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Summary of "Supersonic Jet and Rocket Noise"

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This paper summarizes a two-part special session, "Supersonic Jet and Rocket Noise," which was held
during the 174th Meeting of the Acoustical Society of America in New Orleans, Louisiana. The sessions
were cosponsored by the Noise and Physical Acoustics Technical Committees and consisted of talks by
government, academic, and industry researchers from institutions in the United States, Japan, France, and
India. The sessions described analytical, computational, and experimental approaches to both fundamental
and applied problems on model and full-scale jets and rocket exhaust plumes.

1. SESSION OVERVIEW

This paper summarizes a two-part session, "Supersonic Jet and Rocket Noise," which consisted of 24 talks that addressed a diverse set of topics related to launch vehicle and jet aircraft noise problems. Liftoff noise can create a damaging vibrational response in the vehicle and its payloads, whereas radiated jet noise creates a high noise environment for ground personnel and communities. With an improved understanding of the turbulent noise source, sound suppression techniques can be utilized to attenuate the noise or operations can be altered to minimize impact. The subject matter for these two sessions is grouped into four broad categories. First, launch pad environments, including jet impingement noise, are described. Next are described jet and rocket prediction efforts involving analytical, experimental, and numerical methods. Third, full-scale jet noise measurements and analyses, mostly involving the F-35, are described. Finally, a number of valuable studies that related to personnel and community impacts of rocket and jet noise are summarized. Together, the papers presented during a full-day session represent significant advances in understanding of supersonic jets across a range of Mach numbers, while pointing to areas of further research needed.

One of the purposes of these organized sessions is to help bring together the often separated "rocket" and "jet" noise communities. Despite different motivations, both research communities treat the same problem at their core: the generation, propagation, and effects of noise from high-speed, highly heated, turbulent jets under various conditions. The sponsorship of jet/rocket noise sessions by ASA began in 2010, with the spring meeting in Baltimore, MD. Since then, these sessions have continued annually, at the fall meetings. The most recent 2016 jet aeroacoustics session is summarized in Ref. [1]. An additional launch-vehicle session was held at the 2015 International Symposium on Space Technology and Science (ISTS) meeting in Kobe, Japan, which has helped significantly to broaden the international community.

A. Launch-pad Noise

There were seven talks on launch-pad noise. Caroline Lubert of James Madison University opened the session with a review of the development of the discipline of rocket launch acoustics over the past sixty years, including an overview of existing experimental and theoretical approaches, and a discussion of some current work related to flame trench noise modelling. Subsequent speakers then described a variety of such approaches.

Four talks focused on scale-model tests. Karthikeyan Natarajan of the Council of Science and Industrial Research (CSIR)-National Aerospace Laboratories discussed the effects of cutouts in a model-scale launch pad. Both near and far-field acoustic measurements were carried out for single and twin-jets at varying liftoff distances. Based on the results of Schlieren flow visualization work, the paper attempted to relate changes that occurred in the acoustic field due to the pad perforations, to changes in the flow field. Wataru Satare of Japan Aerospace Exploration Agency (JAXA) presented preliminary results from 1/42 subscale model acoustic tests on Japan's next generation launch vehicle – the H3. Both near and far-field experiments were carried out using different flame duct configurations (covered and uncovered) and two water injections systems – one above the deck, and one within the duct. In these scale tests, the real-life multiple liquid-propellant rocket engines were replaced by a simpler single liquid-propellant rocket engine with equivalent nozzle exit area in sub-scale. Hadrien Lambaré from Centre National D'Etudes Spatiales (CNES) discussed research using the CNES MARTEL test bench. Although this facility has been used for more than 20 years, it has typically only been used to investigate the noise from single supersonic jets. However, there is more than one rocket engine in real-life launch vehicles. Thus, recent work has focused on the interaction between two supersonic hot jets. In the preliminary research presented here, acoustic and PIV measurements were made on the free-jet configuration. Future work will study the aeroacoustic interaction of the jets inside the flame duct, and their launch pad impingement. The work of Masahito Akamine and Koji Okamoto of the University of Tokyo also focused on the acoustic phenomena related to the impingement of a supersonic jet onto an inclined flat plate, which is important to understanding of plume impingement on flame deflectors (or for the military jet problem, jet blast deflectors). Their results indicate that the plate angle has a significant effect on the characteristics of the acoustic waves generated from shocks located around the impingement region.

Two speakers presented the results of computational aeroacoustics (CAA) work. Julien Troyes of Office National d'Etudes et de Recherches Aérospatiales (ONERA) discussed recent CAA modeling of the launch noise from a scale-model flame trench, aimed at comparing the effect of trench length. Both the CFD and acoustic computations used in-house ONERA codes (CEDRE and KIM, respectively). Predictions were compared with experimental results from 48 microphones, and were found to be reasonably accurate. Significant differences were observed between results for the long and short flame trench. Seiji Tsutsumi of JAXA presented the results of a validation of both time and frequency-domain aero-vibro acoustic simulation technique. Large-eddy simulation (LES) with CAA was used to predict the generation of the acoustic waves and their propagation to the vehicle fairing. A coupled vibro-acoustic analysis (based on finite-element modeling) was then used to compute the transmitted internal acoustics within the fairing. Experimental data on a scale model appears to validate this technique, particularly in terms of the gross features. However, further work is necessary to obtain quantitative agreement.

Overall, all speakers addressed the significance of the launch pad as a noise source to the launch vehicle, the importance of estimating its contribution to the vibro-acoustic profile experienced by the launch vehicle, payload, and environs, and the inherent difficulties therein.

