Geometric near-field characteristics of supersonic jets: Full and laboratory scales[1,2]

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Sound pressure measurements were made in the geometric near field of a full-scale jet installed on a military aircraft. In this work, levels at 11.7 m (near the 42-ft foul line) are reported. Weighting curves that account for listener factors are applied to the overall sound pressure level, including A-weighting, C-weighting, and D-weighting. In addition, the effect of representative double hearing protection on A-weighted overall level is shown.

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A useful limited comparison is made between a laboratory-scale, Mach-2.0, unheated jet and the full-scale jet engine at the same scaled distance from the jet centerline.

1 INTRODUCTION

A principal reason for the study of military jet noise is military personnel hearing protection. Whether during post maintenance run-ups or takeoff, *unprotected* personnel in the geometric near field of the jet would be exposed to levels greater than the threshold of pain. Therefore, it is essential to understand the properties of jet noise to implement sufficient hearing protection and/or operational changes.

Within the body of jet noise literature, there are several studies involving measurements and analysis of installed and test-stand mounted military jet engines. Although a few deal explicitly with reduction or human impact, most focus solely on characterization and/or prediction of the noise. Some involve static run-ups and others, flyover measurements. Prior reports of full-scale jet noise (engines and aircraft) include the F-15,[1] F-16,[2,3], the F/A-18E/F,[4-9] the F-22A Raptor,[10-13] the F-35AA Joint Strike Fighter,[14] and other aircraft and engines not explicitly disclosed.[15,16]

The previous studies notwithstanding, experiments with full-scale aircraft are relatively infrequent due to the scope, expense, time, outdoor environment, and other logistics. For these reasons it is helpful to compare the acoustical characteristics of supersonic, laboratory-scale jets and full-scale jets. To facilitate meaningful comparisons, laboratory-scale jet data must be scaled in terms of frequency and nozzle diameter. The scaling of laboratory data to the frequency range of full-scale data is made possible, at least in the maximum radiation direction, by knowledge that the peak Strouhal number (~0.2) is relatively invariant for different jet conditions.[17] If in fact the scaled comparisons are similar, a model supersonic jet may prove useful in examining some acoustical features of interest for the full-scale jet. These insights can include the overall sound pressure level (OASPL), the spectral shape, weighted levels, and need for and anticipated effect of hearing protection, all of which could guide the scope of required full-scale experiments.

This paper describes weighted level-based analyses of data from the F-22A Raptor and a laboratory-scale Mach 2.0 unheated jet, taken at equivalent scaled locations. As the scope of this paper is primarily analytical, only summaries of each experiment are provided. General results of levels and directivity are given for both experiments. The application of weighting curves is described, followed by a discussion of the attenuation provided by properly used double hearing protection. The effect of hearing protection is analyzed for one F-22A engine at idle and military power. As a comparative analysis, the laboratory and full-scale OASPLs and the spectra in the maximum radiation directions are compared. Application of weighting and hearing protection curves to a frequency-scaled version of the laboratory jet spectrum shows that the laboratory-scale jet can be used as a credible predictor for level and frequency content of the military jet engine in the peak radiation direction.

2 FULL-SCALE RESULTS AND ANALYSIS

2.1 F-22A Experiment

Noise measurements were made in the vicinity of a Lockheed Martin/Boeing F-22A Raptor tied down to the runway with one engine firing. Data were taken at an array of 50 microphones placed on the ground 11.7 m to the side of the jet centerline, which is near the foul line where military personnel often stand during takeoff and landing. They were spaced 0.61 m (2 ft) apart (shown as blue dots and yellow circles in Fig. 1). These microphones spanned 30 m, which was longer than the spatial extent of the dominant overall jet noise region. The engine was cycled through four different power conditions: idle, intermediate, military, and afterburner. More details of the experiment are available in Refs. [18] and [12].

