Near-field shock formation in noise propagation from a high-power jet aircraft

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Abstract: Noise measurements near the F-35A Joint Strike Fighter at military power are analyzed via spatial maps of overall and band pressure levels and skewness. Relative constancy of the pressure waveform skewness reveals that waveform asymmetry, characteristic of supersonic jets, is a source phenomenon originating farther upstream than the maximum overall level. Conversely, growth of the skewness of the time derivative with distance indicates that acoustic shocks largely form through the course of near-field propagation and are not generated explicitly by a source mechanism. These results potentially counter previous arguments that jet "crackle" is a source phenomenon.

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1. Introduction

Early studies[1,2] of nonlinear propagation effects in noise radiated from full-scale supersonic jet engines have been extended recently[3–9] and include a far-field analysis of F-35A static run-up data.[10] Comparison of the measurements in Ref. 10 with results from a nonlinear propagation model between 76 and 305 m was quite favorable for the military engine power reported. However, that same experiment had a relatively dense measurement array within a 38 m radius arc of the aircraft. This Letter describes analyses of those data with the intent of understanding how the effects of nonlinear propagation evolve throughout the geometric near field of a full-scale, high-performance military jet engine.

Analysis of near-field nonlinearity is complicated because assumptions like spherical spreading or propagation exclusively along a given observation radial may not be valid for some frequencies. Higher-order spectral analysis techniques, including the bispectrum[11] and quadspectrum-based indicators,[3,12–14] have proven useful in nonlinearity analysis. However, because wave steepening and shock formation result in large changes in the waveform's time derivative, derivative-based measures for analysis of nonlinear propagation seem convenient.

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The works of McInerny and Olcman[12] and McInerny[15] with rocket noise identified the skewness of the pressure waveform's time derivative as a useful indicator of acoustic shocks and nonlinear propagation. The skewness, the normalized third central moment of the probability density function, is a measure of the data distribution's asymmetry. The large derivative values present at acoustic shocks result in a highly positive skewed distribution.

Skewness of the jet pressure data has long been synonymous with the phenomenon of "crackle," associated with *N*-wave-like phenomena in the broadband waveform. Ffowcs Williams *et al.*[16] indicated that a skewness greater than 0.4 distinctly crackled and subsequent experimental[17] and numerical[18,19] studies have focused on quantifying pressure skewness. The conclusion has been that positive skewness (i.e., an asymmetric waveform with relatively infrequent large positive values, and many smaller negative values) is generated at the source, and therefore crackle is also a source phenomenon. However, Gee *et al.*[20] recently showed that crackle appears to be more linked to the statistics of the derivative than of the pressure waveform itself, and that a crackle-like quality can be perceived in far-field jet data without significant waveform skewness.[21] The nonlinear propagation analysis in this Letter has bearing on the question of whether crackle is a source or a propagation phenomenon.

2. Results and analysis

Measurements of the tied-down F-35A Joint Strike Fighter were made at several engine conditions,[9] but military power is the focus of this Letter. The data were collected at a sampling rate of 96 kHz with 6.35 mm, Type 1 microphones at a height of 1.5 m (5 ft). Displayed in Fig. 1 are overall sound pressure level (OASPL) and one-third-octave band pressure levels for the 200 and 2000 Hz bands. Microphone locations are denoted by markers, with a cubic interpolation between data points. Note that the data immediately around the aircraft for this and subsequent figures are interpolated values whose accuracy is likely reduced by aircraft shielding or scattering.

In Fig. 1(a), the maximum directivity of the OASPL at 38 m occurs around 110°–140°, as defined relative to the engine inlet and an origin positioned 6.6 m downstream (denoted by a cross along the centerline). The origin was intended to approximate the dominant source region in the plume and tracing from ∼125° and 38 m inward suggests this to be the case. For the two band level maps in Figs. 1(b) and 1(c), 200 Hz is around the spectral peak frequency in the maximum radiation direction, and 2000 Hz is representative of high-frequency spectral characteristics. First, note the differences in directivity between Figs. 1(b) and 1(c), as the 38 m maximum has shifted forward from 130° to 120°, with less directionality in Fig. 1(c). Comparison of the 200 and 2000 Hz levels shows evidence of the expected contraction and movement of the dominant noise source upstream with frequency. For the 200 Hz data in Fig. 2(a), a ground reflection null is visible in the aft direction as a decrease in level over the ∼8–14 m range, measured from the estimated maximum source region.

