Noise Testing of an Advanced Design Propeller in a Wind Tunnel

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Noise tests using the NASA SR-6 advanced design propeller in the Boeing Transonic Wind Tunnel have recently been completed. Measurements were taken both with and without an acoustically treated test section. A wide range of helical tip speeds and power loadings were explored. Noise test techniques previously not applied to advanced design propeller testing have shown results indicating an increased level of confidence in the measured signatures. Typical results are presented, along with recommendations for future noise tests and elementary empirical prediction methods for the SR-6.

Nomenclature

BTWT	= Boeing Transonic Wind Tunnel
D	= propeller diameter (27.4 in.)
J	= advance ratio
log	= base 10 logarithm
LTC	= large test chamber (anechoic)
M	= freestream Mach number
M_{ht}	= helical tip Mach number
R_2	= coefficient of determination
S.E.	= standard error
SHP	= shaft horsepower
SHP/D_2	= power loading
SPL	= sound pressure level
β	= pitch angle (75% radius)
θ_e	= emission angle ($\theta_e = \theta_{m-\mathrm{arscin}} M_{\sin} \theta_m$)
θ_m	= observation angle

Introduction

THE NASA-owned SR-6 propeller is one of a series of single rotating tractor (SRT) advanced design propellers (ADP), which have a high solidity, thin blade section, and swept tips. These propellers are designed to operate at helical tip speeds in the transonic region. As such, the SR-6 is part of a new generation of propellers which have potential application to large aircraft and could provide substantial fuel savings as compared to the current generation of turbofan-powered aircraft. Noise is one of several key technologies involved in successful implementation of ADP on commercial aircraft. The SR-6 test results have been used by Boeing to assist in development of test techniques, facilities, and procedural requirements for future ADP testing.

Tests were conducted in late 1983 and early 1984 both in an anechoic chamber with a freejet[1] and as described in this article, in a closed test-section wind tunnel. See Fig. 1 for test parameter variations. The wind-tunnel tests included the use of an acoustically treated section and, alternately, a hard-walled section. The purpose of soft-wall and hard-wall comparison tests was to determine whether or not a soft wall provided substantial benefits in making acoustic measurements of ADP, since successful acoustic measurement capability in a closed wind tunnel would greatly reduce development costs of new ADP-powered aircraft. This article reports the results of these comparison tests and some indicated data trends.

Treatment Characteristics and Comparison Test Conditions

The acoustically treated test section was designed to be an add-on type of installation which could be temporarily attached inside the original test-section walls (see Fig. 2). The resulting cross-sectional area of the test section was 25% less than the standard hard-walled cross section. This restricted the maximum achievable Mach number to 0.49, due to reduced efficiency in the wind-tunnel drive system. However, $M = 0.49$ appears adequate for determining whether or not acoustic treatment is required. The treatment used for these tests was a 1.75-lb/ft^3 density bulk absorber (Scott Hyfonic) foam of 8 in. thickness (Fig. 3). A 22-ft-long section was treated. As shown in Fig. 4, reflections from the tunnel walls were greatly reduced by the treatment. (The results shown in Fig. 4 were produced using a point source and with the tunnel flow off.) Propeller tests were conducted with microphones on 2-, 3-, 4-, and 5-ft side lines (nominal re the propeller axis). Microphones (0.25-in. diam) with nose cones were mounted in a Boeing-designed holder and strut which allowed continuous movement along a streamline in the test section while the data were recorded. The rate of movement was held to approximately 2 ft/min. Spectral data were presented in an as-measured format while directivity data (SPL vs θ_e at a given frequency) has been normalized to a common distance assuming spherical divergence and using standard atmospheric attenuation corrections.[2] Continuous sampling techniques such as these have not been previously reported in ADP testing, though similar methods have been used for more conventional propellers (e.g., Ref. 3).

