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3aNSb4. Comparison of supersonic full-scale and laboratory-scale jet data and the similarity spectra for turbulent mixing noise

Tracianne B. Neilsen*, Kent L. Gee, Alan T. Wall, Michael M. James and Anthony A. Atchley

***Corresponding author's address: Physics and Astronomy, Brigham Young University, N311 ESC, Provo, Utah 84602, tbn@byu.edu**

Broadband, partially correlated noise radiated from supersonic jets has characteristics that scale with nozzle size and flow properties. In particular, the spectral content of jet noise and variation with angle in many cases agree with empirically derived similarity spectra for large and fine-scale components of turbulent mixing noise [Tam et al., AIAA paper 96-1716]. In previous studies, measurements made near the F-22A Raptor agreed remarkably well with the similarity spectra, with two exceptions. First, the high-frequency slopes seen in the data were shallower than the similarity spectra at many angles. Second, the data exhibit a double frequency peak, which is absent from the similarity spectra [Neilsen et al., J. Acoust. Soc. Am. 132, 1993 (2012)]. These observations are explored further by examining the spectral characteristics of noise from a different military jet and a laboratory-scale, unheated jet. In both cases, there is evidence that for supersonic cases the measured spectra are shallower than the similarity spectra due to nonlinear propagation effects. In addition, the military data support the observation that the double spectral peak is a feature of full-scale jet noise. Recommendations are made for applying the similarity spectra to predict spectral levels for full-scale jets. [Work supported by ONR.]

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INTRODUCTION

Turbulent mixing noise in jets is composed of radiation from fine and large-scale turbulent structures.[1, 2] Far-field data from a range of cold and heated laboratory-scale jets were used to develop two similarity spectra that match the primary features of the noise from the fine-scale structures (FSS) and the large-scale structures (LSS).[3, 4] The LSS similarity spectrum, which has a relatively narrow peak and power-law decay on both sides, was reported to fit the data for aft angles. On the other hand, the FSS similarity spectrum, with its broader peak and a more gradual roll-off at both high and low frequencies, matched the radiated spectra to the sideline direction. In addition, it was proposed that the turbulent mixing noise at any radiation angle is a sum of LSS and FSS similarity spectra. The agreement between the similarity spectra and laboratory-scale jets at a variety of operating conditions is summarized in Refs. [5] and [6], but only recently has the applicability of the spectral shapes to the noise radiated by high-power engines installed in military aircraft been explored.[7]

Comparisons of the similarity spectra and full-scale jet spectra are limited. In the investigation by Schlinker *et al.*,[8] the LSS spectral shape agrees reasonably well with the measured spectra at aft angles in the far field of a high-performance jet engine with a round nozzle at its full-thrust set point, except for high frequencies where the spectral slope was appreciably shallower than predicted by the LSS spectrum. In recent work, the authors[7] compared noise measured in the vicinity of a tied-down F-22A Raptor[9] with the similarity spectra over a 90° angular aperture at ground-based microphones located 11.7 m (~18 D_j) from the jet centerline. Even though the nozzle geometry is complex and the jet from the single engine is nonideally expanded, the similarity spectral shapes do agree with large portions of the measured spectra. Toward the sideline of the aircraft, the fine-scale similarity spectrum agrees well, while the large-scale similarity spectrum provides a good fit around the area of maximum radiation. Combinations of the two similarity spectra are shown to match the data in between those regions. Surprisingly, a combination of the two is also evident at the farthest aft angle (150°). However, at high frequencies, the degree of congruity between the similarity and the measured spectra changes with engine condition and angle. At the higher engine powers, there is systematically shallower measured high-frequency slope, with the largest discrepancy occurring in the region of maximum radiation. In addition, a feature not captured by the similarity spectra is the presence of a double peak in the measured spectra in high-amplitude regions.