B. Jet and Rocket Noise Prediction

A number of talks described the prediction of jet noise. Three of these talks used data to derive characteristics of the source and/or radiation. First, Chris Tam of Florida State University used measurements made in the vicinity of a small rocket nozzle at low and high-burn conditions to show agreement with analytical spectral shapes corresponding to fine and large-scale turbulence structures. Using the low-burn case to develop a model for the regions of fine and large-scale turbulence noise, he then predicted the regions where these different spectra dominated for the high-burn case. He further illustrated agreement of the similarity spectra for a large-diameter solid rocket motor at two different angles. Second, Jacob Ward, a student at Brigham Young University (BYU), used band-limited cross correlation analysis between the near and far fields of a Mach 1.8 laboratory-scale jet to determine the location, extent, and directivity of the correlated source region, as a function of frequency. He further showed that as the near-field microphone was moved closer to the shear layer, the correlation with the far field decreased. This demonstrated the lack of correlation between the hydrodynamic and radiated fields. Third, Kent Gee's tutorial talk on military jet and rocket characteristics built upon prior work by Greska to demonstrate how various jets and rockets' overall levels in the maximum radiation direction could be scaled in terms of the Oertel convective Mach number.

Other talks focused on numerical prediction of jet noise. Chris Ruscher of Spectral Energies described large-eddy simulations off axisymmetric and offset, three-stream nozzles applicable to commercial aircraft. Advanced analyses methods, e.g., proper orthogonal decomposition and wavelet decomposition, were used to show how the thickening of the shear layer in vicinity of the thicker portion of the nozzle leads to reduced noise in that direction. Conversely, thinning of the shear layer on the opposite side of the nozzle resulted in a noise increase. This slight offset in the 3rd stream causes subtle difference that results in appreciable, directional noise reduction potential. Vasileios Sassanis of Mississippi State gave a pair of talks that described new computational aeroacoustics methods for jet noise predictions. The first promising approach sought to improve upon the bandwidth of LES without requiring finer grid discretization. High-frequency, fine-scale turbulence, is represented by a stochastic model derived from an axisymmetric Reynolds-averaged Navier-Stokes (RANS) simulation; these small scales are convected downstream by the larger scales. Noise predictions are obtained using a linearized Euler equation or Ffowcs Williams-Hawkings approach. The second approach couples LES with the (nonlinear) Euler equations, rather than using a linear propagator. The LES output is interpolated and penalized in a buffer region to form the sources for the Euler domain solution. This approach allows for the efficient computation of noise propagation in the acoustic domain while including nonlinear propagation effects and interactions with physical obstructions. Validation studies using both these methods are promising, and work is on-going.

C. Full-Scale Jet Noise Measurements and Analysis

The sessions included several papers involving full-scale jet noise measurements and analysis. Kent Gee's overview talk on full-scale tactical jet and rocket phenomena contained various observations from various static measurements that highlighted key differences between these two classes of heated supersonic jets. These included various different Mach numbers (rockets greater), Mach wave angle (rockets farther forward), peak Strouhal number at the Mach wave angle (rockets lower), peak source location and extent (rockets farther downstream and broader), and spectral shape away from the maximum radiation direction. In this last case, a solid rocket booster that did not fit the fine-scale similarity spectrum shape at the sideline in the far field was given.

Five papers focused specifically on analysis of F-35 noise measurements. The first four discussed various analyses of data at a near-field, ground array that spanned the source region. Hales Swift, a BYU postdoctoral scholar, described a spatio-temporal-spectral analysis that showed different regions of correlation and coherence. These helped to identify correlation properties of broadband shock-associated noise (BBSAN) and multi-lobe phenomena. The study of BBSAN properties of the F-35 was also the focus of talks by Tracianne Neilsen and Aaron Vaughn of BYU. Neilsen discussed properties of the BBSAN peak frequency, width, and level, as a function of engine condition and angle, and compared with laboratory-scale findings and other full-scale observations. While the F-35 BBSAN matched some previous trends, it did not for others, which pointed to the need for an improved understanding of BBSAN in full-scale, heated, supersonic jets. Vaughn used an analytical model for BBSAN spectral shape to perform a three-way decomposition of the F-35 noise into large-scale, fine-scale, and BBSAN spectra. He further identified the spatial regions where the various types of spectra contributed to the overall spectrum at a given location, which helps in the development of improved equivalent source modeling. Kevin Leete of BYU examined the linear ground-based array used in the previous papers, but for the purposes of performing near-field acoustical holography. He showed the results of a numerical experiment to determine the aperture over which the source and field reconstructions could be considered accurate and further examined the ability of the ground array to reconstruct the radiated field off the ground.

The final F-35 measurement analysis talk was given by BYU doctoral candidate Brent Reichman, who described time-domain characteristics of the acoustic shock waves generated through nonlinear propagation. He showed that numerical modeling of the propagation captured many properties of the measured acoustic shocks, but that further research into atmospheric turbulence and measurement artifacts was needed.

D. Personnel Impact and Community Response

There were six papers in the sessions that dealt with specific measurement and modeling efforts directed at the assessment of noise impacts on personnel and communities within and around rocket launch pads, military airbases, civilian airports, and weapons firing ranges.