Comparison Results

Direct overlay comparisons of propeller directivity measurements from both the soft and hard tunnel are shown in Fig. 5-8. Virtually identical test conditions are compared for several measurement locations. These illustrate significant differences in the indicated shape of the curves, peak level, and angle of peak level when comparing treated and untreated test-section results. Spectral comparisons, as shown in Fig. 9-11, exemplify marked changes between treated and untreated test-section measurements for similar locations and operating conditions. Notably, the harmonics are more evident and persist over all angles in the hard tunnel. This indicates that they are reflections rather than measures of the direct field alone. Finally, comparisons of measurements taken at multiple distances from the propeller and then normalized using free-

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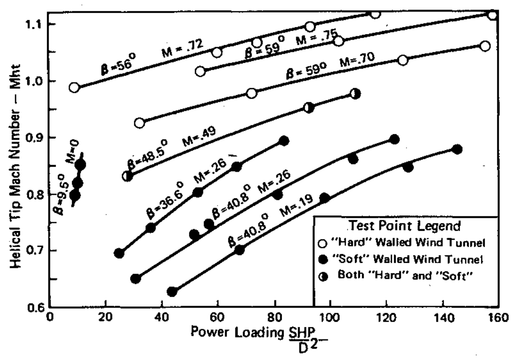

Fig. 1 Test parameter variation.

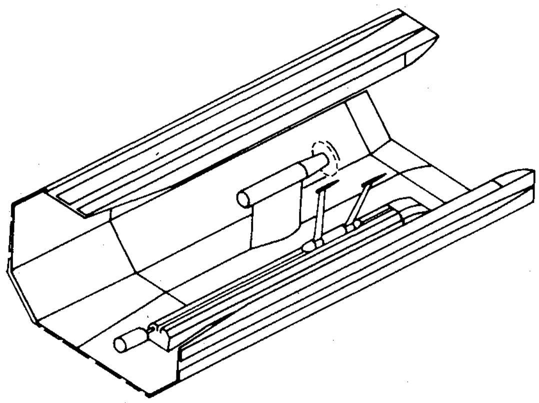

Fig. 2 Cutaway view of BTWT acoustic test section with SR-6 propeller installed.

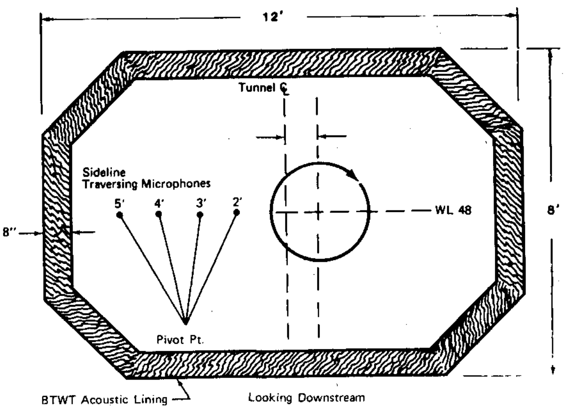

Fig. 3 Tunnel wall acoustic treatment.

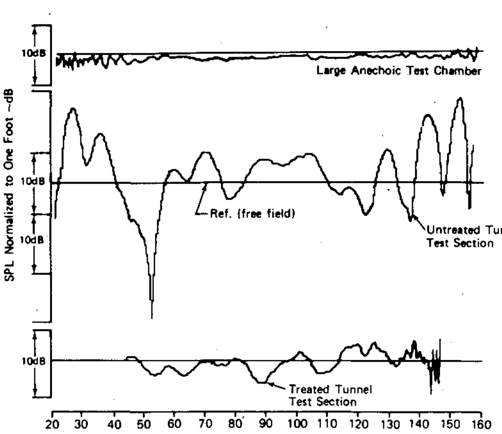

Fig. 4 Reflection test results.

