Summary of "Supersonic Jet Aeroacoustics" Special Session

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Summary of "Supersonic Jet Aeroacoustics" Special Session

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This paper summarizes a two-part session, "Supersonic Jet Aeroacoustics," that took place during the 176th Meeting of the Acoustical Society of America. 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, Canada, Japan, South Korea, 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.

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1. SESSION OVERVIEW

This paper summarizes a two-part session, "Supersonic Jet Aeroacoustics," which consisted of twenty four 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. Firstly, jet and rocket noise prediction efforts – involving analytical, experimental, and numerical methods – are discussed. Second, full-scale jet noise measurements and analyses, mostly involving the F-35 fighter aircraft, are described. Third, various supersonic noise reduction techniques for both jets and rockets are presented. Finally, a number of valuable studies that relate to personnel and community impacts of rocket noise, jet noise, and sonic booms, 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. Recent 2016 and 2017 jet aeroacoustics sessions are summarized in References [1] and [2]. 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 to significantly broaden the international community.

A. JET AND ROCKET NOISE PREDICTION

The sessions contained six talks on rocket and jet noise prediction, including numerical prediction. Both Junhui Lui of the Naval Research Lab and Won-Suk Ohm of Yonsei University discussed Large Eddy Simulation (LES). The former conducted LES of a model GE 404 nozzle, taking a finite element wall modelling approach to the boundary layer effect within the nozzle, and using the JENRE flow solver. Comparison of the LES approach with available Particle Image Velocimetry (PIV) and noise data for this nozzle indicated that the downstream shock cell structure is very sensitive to the wall modelling characteristics. Ohm discussed the often overwhelming computational costs (time and memory) associated with LES and presented an alternative 'poor man's computational fluid dynamics (CFD)' based on calculation of the flow field using a 2D hybrid RANS/LES scheme which was fed into the Helmholtz-Kirchoff integral to predict the acoustic far-field. Three different CFD grids (fine/coarse/coarser) were compared in terms of OASPL, directivity and spectra. Comparison with these data indicate that the acoustic metrics are less sensitive to the grid differences than is the flow field and that, with some further work, the method with less computational costs has considerable possibilities for acoustic load prediction.

Seiji Tsutsumi of Japan Aerospace Exploration Agency (JAXA) presented the results of a validation of both time and frequency-domain aero-vibro acoustic simulation technique. LES with Computational Aeroacoustics (CAA) based on the full Euler equations was used to predict the generation of the acoustic waves and their propagation to the exterior of a payload fairing. A coupled vibro-acoustic simulation (based on finite-element modeling) was then used to compute the transmitted internal acoustics within the fairing. Previous validation work had indicated poor agreement between numerical and experimental data on a scale model. Recent work indicated that the primary cause of the discrepancy was that the two sets of screws that connected the three parts of the fairing model disrupted the axisymmetry modal shape of the model. Additionally, the effect of the damping ratio (whose exact value is unknown) was found to be much more significant than previously realized. These modifications considerably improved agreement between numerical and experimental data.

B. FULL-SCALE JET NOISE MEASUREMENTS AND ANALYSIS

A number of talks described full-scale jet noise measurement and analysis. Rich McKinley of the U.S. Air Force Research Laboratory (retired) opened the session with a history of aircraft noise over the past 100 years. His talk traced the development of the jet engine from its original design in the 1940s to the present day, and presented related issues such as the design of various types of headset and early community noise monitoring. In particular, the 1964 Oklahoma City sonic boom study was discussed. The results of experiments on modern fighter jets which led to the discovery of the phenomenon of nonlinear propagation, and the development of noise standards was also mentioned. Many of these topics were then picked up on by subsequent speakers. For example, Alan Wall of the U.S. Air Force Research Laboratory discussed how techniques such as near field acoustical holography (NAH) allow jet noise source imaging. Multisource statistically optimized near-field acoustical holography (M-SONAH) is a major improvement over traditional NAH, but such methods are still bandwidth-limited due to the spatial resolution and extent of the associated holography arrays. A new tool – UPAINT - was recently developed, which offers additional improvement in terms of obtaining the full spectrum required (but currently unobtainable) for a complete high performance military aircraft noise model.

Four speakers from Brigham Young University (BYU) also addressed issues related to high-performance military aircraft noise, which is complicated in nature, since it derives from many different sources. Phased array methods such as beamforming can help characterize some of these noise generation mechanisms. David Van Komen discussed application of the hybrid beamforming (HBF) method to such a jet. When applied to the full-array, an overall equivalent noise source is created which can predict the overall field radiation, but does not separate the different noise sources. However, when HBF is applied to subarrays rather than the full-array, the broadband shock associated noise (BBSAN) can be separated from the main turbulent mixing noise lobes. The method identifies equivalent noise sources which overlap and are frequency dependent. Aaron Vaughn also studied data from high performance military jet aircraft in an attempt to understand the source (locations and events) related to the generation of crackle. Crackle is an annoying component of supersonic jet noise that, in the far field, is related to the presence of acoustic shocks that develop due to nonlinear propagation. Unfortunately, the events that drive its generation – which are intermittent in nature –` are currently not well understood. The event-based beamforming method (EBBM) was used to obtain insight into these events. As discussed previously, since direct flow measurements of such aircraft are not feasible, array processing methods must be used to obtain acoustic source characteristics. Jacob Ward compared two different array processing methods, namely HBF and M-SONAH. When both methods were applied to high performance military jet aircraft experiment data – a 71-element linear array of equally spaced microphones placed parallel to the shear layer, covering 32m – favorable agreement between the methods was obtained in terms of maximum source location, source shape and source extent. On a slightly different topic, Brent Reichman investigated how meteorological effects – specifically atmospheric refraction – affects long-range nonlinear jet noise propagation. In particular, acoustic shock strength was found to vary greatly with seemingly small changes in the atmospheric conditions, indicating the need for further work in this area.