Two of these papers, both from the U. S. Air Force Research Laboratory, were focused on protection of personnel from F-35 noise. Alan Wall presented spatial maps of noise levels measured on the flight deck of an LHA amphibious assault ship during F-35B short-takeoff and vertical-landing operations, where the highest noise levels exceeded 140 dB for short durations. These data will be used as inputs to develop and/or spot check F-35B on-deck noise models for a personnel noise exposure calculation tool. Wall, on behalf of first-author Rich McKinley, also discussed noise measurements of the F-35A inside a hardened aircraft shelter in the Netherlands targeted toward the protection of maintainers working inside the shelter and the prevention of acoustic fatigue damage to the aircraft airframe. Spatially constant level distributions inside the shelter and abnormally flat spectra for jet noise suggested that the acoustic space might be modeled as a diffuse field, with a modified equivalent source "portion" of the jet plume inside the shelter while the remainder of the source radiated sound energy to the exterior environment.

Four papers dealt with community noise. Michael James of Blue Ridge Research and Consulting demonstrated RUMBLE, a high-fidelity launch vehicle noise simulation system to predict noise impacts on the environment and local communities. The physical source and tracking modeling, initial validations using multiple full-scale launch measurements, and an event visualization tool were shown. The specific issue of psychoacoustic annoyance from high-performance jet aircraft was addressed by Hales Swift of

BYU, who calculated various sound quality metrics for F-35 recordings. From these data, perception effects were quantified to inform future efforts to reduce not only noise levels, but the specific indicators of annoyance that level-based analyses alone may miss. Ed Nykaza of the U.S. Army Engineer Research and Development Center demonstrated the accuracy of spatial interpolation algorithms for noise environment mapping of military blast noise over large areas using sparse sampling with cost-effective noise monitors. It was found that accuracy of the interpolation was most strongly influenced by the area of the convex hull in the geometrical arrangement of the noise monitors. Finally, Chris Jasinski from Notre Dame presented advanced methods for the assessment of noise-reduction acoustic liners for commercial turbofan engines, driven by the industrial need to drive down aircraft noise to meet government regulations. A force-balance wind tunnel test facility was demonstrated, and it was shown that acoustic excitation of perforated liners in flow can result in significantly increased drag.

2. SESSION ABSTRACTS

Included are session abstracts from both the morning and afternoon sessions. Abstracts have been edited slightly in some cases for clarity or grammar. Note that paper 1aNS9 was withdrawn, but its abstract is included for completeness.

1aNS1. Sixty years of launch vehicle acoustics.[2] Caroline P. Lubert (Mathematics & Statistics, James Madison Univ., 301 Dixie Ave., Harrisonburg, VA 22801, lubertcp@jmu.edu) On 4 October 1957 at 7:28 pm, the first artificial low Earth orbit satellite, Sputnik, was launched by the Soviet Union. Its launch ushered in a host of new scientific and technological developments, and public reaction in the United States led to the so-called "Sputnik Crisis," and the subsequent creation of NASA. A race ensued between the United States and the Soviet Union to launch satellites using carrier rockets. At this time, very little was known about the acoustics of rocket launches, and even less about acoustic suppression. Thus, in the vicinity of the rocket, acoustic levels could reach up to 200 dB during lift-off. Such extremely high fluctuating acoustic loads were a principal source of structural vibration, and this vibro-acoustic interaction critically affected correct operation of the rocket launch vehicle and its environs, including the vehicle components and supporting structures. It soon became clear that substantial savings in unexpected repairs, operating costs, and system failures could be realized by even relatively small reductions in the rocket launch noise level, and a new discipline was born. This paper presents a review of the first 60 years of launch vehicle acoustics.

1aNS2. On the acoustic near field of a solid propellant rocket.[3] Christopher Tam (Mathematics, Florida State Univ., 1017 Academic Way, Tallahassee, FL 323064510, tam@math.fsu.edu) Recently, Horne et al. presented NASA Ames measurements of the acoustic near field of a solid propellant rocket. The experiment consists of two phases: the high-burn and the low-burn phase. The main objective of this investigation is to use this set of data for the determination of the dominant components of near field rocket noise. The data consist of spectral measurements of an array of 14 near field microphones and a single far field microphone. By itself, the data are insufficient to accomplish the stated objective. We supplement the data with information provided by the two-noise source model of hot supersonic laboratory jets. The two-noise source model is supported by the existence of two similarity spectra. By applying the similarity spectra to the data of Horne et al. at low-burn, we are able to show that the dominant components of near field solid propellant rocket noise are the same as those found in the far field of supersonic jets. Further, the data allow the development of a model for the spatial distribution of the dominant noise components. On applying the model to the high-burn phase of the experiment, excellent agreements are found.

1aNS3. Investigation of single and twin jet interactions with plates with cut-outs.[4] Karthikeyan Natarajan (Experimental AeroDynam. Div., CSIR-National Aerosp. Labs., EAD, PB 1779, Old Airport Rd., Bangalore 560017, India, nkarthikeyan@nal.res.in) and Lakshmi Venkatakrishnan (Experimental AeroDynam. Div., CSIR-National Aerosp. Labs., Bangalore, Karnataka, India) The design and testing of the launch vehicle structure and its subsystems to withstand the lift-off acoustic loads is quite a daunting task in itself. Any effort to minimize these loads can prove to be highly beneficial as it directly influences

the design, weight, and qualification of the launch vehicle components and hence the overall vehicle operating cost and time. The components of launch pad such as the launch platform and jet blast deflector are known to be the principal noise sources of the intense acoustic loads generated during liftoff. They contribute to the overall noise levels experienced by the launch vehicle by either reflecting the noise generated by the jet exhaust or by creating additional sources of noise. Earlier studies showed that the presence of cut-outs in the launch platform significantly affects the overall acoustic loads experienced by the launch vehicle. The present paper attempts to characterize the influence of cut-outs in the launch platform on the noise levels experienced by the launch vehicle, by investigating single and twin jets impinging on flat plates with and without cut-outs at varying lift-off distances. The results from acoustic measurements carried out in the near and far-field of scaled down single and twin jet launch vehicle models are discussed. The paper also attempts to relate changes in acoustic field, brought about by the different platform configurations, to the changes in flow field through flow visualization using the Schlieren technique.