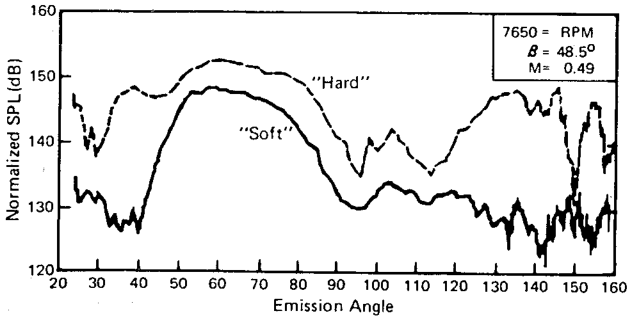

Fig. 5 SPL at fundamental frequency vs angle for hard- and soft-walled tunnel measurements; taken on 2-ft sideline.

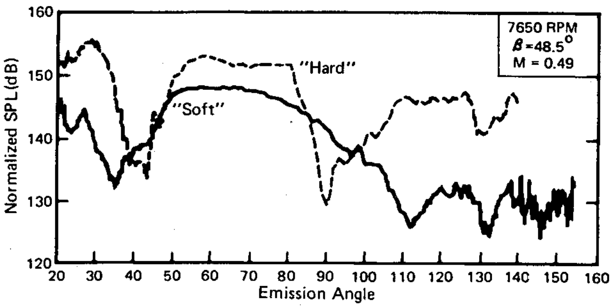

Fig. 6 SPL at fundamental frequency vs angle for hard- and soft-walled tunnel measurements; taken on 3-ft sideline.

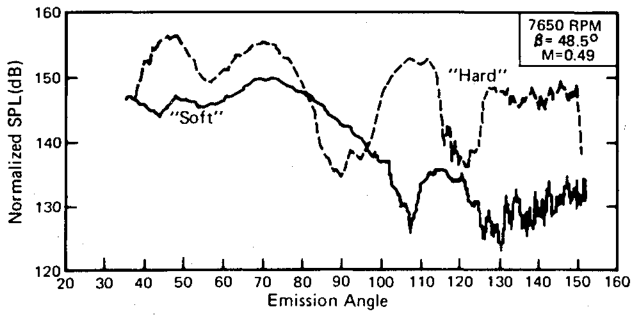

Fig. 7 SPL at fundamental frequency vs angle for hard- and soft-walled tunnel measurements; taken on 4-ft sideline.

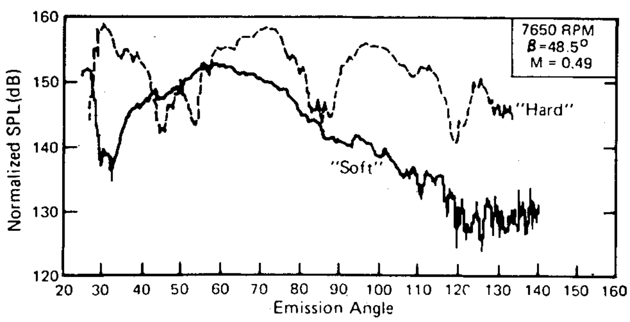

Fig. 8 SPL at fundamental frequency vs angle for hard- and soft-walled tunnel measurements; taken on 4-ft sideline.

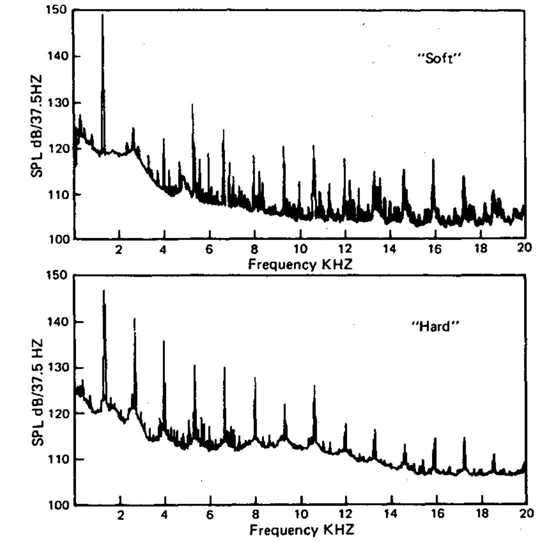

Fig. 9 Typical soft vs hard spectral comparisons; forward emission angle.

