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CRITICAL ISSUES IN EXPERIMENTAL JET AEROACOUSTICS

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Abstract

Experimental investigations, both at model and engine scales, constitute the primary means of gaining quantitative and qualitative information on jet noise, because a complete theory capable of predicting the spectral characteristics at all radiation angles is not available even for the simplest geometry of a round jet. It is of paramount importance then to ensure that the experimental measurements are accurate and free of extraneous contamination. Issues that are important for jet aeroacoustic tests and the critical role of good data in the development of jet noise technology are reviewed and discussed. With careful consideration of several factors in the design of both the jet rig and the instrumentation system, the pitfalls associated with testing can be avoided. Given the high cost and complexity of full-scale tests, model scale tests are preferred. Several issues need to be addressed first, before comparisons of model data with engine data can be made. These pertain to the noise measurement system, effects of the flow state and conditions at the nozzle exit, effects of Reynolds number, atmospheric attenuation corrections, scaling, etc. These issues are examined in detail with concrete examples. Aeroacoustic measurements in a well-controlled anechoic facility have been made over a wide range of jet conditions; these include thrust performance, far-field spectra, as well as the location of acoustic sources using a directional microphone system. Details of a special test, carried out with the goal of measuring pure jet noise from a jet engine at all angles, are provided. With proper scaling, both narrowband and one-third octave spectra can be collapsed. Excellent agreement between scaled model and engine spectra is demonstrated at all angles and frequencies for a variety of power levels. It is firmly established that jet noise research carried out at model scale is applicable to jet engines.

1. INTRODUCTION

Jet noise continues to be a major component of aircraft noise, especially during take-off. This is so even for modern turbofan engines, with ever-increasing bypass ratios. The location of airports close to populated areas, the rising demand for air travel and the attendant increase in aircraft operations, and the consolidation of military bases have brought the nuisance of aircraft noise to the forefront. The best way to minimize the impact of aircraft noise on communities close to airports is to reduce the noise at the source. As such, jet noise research that focuses on gaining a better understanding of the noise generation mechanisms and the effects of realistic geometry and engine/airframe integration on the radiated noise is clearly warranted. Nearly five decades of research on jet noise has helped in our understanding of the fundamental mechanisms. However, to this day, no theory based on first principles that is capable of predicting the absolute spectral characteristics of the noise radiated to all angles by even a simple round nozzle exists. Most of the knowledge gained so far has been gleaned from jet noise measurements. All jet noise theories and methodologies based on these theories contain some level of empiricism, derived from measured data. Furthermore, all practical prediction methods for jet noise are empirical in nature; as such, they are only as good as the quality of the database on which they are based. Apart from the afore-mentioned needs of the theoretical community and practical prediction methods, there is the more pressing requirement of developing low-impact suppression devices for minimizing the acoustic signature of aircraft and mitigating community noise. Therefore, one cannot overstate the importance of acquiring good quality data and the critical role that data play in the development of noise reduction technology.

There are several issues that must be clearly understood, when conducting jet aeroacoustic tests so as to ensure high quality data. For aircraft applications, it is important to obtain accurate measurements at all frequencies and at all angles. For full-scale tests, the spectral characteristics are needed over a frequency range of 50 Hz to 10 KHz. It is well known that the non-dimensional Strouhal number is the appropriate parameter when comparing spectra from different nozzle diameters. Therefore, accurate measurements to very high frequencies are needed in model scale tests to resolve the entire full-scale range of frequencies. This is a formidable challenge and most existing spectral measurements are woefully inadequate. Viswanathan [1, 2] examined the jet noise spectra from several anechoic facilities and concluded that the spectra are contaminated by extraneous noise. A detailed description of the jet rig and a discussion of a rig refurbishment effort at Boeing's Low Speed Aeroacoustic Facility are provided in [1] and [2]. In this paper, an overview of the proper measurement procedure and the pitfalls associated with jet noise testing are provided. The steps involved in scaling spectra are also discussed.

