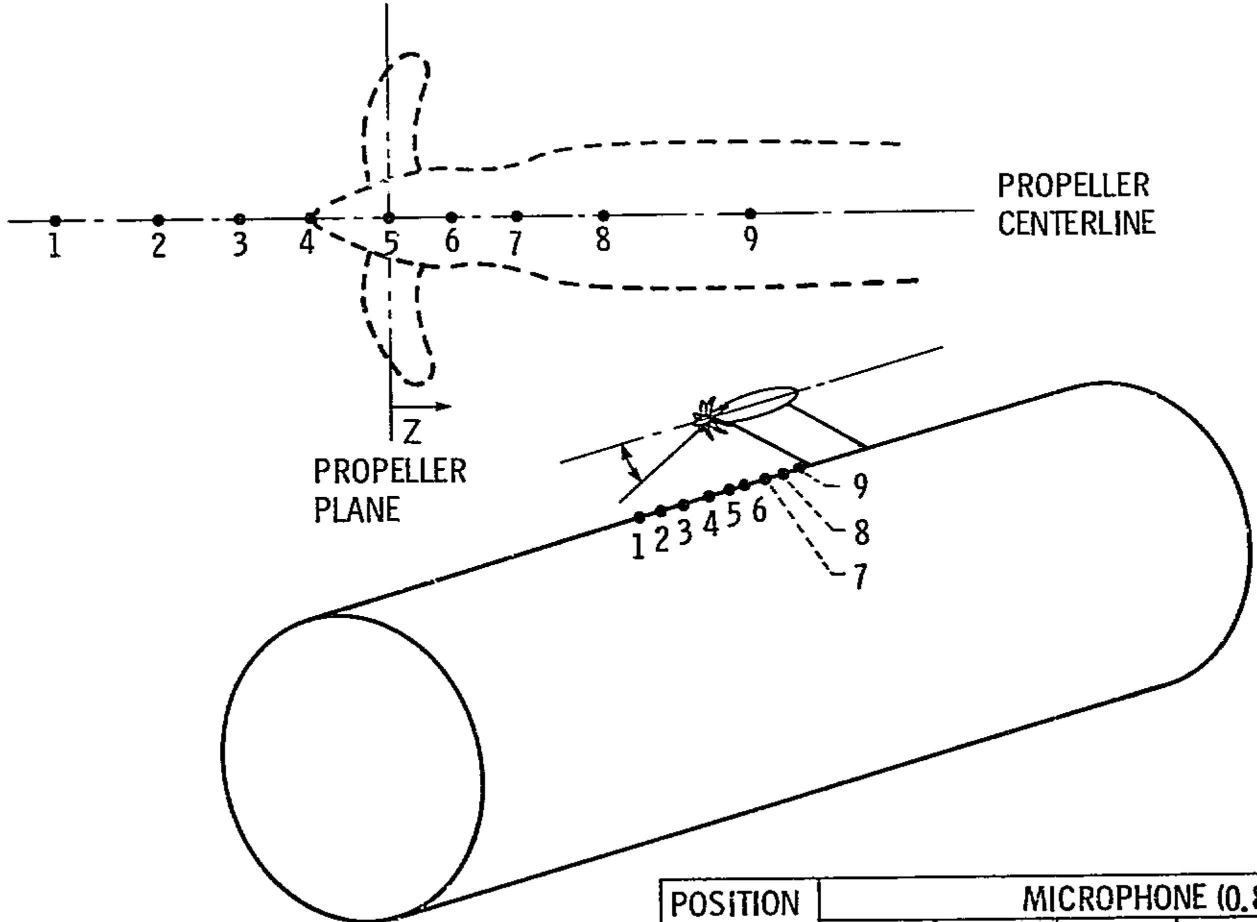
(b) SR-3 positions.

Figure 2. - Concluded.

(a) Fuselage microphone experiments.

(b) Boom microphone experiments.

