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Technical Notes

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Application of Atmospheric Attenuation Correction in Scaling Jet Spectra

K. Viswanathan*
The Boeing Company, Seattle, Washington

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I. Introduction

SCALE model tests of exhaust nozzles are usually carried out to establish the characteristics of jet noise because of significantly lower cost relative to full-scale engine tests. Model tests also allow the flexibility to independently control and vary the jet Mach number and jet total temperature, which is not possible with jet engines. Further, acoustic data may be acquired in a controlled anechoic environment with systematic parametric variation. Much of the knowledge on jet noise gained in the last six decades has come mainly from scale model tests conducted at various laboratories. Suitable theories that explain the observed characteristics, and scaling laws to collapse spectra, have also been attempted. To facilitate direct comparison of jet noise spectra obtained from nozzles of different diameters and varying test-day weather conditions, the measured data must be normalized in some fashion. Recently, Viswanathan [1] investigated several issues that are relevant in the scaling of model scale spectra so as to permit comparison with engine noise. Some of these issues addressed include the requirements of the instrumentation system for model and engine tests, a suitable methodology for the calculation of the atmospheric attenuation coefficients, the propagation effects, the repeatability of data, the effects of the disparate Reynolds numbers, etc. It was clearly demonstrated that 1) spectra obtained with nozzles of different diameters can be collapsed perfectly at all frequencies; and 2) a model scale nozzle emits the same jet noise as a jet engine. Viswanathan [2] developed new scaling laws based on the explicit recognition that 1) the variation of the overall sound power level with jet velocity has a weak dependence on jet stagnation temperature ratio; and 2) the variation of the overall sound pressure level with velocity at every radiation angle is a function of jet stagnation temperature ratio. Excellent collapse of the spectra over the entire measured frequency range, at various jet stagnation temperature ratios and at several radiation angles, has been shown in [1–4].

However, some confusion still prevails on the application of the atmospheric absorption corrections in the scaling of spectra. It is well established that the amplitude of acoustic waves is attenuated by the atmosphere during sound propagation. It is also well known that the effect of atmospheric absorption is a strong function of frequency, with the coefficients of absorption increasing with increasing frequency. Several methods have been developed for calculating the absorption coefficients. It was shown in [1] that the method due to Shields and Bass [5] is best suited for the high frequencies of interest in model tests. Some clarification on the proper application of the atmospheric corrections, with concrete examples, is provided in this paper.

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*Associate Technical Fellow, Aeroacoustics and Fluid Mechanics, Mail Stop 67-ML, Post Office Box 3707, Seattle, WA 98124-2207; k.viswanathan@boeing.com. Associate Fellow AIAA.

II. Results and Analysis

The experimental jet noise database used here is already described in [2–4]. Detailed descriptions of the anechoic facility, the instrumentation system, the acquisition and processing of acoustic data, etc., may also be found in these references; therefore, this information is not included here. In the analysis performed here, the acoustic data at various jet conditions (Mach numbers and stagnation temperature ratios) have been obtained with three nozzles of different diameters of 1.5, 2.45, and 3.46 in. (3.81, 6.22, and 8.79 cm, respectively). The microphones were laid out on a linear array at a constant sideline distance of 15 ft (4.57 m) parallel to the jet axis. Spectra from the microphone located at a polar angle (measured from the inlet) of 145 deg are shown here; the microphone distance is 26.15 ft (7.97 m).

Figure 1 shows narrowband power spectral densities from an unheated jet with a Mach number M of 1.0, obtained with the three nozzles. Note that the test-day weather conditions vary depending on the location of the test site as well as the season (summer or winter). The sound pressure level (SPL) has been corrected to standard day conditions (77°F and 70% relative humidity) using the method of [5] and to a common distance of 20 ft (6.09 m) from the origin of the coordinate system, as follows:

$$\mathrm{SPL}_{(r\ \mathrm{ft})} = \mathrm{SPL}_{\mathrm{measured}} - 10\log_{10}\left(\frac{r}{R}\right)^2 + R[\mathrm{AA}_{(\mathrm{test\ day})}] - r[\mathrm{AA}_{(\mathrm{std\ day})}]$$