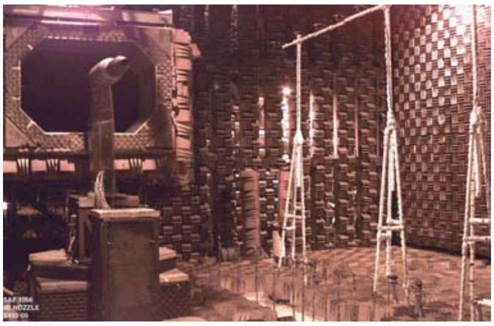
2. DESCRIPTIONS OF THE TEST PROGRAMS

2.1 Model Scale Tests

Detailed descriptions of the test facility, the jet simulator, the data acquisition and reduction process, etc., may be found in Viswanathan [1]. Figure 1a and shows a photograph of the anechoic facility and the jet rig, with the layout of the microphones also included. The jet simulator is embedded in an open-jet wind tunnel, which can provide a maximum free-stream Mach number of 0.32. Typically, several microphone arrays at different azimuthal angles were used. The microphones were at a constant sideline distance of 15 feet (4.572 m) from the jet axis. All angles are measured from the jet inlet axis, with a polar angular range of 50º to 155º. The microphones were set at normal incidence and without the protective grid, which yields a flat frequency response up to 100 KHz. Narrowband data with a bin spacing of 23.4 Hz were acquired and synthesized to produce 1/3-octave spectra, in the range of centre band frequencies of 200 Hz to 80,000 Hz. A detailed description of the instrumentation system and the corrections that need to be applied to the raw spectra may be found in Viswanathan [3]. Great care and attention were taken during the current tests to ensure that extraneous noise did not cloud the issues. Detailed assessments provided in Ref. [1-3] establish unambiguously that the spectra are not contaminated by rig noise; hence this topic is not addressed here.

2.2 Engine Test

A low bypass ratio turbofan engine with BPR ≅ 0.30 was chosen as the candidate engine. Several measures that would enhance the measurement of pure jet noise at all angles were taken. Figure 1b shows a schematic of the test set-up; a treated inlet duct was incorporated upstream of the engine to minimize inlet noise. The inlet duct was preceded by a very long duct with a length of 100 feet; this long duct served the dual purpose of preventing the re-ingestion of the hot exhaust gas as well as eliminating/minimizing the radiation of the inlet noise to the microphones at the lower polar angles. An acoustically treated spool piece was added to the back of the engine, downstream of the turbine, so as to minimize turbine noise and the aft-radiating component of fan noise. Given the low BPR and the small size of the fan, the aft-fan component is not expected to be significant for this engine. Finally, long nozzles of different designs were attached to the downstream-end of the spool duct and aeroacoustic measurements were made at different cycle conditions.



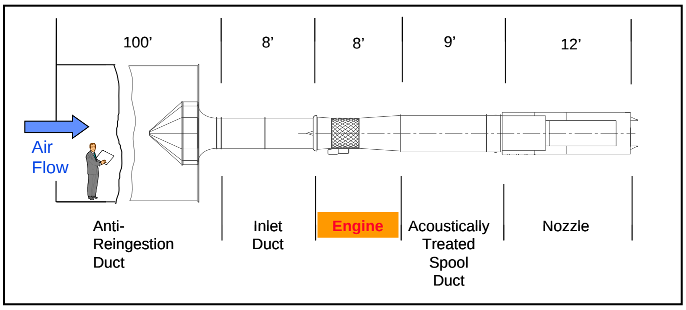


Figure 1. (a) Photo of LSAF with jet rig and wind-tunnel; (b) schematic sketch of engine test.

3. CRITICAL ISSUES

The requirements for model scale tests and engine tests are different. Fundamental issues concerning the instrumentation system, the microphone incidence and its effect on the measured spectra must be considered. In addition, the effects of the flow state and conditions at the nozzle exit, effects of disparate Reynolds number between model and engine scales, atmospheric attenuation corrections, scaling, etc. need to be quantified before comparisons between model and engine spectra can be attempted.