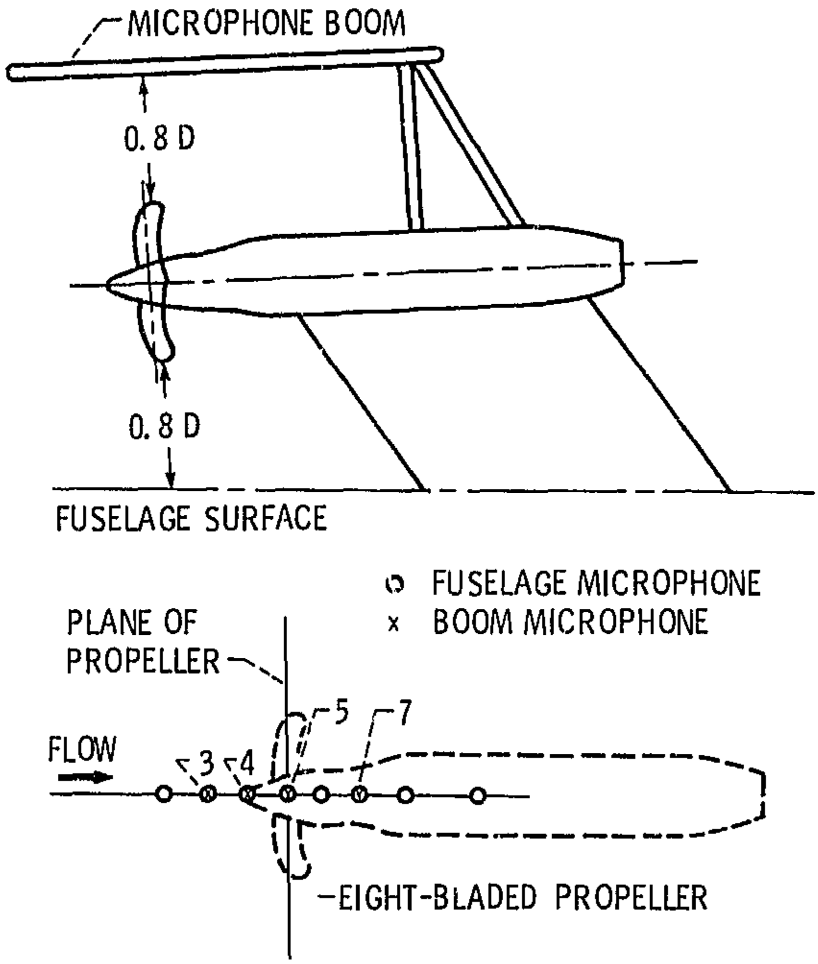
Figure 3. - SR-3 Propeller on Jetstar airplane.



POSITION	MICROPHONE (0.8 DIAMETER FROM TIP)								
	1	2	3	4	5	6	7	8	9
	MICROPHONE POSITION cm (in.)								
Z	-66.0 (-26.0)	-46.7 (-18.4)	-30.5 (-12.0)	-16.0 (-6.3)	.76 (.3)	12.4 (4.9)	25.1 (9.9)	42.4 (16.7)	71.1 (28.0)
NOMINAL ANGLE, θ, deg.	51	59	69	79	91	98	107	117	130

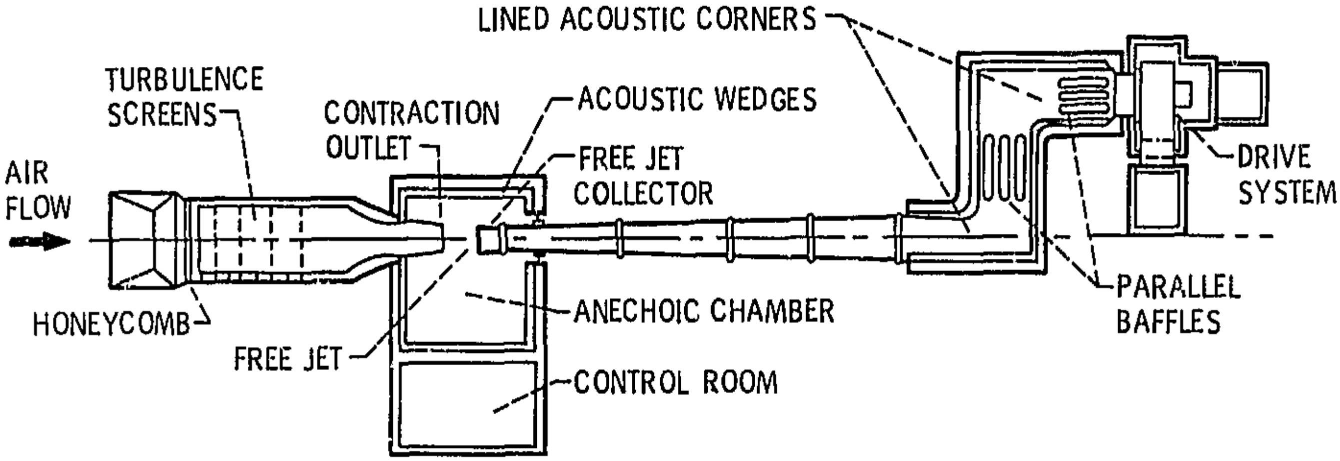
(a) Fuselage microphones on airplane.