In the preceding equation, R is the distance of the microphone in feet from the origin of the coordinate system, [AA] are the atmospheric absorption coefficients (which are frequency dependent) per foot, and r is any desired observer distance (equal to 20 ft in Fig. 1). Implicit in this process is the assumption of linear propagation, with the sound pressure level obeying the $(1/r^2)$ dependence. The effect of the different nozzle diameters on the measured spectral levels is factored out through the subtraction of the term $[10 \times \log(A)]$ and the normalized spectra per unit area are plotted as a function of the Strouhal number; see [1] for more details. A is the nozzle exit area.

It is clear in Fig. 1 that there is excellent collapse of the spectra at the lower frequencies and up to a Strouhal number of ~1.0. At higher frequencies, the spectral level from the smallest nozzle ($D = 1.5$ in.) is lower than those from the larger nozzles; further, the discrepancy in the spectral level keeps increasing with increasing frequency. At a Strouhal number of 5.0, the mismatch is ~6 dB. This mismatch at a Strouhal number of 10.0 is ~15 dB relative to the level for the $D = 3.46$ in. nozzle. The spectral levels from the two larger nozzles ($D = 2.45$ and 3.46 in.) are identical up to a Strouhal number of ~5.0; at higher Strouhal numbers, the spectrum from the

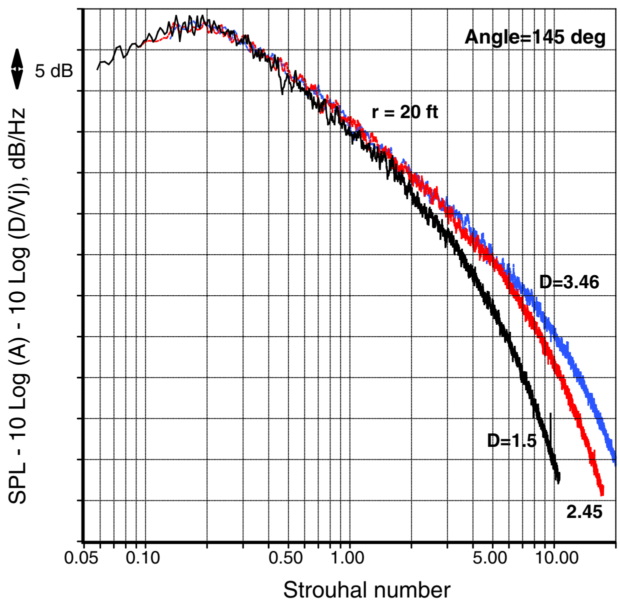

Fig. 1 Comparison of normalized narrowband spectra; $M = 1.0$, $Tt/Ta = 1.0$.

$D = 2.45$ in. nozzle has lower amplitude, with the magnitude of the mismatch again increasing with increasing frequency.

The same exercise has been carried out with one-third octave spectra and is shown in Fig. 2. The spectra at two observer distances of 20 and 100 ft are displayed. There is good agreement at the lower Strouhal numbers and just beyond the spectral peak for both distances. As seen in Fig. 1, the spectral levels from the smallest nozzle ($D = 1.5$ in.) are lower than those from the larger nozzles at the higher frequencies. However, there are pronounced differences in the spectral shapes as well as the magnitudes of the mismatch at the higher frequencies for the two distances shown.

What is the reason for the observed trends in Figs. 1 and 2? Based on similar trends, it has been proposed by some researchers (see [6], for example) that there could be a Reynolds number effect at the higher frequencies. Followers of this line of thought conjecture that, due to the lower Reynolds number associated with the smaller nozzles, there is less fine-scale turbulence and hence potentially lower levels of high-frequency noise. However, as explained next,