These level-based data in Fig. 1 help lend insight into the spatial properties of the skewness of the acoustic pressure waveform and its time derivative. Displayed in Figs. 2(a) and 2(b) are skewness maps for the pressure and derivative, respectively. In Fig. 2(a), the pressure skewness values range between ∼0.13, which occurs close to the shear layer downstream, and 0.41 in the sideline and aft directions. The values in the broad maximum region range between 0.3 and 0.4. The relative constancy, without strong evidence of growth or decay provides evidence that the waveform asymmetry (i.e., skewness) is produced as a source phenomenon. This qualitatively agrees with previous findings of laboratory and numerical studies.[17–19] Further, there is greater congruity between the pressure skewness in Fig. 2(a) and the spatial map of the 2000 Hz data in Fig. 1(c) than the 200 Hz data in Fig. 1(b). That the pressure skewness (a) appears to originate near the nozzle, (b) has relatively low values downstream along the shear layer, and (c) has significant values toward the sideline all indicate that the waveform asymmetry is a high-frequency source phenomenon. Note that the

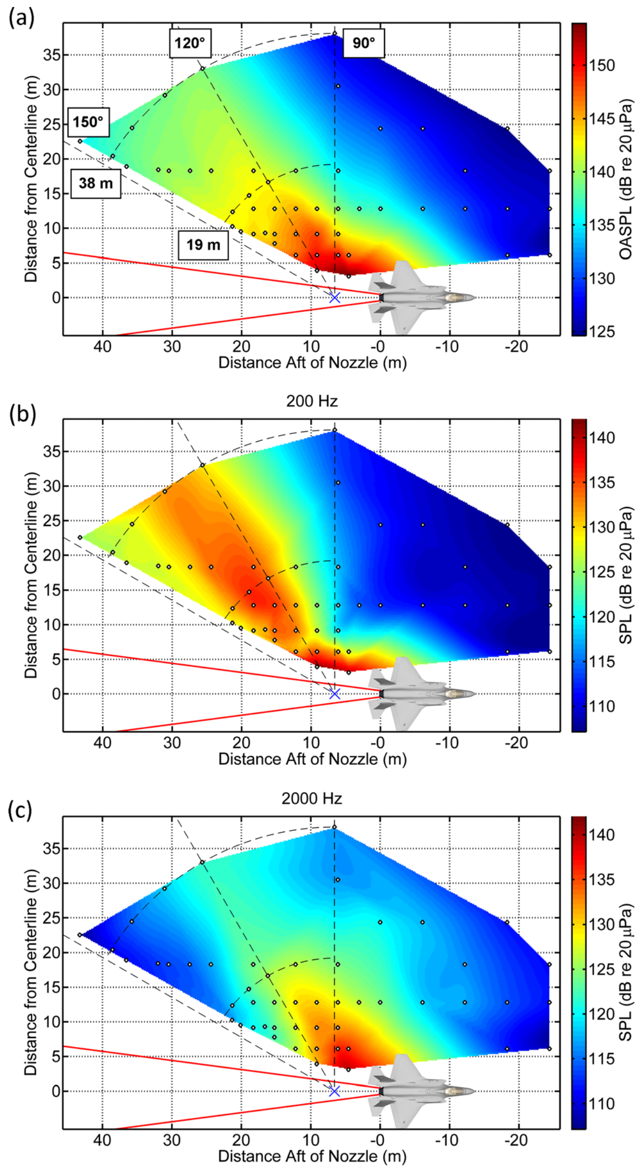

Fig. 1. (Color online) Interpolated maps of (a) overall sound pressure level (OASPL), (b) 200 Hz one-third octave band pressure level, and (c) 2000 Hz band pressure level. The estimated maximum source region is denoted with an cross, with radials and arcs measured from that point. Part (a) is annotated to define the radials and arcs; microphone locations are also shown.

decrease in near-shear-layer pressure skewness with increasing downstream distance agrees with the results of Nichols *et al.*[18]

It is important to note that the skewness values for the F-35A at military power, with the maximum region ranging between 0.3 and 0.4, would be considered "borderline" by the Ffowcs Williams *et al.*[16] crackle criterion. They defined skewness values less than 0.3 to be non-crackling and greater than 0.4 to be distinctly crackling. However, despite the qualitative nature of words like "distinctly," there is no question that crackle is readily audible in noise from the F-35A at military power. Hence, Fig. 2(a) provides further evidence beyond the original caution by Gee *et al.*[20] that the choice of metrics used to define crackle should be revisited.