3.1 Instrumentation System

As already noted, accurate measurements at the higher frequencies are needed. It is possible to obtain good spectra up to 80 KHz in model tests, so long as proper care is taken. Two different microphone orientations, at either normal incidence or at grazing incidence, are adopted in acoustic tests. For normal incidence, the microphones are usually pointed at the centre of the jet at the nozzle exit plane with the implicit assumption that the sources of jet noise can be regarded as a point source concentrated at this location. The high frequency sensitivity of condenser microphones varies substantially as the angle of the incident acoustic ray on the microphone diaphragm changes from normal to grazing incidence, see Ref. [4]. For aeroacoustic tests at Boeing, the typical choice has been Bruel & Kjaer Type 4135 quarter-inch microphones (or the newer Type 4939) for normal incidence and Type 4136 for grazing incidence, with the as-measured data fully corrected for bias errors in the frequency response of the measurement chain. These corrections are strong functions of frequency: whereas the magnitudes are extremely small (~0.1 dB) at lower frequencies (≤ 10 KHz), they could add roughly 8 to 10 dB at the higher frequencies of interest in scale-model tests if the microphones are at grazing incidence (see Fig. 3 in Ref. [4]). It is clear then that though negligible at full-scale frequencies, these corrections could be substantial at model scale frequencies. Hence, the instrumentation system should be designed suitably to minimize these corrections. It was demonstrated clearly by Viswanathan [3] that with the application of the appropriate corrections, identical spectral shapes are obtained whether the microphones are set at normal or grazing incidence provided the measurements are made in the true far field. A more important factor pertains to the dynamic range requirements for the measurement system. The dynamic range of the measurement system should be adequate to span the range of the overall sound pressure level and the lowest level of interest at every measurement angle. When narrowband spectrum analysers are used, the issue of adequate dynamic range becomes more critical; this could be ~80 dB in the peak radiation angles for a high speed jet as shown in Ref. [3]. Contrast this requirement for the model test with that for the static test of a high bypass ratio engine. The dynamic range is much less at lower engine power because of the contribution from the other sources at the higher frequencies; notably the aft-fan and turbine components tend to increase the levels at the higher frequencies thereby reducing the dynamic range of the spectra. Therefore, the dynamic range requirements for model scale tests are more stringent. See Ref. [3] for a comprehensive treatment on the instrumentation system.

3.2 Proper Application of Atmospheric Corrections

It is well known that the effect of atmospheric absorption is a strong function of frequency, with the coefficients of absorption increasing with increasing frequency. There are also several methods for calculating these coefficients. The suitability of the various methods was examined in detail in Ref. [5] and it was demonstrated that the method due to Shields and Bass [6] was the most accurate at the higher frequencies of interest in model tests. The proper procedure for the application of corrections has been illustrated with concrete examples, both for narrowband and one-third octave spectra in Ref. [7]. Comparisons of spectra from nozzles of different diameters, corrected to standard day or any test-day weather conditions, will indicate that the spectral level at the higher frequencies from a smaller nozzle is always lower. This trend has been misinterpreted as being due to effects associated with lower Reynolds number for the smaller nozzle. It has been explicitly demonstrated in Ref. [7] that the different attenuation levels at different raw frequencies contribute to the observed trend of lower noise level for the smaller nozzle. This problem can be easily avoided through comparisons of lossless spectra.

3.3 Scaling of Jet Noise Spectra

Both the amplitude and frequency must be scaled. In acoustic tests at engine and model scales, the engine cycle conditions (nozzle pressure ratio (NPR) and stagnation temperature) are matched exactly. Thus, the thermodynamic states are identical except for the difference in the physical size. When data are acquired from nozzles of different diameters, it is important to scale the sound level for constant thrust. It is straightforward to show (see Ref. [5]) that this is easily accomplished by calculating the noise per unit area. Normalized spectra from unheated jets at three Mach numbers of 0.8, 0.9 and 1.0 and from three nozzles of diameters 3.81 cm, 6.22 cm and 8.79 cm are presented in Figure 2. The spectra have been normalized to a common distance of 6.09 m (R = 6.09 m), using the following equation:

$$SPL_{(R\ feet)} \quad = \quad SPL_{measured} - 10\,Log_{10}\left(\frac{R}{r}\right)^2 + r\ [AA_{(test\ day)}] - R\ [AA_{(std\ day)}]$$