Figure 4. - Airplane measurement locations.

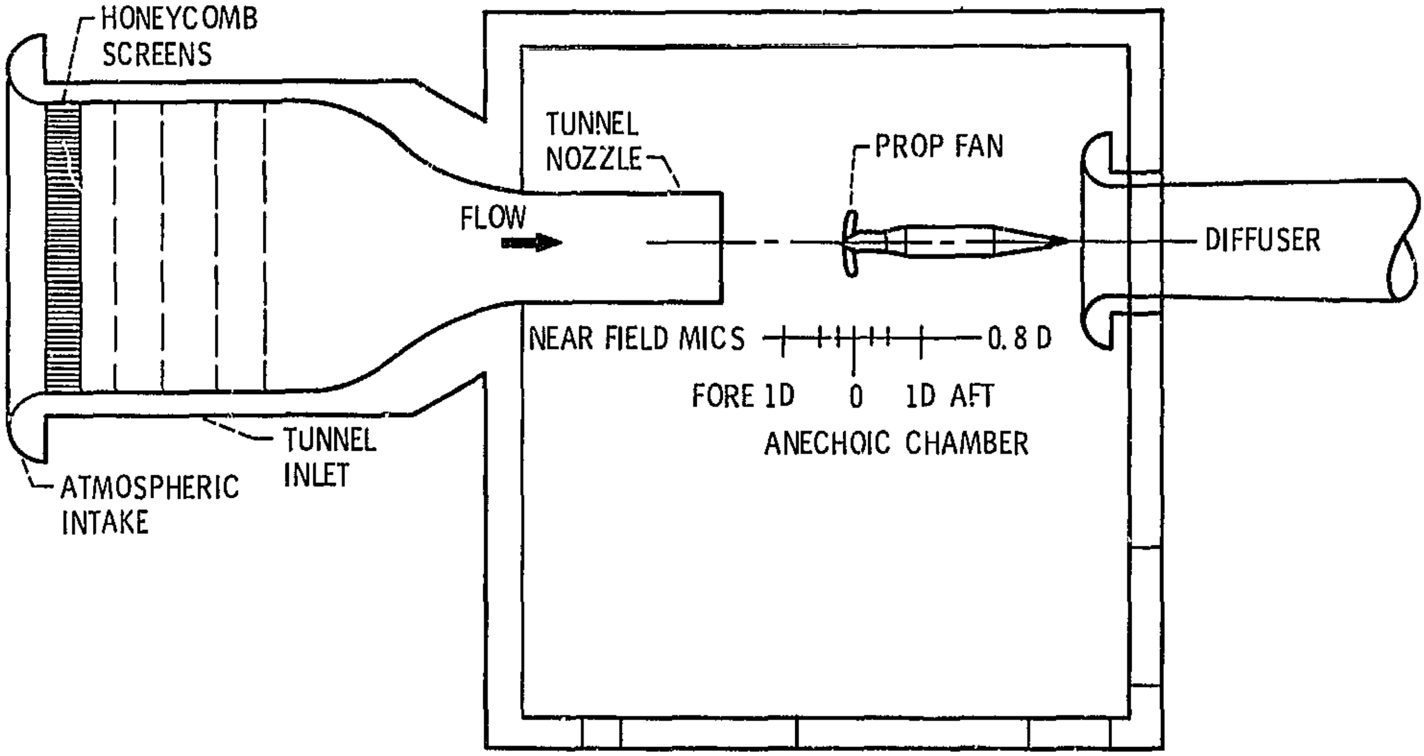


(b) Boom microphones.

