THE “SOUND OF FREEDOM”: CHARACTERIZING JET NOISE FROM HIGH-PERFORMANCE MILITARY AIRCRAFT

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Introduction

In 1932, the applied mathematician Horace Lamb, a notable contributor to the field of acoustics, addressed the British Association for the Advancement of Science. He reportedly quipped, “I am an old man now, and when I die and go to heaven there are two matters on which I hope for enlightenment. One is quantum electrodynamics, and the other is the turbulent motion of fluids. And about the former I am rather optimistic.” More recently, Richard Feynman dubbed turbulence “the most important unsolved problem in classical physics.”[1] Between the difficulties in characterizing its source and understanding the transition from mean fluid flow to wave motion, the noise radiated from turbulent jets is a topic that remains ill understood. Numerous research studies, beginning with the seminal works of Sir James Lighthill in the 1950’s,[2,3] have probed the origins or properties of jet noise. For example, a Google Scholar® search for publications containing the exact phrase “jet noise,” yielded 678 results for the year 2012 alone.

> *“[T]urbofan engines that propel today’s high-performance tactical aircraft also produce “the sound of freedom” – noise levels sufficient to cause concern regarding personnel hearing loss on airfields and aircraft carriers and increased annoyance for communities near bases.”*

Although greater reductions are still required, significant progress has been made to reduce commercial aircraft engine noise through the introduction of regulations[4] and technological advancements, including the development of high bypass flow ratio engines with chevrons. However, the low bypass turbofan engines that propel today’s high-performance tactical aircraft also produce “the sound of freedom” – noise levels sufficient to cause concern regarding personnel hearing loss on airfields and aircraft carriers (see Figure 1 for typical maintainer positions) and increased annoyance for communities near bases. Figure 2, which shows compensation, through 2005, to U.S. military veterans whose primary disability is hearing loss, indicates an alarming trend in hearing impairment. Though not all military hearing loss can be attributed to jet noise, noise reduction strategies designed to alter the turbulent flow, including various means of injecting fluid at the nozzle exit,[5] advanced chevrons[6] and corrugations,[7,8] have been proactively explored for many years. In a present Navy program, advanced chevrons (see Figure 3) are being installed on F/A-18E/F Super Hornet nozzles[9] and new corrugation designs are being developed and tested. However, additional significant advances in reducing noise from high-performance aircraft require better understanding and quantification of the jet noise problem – both source and human impact. With this goal in mind, research offices (Office of Naval Research (ONR), Air Force Research Laboratory (AFRL), Strategic Research and Development Program, etc.) are sponsoring programs aimed at characterizing the physics of military jet noise generation and propagation. This article describes characteristics of supersonic jet noise as observed from recent analyses of extensive military jet aircraft measurements by the authors. Also described are concurrent efforts by other investigators under a jet noise reduction[10] program sponsored by ONR and NASA.

Supersonic Jet Noise: An Overview

The turbulence generated in supersonic, high-speed jet flows is responsible for the dominant noise associated with high-performance military engines. Supersonic jet noise can have multiple components, referred to as mixing noise, screech, and broadband shock-associated noise. Tam[11] and Morris and Lilley[12] provide reviews of these noise phenomena for the interested reader. Because mixing noise in the aft region dominates the overall noise radiation, its characteristics are emphasized in this article.

The acoustic radiation associated with mixing noise from a jet is understood to originate both from unsteady fluctuations from small-scale eddies and from coherent interaction between larger-scale turbulent features.[13-15] This large-scale turbulence is comprised of varying lengths, amplitudes, and convection speeds, with an associated wavenumber spectrum. Some combinations of wavenumbers and axial velocities will result in a sonic disturbance and subsequent radiation to the far field. Other local pressure distur-

Fig. 1. Military jet catapult launch in the USS Theodore Roosevelt. Courtesy of the U.S. Office of Naval Research.