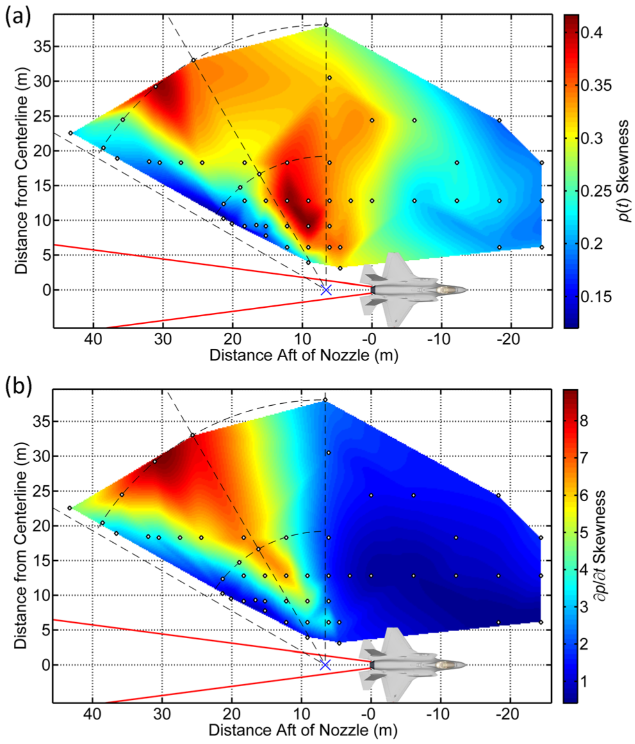

Fig. 2. (Color online) Interpolated maps of the skewness of the (a) pressure waveform and (b) the pressure waveform time derivative around the F-35A Joint Strike Fighter at military power. See Fig. 1(a) for radial and arc annotations.

Figure 2(b), which displays the skewness of the waveform time derivative, provides significant insight into the nature of the radiation of finite-amplitude noise from military jets. Whereas there is a broad spatial region with relatively constant pressure skewness, the skewness of the derivative—an indicator of the formation of acoustic shocks—has a rapid growth in the aft direction corresponding to maximum OASPL [see Fig. 1(a)]. There is also slight growth of the derivative skewness in the sideline and forward directions, suggesting nonlinear wave steepening is occurring, but not nearly as quickly. The maximum derivative skewness occurs in areas along the principal radiation lobe [$\sim$110°–140°, from Fig. 1(a)], indicating correlation of nonlinear propagation with Mach wave radiation. However, the apparent origin of the evolving derivative skewness appears to be quite close to the nozzle, upstream of the estimated maximum overall source location. This also suggests the importance of the initial high-frequency content in the nonlinear evolution and waveform steepening.

Until recently, there was no quantitative work relating the skewness of the derivative to shock formation. However, Shepherd *et al.*[22] have studied the nonlinear evolution of an initial sine wave in the preshock region while calculating the skewness of the time derivative. They show that the skewness increases exponentially from 0 to values greater than 10 as the shock formation distance is approached. Extension of the sine-wave study to broadband noise, where shocks form at varying distances, is not fully known, but preliminary experimental work by Muhlestein and Gee[23] suggests similar behavior of the derivative skewness for noise in the preshock region. Thus, with present quantitative understanding, a derivative skewness value of $\sim$1.8 near the shear layer that exceeds 8.5 by 38 m, as in Fig. 2(b), indicates that slightly steepened waveforms at the shear layer undergo rapid waveform steepening and shock formation. This is confirmed by examining an amplitude-normalized, retarded time-aligned

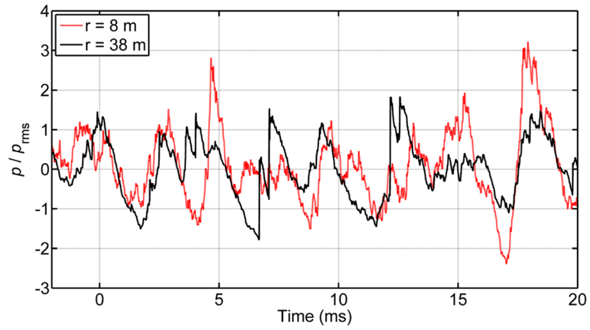

Fig. 3. (Color online) Comparison of time-aligned waveform segments along 130° for the F-35A Joint Strike Fighter at military power. The waveforms have been normalized by their respective root-mean-square (rms) pressures.

waveform segment along 130° at 8 and 38 m in Fig. 3. The overall waveform shapes do not track very well because 8 m is in the extreme geometric near field. However, the salient point is that positive skewness is evident in both waveforms [cf. Fig. 2(a)] with possible evidence of steepening at the highest amplitude portions, but significant shock-like content is only seen in the 38 m data [cf. Fig. 2(b)].

3. Concluding discussion

The analysis has shown that the high-amplitude noise from an F-35A at military power is not radiated with well developed shocks, but rather as skewed pressure waveforms that rapidly evolve into shock-rich signals in the dominant radiation direction. Because far-field nonlinear propagation has been observed from 90°–155° for even intermediate engine conditions on the F-22A Raptor,[8] the small changes in derivative skewness to the sideline and forward directions indicate slower nonlinear evolution in these regions.

Because of recent efforts tying crackle to jet noise reduction,[24] this analysis points to a further need to understand crackle as a perceptual phenomenon. Currently, the jet aeroacoustics community predominantly views crackle as a source phenomenon. If defined as waveform asymmetry, this is true, as both this study and recent numerical simulations[18] indicate that pressure skewness originates relatively close to the nozzle. However, if perception is linked to the steepness of the acoustic shocks, this study uniquely indicates that the crackle is more pronounced farther from the jet. Jet engine noise reduction measures that reduce pressure skewness without a significant change in overall level may not be effective in practice as near-field nonlinear propagation could still produce a strong crackle-like perception.

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