Figure 4. - Concluded.

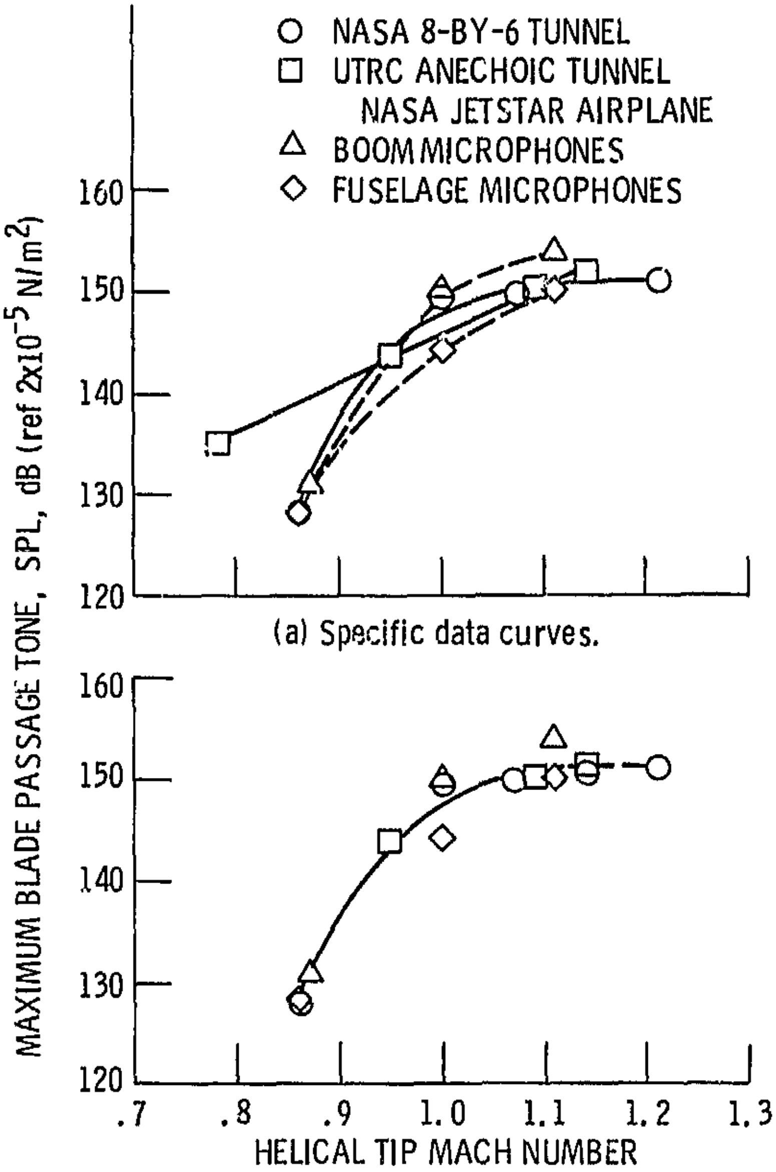


(a) Top view.



(b) Microphone locations.