2.2 Overall Levels

Using the data collected by the ground-based microphones, the OASPL was calculated as a function of location downstream from the jet nozzle for each engine condition (see Fig. 2). The overall levels for both the military and afterburner conditions exceed the threshold of pain, which emphasizes the need for hearing protection in the vicinity of the jet during takeoff. Note, however, that because these microphones were on the ground, the levels at the ear may be somewhat less, depending on how geometry-dependent interference nulls impact the spectra.

2.3 Weighted Levels

Although the maps of overall levels are important, weighted overall levels provide a more accurate representation of noise exposure. Various weighting curves [e.g., A, B, C, and D, whose gains are show in Fig. 3(a)] have been designed to compensate for the fact that our ears are most sensitive in the 1-4 kHz region and less sensitive at low and high frequencies. The A-weighting (blue) was initially designed for use with low level sounds but has become the standard in most noise measurements. The C-weighting (red) was intended for louder sounds and designed to approximate the somewhat flatter frequency response of our hearing at louder noise levels. The D-weighting (green) was not based on the equal loudness contours, which were developed using pure tones, but was created to reflect how the ears respond to random noise, such as jet noise. The IEC 537 measurement standard, though currently inactive, indicates that D-weighting is useful when studying the noise of non-bypass engines, such as those in military jets.[19]

These weighting curves have been applied to one-third octave band spectra for all four engine conditions on the ground-based microphones. Figure 4 shows the weighted OASPLs at these locations for idle and military engine conditions. For both engine conditions, the C-weighted OASPL closely follows the unweighted OASPL indicating the extremely high (above 6,000 Hz) and very low frequencies (below 50 Hz) are relatively unimportant in determining overall level. For idle conditions [see Fig. 4(a)], the D-weighted OASPL is consistently higher than unweighted, suggesting frequencies between 1 and 10 kHz are prevalent at all distances from the engine. This is related to the presence of high-frequency engine tones. The A-weighted OASPL tracks the unweighted OASPL but about 4 dB lower. The lack of spatial variation in the difference between unweighted and weighted levels indicate that at idle power the relative amount of high and low frequencies does not change significantly with distance downstream.

The consistency seen at idle is substantially different from the behavior of the weighted overall levels at military power, indicating physically different noise-generating mechanisms. At military power [see Fig. 4(b)], the A-weighted OASPL tracks the unweighted OASPL initially, but at around 7 m downstream, the difference between the two curves gradually begins to increase, with the A-weighted levels being consistently lower. On the other hand, the D-weighted OASPL is initially greater than the unweighted OASPL, demonstrating the prevalence of the high-frequency energy to the side of the nozzle. However, the difference between the D and unweighted OASPL gradually decreases until approximately 16 m downstream, beyond which the D-weighted levels are lower than the unweighted OASPL. This suggests an increase in the proportion of energy contained in frequencies below 1000 Hz farther downstream. Note that the spatial dependence of the weighted levels for intermediate power and afterburner share the main features seen at military power (see Fig. 2). The noise radiation for these three engine conditions is dominated by jet mixing noise, and the region of maximum radiation moves upstream as engine power increases.

2.4 A-Weighted Levels with Hearing Protection

The effectiveness of hearing protection depends both on the type used and the spectral content of the sound. For the purpose of this research, attenuation data (in octave bands from 125 to 8000 Hz) for double hearing protection provided by the Air Force Research Laboratory are used. These data were obtained for properly trained users with 100% insertion of the plugs. While the 125-8000 Hz frequency range is sufficient in many cases, jet noise contains so much low-frequency noise, that an estimate of the attenuation is required below 125 Hz. Figure 3(b) displays the provided attenuation values and demonstrates two different methods of extrapolating the values outside of the range given. The plus signs indicate possible values for the attenuation if the slope between 250 and 125 Hz (on the log scale) is continued towards 20 Hz. The triangles represent the assumption that the 125-Hz attenuation remains constant for lower frequencies. In both cases, it was also assumed the 8000-Hz attenuation would hold for higher frequencies.

Both sets of attenuation curves in Fig. 3(b) have been applied to estimate the combined hearing-protected/A-weighted levels as a function of distance downstream for idle and military power, as shown in Fig. 5. Both methods of extrapolating the values below 125 Hz are shown to yield equivalent protected, A-weighted levels, suggesting that while the actual low-frequency attenuation is unknown, a reasonable assumption regarding the attenuation is likely sufficient. The double hearing protection can reduce the A-weighted exposure by about 40 dB along the sideline.