r (m) is the distance of the microphone from the origin of the coordinate system, [AA] are the atmospheric absorption coefficients (which are frequency dependent) per meter. The above equation provides spectra corrected to standard day conditions; for lossless data, the last term in the equation is omitted. First we demonstrate that the scaling of spectra can be carried out with both narrowband and one-third octave spectra. For narrowband data, the spectra are normalized as follows: the effect of nozzle diameter on spectral levels is scaled out and the parameter [SPL - 10*Log10 (A) – 10*Log10 (D/Vj)] (A is the nozzle exit area) is plotted against the Strouhal number (fD/Vj, where f is the frequency in Hertz) in Figure 2a, at two Mach numbers of 0.8 and 1.0. The spectra at a polar angle of 145°, corrected to lossless conditions using the method of Ref. [6] are shown. There is excellent collapse of the two sets of spectra over the entire frequency range. The one-third octave spectra are normalized as follows: the effect of nozzle diameter on spectral levels is scaled out and the parameter [SPL - 10*Log10 (A)] is plotted against the Strouhal number. The lossless spectra at the same polar angle of 145°, at three Mach numbers of 0.8, 0.9 and 1.0, are presented in Figure 2b. Again as seen, there is excellent agreement throughout the frequency range, when the noise per unit flow area (or constant thrust) is examined.

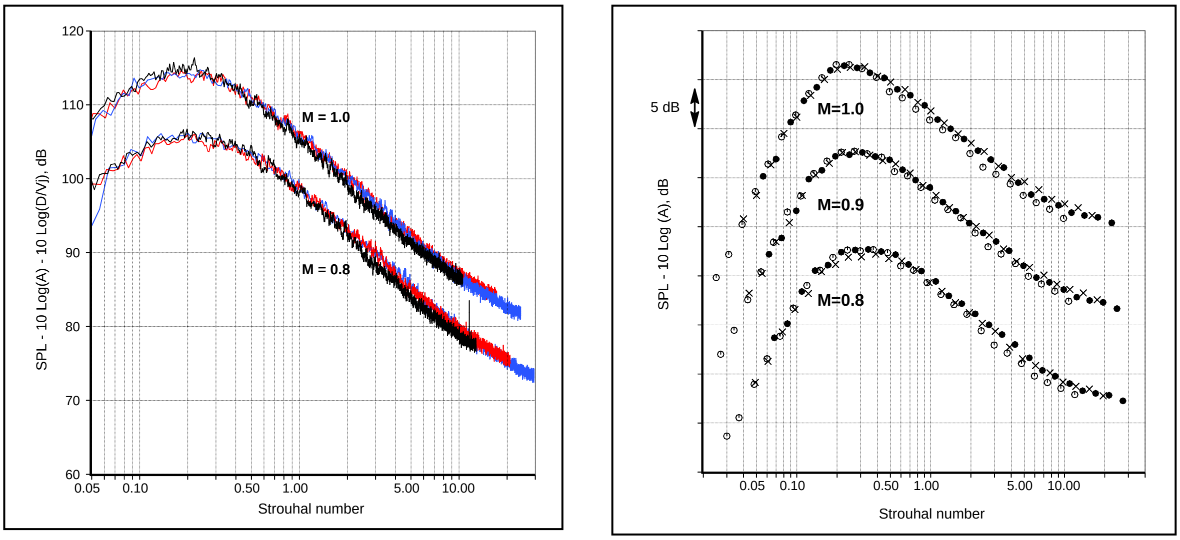


Figure 2. Normalized spectra from unheated jets. Angle = 145°. (a) narrowband spectra; (b) one-third octave spectra. o, black: D=3.81 cm; x, red: D=6.22 cm; •, blue: D=8.79 cm.