1aNS4. Results of subscale model acoustic tests for H3 launch vehicle.[5] Wataru Sarae, Keita Terashima (JAXA, 2-1-1 Sengen, Ibaraki, Tsukuba 305-8505, Japan, sarae.wataru@jaxa.jp), Seiji Tsutsumi (JAXA, Sagamihara, Kanagawa, Japan), Tetsuo Hiraiwa (JAXA, Kakuda, Japan), and Hiroaki Kobayashi (JAXA, Kanagawa, Japan) A subscale acoustic test, the H3-scaled Acoustic Reduction Experiments (HARE), was conducted to predict liftoff acoustic environments of the H3 launch vehicle currently being developed in Japan. The HARE is based on 2.5% scale H3 vehicle models, which is composed with a GOX/GH2 engine and solid rocket motors, Movable Launcher (ML) models with upper deck water injection system and Launch Pad (LP) models with deflector and lower deck water injection systems. Approximately 20 instruments measured far/near field acoustic and pressure data. Preliminary results are presented in this presentation.

1aNS5. Experimental study of the aeroacoustic interaction between two supersonic hot jets.[6] Hadrien Lambaré (CNES, CNES Direction des lanceurs 52 rue Jacques Hillairet, Paris 75612, France, hadrien.lambare@cnes.fr) The first stage of space launchers often use multiple engines. The supersonic jet noise at lift-off is a major source of vibrations for the launcher's equipments and payloads. In parallel with the development of the Ariane 6 launcher and its launch pad ELA4, the CNES MARTEL test bench have been improved in order to study experimentally the aeroacoustic interaction between two hot supersonic jets (Mach 3, 2000K). In collaboration with the PPRIME laboratory of the University of Poitiers, acoustic and PIV measurements have been made in the free jets configurations. Further test campaigns will study the interaction of jets inside the flame duct, and their impingement on the launch table.

1aNS6. Experimental study of plate-angle effects on acoustic phenomena from a supersonic jet impinging on an inclined flat plate.[7] Masahito Akamine, Koji Okamoto (Dept. of Adv. Energy, Graduate School of Frontier Sci., Univ. of Tokyo, 5-1-5, Kashiwanoha, Kashiwa, Chiba 277-8561, Japan, akamine@thermo.t.u-tokyo.ac.jp), Susumu Teramoto (Dept. of Aeronautics and Astronautics, Graduate School of Eng., Univ. of Tokyo, Bunkyo, Tokyo, Japan), and Seiji Tsutsumi (Aerosp. Res. and Development Directorate, Res. Unit III, Japan Aerosp. Exploration Agency, Sagamihara, Kanagawa, Japan) Acoustic waves from a rocket exhaust jet cause the intense acoustic loading. Because the exhaust jet impinges on a flame deflector at liftoff of a launch vehicle, an adequate understanding of the acoustic phenomena from a supersonic impinging jet is required for prediction and reduction of the level of the acoustic loading. The previous numerical studies on a supersonic jet impinging on an inclined flat plate[8,9] suggested that the plate angle has a large impact on the characteristics of the acoustic waves from the impingement region. In the present study, experiments were carried out to discuss the effect of the plate angle on this acoustic phenomenon. By applying the acoustic-triggered conditional sampling to the Schlieren visualization movies, which was proposed by the authors[10], the phenomena around the impingement region were observed in detail. The results revealed that the plate-angle variation leads to the

change in the characteristics of the acoustic waves from the impingement region, such as the source locations.

1aNS7. Modeling community noise impacts from launch vehicle propulsion noise.[11] Michael M. James and Alexandria R. Salton (Blue Ridge Res. and Consulting, 29 N Market St., Ste. 700, Asheville, NC 28801, michael.james@blueridgeresearch.com) Commercial space is an emerging and evolving market as evidenced by the vast array of launch vehicles under development as well as the growing number of active and proposed launch sites. Federal Aviation Administration regulations require all new spaceports and launch vehicles to acquire a license. Part of the application process requires an environmental review to address the potential noise impacts to the environment and local communities. Accurate predictions of noise exposure from launch vehicles require models that have been validated over a range of vehicle types, operations, and atmospheric conditions. A high-fidelity launch vehicle simulation model, RUMBLE, has been developed to predict community noise exposure from spaceport launch, reentry, and static rocket operations. RUMBLE implements industry standard modeling practices to efficiently compute sound pressure level time histories, maximum levels, and sound exposure levels using the vehicle's engine parameters and geo-referenced source/receiver definitions. An overview of RUMBLE's underlying physics and the results of initial validation efforts (using multiple full-scale launch measurements) will be presented.

1aNS8. Large eddy simulations of launcher lift-off noise and comparisons to experiments on model flame trenches.[12] Julien Troyes (ONERA, Chatillon Cedex, France), Francois Vuillot, Adrien Langenais (ONERA, 29 Ave. de la Div. Leclerc, CHATILLON F92322, France, francois.vuillot@onera.fr), Hadrien Lambare, and Pascal Noir (CNES, PARIS, France) During the lift-off phase of a space launcher, rocket motors generate harsh acoustic environment that is a concern for the payload and surrounding structures. Hot supersonic jets contribute to the emitted noise from both their own noise production mechanisms and their interactions with launch pad components, such as the launch table and flame trenches. The present work describes the results of computations performed by ONERA to predict the lift-off noise from reduced scale models of a flame trench. The results include both unsteady flow solution inside the flame trench and the computed noise on near and far field microphone arrays. Numerical computations involve two in-house codes: the flow solver CEDRE, used in LES mode to accurately predict the noise sources, and the acoustic code KIM to reconstruct the far field noise, thanks to an integral Ffowcs Williams and Hawkings porous surface approach. The computational model exactly reproduces the flame trench configurations used in a test campaign carried out by CNES at the MARTEL facility. Results are discussed and compared with experimental acoustic measurements on 48 microphones. Overall, the numerical results reproduce the acoustic measurements within 3 dB. To further improve these results, work is ongoing on acoustic nonlinear effects.