To investigate the generality of the conclusions from the F-22A analysis, the similarity spectra are compared to additional data sets. In this paper, both laboratory-scale subsonic (Mach 0.85) and supersonic (Mach 2.0), ideally expanded, unheated jet data and from the tied-down F-35AA Joint Strike Fighter are considered. The comparison between these additional measurements and the similarity spectra help establish the applicability of the similarity spectra to high-power jets and the need to further understand the additional features in the spectral shapes of full-scale, high-performance engines.

F-22 ANALYSIS

To briefly review the findings in Ref. [7], a discussion of the agreement between the measurements from ground-based microphones located 11.7 m (~18 D_j) from the jet centerline F-22A[9] is first provided. Figure 1 compares the LSS and FSS spectral shapes with the measured spectra for afterburner in different directions; the angles are measured relative to the jet inlet and an origin located 5.5 m downstream of the nozzle exit, which estimates the maximum aeroacoustic source region. As expected, the FSS spectrum provides a good fit at the sideline angles (60°-80°), except at the highest frequencies. As discussed previously, other than an incorrect high-frequency slope and the double frequency peak, the measured spectral shapes match the LSS spectrum in the region of maximum radiation (120°-140°). A combination of the FSS and LSS spectra is used to match the measured spectra in between those regions (90°-100°). In addition to showing that the similarity spectra describe many of the features of full-scale jet noise, a significant, new observation is also seen at 150°, where the measured spectrum has a distinctly different spectral shape from that measured at 140°. For the F-22, this position is farther aft than the maximum lobe, and because of the decreased level of the LSS, a combination of the LSS and FSS again is needed to obtain a good representation of the measured spectrum. This was also seen for the case of military power and is discussed in more detail in Ref. [7].

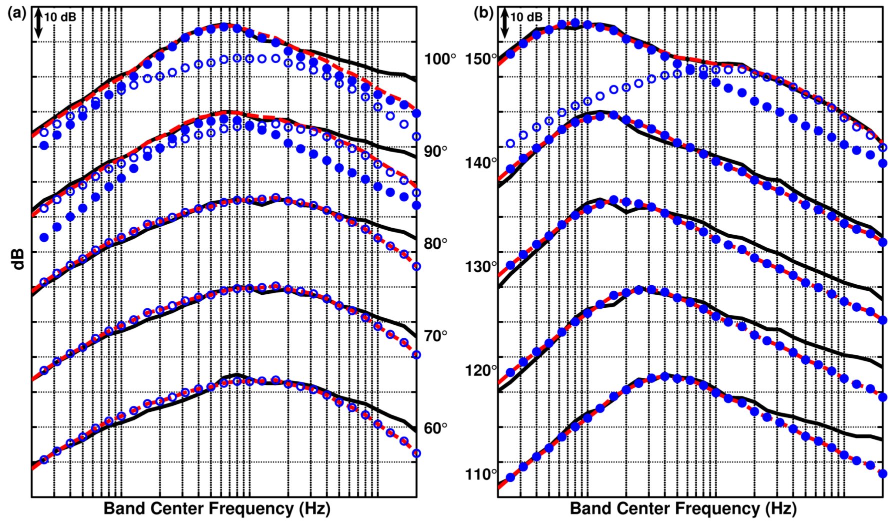

FIGURE 1. Comparison of the F-22 afterburner one-third octave band spectra (black solid) measured at ground-based microphones with the total similarity spectra (red dashed). The total spectra are the combination of the fine-scale (empty) and the large-scale (filled) similarity spectra. The angles (relative to the inlet) corresponding to each spectrum are listed in the center.

A concise way to summarize the similarity-spectra analysis of the F-22 data for different directions and engine conditions is to look at the contributions to overall sound pressure level (OASPL) for the different components, as shown in Fig. 2(a). In all cases, the OASPL of the similarity spectra agree with the measured values. In addition, smooth trends are seen with increasing angle as the FSS contribution peaks at 80° and then declines, while the LSS contributions peaks at 110° for afterburner, 120° for military power, and 140° for intermediate power. These are not the same as the far-field directivity because of the proximity to the jet and the geometry of the measurement array. A more complete discussion is given in Ref. [7], but there are three primary conclusions that provide guidance when analyzing other data sets. First, the OASPL for intermediate power does not change significantly, in contrast to the military and afterburner cases where there is an increase in OASPL in the region of maximum radiation. Second, the region where a combination of the LSS and FSS spectra is needed to match the measured spectra narrows as engine power increases. Third, the FSS contribution at 150° needed to match the spectral shape for military and afterburner does not change the OASPL significantly.