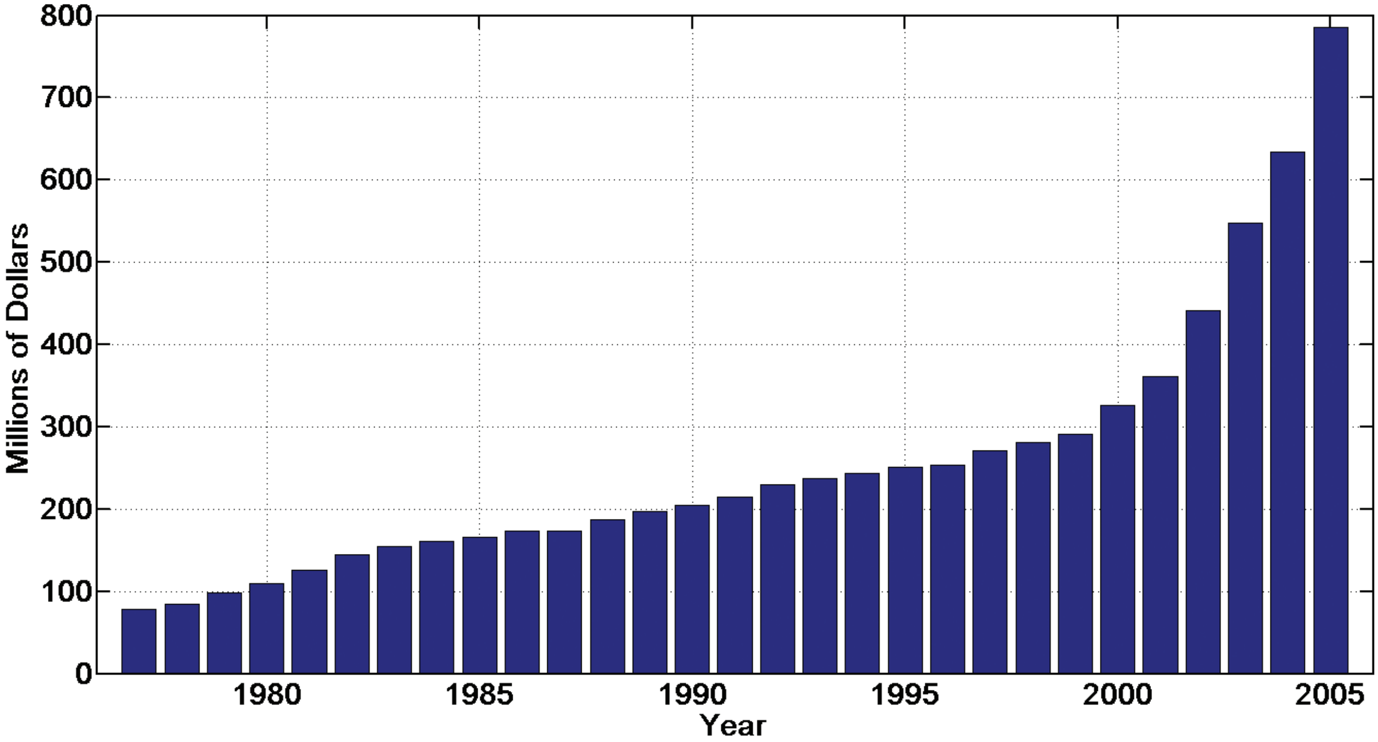

Fig. 2. U.S. Veterans disability benefits for hearing loss as primary disability. Total cost to Department of Defense, in millions of dollars for the years 1977-2005. Data from Ref. 11.

Fig. 3. Chevrons installed in the engine nozzles of an F/A-18E/F Super Hornet. Courtesy of the U.S. Naval Air Systems Command (NAVAIR).

bances in the linear hydrodynamic (i.e. acoustic) near field decay exponentially, or evanesce, in the radial direction. When the mean convective jet velocity is supersonic with respect to the ambient medium, the radiation efficiency is enhanced by Mach wave radiation. The Mach waves' directionality is determined by trace velocity matching of the mean convection speed of the turbulence near the shear layer with the sound speed outside. Readers familiar with structural acoustics will ientify parallels between jet noise radiation mechanisms and subsonic and supersonic wave motion in plates.[16]

Because of the dominance of the Mach wave radiation, the overall noise from supersonic jets is directional, with the maximum levels often occurring 30-60° relative to the downstream jet axis. This principal lobe in overall sound pressure level (OASPL) shifts upstream with increasing jet velocity and broadens with increases in temperature.[12] In terms of the mixing noise spectrum, the peak frequency and the shape change as a function of angle. The characteristic Strouhal number, ($St=fD/u_j$, where f is frequency, D is nozzle diameter, and u_j is jet velocity) changes from ~0.1-0.3 in the peak radiation direction to higher values toward the sideline (90°) and the spectral shape evolves from a relatively peaked "haystack" spectrum near the maximum radiation angles to a rounder spectral shape toward and upstream of the sideline.

This basic variation in spectral shape, present under a wide variety of jet conditions, prompted the empirical development of two characteristic spectral shapes, i.e. *similarity* spectra,[17,18] and connection of these two spectra to a two-source model for jet noise.[19,20] These spectra and a schematic representation of the two-source model are shown in Figure 4. Based on a variety of experimental observations,[19] the peaked spectra around the maximum radiation angle are linked to the large-scale, relatively coherent, quasi-stable turbulent structures in the plume. The source coherence and wave interference effects in these large-scale structures (LSS) can be used to explain the source directivity. The more rounded spectra to the sideline and upstream are believed to be associated with fine-scale structures (FSS) in the turbulence. According to Tam *et al.*,[19] they are distributed throughout the plume, radiate incoherently, and are more observable in regions not dominated by the LSS radiation.

Because the maximum radiation appears to be tied to LSS-type turbulence, recent efforts have focused on explor-

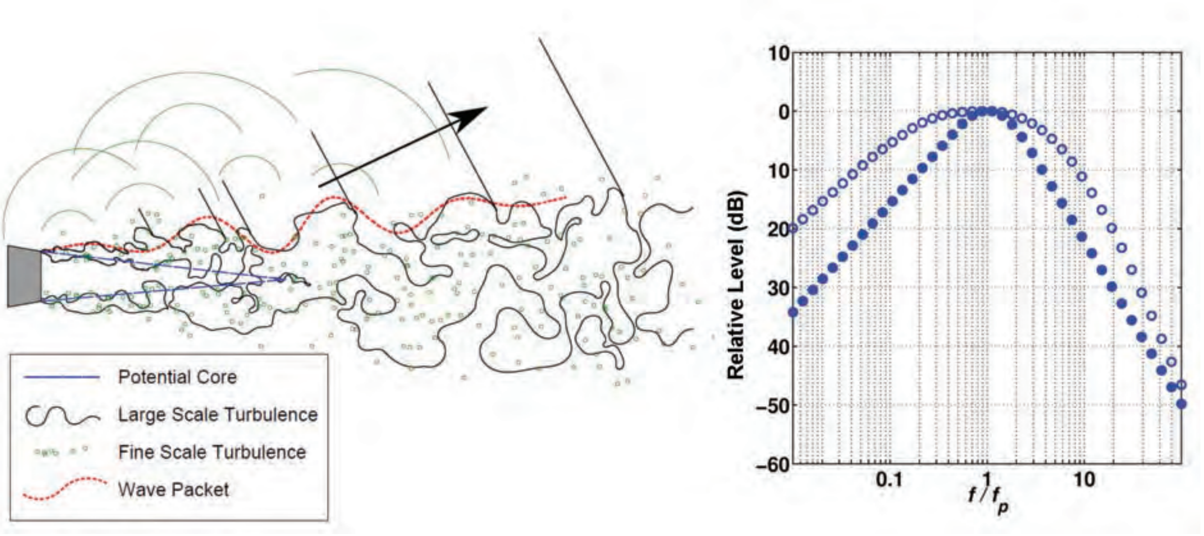

Fig. 4. Left: A schematic represenation of the two-source model of jet noise, comprised of large-scale structures (LSS) and fine-scale structures (FSS). Right: The empirical FSS (open circles) and LSS (filled circles) similarity spectra, relative to an arbitrary peak frequency f_p*, from Tam et al.*[18,19]