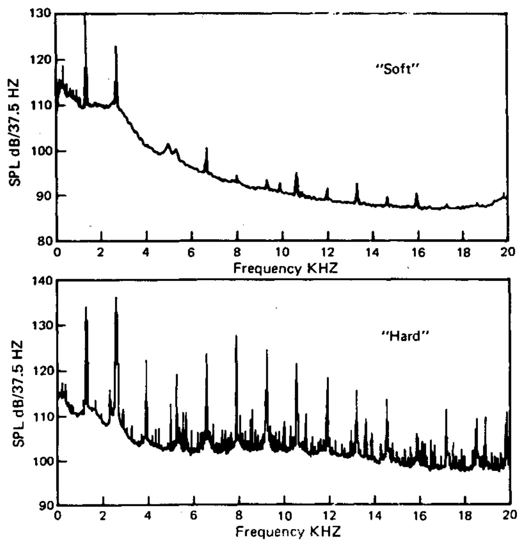

Fig. 10 Typical soft vs hard spectral comparisons—emission angle 90 deg.

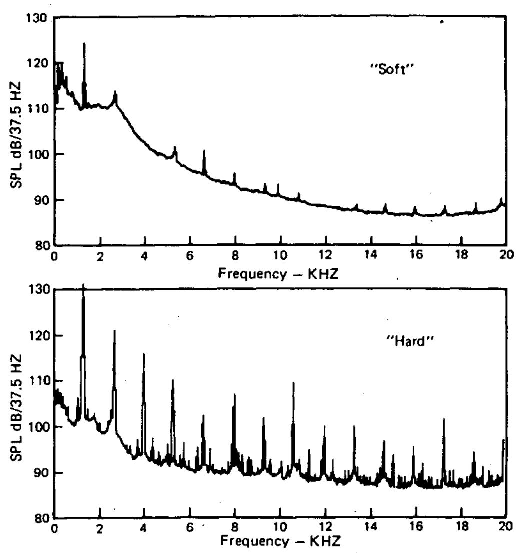

Fig. 11 Typical soft vs hard spectral comparisons aft emission angle.

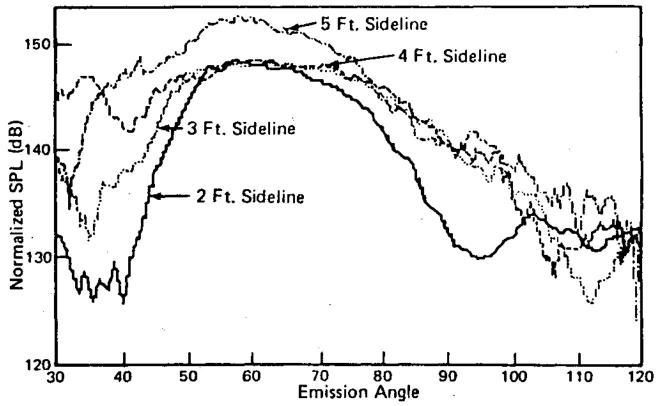

Fig. 12 Collapse of multiple sideline data in soft-walled wind tunnel.

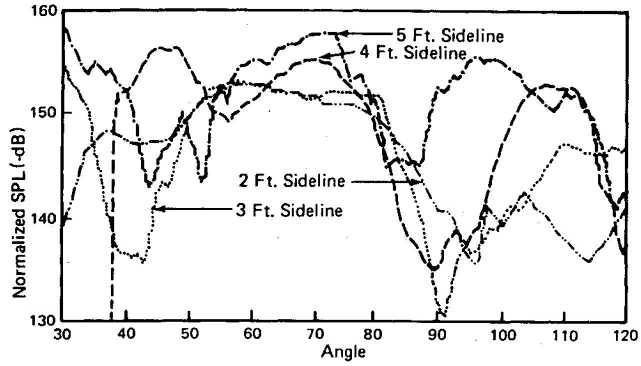

Fig. 13 Noncollapse of multiple sideline data in hard-walled wind tunnel.