3 LABORATORY-SCALE JET RESULTS AND COMPARISON

Although a supersonic laboratory-scale jet does not approximate the full-scale engine in many ways, the similarity seen in peak Strouhal number in the maximum radiation direction[17] could allow for some comparisons, even when the jet flow conditions are dissimilar. For example, Mach 2.0, unheated jet data shown below compares favorably with certain aspects of the F-22Adata. However, this is not to say that the F-22Ajet conditions are those of a Mach 2.0, unheated jet. But, since the overall levels agree favorably with those of the F-22, a beneficial comparison can be made. Level-based and spectral comparisons provide insight into the connections between laboratory and engine-scale measurements.

3.1 Laboratory Experiment

Acoustic pressure data[20, 21] were collected on an unheated jet produced by a 3.49 cm, Mach-2.0 convergent-divergent nozzle operated on design at the National Center for Physical Acoustics anechoic jet noise facility, whose dimensions yield a maximum scaled propagation distance of 80 nozzle diameters (D_j). There were six microphones mounted on a boom, which was rotated between 80°-150° (relative to the nozzle inlet), in 5° increments. An interpolated map of OASPL in the vicinity of the laboratory jet is shown in Fig. 6, where the white marks indicate the microphone locations.

3.2 Comparison

For comparison with the F-22A data, the interpolated OASPL, at the same scaled locations as the reference array (about 20 D_j in Fig. 6), is shown in Fig. 2. To more accurately compare the levels, 6 dB has been added to the laboratory jet to compensate for the absence of the ground reflections in the anechoic environment. With this adjustment, the maximum OASPL of the laboratory data is approximately 146 dB, as indicated by an arrow in Fig. 2. This maximum level is close to the maximum obtained when the F-22Ais operated at military condition, also indicated by an arrow. Consequently, all subsequent comparisons are made between the laboratory data and military condition. Again, this is not to say that the laboratory Mach 2.0, unheated jet is a scale model of the F-22, but that the fortuitous agreement between these two subsonic jets at the same scaled sideline distance permits further examination.

The OASPLs of the laboratory and military-power data, shown in Fig. 2, exhibit different spatial dependence, which demonstrates information about the angle of peak radiation and the dominant source region. The difference in the scaled location of maximum levels is indicative of dissimilarities in jet exhaust conditions. Previous far-field studies have shown that for military power, the maximum radiation angle is about 50° relative to the exhaust.[10] The laboratory jet levels peak at about 35° (see Fig. 6). These far-field directivities, coupled with possible peak source location variations, are responsible for the difference in maximum-level location seen in Fig. 2. Because of this difference, the most useful comparison between the laboratory and full-scale, military power data is a spectral comparison *at the respective peak radiation locations*, where the characteristic Strouhal numbers are expected to be approximately equal.

Figure 7 displays the calculated one-third octave band spectra for the laboratory jet and military power at locations shown by the arrows in Fig. 2. The laboratory jet spectrum has a peak at about 6.3 kHz, while the full-scale jet spectrum peaks at about 250 Hz. To compare them, the laboratory spectral peak is shifted to 250 Hz, and the resulting shifted spectrum is represented by the circles in Fig. 7. It is clear that, not only are the levels similar, the spectral shapes are very similar over the shifted measurement bandwidth at the respective maximum radiation directions.[22]

With the laboratory spectrum shifted, the impact of A-weighting and hearing protection can be compared between the laboratory and F-22Amilitary power data. The A-weighted spectra of both jets are displayed as triangles in Fig. 7, and their overall A-weighted levels at their respective maximum locations are 140 dB re 20 µPa (laboratory) and 139 dB re 20 µPa (F-22), respectively. The hearing protection attenuation data discussed in Section 2.4 have been applied to both spectra in Fig. 7 to find the A-weighted attenuation. The hearing protector data result in an A-weighted attenuation of 44 dB for the laboratory jet and 42 dB for the F-22Aat military power. The agreement seen shows the possible utility of applying weightings and hearing protector curves to laboratory-scale data of comparable overall levels to provide insight into engine-scale measurements and analyses.