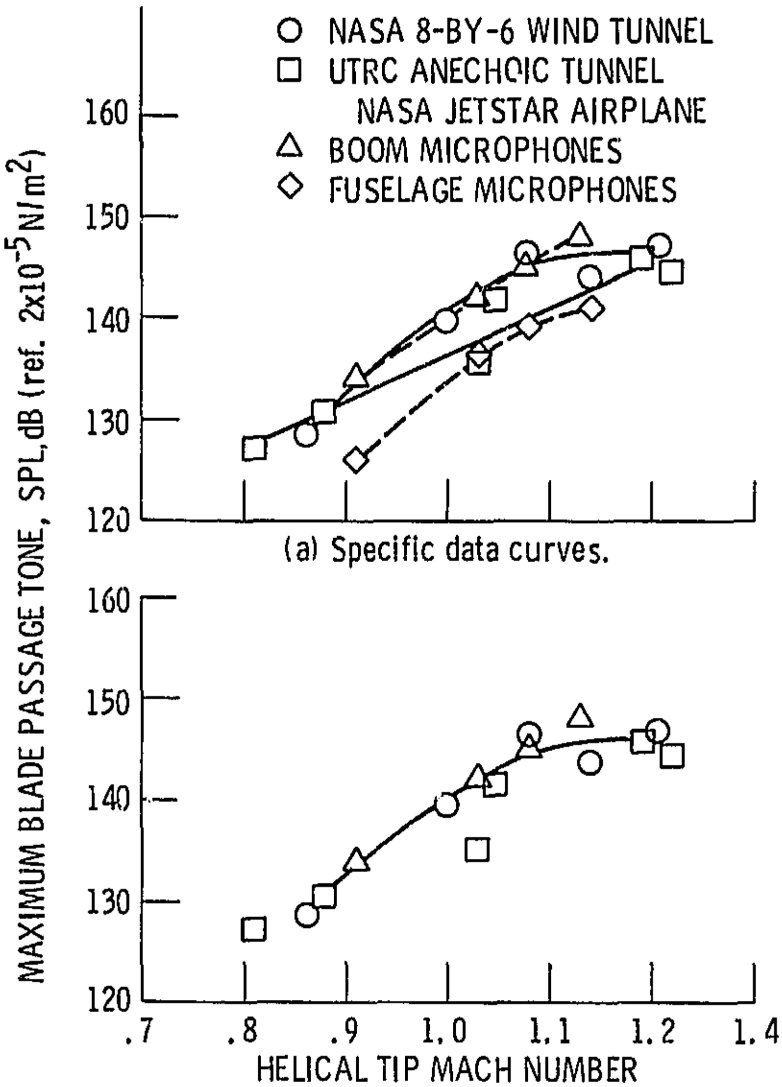
Figure 5. - United technologies acoustic research tunnel.



(a) Specific data curves.

(b) General data curve.

Figure 6. - Maximum blade passage tone variation with helical tip Mach number, SR-2 propeller corrected to fuselage conditions.



(a) Specific data curves.

(b) General data curve.

Figure 7. - Maximum blade passage tone variation with helical tip Mach number, SR-3 propeller corrected to fuselage conditions.