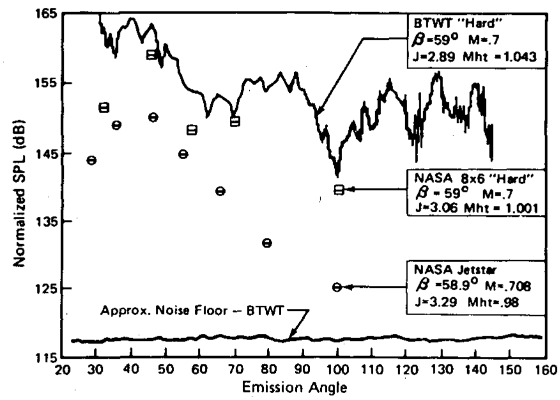

Fig. 14 Comparison directivities of two hard-walled tunnels vs NASA Jetstar data—fundamental.

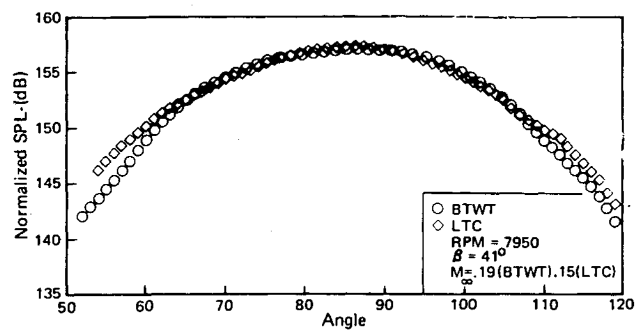

Fig. 15 LTC vs soft BTWT comparison.

field assumptions show that treated tunnel data collapse more readily than untreated tunnel data (Figs. 12 and 13). This is the case even at distances of only two feet from the propeller. The tunnel treatment is not perfect, and some averaging and smoothing is required to obtain results that can be considered truly representative of free field.

In addition to back-to-back comparison measurements, some higher relative flow velocity data were taken in the hard-walled wind tunnel. These data can be compared with previously reported SR-6 data from NASA hard-walled tunnel and test-bed aircraft tests.[4,5] Normalized data are shown in Fig. 14, which illustrates that the two hard-walled tunnel tests give results very different from each other and very different from test-bed aircraft results. The test-bed aircraft installation is thought to be the most representative of free field since the propeller is not surrounded by potential reflecting surfaces. Given the three sets of data in the same format, it seems the test-bed data most closely resemble a true directivity curve, while neither set of hard-walled tunnel data gives the proper directivity curve. This is further evidence that a free field, or nonreflective, test environment is desirable for propeller noise testing.

Low speed testing of the SR-6 in the Boeing Transonic Wind Tunnel (BTWT) with soft walls also compares favorably with testing in an anechoic chamber with a freejet, as typically shown in Fig. 15.

Data Trends

Assuming the smoothed and averaged results of BTWT testing of the SR-6 with soft walls to be representative of free-field measurements, and combining the results from Boeing-conducted anechoic chamber testing, several data trends can be examined. As discussed above, data taken at distances of greater than 1 diam from the propeller center tend to collapse through simple distance normalization procedures. The degree of collapse is very high at the peak values; however, agreement at angles away from the peak is complicated by the need for smoothing and averaging. Discrepancies are probably due to the imperfect nature of the acoustic lining rather than a true noise source characteristic. For example, the 5-ft sideline is only 16 in. from the tunnel wall and therefore very susceptible to any remaining energy not absorbed by the treatment. This explains why the 5-ft data are not in agreement with the other sidelines. Removal of uncertainty at off-angles and all sidelines would require improvement in lining characteristics or further data processing development. Possibly signal enhancement methods could also assist this effort.