4 CONCLUSION

In this paper, weighted levels and hearing-protector data have been applied to F-22A Raptor and laboratory-scale jet noise measurements. These analyses help determine realistic exposure levels and anticipated effectiveness of hearing protection encountered near the jet. Furthermore, application of the weighting and hearing-protection curves to a frequency-scaled version of the laboratory jet spectrum shows that the laboratory-scale jet data compare well with level and frequency content of the military jet engine in the peak radiation direction. This is not to say that other Mach numbers or temperature ratios would provide the same or similar comparison, as the analysis is simply limited to an unheated, Mach 2.0 jet. However, the analyses do lend increased insight into the hearing protection of military personnel working near high-performance military jet aircraft.

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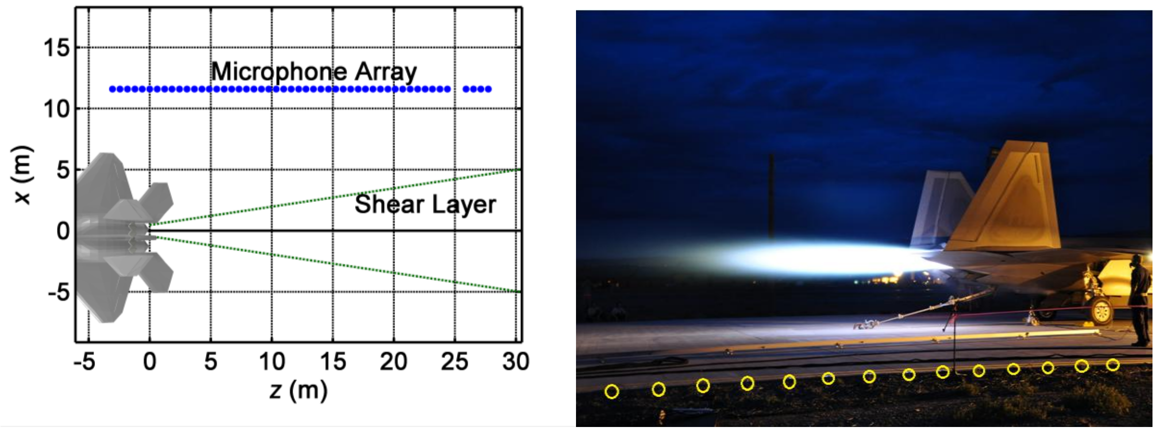


(a) **(b)**

Fig. 1 – Placement of ground-based microphones during the F-22Aexperiment 11.7 m from the jet centerline. Microphones for this experiment are represented by the blue dots parallel to the centerline of the jet plume on the left and the yellow circles on the right.