(a) (b)

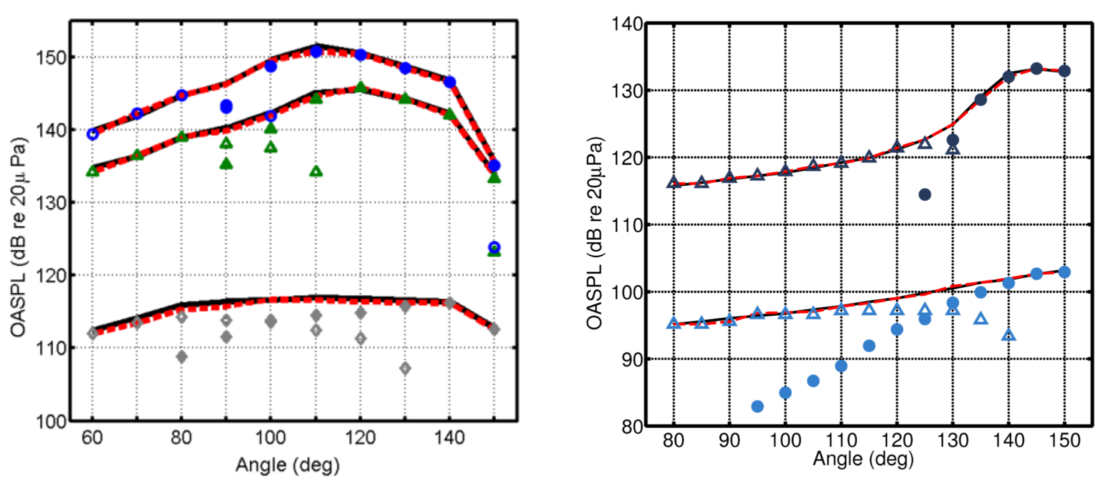

FIGURE 2. Overall sound pressure levels (OASPL) of data (black solid), total predicted similarity spectra (red dashed), LSS contributions (filled), FSS contributions (open) for (a) a single F-22A engine operating at afterburner (upper), military (middle), and intermediate 80% (lower) and (b) an unheated, laboratory-scale jet operating at Mach 2.0 (upper) and Mach 0.85 (lower).

LABORATORY-SCALE ANALYSIS

The conclusions drawn from the F-22A similarity-spectra analyses are now evaluated for laboratory-scale subsonic (Mach 0.85) and supersonic (Mach 2.0), ideally expanded, unheated jet data. In the experiment, described in Ref. [10], measurements were made of noise from 3.49-cm diameter nozzles. The present analysis focuses on data from a Type-1 3.18 mm pressure microphone mounted at 75 nozzle diameters (D_j) on a boom that swept out a measurement arc between 80 – 150° (relative to the inlet and to a reference position 4 D_j downstream) in 5° increments. The anechoic environment of this experiment makes it an ideal case for studying the applicability of the similarity spectra to subsonic and supersonic jet noise.

Some significant differences are found between the subsonic and supersonic cases. Figure 3 displays the unheated, Mach 0.85 spectra. As expected, the FSS spectrum provides a good fit at the sideline angles (80° - 90°). A combination of the FSS and LSS spectra is needed to match the measured spectra over a large angular aperture (100° - 140°). At 145°, the LSS spectrum alone agrees well, which matches others' findings for subsonic jet noise at aft angles. In Fig. 4, the FSS spectrum predicts the measured, Mach 2.0 spectra fairly well until 120°, with slight discrepancies at the very lowest and highest frequencies. A combination of FSS and LSS spectra represents the spectrum at 130°, while the LSS spectrum alone matches at 140°-145°, except for having a steeper predicted high-frequency roll-off than measured. For this unheated jet, the angular aperture over which a combination of FSS and LSS spectra is needed is significantly narrower for supersonic than subsonic conditions. This corroborates previous work on laboratory-scale jets.[5, 6]