3.4 Effect of Reynolds Number

There is a vast disparity in the Reynolds number between model nozzles and jet engines. One needs to consider if there are any effects on noise associated with the lower Reynolds number in model tests and if these effects would play a role in the comparison of scaled model spectra with engine data. In nearly 50 years of noise research, it was never suspected that the Reynolds number could have an effect on the jet noise spectra. This is in spite of the well-established fact that at lower Reynolds number, the nozzle discharge coefficient has lower values. Only recently, Viswanathan [2] carried out a careful study to specifically quantify the effects of Reynolds number on noise. The salient results from this study are summarized below. Data were presented from three nozzles of different diameters (same as those shown in Figure 16 above) over a wide range of Mach numbers and temperature ratios. First it was shown that the spectral shape at the lower polar angles does change with increasing temperature, with an extra hump near the spectral peak, especially at lower Mach numbers. This trend had been noted in the experimental measurements in the 1970s and the extra hump had been attributed to the contributions from an additional dipole source for hot jets. To aid the discussion, two of the figures from Ref. [2] are reproduced here as Figures 3 and 4. The spectra at 90° from a jet of Mach number 0.7 and temperature ratio 3.2 from three nozzles of diameters 3.81 cm, 6.22 cm and 8.79 cm and comparisons with the fine-scale similarity spectrum (FSS) of Ref. [8] are shown. The extra hump is obvious in the spectra obtained with the smallest nozzle (D=3.81 cm). The magnitude of the discrepancy between the data and the similarity spectrum near the spectral peak decreases for the nozzle with D=6.22 cm and almost completely disappears for the largest nozzle. The only parameter different in the three cases is the Reynolds number, with values of 204 000, 333 200 and 470 600 for the three nozzles, respectively. Figure 4 provides a quantitative measure of the change in spectral shape due to Reynolds number, with a comparison of the normalized spectra for the various Mach numbers of 0.6, 0.7, 0.8, 0.9 and 1.0 and at a temperature ratio of 3.2. The spectra obtained with the smaller nozzle (D=3.81 cm) and denoted by the open symbols collapse to a single curve. The spectra for the larger nozzle (D=8.79 cm), denoted by the closed symbols, collapse on to a different curve. The biggest difference between these two families of curves occurs near the spectral peak and at Strouhal numbers slightly lower than the peak, with the normalized levels being higher for the smaller jet. Thus, the observed change in spectral shape was unambiguously demonstrated to be an effect due to low Reynolds number. A critical value of the Reynolds number that would need to be maintained to avoid the effects associated with low Reynolds number was estimated to be ~400, 000. For the model scale data used for comparison with engine data, it is made sure that the Reynolds number is above the threshold value so as to remove any effect of low Reynolds number on the spectra.

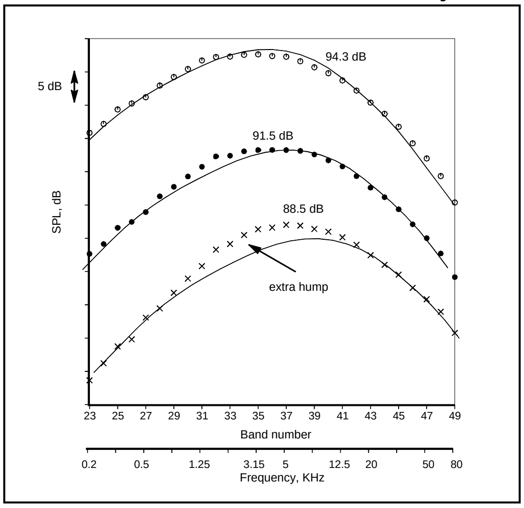


Figure 3. Measured spectra and fine-scale similarity spectrum. M=0.7, Tr/Ta=3.2, angle =90°. x: D=3.81; •: D=6.22; o: D=8.79 cm.

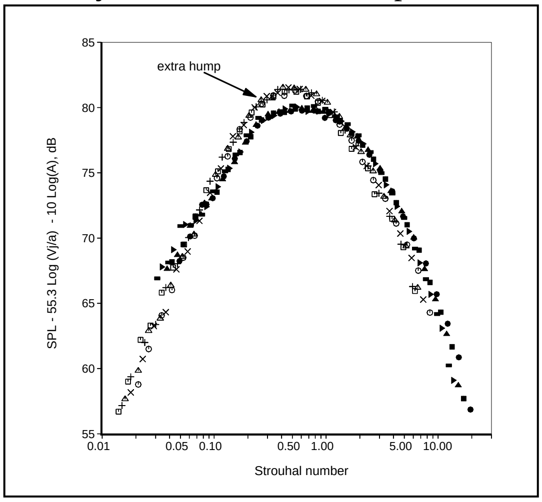


Figure 4. Comparison of normalized spectra. Tr/Ta=3.2, angle=90°. Open symbols: D=3.81 cm; closed symbols: D=8.79 cm.