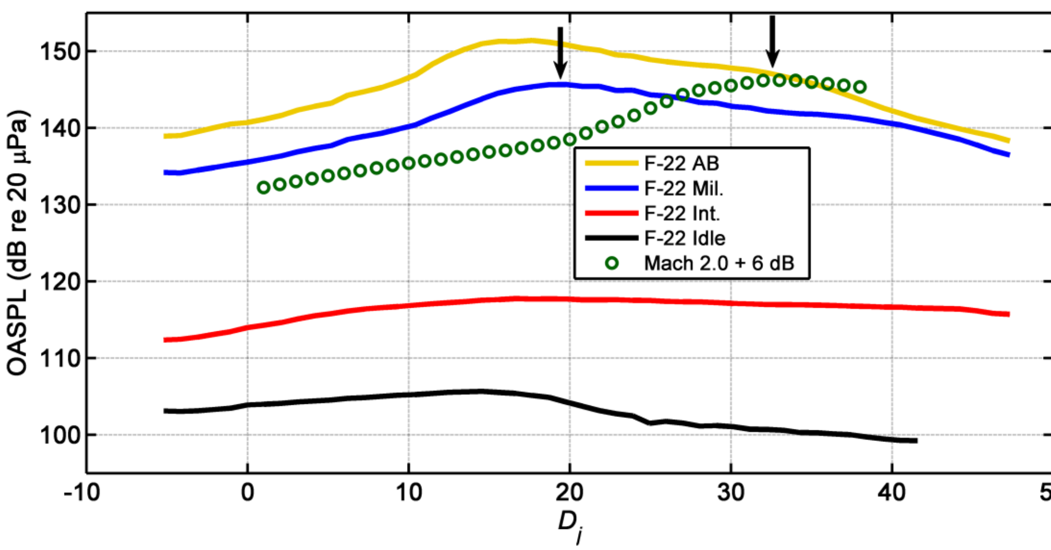
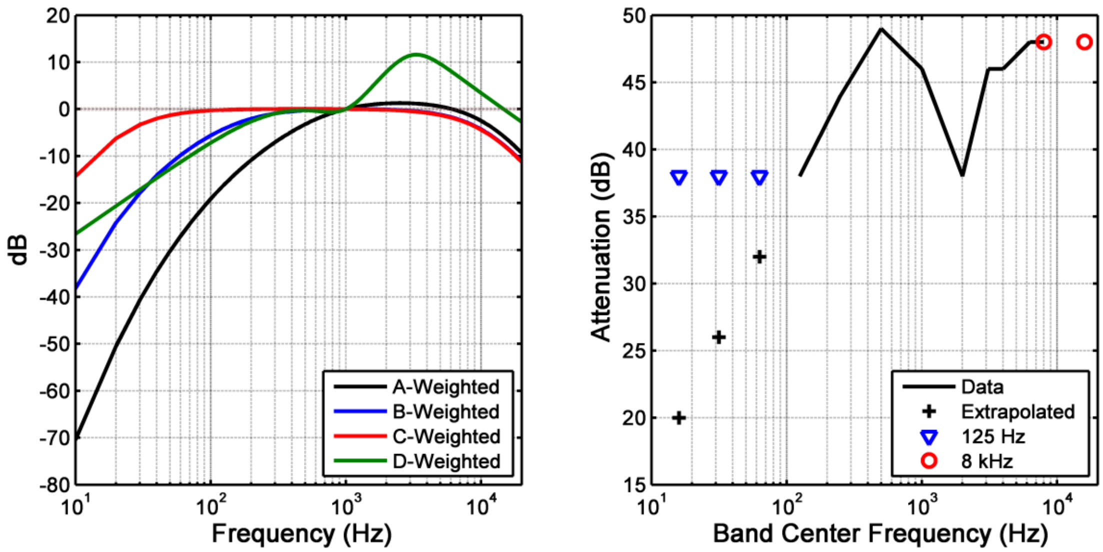
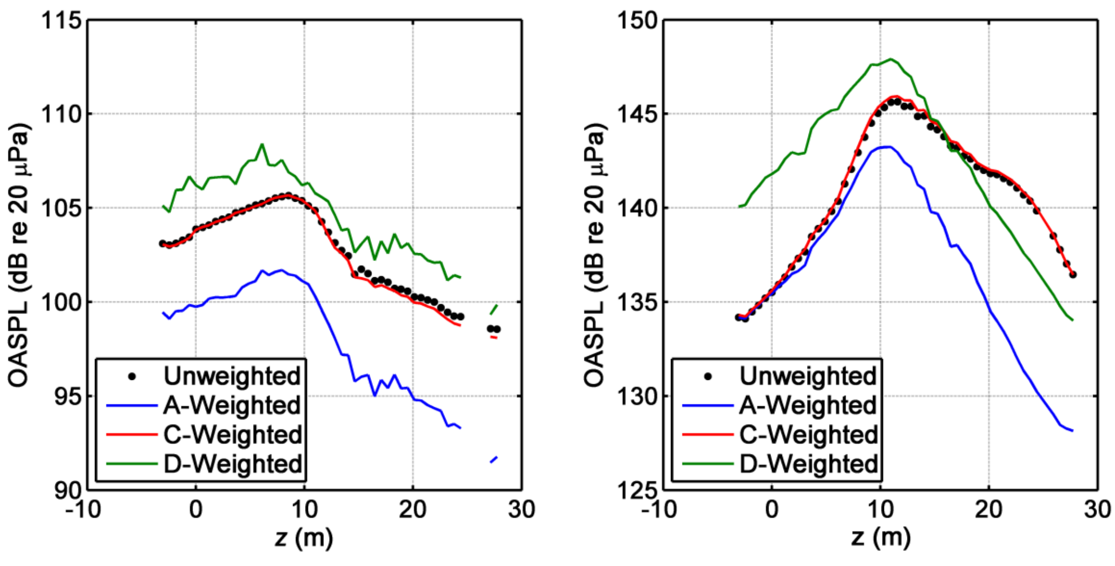