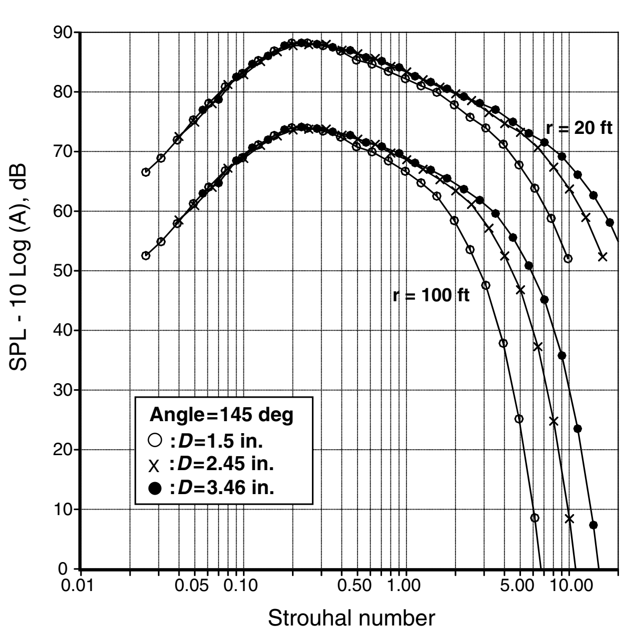

Fig. 2 Comparison of normalized one-third octave spectra; $M = 1.0$, $Tt/Ta = 1.0$.

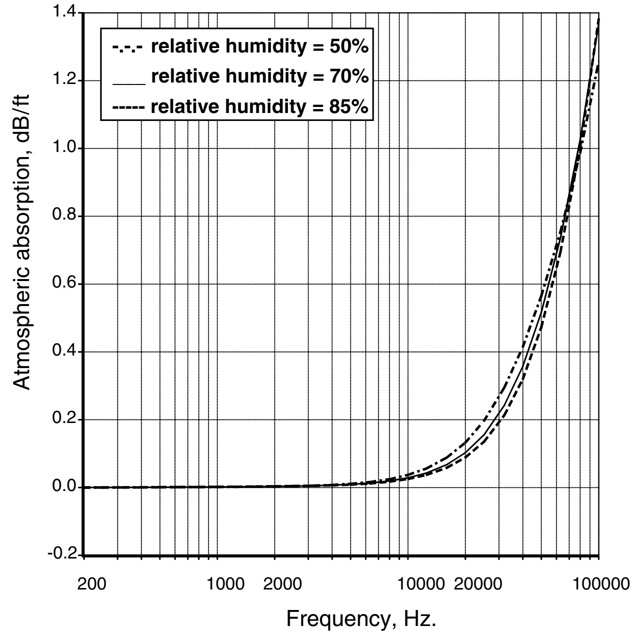

Fig. 3 Atmospheric absorption coefficient per [5]; ambient temperature = 77°F (25°C).

there is an entirely different reason, completely unrelated to Reynolds number, for the observed trends.

Figure 3 shows a plot of the atmospheric absorption coefficient (dB/ft) as a function of frequency for three values of relative humidity and at a fixed temperature. One may generate these types of curves for any given ambient conditions of temperature, pressure, and relative humidity as per the procedure given by Shields and Bass [5]. It is obvious from this sample figure that the atmospheric absorption is very strong at higher frequencies, with absorption coefficients of ~1 dB/ft at a frequency of 80 kHz.

Now, let us examine the cause for the trends seen in Figs. 1 and 2. The data have been corrected to standard day conditions in these figures. The normalized frequency on the x axis is calculated as $Sr = fD/V_j$, where f is the frequency in hertz, D is the jet diameter, and V_j is the jet velocity. For the comparisons shown, the jet condition V_j is maintained the same for the three nozzles. For a fixed Strouhal number then, the raw frequency is higher for the smaller nozzle. For the $D = 1.5$ and $D = 3.46$ in. nozzles, the ratio of the raw frequencies that produce the same Strouhal number is given by the ratio $D_2/D_1 = 3.46/1.5 = 2.31$. For a Strouhal number of ~10.0, the raw frequency for the smallest nozzle is ~80 kHz, whereas it is ~34.68 kHz for the largest nozzle used here. The atmospheric absorption coefficients for these two raw frequencies are ~1 and ~0.3 dB/ft, respectively, from Fig. 3. For a fixed microphone distance, the sound amplitude at ~80 kHz is obviously attenuated more than at the lower frequency of ~34.68 kHz. For the microphone distance of 20 ft, the extra attenuation is ~14 dB (20×0.7), which is reflected in the mismatch in levels at this Strouhal number in Figs. 1 and 2.