3.5 Effect of the State of the Flow at the Nozzle Exit

In addition to the Reynolds number, the state of the boundary layer at the nozzle exit plane could play a role in the comparison of model scale data with engine data. Whereas the boundary layer in a model scale nozzle could be laminar in many instances, the boundary layer in a jet engine is always turbulent. It has been traditionally believed that jets with a laminar boundary layer produce more noise than their turbulent counterparts, especially at the higher frequencies. In order to understand the effect of the thickness and the state of the boundary layer upstream of the nozzle convergent (entrance) section and in the nozzle itself, Viswanathan and Clark [9] carried out a computational and experimental investigation. The main results of this study are summarized below.

Three nozzles of identical exit diameter, and hence the same Reynolds number for a given jet condition, were designed and tested. These three nozzles had a shallow conic section, a short cubic contraction and an ASME flow path (contraction followed by a constant section), respectively. The internal contours of the nozzles were carefully shaped to control the thickness of the boundary layer. Detailed flow field analyses and measurements indicated that the boundary layers were laminar and turbulent for the cubic and conic nozzles, respectively. Figure 5 shows spectral comparisons from an unheated jet at a Mach number of 1.0 at two angles of 50°and 145°, for the two nozzles. These two angles cover a wide polar angular range; the first one is a low radiation angle, the second one is normal to the jet and the third in the peak radiation sector. The spectral levels for the cubic and conic nozzles are virtually identical. The important conclusion of this study is that the radiated noise is insensitive to the state of the flow and the thickness of the boundary layer at the nozzle exit plane, contrary to conventional belief. For more details, see Ref. [9]. Therefore, it should be possible to compare noise measurements from different facilities and different nozzle sizes.

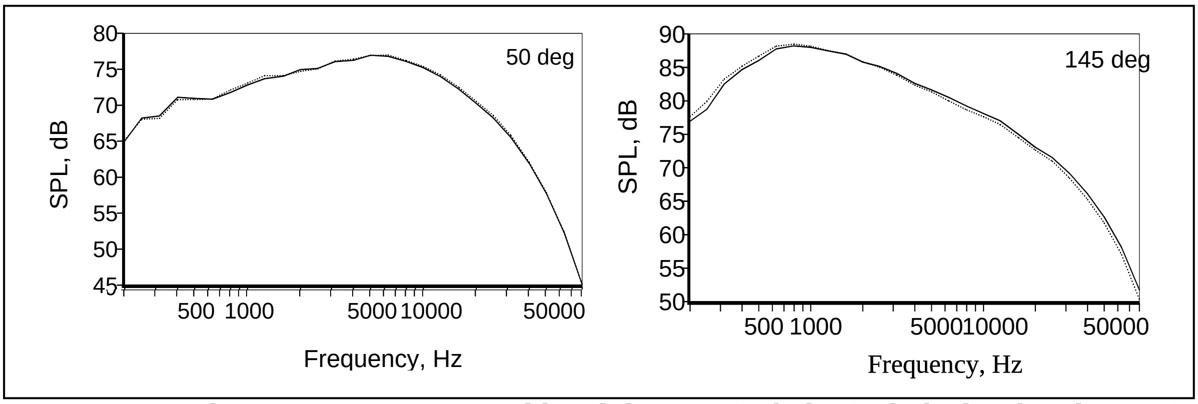


Figure 5. Spectral comparison. M=1.0, cold. Solid: conic (turbulent); dashed: cubic (laminar).

3.5 Comparison of Model Data with Engine Data

Finally, comparisons of scaled model data with engine data are presented. The measured one-third octave spectra in LSAF are first converted to lossless levels using the method of Shields and Bass [6]. The lossless spectra are then scaled and propagated to the measurement distances in an engine test.