Nevertheless, normalized $\mathrm{SPL}_{\max}$ data can be examined with confidence for trends in apparent noise with changes in various operating conditions. Plots of $\mathrm{SPL}_{\max}$ vs M_{ht} illustrate nearly constant slope lines (Fig. 16). Plots of $\mathrm{SPL}_{\max}$ vs SHP/D^2 again show a family of closely related curves (Fig. 17). Note that the conditions without relative flow (static) produce $\mathrm{SPL}_{\max}$ data that fit well with M_{ht} variation but does not fit with SHP/D^2 variation. This indicates the noise mechanisms are different for static operation than for "with-flow" operations. Such a finding can be supported from the difference in aerodynamics between static and with-flow cases.

A simple multivariable linear regression technique can be used on all of the similar data (free field with flow) to produce empirical prediction formulas for data normalization, interpolation, and extrapolation.

These are useful in judging the general quality of data as well as trends important to design and trade studies.

$\mathrm{SPL}_{\max}$ can be predicted for this data set with the equation

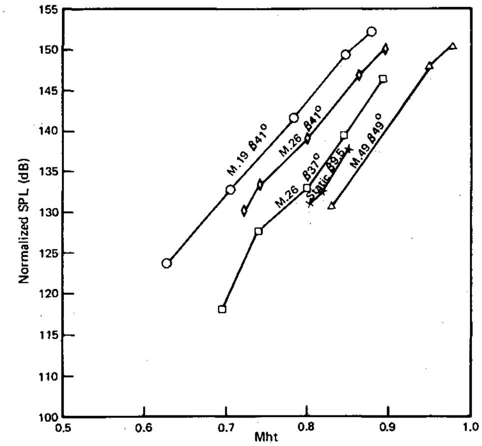

Fig. 16 $\mathrm{SPL}_{\max}$ vs M_{ht}—fundamental.

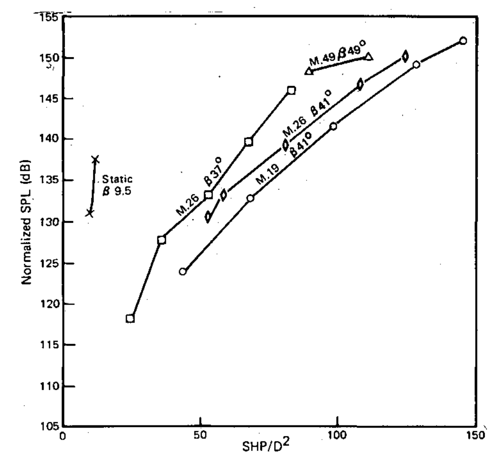

Fig. 17 $\mathrm{SPL}_{\max}$ vs SHP/D^2—fundamental.

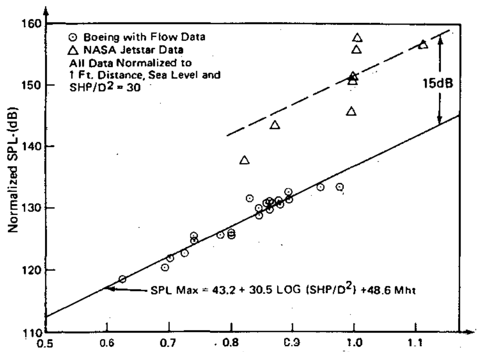

Fig. 18 Regression on $\mathrm{SPL}_{\max}$—NASA data added for comparison.

While M_{ht} is the most important parameter, as previous researchers have found, it was surprising to find that power loading has such a large coefficient. Approximately 9-dB increase per doubling of horsepower is indicated by the Boeing SR-6 data set.