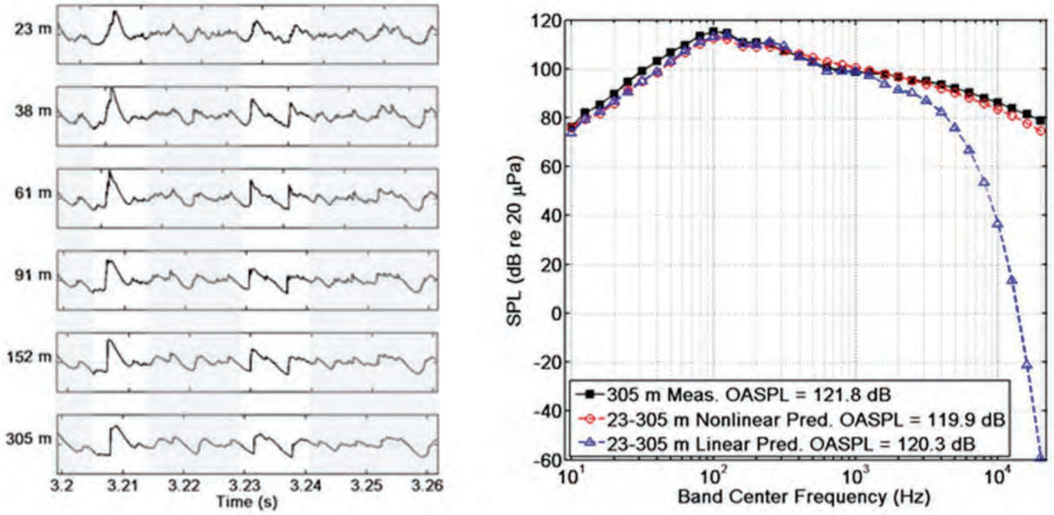

Fig. 5. Left: Waveforms from an F-22A Raptor ground run-up measured at the specified distances along the 55° radial. Right: Measured and predicted spectra at a distance of 305 m. See Ref. 29 for additional details.

ing its properties. Azimuthal modal decompositions[21,22] of numerical and experimental data have revealed relatively axisymmetric radiation at low frequencies, with the significance of higher-order helical modes increasing as a function of frequency and toward the sideline direction. These modes can be described in terms of wave packets, wave-like functions that mimic the growth and decay of turbulence instabilities with downstream distance (see Figure 4), and whose coherence extends over multiple characteristic wavelengths. Jordan and Colonius[23] have recently reviewed the use of wave packets to characterize LSS radiation from jets; wave packets' tie to jet noise reduction efforts are described near the conclusion of this article.

A characteristic of high-power military jet noise that is particularly important to human perception is the presence of acoustic shocks that produce a highly audible irregular popping sound in the waveform. Historically, Ffowcs Williams *et al.*[24] described jet "crackle" as being due to sharp shock-like compressive features in the waveform. Although they believed the shocks were radiated from the jet directly, shocks may also form and steepen as high-amplitude noise propagates nonlinearly. Nonlinear acoustic wave propagation[25,26] in air results when the source characteristics (amplitude, frequency, spatial extent) are such that an amplitude-dependent sound speed occurs, resulting in an alteration of waveform shape and possible shock formation. Recent studies[27-29] on the nonlinear propagation on noise from military jets have shown that the evolution of these shocks has a significant impact on the high-frequency portion of the spectrum. Nonlinear effects in jet noise have also been observed in supersonic laboratory[30,31] scale jets.

As an example[28] of acoustic shocks in jet noise propagation, Figure 5 displays measured waveforms from a static, afterburning F-22A Raptor at locations between 23 and 305 m along the maximum radiation angle 55° from the downstream jet axis. Highlighted is the steepening of acoustic shocks around 3.21 and 3.23 s over the propagation range. Also shown in Figure 5 is the measured one-third octave band spectrum at 305 m, along with numerical predictions based on propagating 23 m measured data to 305 m using both linear and nonlinear propagation models. Note the impact of the shocks on the measured and nonlinearly predicted high-frequency spectra, where the levels at 20 kHz are about 80 dB at a distance of 305 m (1000 ft) from the aircraft! Although the increase in high-frequency energy does not significantly impact level-based loudness metrics,[32,33] the presence of shocks affects perception[34] in the near and far fields, making their study important. These effects are the subject of ongoing work, some of which is summarized in this article.

The remainder of this article describes static engine run-up measurements of the F-22A Raptor and F-35AA-1 Lightning II Joint Strike Fighter and the results of recent data analyses. Because important insights about jet-noise source and radiation characteristics can be obtained from near-field measurements, these analyses help to demonstrate how the body of knowledge regarding supersonic jet aeroacoustics – much of which has been gained using laboratory-scale jets and numerical simulations – applies to actual military jet aircraft noise. Also included are reports on concurrent ONR and NASA-sponsored[10] efforts that target characterization or reduction of the noise generation.

Recent Military Jet Noise Investigations

Measurements

Near-field measurements[35] of military jet aircraft noise are challenging. High levels (peak levels exceeding 170 dB) and large signal bandwidth (from 10 Hz to more than 20 kHz) require low-sensitivity 6.35 or 3.18 mm Type 1 microphones with appropriate peak-handling capability for the microphone, preamplifier, cables, and the data acquisition system. Furthermore, sampling rates of at least ~100 kHz are required to capture shock-like features of the waveform, and excessive vibration of the data acquisition system must be avoided. The combination of instrumentation demands and harsh measurement environment makes extensive datasets of military jet noise relatively rare.

The F-35AA-1 static run-up measurements were conducted in 2008 at Edwards Air Force Base (AFB) by a Joint

Fig. 6. Top: 2008 F-35AA Joint Strike Fighter measurements at Edwards AFB. The microphones were located on thin rods attached to the top of the tripods. Bottom: Near-field measurements of the F-22A Raptor at Holloman AFB in 2009. The measurements consisted of a ground-based linear array of microphones and a rectangular 90-microphone near-field acoustical holography array.