Fig. 2 – Unweighted OASPLs for all engine conditions of the F-22, recorded along the ground-based microphone array, as a function of distance downstream in nozzle diameters D_j. The circles indicate the unheated, Mach 2.0 laboratory data (described in Section 3) adjusted by 6 dB to account for the absence of ground reflections in the anechoic chamber. The arrows indicate the maximum OASPLs for the laboratory jet and the F-22Aat military power.



(a) **(b)**

Fig. 3 – (a) Weighting curves and (b) octave-band attenuation for 100% inserted foam plugs with muffs worn by properly trained personnel. The markers represent different ways of handling the data outside the 125 Hz – 8 kHz bandwidth.



(a) **(b)**

Fig. 4 – Weighted OASPLs for (a) idle and (b) military engine conditions.

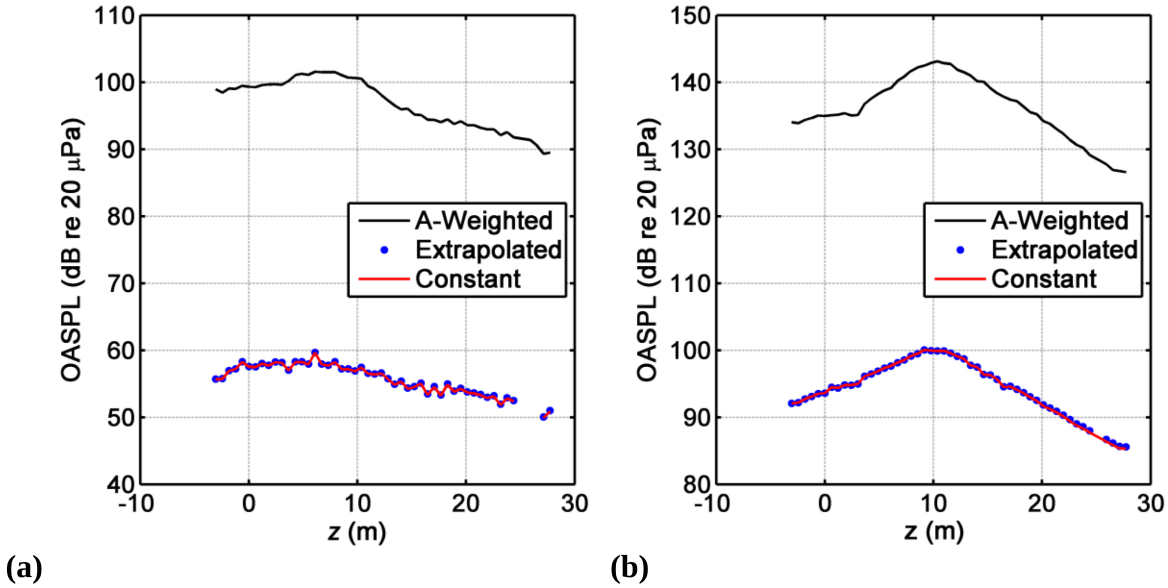


Fig. 5 – Hearing protection gains applied to the A-weighted data for (a) idle and (b) military engine conditions.