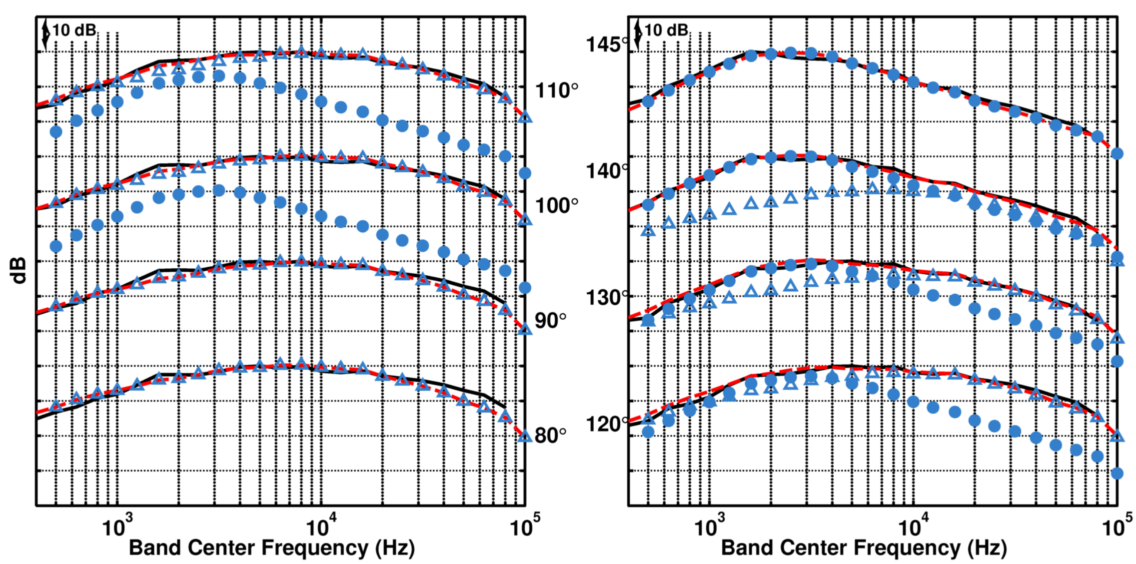

FIGURE 3. Comparison of the unheated, Mach 0.85 spectra (black solid) at 75 D_j and the total similarity spectra (red dashed), which is the combination of the fine-scale (empty) and the large-scale (filled) similarity spectra.