Strike Fighter Program Office (JPO) team consisting of AFRL, Blue Ridge Research and Consulting, LLC (BRRC), Brigham Young University (BYU). The measurements were sponsored by the Australian Ministry of Defence, an international JPO partner. A photograph of the tied-down, pre-production aircraft is displayed in Figure 6. Measurements[29,36] were made using 6.35 mm Type 1 microphones at a height of 1.5 m. The 2009 near-field F-22A measurements[37] at Holloman AFB, made by BRRC and BYU, involved one engine on the static aircraft being cycled through multiple engine conditions from idle through afterburner while the other engine was held at idle. Microphones were located along a ground-based linear array that was parallel to the jet centerline and on a rectangular microphone grid (15.2 cm spacing) that was moved to different positions between run-ups (see Figure 6). For both experiments, data were collected at sampling rates from 96 – 204.8 kHz using a National Instruments® 24-bit recording system.[36]

Overall and Weighted Level and Waveform Characteristics

The overall pressure levels (OASPLs)[36,37] in the vicinity of the two aircraft at "military power" (maximum thrust, but without afterburners) are shown in Figure 7. Note first the intense levels, approximately 150 dB re 20 µPa at a distance of 5 m from the shear layer. Furthermore, the radiated levels from both aircraft show strong directionality of the acoustic radiation in the aft direction, which is presumably due to the LSS turbulence. Although level maps such as these give some indication of the aircraft maintainer environment, frequency-dependent weighting curves can be applied to the measured spectra to provide a more realistic idea of the actual noise exposure of personnel. For example, in Figure 8 an A-weighting filter has been applied[38] to measurements from a ground-based microphone array 11.7 m from the engine centerline of the F-22A, spanning from 3 m upstream to 28 m downstream of the nozzle. (This sideline distance is near where a maintainer might be.) The A-weighting filter approximates the frequency response of human hearing by removing energy from the lowest and highest frequencies, while slightly boosting levels in the 1-5 kHz frequency range. The A-weighted OASPL follows the unweighted OASPL until about 5 m downstream, indicating most of the spectral content is at relatively high frequencies. Thereafter, the A-weighted levels begin to deviate because of the shift of the radiated energy to lower spectral peak frequencies farther downstream until there is a nearly 10 dB difference between the two levels. The difference suggests that the choice of metric to quantify personnel exposure could result in different conclusions, pointing toward the need to correlate exposure limits and auditory risk with various measures.

In addition to the overall level maps and the time-aver-

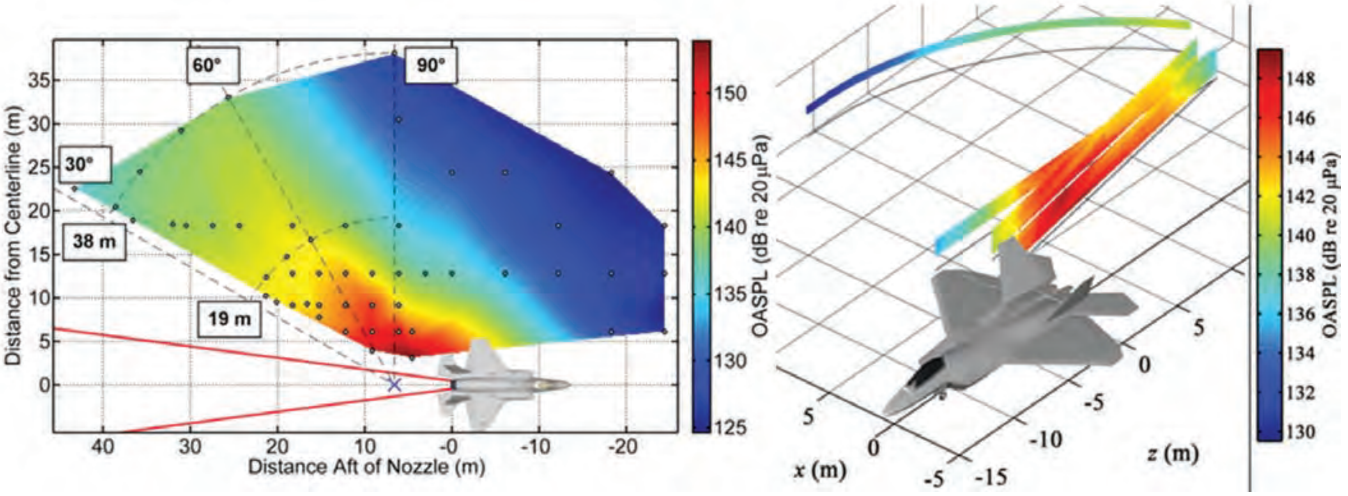

Fig. 7. Overall sound pressure levels (OASPL) near the F-35AA and F-22A aircraft (one engine) at military power. For the F-35AA measurements, the circles represent measurement locations at a height of 1.5 m, with a cubic interpolation in between. For the F-22A measurements, the data was collected along planes approximately 2 m tall and 23 m long and along an arc at 23 m.

aged spectra, the time waveforms reveal an important aspect of the perceptual environment in the jet vicinity. The waveforms of the high-amplitude signals typical of military jets are characterized by frequent pulses of large peak pressure values that can exceed the root-mean-square pressures by a factor of 10: a crest factor of approximately 20 dB![39,29] Figure 9 shows short waveform segments for the F-22A as a function of engine condition, from idle through afterburner, at the ground-based microphone array. Note the transition in amplitude scales (4000 Pa is a peak level of 166 dB) and in waveform shape as a function of engine condition, as both a positive waveform asymmetry (known as skewness) and shock-like features are present at military and afterburner powers. These waveform characteristics are significant because of the definition of a crackling waveform as one that contains shocks. Further exploration of these temporal features can lend insight into the phenomenon of crackle.[40]

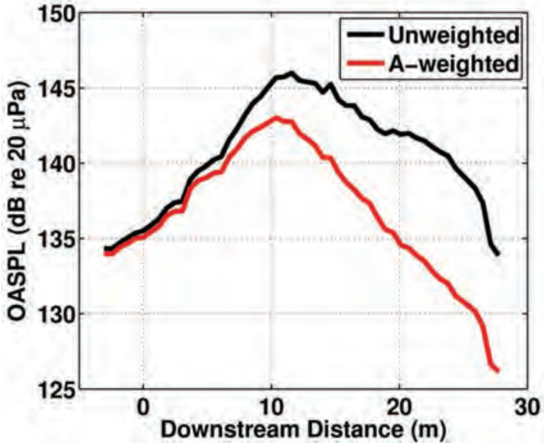

Fig. 8. Unweighted (black) and A-weighted OASPL (red) at a ground-based array 11.6 m to the side of an F-22A with one engine at military power.