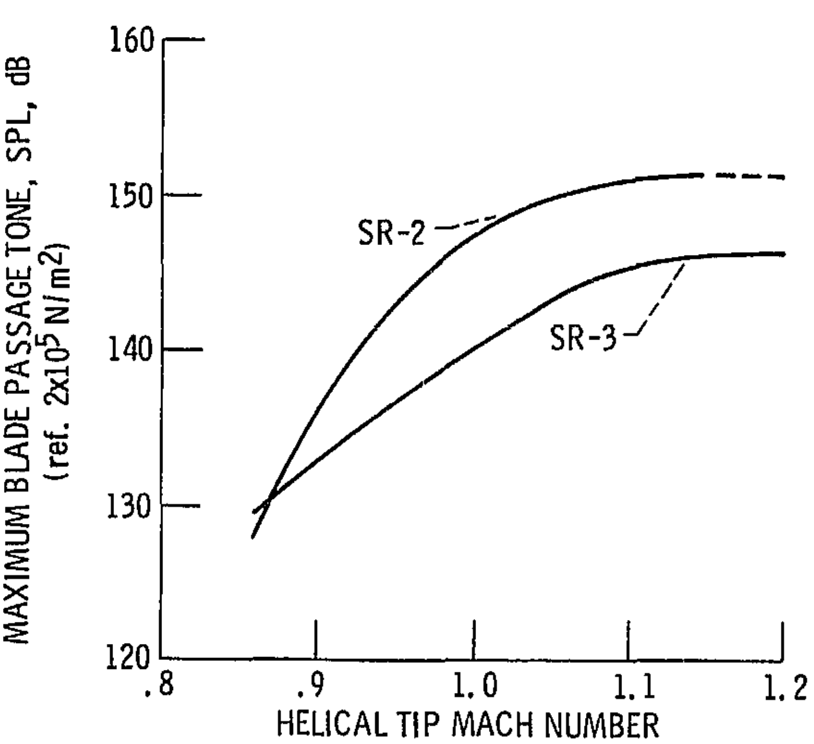
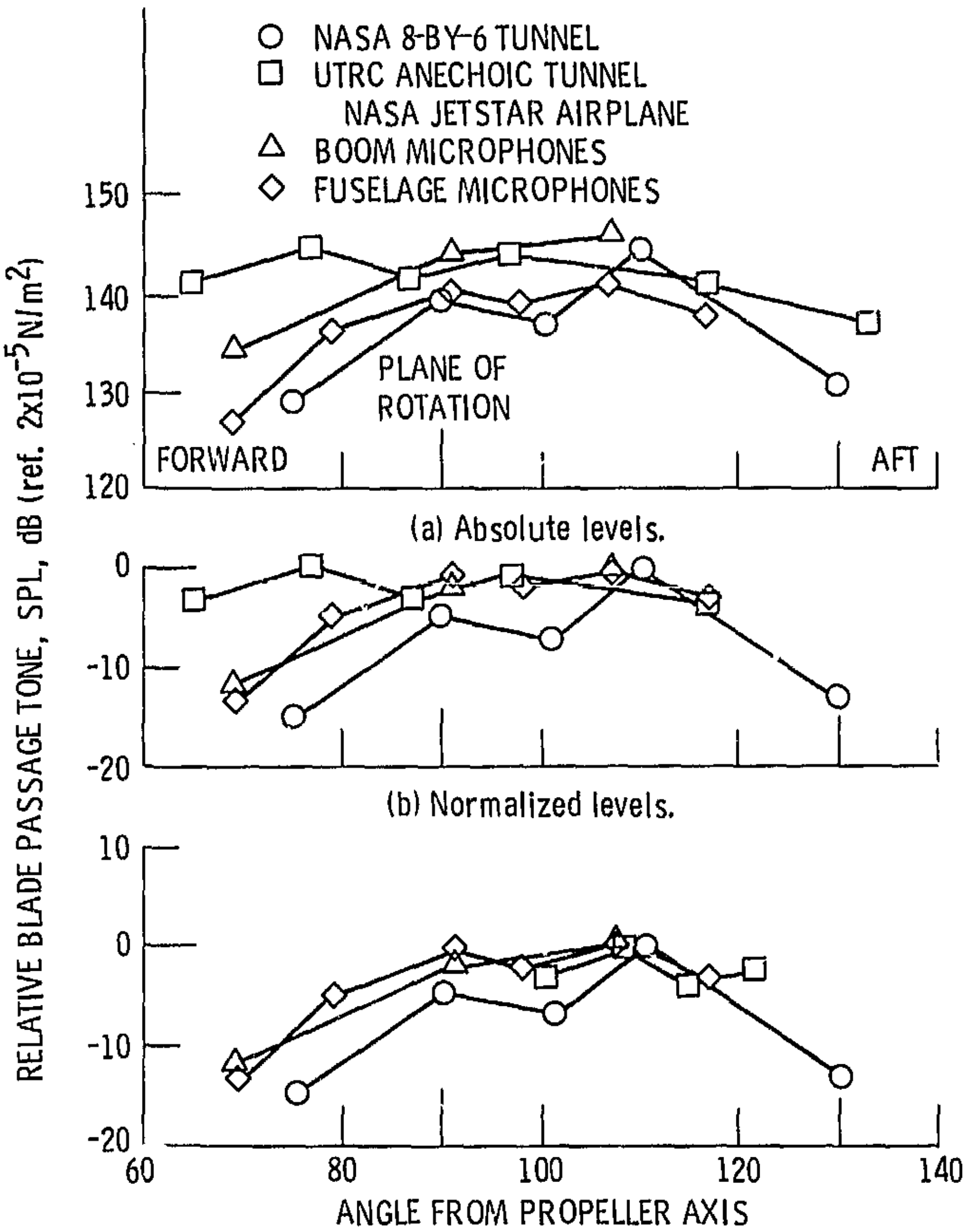


Figure 8. - Comparison of general curve fits for the SR-2 and SR-3 noise data.