Similarly, for a Strouhal number of 6.0, the raw frequency for the smallest nozzle is ~49 kHz, whereas it is ~21 kHz for the largest nozzle used here. The atmospheric absorption coefficients for these two raw frequencies are ~0.5 and ~0.1 dB/ft, respectively, from Fig. 3. For the microphone distance of 100 ft, the extra attenuation is ~40 dB (100×0.4). An examination of Fig. 2 indicates that the magnitude of the mismatch in the sound amplitude levels is again ~40 dB at a Strouhal number of 6.0. From these two examples, it should be clear that the discrepancy seen at the higher frequencies is due to different levels of atmospheric attenuations for the raw frequencies. Two factors control the magnitude of the mismatch; the ratio of the nozzle diameters (D_2/D_1) and the distance to the observer, as seen in Fig. 2. When spectra from nozzles of different diameters, corrected to standard day or any test-day weather conditions, are compared, the smaller nozzle will always appear to

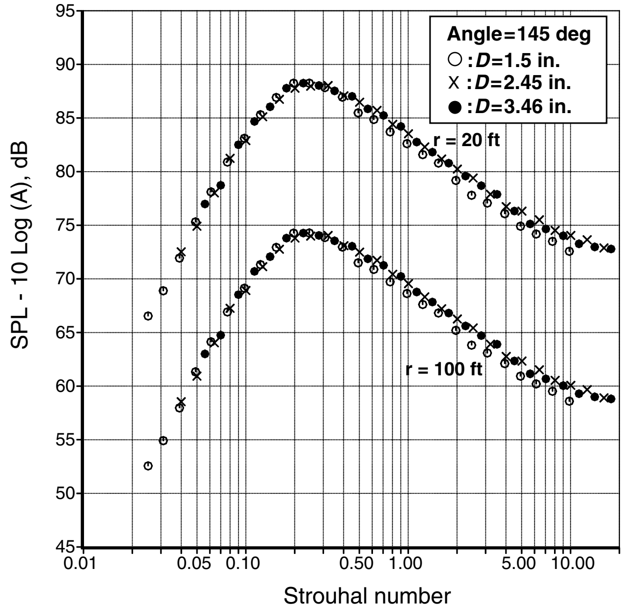

Fig. 4 Comparison of normalized lossless spectra; $M = 1.0$, $Tt/Ta = 1.0$.

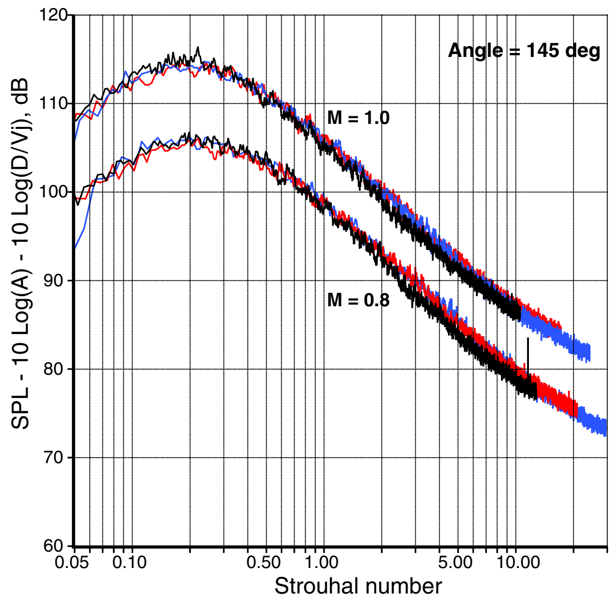

Fig. 5 Comparison of normalized lossless narrowband spectra from unheated jets.

produce lower noise levels at the higher frequencies (Strouhal numbers).