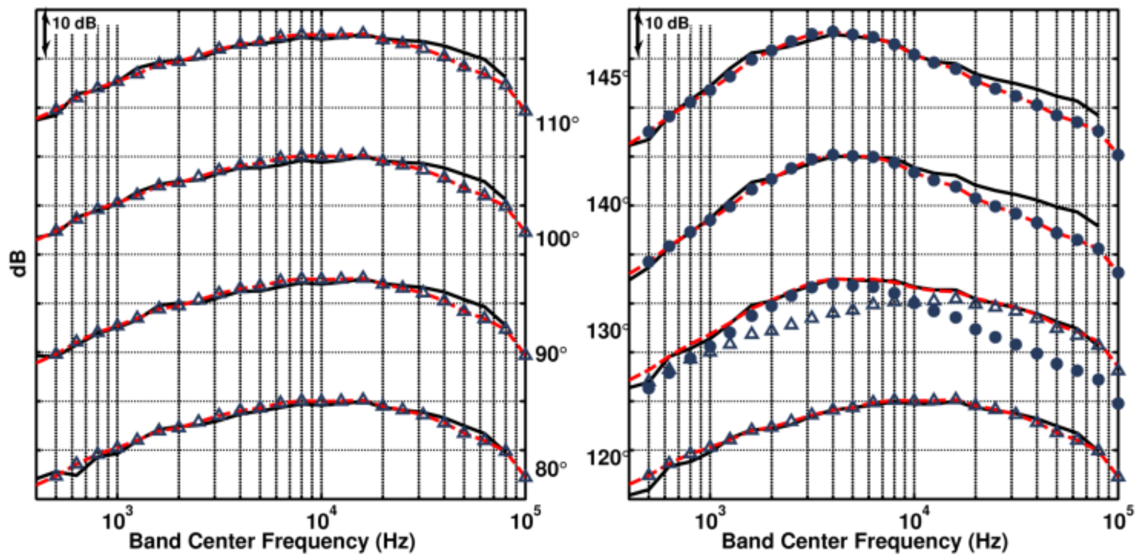

FIGURE 4. Comparison of the unheated, Mach 2.0 spectra (black solid) at 75 D_j and the total similarity spectra (red dashed), which is the combination of the fine-scale (empty) and the large-scale (filled) similarity spectra.

The relative contributions of the FSS and LSS spectra are examined by considering the overall sound pressure level (OASPL) associated with each, shown in Fig. 2(b) at every measurement location along the 75 D_j arc (5° increments). Not only is there remarkable agreement between the measured and predicted OASPL, but there are significant differences between the subsonic (lower) and supersonic (upper) cases. There is much less variation in OASPL over the 70° aperture in the subsonic case. For Mach 2.0, there is a significant difference in OASPL between the FSS and LSS dominated regions. For Mach 0.85, the combination region is significantly wider.

In comparing the laboratory-scale results to those of the F-22A, there are two types of comparisons to be made: the OASPL and the spectral shapes. The OASPL of the subsonic, Mach 0.85 jet in Fig. 2(b) looks similar to the intermediate condition for the F-22A in Fig. 2(a); both are relatively flat over the measurement aperture. For the Mach 2.0, military, and afterburner cases, the significant OASPL increase in the downstream direction is likely caused by Mach waves being present. The larger increase in the relative importance of the LSS contribution for the unheated, supersonic, laboratory-scale jet than for the F-22 at military power and afterburner may be explained by differences in geometry. The F-22 measurements involved a sideline array parallel to the centerline, whereas the laboratory data came from an arc, with all points approximately equidistant from the noise source region. Figure 2 also shows that the combination region, where LSS and FSS spectra are both important, is wider for subsonic conditions (presumably due to the absence of Mach wave radiation) and also for heated jets.[1, 5, 6]

The spectral comparisons for the laboratory-scale jet and the F-22 engine result in similar conclusions. Both the Mach 0.85 and the intermediate engine cases agree with the similarity spectra very well. For the Mach 2.0 and afterburner cases, there is a clear lessening in high-frequency slope relative to the LSS spectrum around their respective maximum radiation directions. In both cases, the slopes approach -10 dB/decade on one-third octave scales, rather than the -17.8 dB/decade predicted by the LSS spectrum.[3] This discrepancy is investigated further in the context of the F-35A analysis.

F-35AA ANALYSIS

Measurements of a tied-down F-35AA Joint Strike Fighter were made at several engine conditions.[11, 12] The data were collected with 6.35-mm Type-1 microphones at a height of 1.5 m (5 ft). It is shown in Ref. [12] that the maximum directivity of the OASPL at 38 m for 100% power occurs around 110-140°, relative to the nozzle inlet and an origin positioned 6.6 m downstream. The general trend, is that the spectral shapes change from being more rounded at sideline to more peaked in the aft direction, as is shown in Figs. 5-7 for the spectra measured at 38.1 m (125 ft) at three engine powers: 75%, 100% (military) and 150% (afterburner).

Comparisons with the similarity spectra are complicated by the presence of ground reflections. The microphone placement (particularly the height of 1.5 m) resulted in significant interference nulls in the 630-2500 Hz band. Unfortunately, this missing information corresponds to the peak-frequency region at the sideline and makes it difficult to see how to apply the LSS and FSS spectra in the combination region. The other peculiar feature is the presence of high-frequency ringing in the spectra at 140° for all three engine conditions, presumably caused by back-scattering off the 8-m tall, 6-cm diameter tripod on which it was mounted. Nevertheless, several observations about the spectra measured at 38.1 m (125 ft) corroborate the findings from the F-22A spectral analysis.