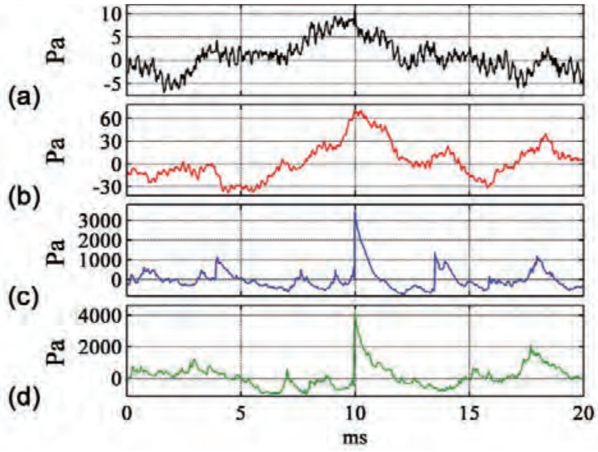

Fig. 9. Pressure waveform segments measured 15.2 m downstream of the nozzle at the ground-based array for the F-22A Raptor at (a) idle, and with one engine at (b) intermediate, (c) military, and (d) afterburner power.

Statistical Features and Crackle

The overall measurement aperture of the F-35AA measurement provides a convenient means for examining the noise spatial properties as related to the phenomenon of crackle. Two statistical measures are of potential significance: the "skewness" or asymmetry of the data probability distribution and the prevalence and strength of shock-like features. Positive skewness for the waveform indicates that there are more large positive values than large negative ones, similar to the waveform in Figure 9(a). A positive value for the skewness of the time derivative of the pressure waveform is correlated with the presence of sharp rise times (large positive slopes) in the waveform. Though crackle was tied originally[24] to the pressure waveform's skewness, a more complete understanding has pointed to quantifying it using the asymmetry of the time derivative of the waveform because of its direct correlation with shock content in the waveform.[34,40] However, because the pressure waveform's skewness is also a unique, ill-understood phenomenon in supersonic jet noise, both are considered.

Displayed in Figure 10 are the pressure waveform's skewness, Sk$\{p(t)\}$, and the pressure time derivative's skewness, Sk$\{\partial p/\partial t\}$ for the F-35AA at military power. At this high power set point, the radiated noise is positively skewed over a broad spatial range. Furthermore, the skewed waveforms

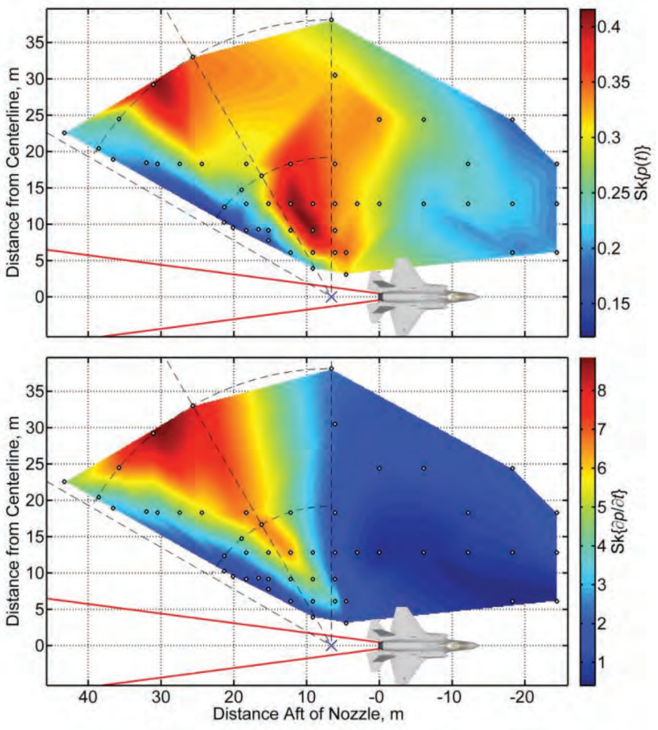

Fig. 10. Spatial map of pressure waveform's skewness, Sk{p(t)}, and the pressure time-derivative skewness, Sk{∂p/∂t} for the F-35AA at military power.

appear to originate in a region relatively close to the nozzle and exhibit little change with range, suggesting that the skewed waveforms are produced at the source. On the other hand, the skewness of the derivative grows dramatically with range, indicating that larger and larger positive slopes are present in the waveform, i.e. revealing that shocks are forming and strengthening through the course of propagation. As discussed by Gee *et al.*,[40] the propagation trends indicate that the perception of crackle is influenced by nonlinear propagation and depends on distance and angle.

Application of Large and Fine-Scale Similarity Spectra

Thus far, we have described characteristics of the overall levels and time waveforms from the F-22A and F-35AA. As has been done for various laboratory-scale jets, additional insight into the properties of military jet noise may be gained by comparing the measured spectra to the LSS and FSS similarity spectra in Figure 4. Displayed in Figure 11 are two sets of comparisons of measured one-third octave spectra from the F-22A and F-35AA at military power and the one-third octave equivalent similarity spectra. The F-22A spectra[41] are from the 11.7 m ground-based sideline array referenced in Figure 8, whereas the F-35AA spectra[42] are from the 38 m arc in Figure 7. Because the microphones for the F-35AA test were 1.5 m above the ground, there is a ground interference null centered at around 800 Hz for all angles. Despite the interference null in the F-35AA measurements, there is good agreement for the both the F-22A and F-35AA comparisons with the FSS spectrum at the sideline positions, where fine-scale radiation is expected, and with the LSS spectrum downstream, where LSS radiation is expected to dominate. However, around the maximum radiation direction, which is believed to be the result of LSS radiation, the measured spectra both have a significantly shallower high-frequency slope than predicted by the LSS. Because the waveform steepening from nonlinear propagation causes a transfer of energy upward in the spectrum, we believe this high-frequency slope (similar to the far field slope seen in Figure 5 and also observed by Schlinker *et al.*[43] in full-scale engine testing) to be the result of nonlinear propagation effects that were not present or not prominent in much of the laboratory-scale data used to create the similarity spectra shapes. These comparisons of military jet noise against the similarity spectra, the first of their kind, are discussed in detail in recent publications by Neilsen *et al.*,[41,42,44] generally lend support to the two-source model[19] of jet noise. Because the spectral comparisons do not provide details regarding the extent and loca-