The problem with spectral comparisons from nozzles of different diameters can be easily overcome with the calculation of lossless spectra. The lossless spectra can be computed by simply omitting the last term on the right-hand side of the equation shown earlier. We illustrate this process in Fig. 4, where comparisons of lossless spectra at two distances of 20 and 100 ft are shown. Now there is excellent collapse of the spectra from the three nozzles over the entire frequency (Sr) range, at both distances. Furthermore, the spectral shape is invariant with distance, with the amplitude increasing (decreasing) as the observer distance is reduced (increased) due to spherical divergence. Note that the discrepancy at a Strouhal number of ~10.0 is ~1 dB; this is due to slight inaccuracies in the estimated values for the atmospheric attenuation coefficients as noted in [1]. The microphone at an angle of 145 deg was specifically chosen for the following reason: the slant distance is quite large (26.15 ft) and the magnitude of the corrections applied is consequently quite large, on the order of ~20 dB for the test-day ambient conditions. Still, there is excellent agreement at the higher frequencies in Fig. 4. Figure 5 shows comparisons of lossless narrowband spectra at two different Mach numbers of 1.0 and 0.8. Again, there is perfect collapse over the entire frequency range.

Contrast the spectral collapse seen in Figs. 4 and 5 with those in Figs. 1 and 2. The problem at the higher frequencies has been eliminated. Viswanathan [7] addressed the issue with atmospheric attenuation in the context of generating similarity spectra; it was recommended that lossless spectra should be used because the spectral shape is then invariant with distance, as demonstrated in Fig. 4 here. Perfect collapse of the spectra, at various jet Mach numbers and from nozzles of different diameters but at a fixed jet temperature, has been demonstrated at a variety of radiation angles and temperature ratios in [1,2,4]. The scaling methodology and a prediction method based on it depend on unambiguous collapse of spectra. The proper application of the corrections for atmospheric attenuation is an integral part of the scaling procedure. It has also been proven that the mismatch seen at the higher frequencies is due to atmospheric attenuation and has nothing to do with Reynolds number effects for these nozzles and test conditions. Clearly, improper scaling techniques lead to incorrect interpretation and misconceptions.

III. Conclusions

The role of atmospheric attenuation of sound spectra in scaling jet noise spectra has been investigated. The proper procedure for the application of corrections has been illustrated with concrete examples, both for narrowband and one-third octave spectra. 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 a lower Reynolds number for the smaller nozzle. However, as shown here, the Reynolds number (so long as it is not very low) has nothing whatsoever to do with this phenomenon. It has been explicitly demonstrated here 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. Lossless spectra also display a desirable feature of being invariant in shape regardless of the propagation distance, thereby permitting the estimation of universal shapes and comparisons from disparate test facilities and weather conditions. The consequences of the variation of the atmospheric attenuation coefficient with frequency must be clearly recognized in scaling spectra, so as to avoid incorrect conclusions.

References

[1] Viswanathan, K., "Does a Model Scale Nozzle Emit the Same Jet Noise as a Jet Engine?," *AIAA Journal* (to be published); also AIAA Paper 2005-2936, May 2005.

[2] Viswanathan, K., "Scaling Laws and a Method for Identifying Components of Jet Noise," *AIAA Journal*, Vol. 44, No. 10, Oct. 2006, pp. 2274–2285.

[3] Viswanathan, K., "Aeroacoustics of Hot Jets," *Journal of Fluid Mechanics*, Vol. 516, Oct. 2004, pp. 39–82.

[4] Viswanathan, K., "Improved Method for Prediction of Noise from Single Jets," *AIAA Journal*, Vol. 45, No. 1, Jan. 2007, pp. 151–161.

[5] Shields, F. D., and Bass, H. E., "Atmospheric Absorption of High Frequency Noise and Application to Fractional-Octave Band," NASA CR 2760, June 1977.

[6] Tam, C. K. W., "Dimensional Analysis of Jet-Noise Data," *AIAA Journal*, Vol. 44, No. 3, March 2006, pp. 512–522.

[7] Viswanathan, K., "Analysis of the Two Similarity Components of Turbulent Mixing Noise," *AIAA Journal*, Vol. 40, No. 2, Sept. 2002, pp. 1735–1744.

C. Bailly
Associate Editor