(a) Absolute levels.

(b) Normalized levels.

(c) UTRC data corrected to account for convection.

Figure 9. - SR-3 propeller directivity at cruise.

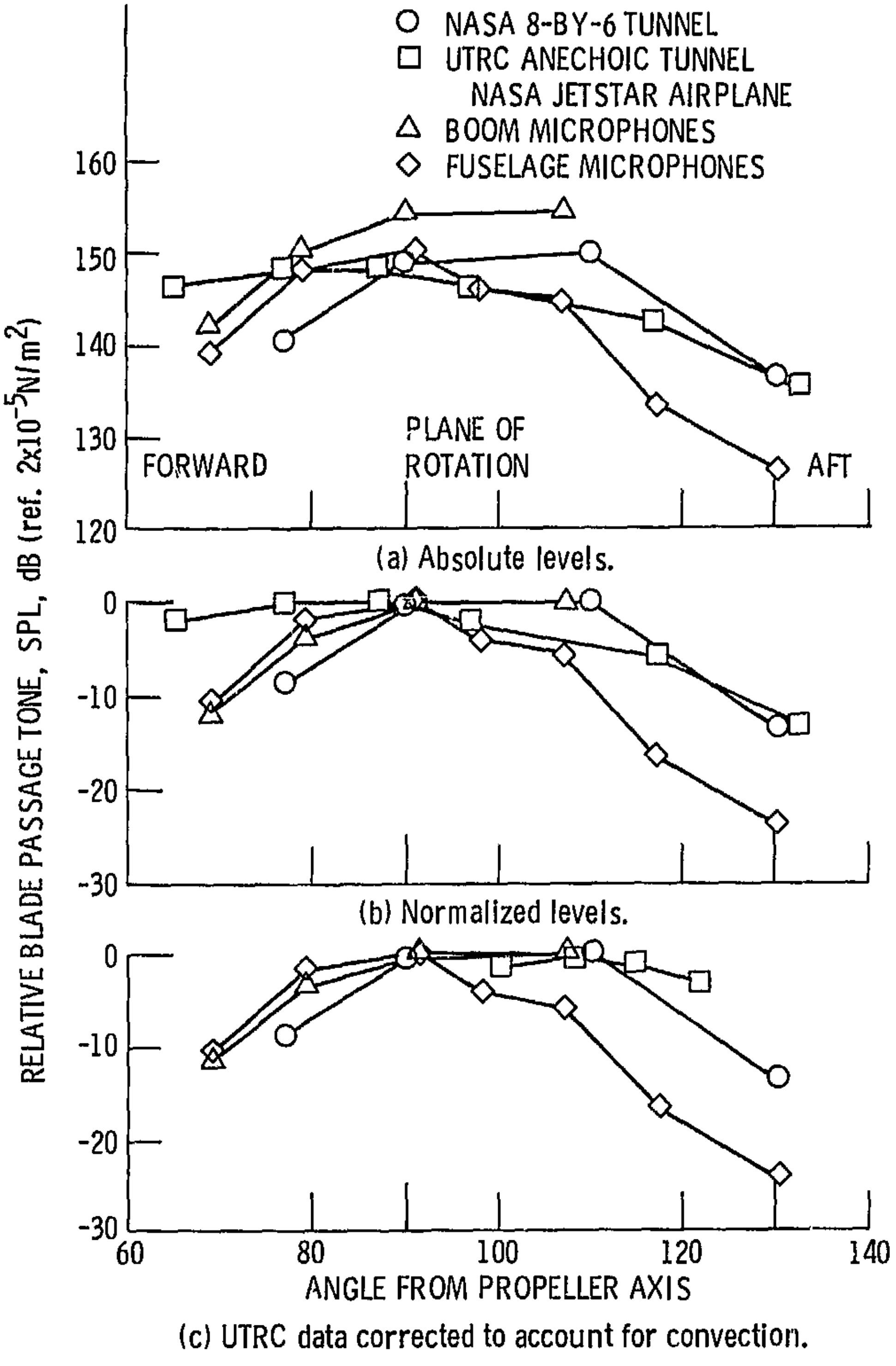


Figure 10. - SR-2 propeller directivity at cruise.