(Withdrawn) 1aNS9. Refinements in RANS-based noise prediction methodology for complex high-speed jets.[13] Dimitri Papamoschou and Andres Adam (Mech. and Aerosp. Eng., Univ. of California, Irvine, 4200 Eng. Gateway, Irvine, CA 92697-3975, dpapamos@uci.edu) Recent efforts on RANS-based modeling of the noise reduction from multi-stream, high-speed jets have underscored the importance of flow properties on the outer surface of peak Reynolds stress (OSPS). In a time-averaged sense, the OSPS is expected to represent the locus of the most energetic eddies in contact with the ambient fluid. The acoustic Mach number on the OSPS is a proxy for the convective Mach number of those eddies, thus has strong impact on the modeling of the noise source and its suppression when the jet plume is distorted into an asymmetric shape. Therefore, accurate detection of the OSPS is a critical ingredient in the modeling. This is complicated by the fact that, in asymmetric jets, the Reynolds stress distribution can be highly irregular and detection of its maximum along a radial line can become problematic. The talk will present advanced algorithms for the detection of the OSPS and resulting improvements in the prediction of noise reduction.

1aNS10. Validation of aero-vibro acoustic simulation technique using experimental data of simplified fairing model.[14] Seiji Tsutsumi, Shinichi Maruyama (JAXA, 3-1-1 Yoshinodai, Chuuou,

Sagamihara, Kanagawa 252-5210, Japan, tsutsumi.seiji@jaxa.jp), Wataru Sarae, Keita Terashima (JAXA, Ibaraki, Tsukuba, Japan), Tetsuo Hiraiwa (JAXA, Kakuda, Japan), and Tatsuya Ishii (JAXA, Tokyo, Japan) To predict harmful acoustic loading observed at lift-off of the launch vehicle, aero-vibro acoustic simulation technique is developed. High-fidelity large-eddy simulation with computational aeroacoustics based on the full Euler equations in time domain are employed to predict generation of the acoustic waves and their propagation to the fairing. Coupled vibro-acoustic analysis based on finite element method are applied to compute the transmitted acoustic wave into the fairing both in the time and frequency domains. Acoustic measurement of a simplified fairing model with a subscale liquid rocket engine is conducted, and validation study of the present technique is performed. Reasonable agreement is obtained for peaks of the acoustic spectrum taken inside the fairing model. Such peaks are found to be related to the internal acoustic modes and ring modes of the faring structure. However, further study is required to obtain quantitative agreement.

1aNS11. Jet noise prediction via coupling large eddy simulation and stochastic modeling.[15] Joshua D. Blake (MS State Univ., MS State University HPC Bldg., Office 365, MS State, MS 39762, jdb621@msstate. edu), Vasileios Sassanis (MS State Univ., Starkville, MS), David Thompson (MS State Univ., MS State, MS), Adrian Sescu (MS State Univ., Starkville, MS), and Yuji Hattori (Tohoku Univ., Sendai, Japan) A novel method for efficient and accurate jet noise prediction is developed and tested in the framework of coupled LES and stochastic noise modeling. In the proposed method, the low frequency range of the acoustic spectrum, which corresponds to large turbulent structures, is resolved with an implicit LES model by employing higher-order spatial and temporal discretizations. The high frequency range, which corresponds to the fine-scale turbulence, is modeled via a stochastic broadband noise generation model. The inputs to the stochastic model are represented by statistics from an axisymmetric RANS jet simulation. The smaller synthetic scales are convected by larger scales, accounting for the effects of sweeping from the larger LES-resolved turbulent scales. The farfield acoustic data is obtained using either the Linearized Euler Equations, or an acoustic analogy based on the Ffowcs-Williams Hawkings method. The method is evaluated on cold and heated jets at different Reynolds numbers.

1aNS12. Validation of a hybrid nonlinear approach for jet noise prediction and characterization.[16] Vasileios Sassanis, Joshua Blake, Adrian Sescu (Dept. of Aerosp. Eng., MS State Univ., 2041 Blackjack RD, 47 Scenic Pass, Starkville, MS 39759, vs501@msstate.edu), Eric M. Collins (Ctr. for Adv. Vehicular Systems, Starkville, MS), Robert E. Harris (CFDRC, Huntsville, AL), and Edward A. Luke (Comput. Sci. and Eng., MS State Univ., Starkville, MS) In this study, a hybrid approach for non-linear jet noise predictions in complex environments is presented and validated. The method differs from traditional approaches in that interactions of the jet with the surrounding structures as well as non-linear disturbances propagating over large distances are taken into consideration in order to quantify their effects on sound generation and propagation. The noise sources founded in the jet plume and the near-field are first computed using the full Navier-Stokes equations. The variables of interest are then interpolated into a second domain. After penalized, they are used as source terms in the non-linear Euler equations to calculate the sound propagation. The interpolation and penalization steps are performed using a buffer region designed by the principles of sponge layers. The effective one-way communication between the two domains and the capabilities of the buffer region to transfer the data from the NS to the Euler domain without any loss of detail is demonstrated. Results from two- and three-dimensional jets both in free space and interacting with solid obstacles are presented. Comparisons with DNC and experimental data in terms of sound pressure level spectra are in good agreement with the ones calculated by our method.