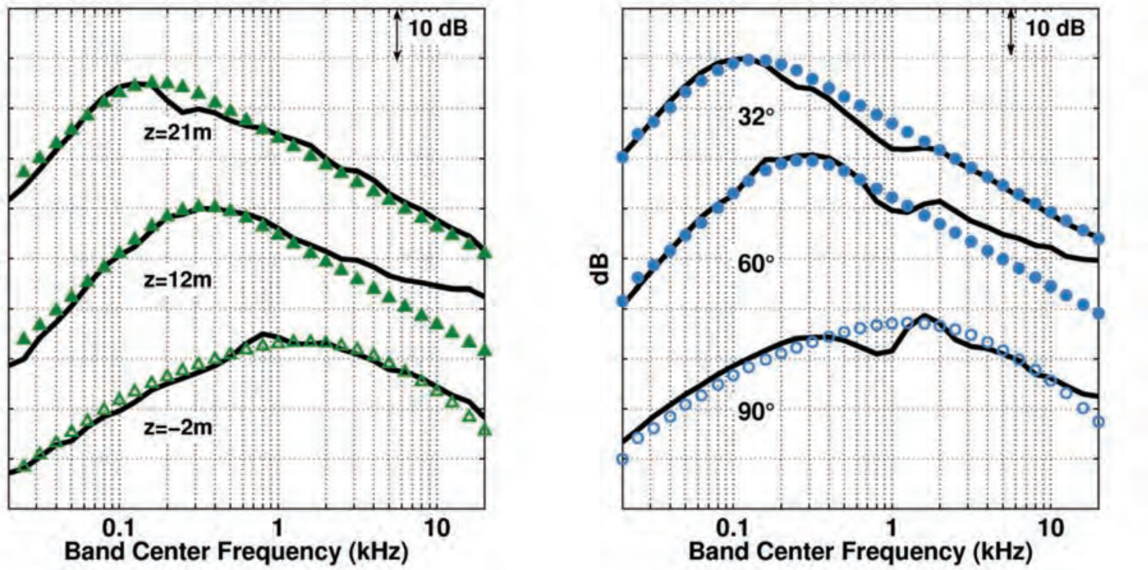

Fig. 11. Left: Comparison of one-third-octave band spectra measured on ground-based microphones 11.6 m to the sideline of an F-22A operating at military power, at the indicated downstream distances, with the one-third octave FSS (empty triangles) and LSS (filled triangles) similarity spectra. Spectra are offset by 25 dB. Right: Comparison of one-third-octave band spectra for the F-35AA at military power on microphones placed at a height of 1.5 m along a 38 m arc. at the angles indicated, with the one-third octave band FSS (empty circles) and LSS (filled circles) similarity spectra. Spectra are offset by 20 dB.

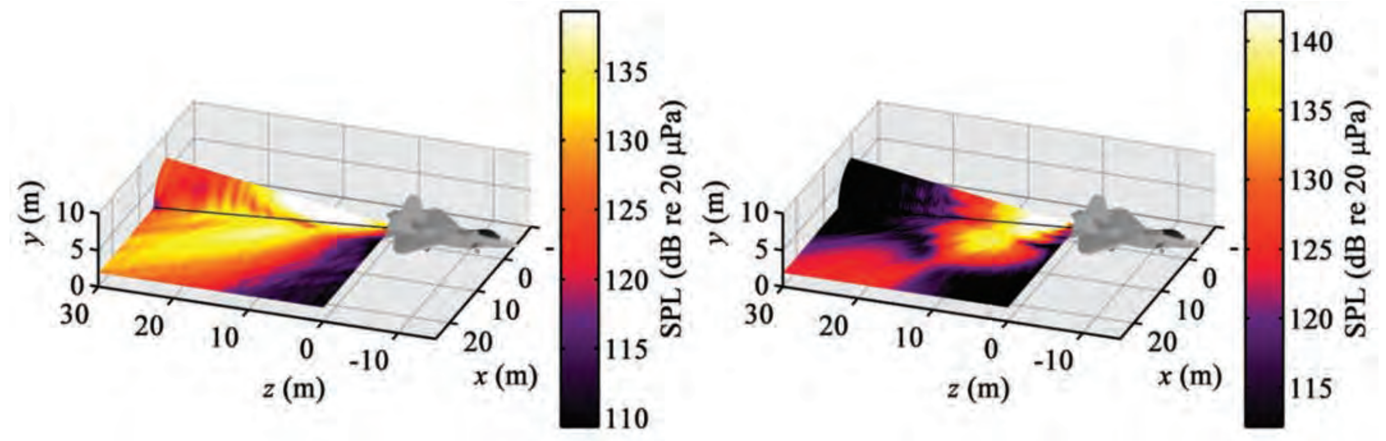

Fig. 12. NAH reconstruction in the vicinity of the F-22A for military power for (a) 125 Hz and (b) 500 Hz. Levels are shown on a half conical surface at the approximate location of the shear layer edge, and over a plane at y = 1.9 m, the height of the centerline of the jet.