Figures 5-7 display the measured data and the similarity spectra for three engine powers: 75%, 100% and 150%, respectively. Because of the interference effects, the efforts to match the FSS similarity spectrum are limited to a single sideline location of 90°; the alignment is guided by the low and high ends of the spectra. In addition, comparisons with the LSS similarity spectrum are shown at four aft angles. For all three engine powers, there is reasonable agreement with a few notable exceptions. First, there is a double peak present in the 120°-140° F-35AA spectra (below 400 Hz) that is not predicted in the model nor was present in the laboratory-scale data. Second, the high-frequency slopes of the measured spectra are shallower than the similarity spectra in the high-amplitude cases. For angles aft of the maximum radiation region, the LSS is closer to representing the high-frequency content, particularly at 148° for 100% power (in Fig. 6) and at 140° for 150% power (in Fig. 7a). However, for 150% engine power the spectral shape at 148° exhibits a high-frequency shape that is better matched by a combination of the LSS and the FSS spectra.

Comparisons of similarity spectra for turbulent mixing noise with the spectral shapes for the F-35AA yield similar results as the F-22A analysis. The FSS similarity spectrum matches at sideline, and the LSS similarity spectrum matches in the region of maximum radiation, except for the presence of double peaks in the measured spectra and a discrepancy in the high-frequency slope that increases as the engine power increases. In both cases, a combination of the FSS and LSS similarity spectra yields the best agreement behind the maximum radiation direction, a region that is within the measurement aperture only at afterburner for the F-35AA but at both military and afterburner for the F-22A.

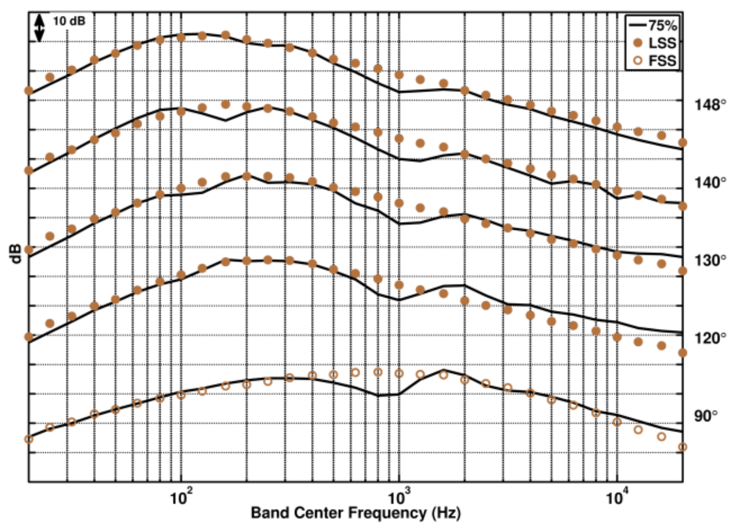

FIGURE 5. Comparison of SPL from JSF at 75% engine power at a distance of 38.1m (125 ft) from the estimated maximum source region (solid black) to the similarity spectra: LSS (filled), FSS (open).