1pNS1. Observations regarding the noise radiated from full-scale heated, supersonic jets.[17] Kent L. Gee (Dept. of Phys. and Astronomy, Brigham Young Univ., N243 ESC, Provo, UT 84602, kentgee@byu.edu) In this presentation, the characteristics of supersonic jet noise are reviewed. Observations from more than a decade's worth of measurements of high-performance jet engines and large solid rocket motors are compared against each other and laboratory-scale findings. These include apparent

source location and extent, directivity, spectral shape, relative importance of different noise components, and presence of nonlinear propagation effects.

1pNS2. Spatiotemporal analysis of high-performance military aircraft noise during ground run-up.[18] S. Hales Swift, Kent L. Gee, Tracianne B. Neilsen (Phys. and Astronomy, Brigham Young Univ., N221 ESC, Provo, UT 84602, hales.swift@gmail.com), Alan T. Wall (Battlespace Acoust. Branch, Wright-Patterson Air Force Base, Air Force Res. Lab., Wright-Patterson AFB, OH), Micah Downing, and Michael M. James (Blue Ridge Res. and Consulting, LLC, Asheville, NC) Recent measurements of high-performance military aircraft noise have revealed that full-scale jet noise has features and structures that are still only partly understood, such as the presence of multiple acoustic radiation lobes in the aft direction at certain frequencies. Spatiotemporal analyses of a ground-based microphone array measurement of the noise from a tethered F-35 at various engine conditions are used to investigate these features of the sound field. The ground array covered an angular aperture of 35–152 degrees relative to the front of the aircraft. The large angular aperture allows for a detailed investigation of the correlation and coherence at frequencies exhibiting multi-lobe behavior. This spatiotemporal analysis yields further evidence of the characteristics of multi-lobe behavior in high-performance, full-scale jet noise. [Work supported by an Office of Naval Research grant, a USAFRL SBIR, and the F-35 JPO.]

1pNS3. Noise sources in a commercial supersonic jet.[19] Christopher J. Ruscher and Sivaram Gogineni (Spectral Energies, LLC, 5100 Springfield St., Ste. 301, Dayton, OH 45431, cjrusche@gmail.com) Stringent noise regulations currently limit commercial aviation. These regulations make supersonic commercial flight impractical. The development of an engine that can meet these strict rules is paramount to making supersonic commercial flight a reality. One method of noise reduction is to add additional streams to an engine. As such, the three-stream jet has potential to help reduce exhaust noise. Understanding the noise sources in the jet plume can help to design nozzles that are quieter. To accomplish this, high-fidelity, high-speed data are required. Data for an axisymmetric and offset three-stream nozzle were generated using the LES code JENRE developed by the Naval Research Laboratory. The simulation data has been shown to match well with experimental data. Advanced analyses methods that are based on Proper Orthogonal Decomposition (POD), wavelet decomposition, and Stochastic estimation have been applied to extract noise sources in the jet plume.

1pNS4. High-performance aircraft short-takeoff and vertical-landing noise measurements on an aircraft carrier.[20] Alan T. Wall, Richard L. McKinley (Battlespace Acoust. Branch, Air Force Res. Lab., Bldg. 441, Wright-Patterson AFB, OH 45433, alantwall@gmail.com), Allan C. Aubert, Russell W. Powers, Michael J. Smith, Charles J. Stouffer (Naval Air Systems Command, Naval Air Station Patuxent River, MD), and James C. Ku (Naval Air Systems Command, Naval Air Station Patuxent River, MD) The noise levels caused by high-performance aircraft are relatively high in the close proximity experienced by crew on board aircraft carriers, which can interfere with communications and may pose a risk for hearing loss. This paper reports on preliminary results of noise measurements of the operations of F-35B aircraft performing short-takeoff and vertical-landing (STOVL) operations on the flight deck of an LHA aircraft carrier. This noise measurement campaign was performed in late 2016, by scientists from the Air Force Research Laboratory (AFRL) in collaboration with the Naval Air Systems Command (NAVAIR) and the F-35 Integrated Task Force (ITF). The measurements were taken using hand-held noise recorder systems, and the recording engineers shadowed actual locations of crew. These data will be used to validate STOVL models of crew noise exposures on deck. [Work supported by F-35 JPO.]

1pNS5. Characterization of broadband shock-associated noise from high-performance military aircraft.[21] Tracianne B. Neilsen, Aaron Vaughn, Kent L. Gee (Brigham Young Univ., N311 ESC, Provo, UT 84602, tbn@byu.edu), Alan T. Wall (Air Force Res. Lab., Wright-Patterson AFB, OH), Micah Downing, and Michael M. James (Blue Ridge Res. and Consulting, LLC, Asheville, NC) For nonideally expanded jets, broadband shock-associated noise (BBSAN) is a feature in the sideline and forward

directions. While BBSAN has been studied fairly extensively for laboratory-scale jets, its presence and characteristics in full-scale, tactical aircraft noise need to be evaluated. Noise measurements on a tied-down F-35 provide the opportunity to characterize full-scale BBSAN using a linear ground array that spanned a large angular aperture: 35–152 degrees relative to the front of the aircraft. The main questions are whether the full-scale BBSAN shares the same characteristics as those observed in laboratory-scale BBSAN and if current models capture the features of full-scale BBSAN. The variation in the spectral shape, peak frequency, and peak level of full-scale BBSAN across angle for different engine powers is explored and compared to prior laboratory studies. Comparisons are also made with models for BBSAN based on stochastic theory [22] and the simplified model used in Kuo et al. [23] for lab-scale BBSAN. Frequency-dependent convective speed estimates obtained from the current BBSAN models are compared to estimates based on directivity. [Work supported by the Office of Naval Research and the F-35 JPO.]