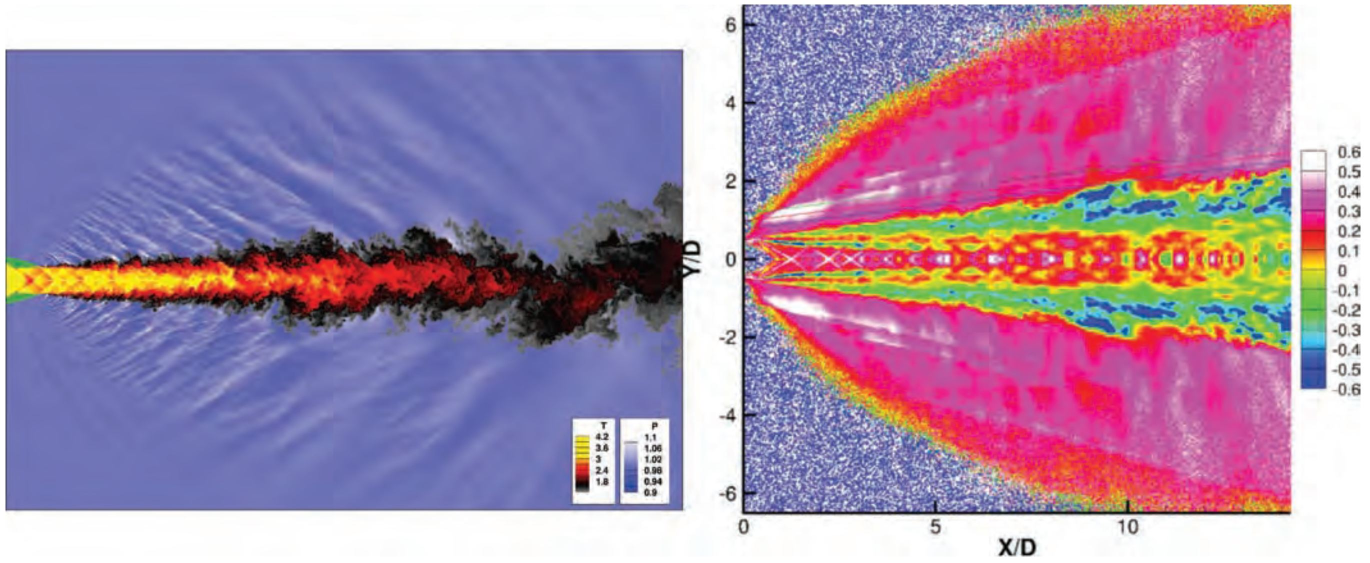

Fig. 13. LES simulations of a highly heated supersonic jet issued from a military-style nozzle using the Charles solver. Left: Contours of temperature (yellow scale) and pressure (blue scale). Right: Skewness of the unsteady pressure field inside and outside the shear layer.[61]

tion of these sources, the nature of the military jet noise sources is being investigated more deeply with near-field acoustical holography and equivalent source models.

Near-field Acoustical Holography

Radiation from large-scale turbulent structures dominates the total energy from all but the most modest flows[45] and thus, has become the focus of current measurement and noise reduction studies. Since large-scale turbulence is highly structured and characterized by high spatial coherence, its radiation can be represented by relatively few, properly selected, low-order basis functions. Consequently, many studies utilize equivalent source models (ESMs) of the large-scale structures in conjunction with application of inverse methods in the jet near field. ESMs make assumptions about the source properties, such as size and distribution, shape, structure, and spatial coherence. These range from developing wave packet models,[46-48] to space-time correlations around the jet, to simple source models[50,51,52] of the jet noise source region. These methods can be used to predict levels at maintainer locations and thus quantify noise exposure.

To study the noise generation without explicit source assumptions, near-field acoustical holography[53,54] has been used to characterize the noise environment around the F-22A.[55,56] The measurement "holograms" are the individual planes of data in the F-22A OASPL maps in Figure 7, constructed from the rectangular array in Figure 6 and the stationary, ground-based linear "reference" array. By matching wave functions to the measured holograph pressures, a model of the field is generated, and the predicted pressures at any other location can be calculated. Figure 12 shows NAH reconstruction of the field for two frequencies. Note that there is a 10-20° forward shift in the directionality of the main lobe from 250 Hz to 500 Hz and that the source region, estimated by the white portions of the conical surface, significantly contracts as it moves toward the nozzle.

Ties to Concurrent Work

Some of the military jet noise analyses described thus far were conducted as part of an on-going jet noise reduction program sponsored by ONR and NASA.[10] Given the wide scope of independent research by program participants, it is

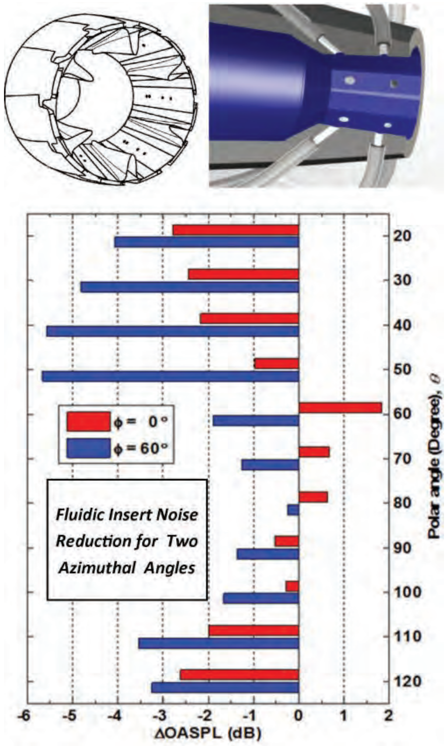

Fig. 14. Top: Engine nozzle corrugations developed by Seiner et al.[66] and PSU fluidic insert design, from Ref. 65. Bottom: Change in OASPL (negative number indicates reduction) due to three fluidic inserts for two different azimuthal angles.

worthwhile to summarize related concurrent research that may result in further understanding and possible reduction of military jet noise. Described are the development of advanced numerical simulation capabilities and application to the study of skewed waveform generation, wave packet modeling and control, and the development of a fluidic nozzle "corrugation."

Modeling Jet Skewness using Large-Eddy Simulations

Numerical modeling of military-style jet flows can be used to probe the flow features for the physics of jet noise production and examine the impact of nozzle design changes on the acoustic field. However, simulation of jet turbulence and noise generation is complicated, in part because of the vastly varying scales needing to be resolved to obtain the dynamic properties of the turbulence responsible for broadband noise generation and associated memory and computational requirements. In one approach, a compressible-flow large eddy simulation (LES) directly resolves the large-scale turbulence and then uses a sub-grid model to account for the fine-scale features within the jet plume. With the incorporation of unstructured mesh capabilities and advancements in massively parallel, high-performance computing (HPC), LES is emerging as an accurate yet cost-effective computational tool for first-principles prediction of turbulent jets from complex military-style nozzles and their acoustic fields.

Researchers at Cascade Technologies and Stanford University have sought to improve understanding and develop predictive capabilities for propulsive jet aeroacoustics, through high-fidelity physics-based simulations with an unstructured LES framework known as "Charles." In past studies, Charles has been used to investigate wide-ranging jet configurations, including various nozzle geometries[57,58] with chevrons[58,59] and faceted military-style nozzles.[60] In these studies, calculations are carried out routinely on tens of thousands of processors at various HPC facilities.