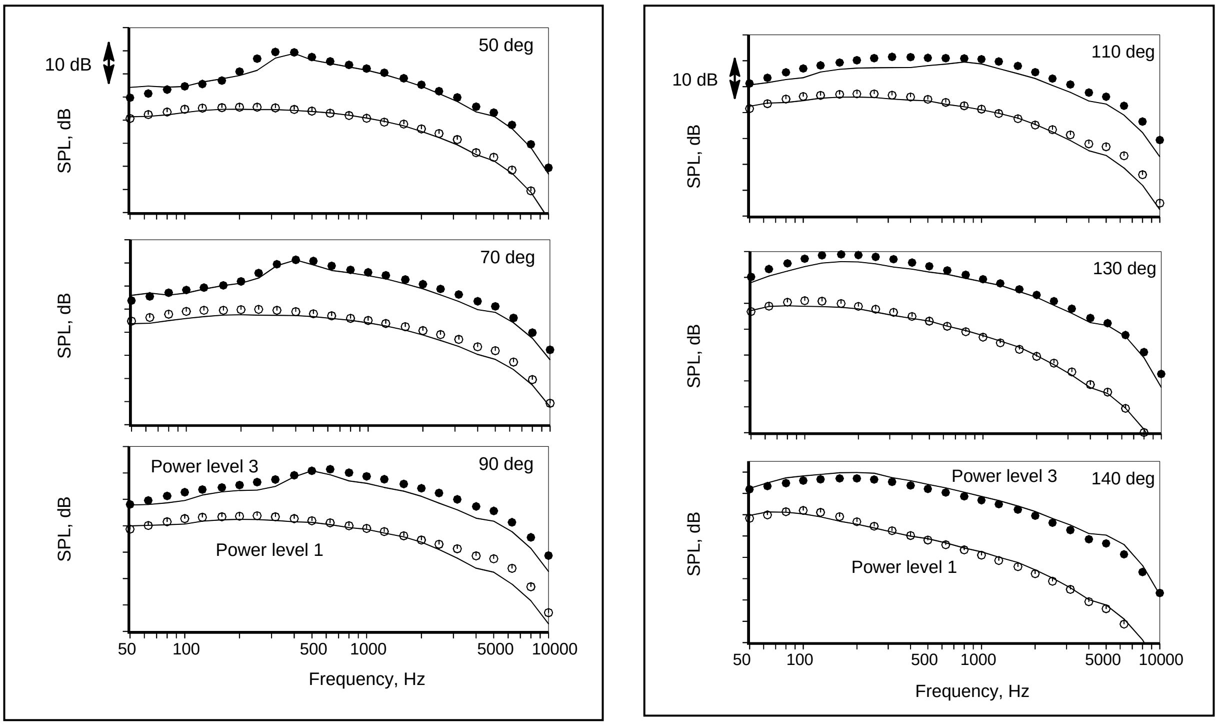


Figure 6. Spectral comparisons at two power levels. Symbols: engine; lines: model scale.

Spectral comparisons over a wide range of polar angles and at two power settings are presented in Figure 6. The symbols denote the engine data and the lines the model data. First of all, we note that there is excellent agreement between the two sets of spectra at all the angles. There is clear demonstration that the good agreement is not confined to a few angles or a few power settings. There is also strong validation for the high quality and accuracy of the model data. These comparisons also validate the scaling methodology adopted here and the recommended choices for the calculation of the coefficients of atmospheric absorptions at model and engine scales.

4. CONCLUSIONS

The critical issues essential for the accurate measurement of jet noise have been examined in detail. Many issues that are pertinent in permitting the comparison of scaled model data with engine data have been investigated. A set of high-quality benchmark data has been acquired in a controlled anechoic environment that would help the development and refinement of prediction methods. With proper scaling factors for nozzle area and velocity, good collapse of both narrowband and one-third octave spectra are achieved. It is possible to acquire high-quality spectra up to 80 KHz in model tests, provided care is taken in planning the test and in designing the instrumentation system. Atmospheric attenuation corrections are quite accurate even at the higher frequencies of interest at model scale (up to 80 KHz); the proper procedure for applying these corrections has been reviewed. The recommended practice here is valid for engineering applications. Sample spectral measurements provided indicate that the radiated noise is insensitive to the state and thickness of the boundary layer at the nozzle exit plane. Conclusive evidence that model data faithfully reproduce engine data is presented. Therefore, the use of model data in the development of prediction methods and noise reduction devices is justified for full-scale applications.

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