1pNS6. Spectral decomposition of turbulent mixing and broadband shock-associated noise from a high-performance military aircraft.[24] Aaron Vaughn, Tracianne B. Neilsen, Kent L. Gee (Brigham Young Univ., C110 ESC, Provo, UT 84602, aaron.burton.vaughn@gmail.com), Alan T. Wall (Air Force Res. Lab., Wright-Patterson AFB, OH), Micah Downing, and Michael M. James (Blue Ridge Res. and Consulting, Asheville, NC) Sound from high-performance military aircraft originates primarily from the turbulent mixing noise, but at smaller inlet angles, broadband shock-associated noise (BBSAN) is present. The similarity spectra of the two components of turbulent mixing noise developed by Tam et al. [AIAA Paper 96–1716 (1996)] represent noise associated with fine and large-scale turbulent structures and provide reasonable fits for ideally expanded, supersonic jet noise. For non-ideally expanded jet flow, BBSAN contributions to the spectral shape need to be included in spectral decompositions in the sideline and forward directions. A model proposed by Tam et al.[22] and later simplified by Kuo et al.[23] provides a spectral function that models the BBSAN spectral shape. The ability of the BBSAN and similarity spectra shapes to account for the measured spectra is evaluated for ground-based microphones that covered a spatial aperture from 35 to 152 degrees. Spectral decompositions at low and high engine powers are compared. Using turbulent mixing noise similarity spectra decomposition in conjunction with BBSAN empirical fits, a better equivalent source model can be developed. [Work supported by the Office of Naval Research and the F-35 JPO.]

1pNS7. Modeling shock formation and propagation in high-performance jet aircraft noise.[25] Brent O. Reichman, Kent L. Gee, Tracianne B. Neilsen (Brigham Young Univ., 453 E 1980 N, #B, Provo, UT 84604, brent.reichman@byu.edu), Alan T. Wall (Battlespace Acoust., Air Force Res. Lab., Wright-Patterson AFB, OH), Micah Downing, and Michael M. James (Blue Ridge Res. and Consulting, LLC, Asheville, NC) Nonlinear propagation can play an important role in both time and frequency-domain features of far-field supersonic jet noise. Many aspects of nonlinear propagation, such as waveform steepening and greater-than expected high-frequency spectral levels, have been previously predicted for select angles and engine conditions. This paper builds on previous successes and presents a comparison of nonlinear and linear predictions for the F-35B aircraft. Results are shown over a wide spatial and angular range and over varying engine power conditions, including showing evidence of nonlinear propagation in the forward direction at the highest engine conditions. In addition, specific features, such as individual shocks, are compared between numerically propagated and measured waveforms, highlighting the successes and deficiencies of current propagation models. Weather and multipath interference effects are also addressed and corrected using an empirical model. [Work supported by USAFRL through ORISE.]

1pNS8. Measurement methods for high-performance jet aircraft noise inside a hardened aircraft shelter.[26] Richard L. McKinley, Alan T. Wall (Battlespace Acoust., Air Force Res. Lab., 2610 Seventh St., AFRL/ 711HPW/RHCB, Wright-Patterson AFB, OH 45433-7901, rich3audio@aol. com), Theo A. van Veen (NLR: Nederlands Lucht- en Ruimtevaartcentrum – Netherlands Aerosp. Ctr., The Hague, Netherlands), and Jaap van't Hof (TNO: Nederlandse organisatie voor Toegepast Natuurwetenschappelijk Onderzoek – The Netherlands Organisation for Appl. Sci. Res., The Hague, Netherlands) High-

performance military aircraft regularly operate inside hardened aircraft shelters (HAS). The F-35A aircraft must be certified as safe to operate inside a HAS before it can be deployed and used in such structures worldwide. Acoustic levels at maintainer locations allow for noise dose estimates and regulation of personnel mission support in HASs to mitigate risks of hearing damage. Acoustic levels impinging on the airframe are compared against engineering design limits in order to prevent a reduction in operational lifespan of the aircraft due to acoustic fatigue. The Air Force Research Laboratory, the Royal Netherlands Air Force, and the Dutch national laboratories NLR and TNO collaborated on a set of acoustic measurements for an F-35A operating inside a HAS at Leeuwarden airbase in the Netherlands. The methods, analysis, and qualitative findings of the acoustic measurements are presented here. [Work supported by RNLAF and by the F-35 JPO.   Cleared 01/24/2017; JSF17-035.]

1pNS9. Calculating the frequency-dependent apparent source location using peak cross-correlation between near-field and far-field microphone arrays.[27] Jacob A. Ward, S. Hales Swift, Kent L. Gee, Tracianne B. Neilsen (Phys., Brigham Young Univ., N243 ESC, Provo, UT 84602, jacob.ward@live.com), Koji Okamoto, and Masahito Akamine (Dept. of Adv. Energy, Graduate School of Frontier Sci., The Univ. of Tokyo, Kashiwa, Chiba, Japan) The apparent acoustic source region of jet noise varies as a function of frequency. In this study, the variation of the apparent maximum source location with frequency is considered for an ideally expanded, unheated, Mach- 1.8 jet with exit diameter of 20 mm and a Reynolds number of 6.58e6. In this study, the source location is ascertained for one-third octave bands by evaluating peak cross-correlation between near-field linear microphone arrays at three sideline distances and a far-field microphone arc. The impact of the hydrodynamic field on correlation results is considered. Source locations determined by these means are compared with intensity analyses for the same jet.[28] Correlational methods, together with filtering, can provide a straightforward measure of the acoustic origin as a function of frequency and thus inform optimal microphone array layout for specific frequency regimes.