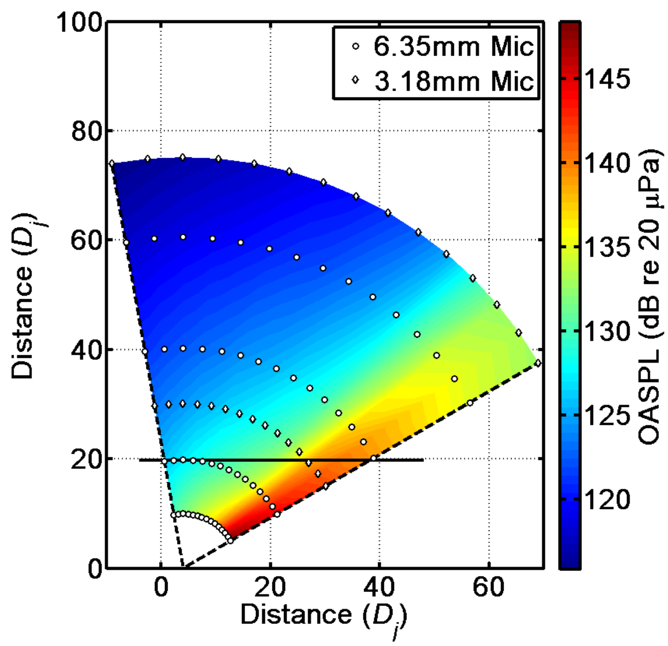


Fig. 6 – Interpolated OASPL of the ideally expanded, unheated, Mach 2.0 laboratory jet, with the nozzle at (0,0) and exhausting to the right. The white marks denote microphone locations. The equivalent scaled location of the F-22Aground-based microphone array is demarcated by the black line.

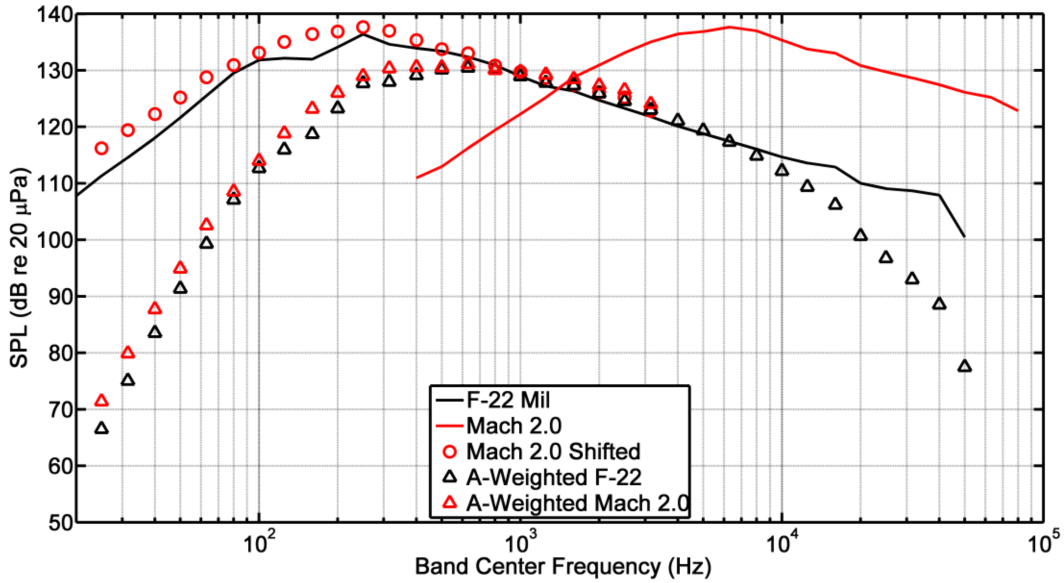


Fig. 7 – One-third octave band spectra of the F-22A at military conditions (black) and the Mach 2.0 laboratory jet (red) at locations of peak radiation (see arrows in Fig. 2), with amplitude scaled upward by 6 dB. The peak-shifted laboratory spectrum is represented with circles, and the A-weighted spectra are represented with triangles.