The angle of peak noise occurrence can also be evaluated with a similar equation, though with some loss of accuracy,

$$\mathrm{SPL}_{\max} = 43.2 + 30.5 \log(\mathrm{SHP}/D^2) + 48.6 M_{\mathrm{ht}} \tag{1}$$

with $R^2 = 0.9893$ and S.E. = 1.1 dB

$$\text{Peak angle} = 85.8 + 44.5 \log(\mathrm{SHP}/D^2) - 111.6\, M_{\mathrm{ht}} \tag{2}$$

with $R^2 = 0.7156$ and S.E. = 5 deg

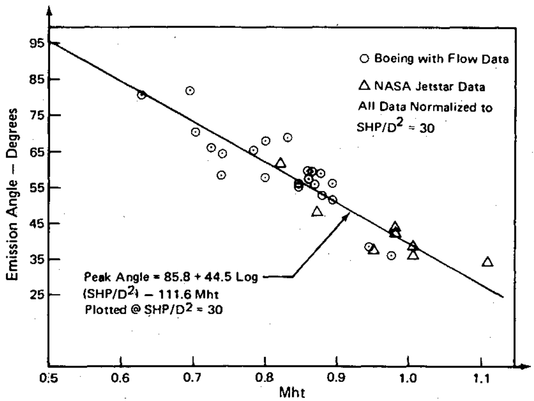

Fig. 19 Regression on angle of SPL_{max}—NASA data added for comparison.

An excellent fit of the data is achieved with these simple equations (see Figs. 18 and 19). Unfortunately only partial agreement with Ref. 5 test-bed data is achieved. While the peak noise angle is well predicted by Eq. 2, absolute SPL_{max} is under predicted by some 15 dB. The inclusion of boundary layer shielding effect corrections, such as have been suggested by previous researchers,[6] would tend to add to this discrepancy rather than to reduce the differences. Perhaps this is an installation effect or some unaccounted for normalization variable. A much closer examination is required to understand the differences between the two data sets. Such an investigation is beyond the scope of this article.

Conclusions and Recommendations

It has been shown that 1) acoustic treatment of the Boeing Transonic Wind Tunnel (BTWT) is required for detailed free-field propeller noise measurements, 2) acoustic far-field assumptions can be applied with success at distances of 1 diam or greater, and 3) multiple moving microphones can be used in a wind tunnel to reveal detailed results and provide confidence in the data.

Wind-tunnel acoustic treatment is necessary for detailed noise studies in the BTWT, regardless of distance from the propeller. Even at 2 ft from the propeller axis, reflections have a substantial effect on the measured noise signature of the propeller. This indicates that ADP noise measurements in hard-walled facilites may be contaminated by factors that make the direct and reflected noise difficult to sort. Acoustic treatment is recommended for all future wind-tunnel testing of propellers where detailed acoustic results are desired.

The apparent acoustic far field of SRT advanced-design propellers, such as the SR-6, occurs at distances of approximately 1 diam and beyond. This was shown by comparisons of measurements taken at multiple distances from the source and normalized to a common distance using simple spherical divergence and atmospheric attenuation assumptions.

The use of multiple, moving microphones with contiguous sampling methods has been illustrated as a technique that can reveal the actual sound field characteristics in a manner that discrete measurements cannot. The added detail allows easier assessment of the test facility environment and provides increased confidence in the measurements.

References

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[2]"Standard Values of Atmospheric Absorption as a Function of Temperature and Humidity for Use in Evaluating Aircraft Flyover Noise," Society of Automotive Engineers, Aerospace Recommended Practice 866, Aug. 31, 1964.

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[4]Dittmar, J. H., Stefko, G. L., and Jeracki, R. J., "Noise of the 10-Bladed 40° Swept SR-6 Propeller in a Wind Tunnel," NASA TM-82950, Sept. 1982.

[5]Dittmar, J. H., Lasagna, P. L., and MacKall, K. G., " A Preliminary Comparison Between the SR-6 Propeller Noise in Flight and in a Wind Tunnel," NASA TM-83341, May, 1983.

[6]Hanson, D. B. and Magliozzi, B., "Propagation of Propeller Tone Noise Through a Fuselage Boundary Layer," AIAA Paper 84-0248, Jan. 1984.