1pNS10. Numerical validation of using multisource statistically optimized near-field acoustical holography in the vicinity of a high performance military aircraft.[29] Kevin M. Leete (Brigham Young Univ., Provo, UT 84604, kevinmatthewleete@gmail.com), Alan T. Wall (Battlespace Acoust. Branch, Air Force Res. Lab., Wright-Patterson AFB, OH), Kent L. Gee, Tracianne B. Neilsen (Brigham Young Univ., Provo, UT), Micah Downing, and Michael M. James (Blue Ridge Res. and Consulting, LLC, Asheville, NC) Multisource statistically optimized nearfield acoustical holography (MSONAH) is an advanced holography technique[30] that has been used to reconstruct the acoustic field from measurements taken in the vicinity of a high-performance military aircraft[31]. The implementation of MSONAH for tactical jet noise relies on creating an equivalent wave model using two cylindrical sources, one along the jet centerline and one below the ground as an image source, to represent the field surrounding an aircraft tethered to a reflecting ground run up pad. In this study, the spatial and frequency limitations of using the M-SONAH method to describe the field of a tethered F-35 is explored by using the same measurement geometry as at a recent test, but substituting the sound field obtained from a numerical source for the measurement data. The M-SONAH reconstructions are then compared to numerical benchmarks. A spatial region and frequency bandwidth where bias errors are low are identified and provide validation for the use of this method in tactical jet noise source and field reconstructions. [Work supported by USAFRL through ORISE and the F-35 JPO.]

1pNS11. Sound quality analysis of far-field noise from a highperformance military aircraft.[32] S. Hales Swift, Kent L. Gee, Tracianne B. Neilsen (Phys. and Astronomy, Brigham Young Univ., N221 ESC, Provo, UT 84602, hales.swift@gmail.com), Alan T. Wall (Battlespace Acoust. Branch, Wright-Patterson Air Force Base, Air Force Res. Lab., Wright-Patterson AFB, OH), Micah Downing, and Michael M. James (Blue Ridge Res. and Consulting, LLC, Asheville, NC) Noise from high-performance military aircraft can pose challenges to community relations near airfields. Accurately predicting and quantifying community impacts is important for efforts to minimize such impacts and reduce annoyance. In this study, sound recordings measured 305 m from a tethered F-35 aircraft operating at various engine conditions are

analyzed using sound quality metrics. The calculated metrics are inputs for a model of perceived annoyance used to estimate the relative contributions of loudness and other sound quality features to annoyance. These results can help inform future efforts at noise reduction by identifying potentially relevant sound quality components of the jet noise as well as helping inform discussions of noise policy on military bases. [Work supported by a USAFRL SBIR and the F-35 JPO.]

1pNS12. Spatial interpolation of noise monitor levels.[33] Edward T. Nykaza (ERDC-CERL, 2902 Newmark Dr., Champaign, IL 61822, edward.t. nykaza@usace.army.mil) Continuously recording noise monitoring stations provide feedback of the noise environment at monitor locations. While this feedback is useful, it only provides information at a few point locations, and in many cases it is of interest to know the noise level(s) at the locations between and beyond noise monitoring locations. In this study, we test the accuracy of several spatial interpolation models with experimental data collected during the Strategic Environmental Research and Development Program (SERDP) Community Attitudes Towards Military Blast Noise study. These datasets include 9 months of blast noise events captured at two different study locations. In both cases, a small number of monitors (e.g., 3–9) were located over a large region of interest (e.g., 1–8 km^2), thus providing realistic operational conditions. The utility of deterministic (e.g., nearest neighbor, Delaunay triangulation, thin plate splines, etc.) and stochastic (e.g., geostistical or kriging) interpolation models for estimating single-event and cumulative noise levels is examined using leave-one-out cross validation. The accuracy of each approach is assessed with the root-mean-square-error (RMSE), and we discuss the practical implications of implementing such approaches in real-time systems.

1pNS13. Acoustic excitation impact on aerodynamic drag measured in aeroacoustic liners.[34] Christopher Jasinski (Univ. of Notre Dame, 54162 Ironwood Rd., South Bend, IN 46635, chrismjasinski@gmail.com) and Thomas Corke (Univ. of Notre Dame, Notre Dame, IN) Research interest has steadily grown for understanding the aerodynamic drag produced by acoustic liners for commercial turbofan engines. This is driven by an aim to understand the phenomena fundamentally as well as for application in flight. Stringent government regulations on aircraft noise and next generation aircraft designs that may include liners on more surfaces are key drivers for industry involvement. While the conventional perforate over-honeycomb liner has proven effective acoustically for decades, liner drag production has not been fully understood. When an acoustic liner sample is excited with sound pressure levels above 140 dB re 20 μPa, a measurable drag increase is observed at flight velocity. Recent measurements have shown that tonal noise at the same level can produce more than a 50 percent increase in drag coefficient for a liner sample at lower test speeds. By testing liner samples at low speed in the Notre Dame Hessert Laboratory, detailed hotwire probe measurements near the wall have been made and drag coefficient comparisons have been made with the use of a linear air-bearing force balance. The development of the measurement setup, the results produced, and a discussion of implications will be included in this paper.

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