Charles was recently used to reach a new HPC milestone when it ran on over 1 million cores in January 2013 during "Early Science" testing of the new Sequoia supercomputer at Lawrence Livermore National Laboratory. The jet noise calculation was performed for a heated supersonic jet from a military-style nozzle and is currently being used[59] to understand how such jets emit the skewed pressure waveforms described previously in this article. The left plot in Figure 13 is an LES snapshot of the temperature field inside the jet plume and the instantaneous pressure field. At the right is an analysis of the spatial variation of the skewness of the unsteady pressure field inside and outside the shear layer, corroborating the F-35 AA results in Figure 10 that positive pressure skewness is produced at the source. The statistical properties of the pressure time derivative from the numerical data are also being analyzed. These results help illustrate the recent advances in the numerical modeling of jet aeroacoustics and should yield an improved understanding of the source mechanisms in supersonic jet noise.

Modeling and Control of Wave Packets

A primary concern in developing jet noise reduction technologies for tactical aircraft is the requirement that aircraft performance is not impacted. Research[46-40,61] conducted at California Institute of Technology and United Technologies Research Center aims at achieving significant jet noise reduction on tactical aircraft without impacting existing engine cycles. This requires active noise control techniques that target the peak low-frequency, aft-angle sound emissions associated with the most energetic large-scale structures. As described previously, the low-frequency large-scale mixing noise generation comprises radiating wave packets that are relatively coherent over multiple characteristic wavelengths. The present effort is aimed at improving understanding of how these wave packets responds to forcing (i.e. excitation by an external disturbances such as a secondary unsteady jet) over a range of frequencies, waveforms, and actuation amplitudes.

The approach builds on successfully characterizing near-field pressure wave packets that are quantitatively related to both large-scale turbulent structures and far-field sound. These instability-wave models directly predict the evolution and radiation of the large-scale flow structures based solely on inputs available from experimental data or computational fluid dynamics codes. The resulting reduced-order models have already been validated for the unforced supersonic unheated and heated turbulent jets that were tested. By injecting unsteady flow disturbances with a harmonic component through two actuator jets near the nozzle lip, and by adjusting their relative phases, the excitation of the wave packets can be manipulated, thereby impacting the sound radiation. To date, the peak-radiation-angle noise from a perfectly-expanded Mach 1.5 heated jet has been reduced by as much as 3 dB OASPL. Calculation of the changes in wave packet behavior as a function of the actuator jet forcing frequency and amplitude should guide strategies for producing greater coupling between different wave packets and larger sound reductions.

Jet Noise Reduction through Corrugations and Fluidic Inserts

Instead of modifying the flow at the nozzle exit as in fluid injection, other attempts to reduce the jet noise are employed prior to the nozzle exit. Tactical aircraft engines involve supersonic, heated jets exhausting from convergent-divergent nozzles with flaps and seals to permit changes in the nozzle area ratio. Seiner *et al.*[7] demonstrated that the replacement of the seals by corrugated inserts could reduce the noise of these engines on take-off when the engines are generally operating in an over-expanded mode (the nozzle exit pressure is less than the ambient, causing the familiar diamond shock cells visible in Figure 1 to form). The corrugations, seen in an engine nozzle schematic in Figure 14, are thought to reduce noise through two mechanisms. First, the corrugations change the effective nozzle area ratio, thereby weakening the shock cell strength and reducing broadband shock-associated noise, which primarily radiates in the forward direction. Second, jet mixing noise in the aft direction is reduced by the generation of streamwise vortices on the corrugated surfaces, which breaks up the LSS turbulence responsible for the noise radiation in the peak noise direction. The change in effective area ratio causes the jet to be closer to an ideally-expanded condition, which actually improves engine performance. Because of the noise reduction yielded by the previous corrugations, the U.S. Naval Air Systems Command has recently further tasked the National Center for Physical Acoustics to develop and test additional corrugation designs.[62]

An approach that combines ideas from fluid injections and corrugations is being developed by researchers at The Pennsylvania State University (PSU). Because the mechanical corrugations were designed for take-off conditions, noise increase and engine performance degradation at other operating points are possible. Consequently, PSU researchers[63] are building on this noise reduction concept by replacing the corrugations with fluidic inserts. These inserts, which have an advantage in that they would be able to be actively altered as needed, are created by injecting air into the divergent section of the nozzle. At present, two injectors are used for each fluidic insert, as shown in the schematic in Figure 14. The pressures and total mass flow rates required for the injection are relatively low and could be accommodated by available engine air. Figure 14 shows the effectiveness of three fluidic inserts on the radiated noise as a function of polar angle from the jet axis for two different azimuthal angles. The OASPL in the peak emission direction is reduced by 5-6 dB and the broadband shock-associated noise at larger angles to the jet downstream axis is almost eliminated. Furthermore, complementary computational fluid dynamics simulations have shown an increase in thrust for this jet operating and injector conditions. Although the use of only three inserts results in non-uniform azimuthal noise reductions, experiments[64] with six hard-wall corrugations show a much more uniform azimuthal behavior. Current experiments are focused on the effect of forward flight as well as the effects of increased scale to further test this promising noise reduction technology.

Conclusion

Our goal has been to introduce the reader to some of the recent research regarding jet noise generation and propagation from high-performance military aircraft and complementary research into noise source characterization and reduction using numerical simulations and laboratory-scale models. The intense sound levels radiated near the jet generally appear to be represented by large and fine-scale turbulence models of jet mixing noise, with the large-scale structures accounting for the dominant directional radiation. Furthermore, a significant step forward in array processing of jet noise has been achieved through an implementation of near-field acoustical holography that can be compared against wave packet and other equivalent source modeling. Finally, the full-scale military jet data show that nonlinear propagation is present in the near and far fields as source-generated skewed waveforms progressively steepen and acoustic shocks form, principally in the maximum radiation direction dominated by the large-scale radiation. The ongoing efforts to reduce large-scale turbulence noise are promising in that they have shown reductions in level in the peak radiation direction.

The improved physical understanding of heated supersonic jets through detailed experiments, numerical simulations, and development of noise reduction methodologies provides additional paths forward toward mitigation of the noise impact of tactical aircraft for both military personnel and nearby communities. Although significant work remains to "solve" the jet noise problem, it is likely that some of the findings thus far could be used to guide study of other heated jets, such as solid rocket motors or volcanoes. Ultimately, in light of the collective advances by aeroacousticians concerning high-speed jet noise generation and propagation, we conclude with a final thought – that perhaps Professor Lamb would find cause for additional optimism when considering present-day understanding of the sound generated by a supersonic, turbulent jet!

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