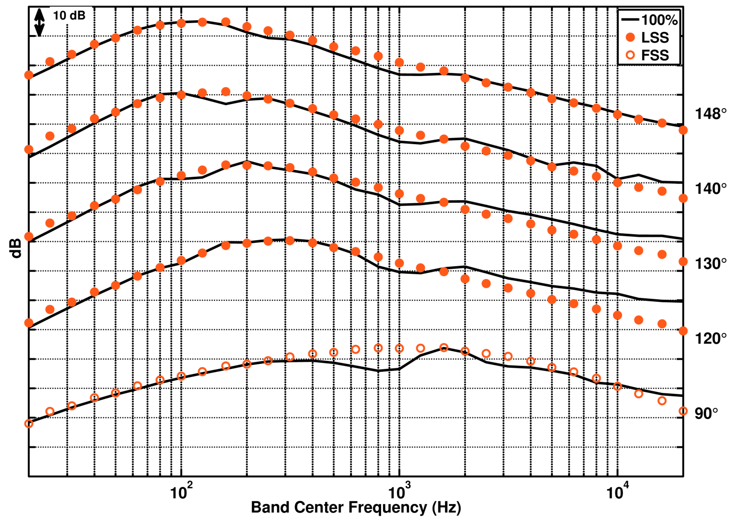

FIGURE 6. Comparison of SPL from JSF at 100% engine power at a distance of 38.1m (125 ft) from the estimated maximum source region (solid black) to the similarity spectra: LSS (filled), FSS (open).

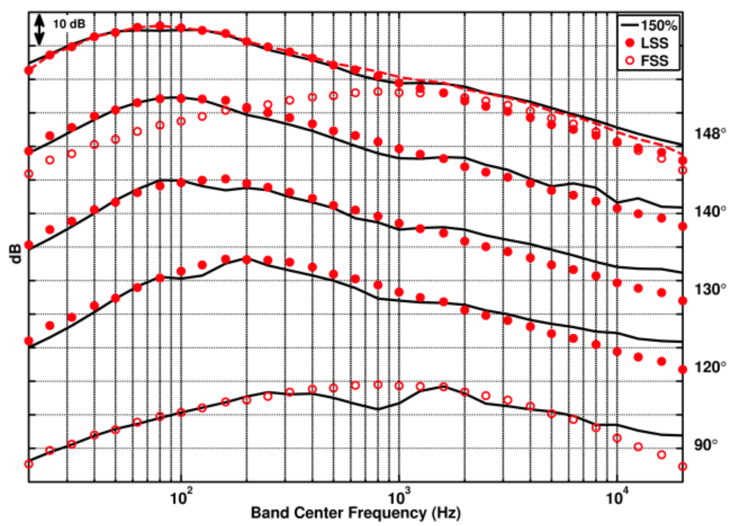

FIGURE 7. Comparison of SPL from JSF at 150% engine power at a distance of 38.1m (125 ft) from the estimated maximum source region (solid black) to the similarity spectra: LSS (filled), FSS (open), combination (dashed).

OVERALL FINDINGS

The similarity spectra for turbulent mixing noise, first proposed by Tam *et al.*,[3] have been applied to the noise radiated by the F-22A, the F-35AA Joint Strike Fighter, and sub and supersonic, unheated, laboratory-scale jets. Coupled with Ref. [7], this work comprises the first in-depth comparison of the similarity spectra with full-scale, high-performance jets. Overall, the agreement is fairly good with the FSS spectrum capturing the general shape of the sideline radiation and the LSS spectrum representing the radiation around the maximum amplitude region. Combinations of FSS and LSS spectra provide reasonable matches for angles between those extremes and, as has been newly observed, angles farther aft than the maximum region.

The discrepancies between the similarity spectra and the three data sets indicate directions for further investigations related to the FSS and LSS models. First, many of the full-scale engine spectra exhibit a double peak that is not captured in the model. The cause of this double spectral peak, which is not seen in the laboratory-scale data, is not presently understood but may be related to an additional source phenomenon[13] and thus warrants further investigation. Second, for the high-amplitude noise, the high-frequency slopes of the similarity spectra do not predict the measured spectra. The measured spectra in the aft direction have a shallower power-law slope than the LSS spectrum, and the sideline spectra for high engine power do not an exponential roll-off as predicted by the FSS spectrum. The high-frequency slopes exhibited by the data are believed to be related to the presence of nonlinear wave steepening and shock formation.[14] It is difficult to predict the actual high-frequency slope expected for supersonic jets because nonlinear propagation may alter it differently as a function of distance, angle, jet condition, and/or scale. Consequently, the similarity spectra need to be revisited more fully in the context of the effects of nonlinear propagation on the spectrum radiated from high-power jets.

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