Other novel experimental techniques were also presented. Koji Okamoto of the University of Tokyo discussed an alternative to near-field microphone measurement (which disturb the flow and acoustic field that is being measured). The proposed method was based on laser optical measurements – essentially a Schlieren system for acoustics. The method was applied to a perfectly expanded supersonic jet and compared with microphone measurements, to determine its validity. When the cross-correlation, spectra and directivity results were compared for the two methods, it was found that the optical method shows promise, although some improvements are needed. In related work, Yuya Sekiguchi, also of the University of Tokyo, used conditional sampling analysis of high speed Schlieren movies to visualize the acoustic field of a correctly expanded supersonic jet in order to investigate the relationship between the flow and acoustic phenomena. Specifically, their acoustically triggered conditional sampling analysis (ATCSA) allows extraction of highly correlated phenomena, thereby allowing characteristics such as propagating direction and source location to be clarified.

C. SUPERSONIC NOISE REDUCTION

Novel data-driven analysis techniques were proposed and discussed in this session. Spectral proper orthogonal decomposition (SPOD) – that is, the frequency domain form of the proper orthogonal decomposition (POD) – is one of the methodologies used to identify the coherent structure of the turbulent jet that radiates the aeroacoustic wave. Intermittency is a feature of the turbulence structure of a jet, and acoustic shock waves resulting in crackle are one of the more well-known intermittent phenomena observed in jet aeroacoustics. As an improvement to conventional SPOD, Oliver Schmidt of the University of California (San Diego) proposed the idea of a conditional space-time POD to extract a burst event in jet aeroacoustics, such as an acoustic shock. In addition to the EBBM (Event-Based Beamforming Method) proposed by Vaughn *et al.,* and the ATCSA (Acoustic-Triggered Conditional Sampling Analysis) employed by Sekiguchi *et al.*, the conditional space-time POD is a promising method for identifying intermittent features of a turbulent jet and its radiated acoustic wave. Ethan M. Pickering of the California Institute of Technology applied resolvent analysis to the LES result of the isothermal Mach 1.5 round jet to seek a low rank approximation for acoustic sources. In addition to SPOD and the conditional space-time SPOD, these data-driven analysis techniques will help to devise reduced order models for prediction and reduction of aeroacoustics from turbulent jets.

The sessions also included several papers which addressed the issue of supersonic jet noise reduction. Kyle Daniel of Virginia Tech suggested a novel technique in which temperature non-uniformity is used for jet noise reduction. Thermal non-uniformities act as flow perturbations and disturb the noise generation mechanisms. A thermally non-uniform Mach 1.5 heated jet with centered and offset thermal non-uniformities was studied, and the non-uniformities were found to reduce the radiated far-field noise by up to 2db at peak frequencies. Other jet characteristics including the length of the potential core and the shear layer thickness were also found to be affected by these thermal effects.

Wataru Sarae of JAXA presented the second-stage results from 1/42 subscale model acoustic tests on Japan's next generation launch vehicle – the H3. A significant measurement campaign is being carried out to predict the liftoff environment of this vehicle. Both near- and far-field experiments were carried out using different flame duct configurations (covered and uncovered) and two water injection 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. Numerous experiments were carried out, with results indicating that the most significant reduction in OASPL (between 2 and 5dB) could be achieved by the use of a flat covering on the openings either side of the flame duct.

Yo Murata of the University of Tokyo discussed the effect on the acoustic field of a supersonic jet impinging to perforated plates. The impact of changing elevation, shape of aperture and sound absorbing material was investigated. Both optical and acoustic model tests were carried out. Results indicate that the acoustics were significantly changed due to the shape of the aperture. It was found that the aperture with rounded fillet is the best for decreasing sound pressure. Porous sound absorbing material on the plate was also found to be effective at reducing reflected sound. The experiments also indicate that interference sound from the hole propagates upstream. The knowledge of this study will help to devise acoustic attenuation of the liftoff noise due to the impingement of the exhaust jet to movable launch platform.

Christopher Jasinski of the University of Hartford 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. This work represents an extension of work previously conducted by Jasinski at Notre Dame. The results of fluid mechanic, acoustic and direct aerodynamic experiments for a number of different liner samples were discussed.

D. PERSONNEL IMPACT AND COMMUNITY RESPONSE

There were four papers in the session 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. Alexandria Salton of Blue Ridge Research and Consulting presented the Launch Vehicle Acoustic Simulation Model (Rumble), a high-fidelity system for predicting 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 described. A measurement protocol has been developed and a number of sets of rocket launch data have been collected. Comparison of predictions from Rumble with some of the measured data was given, and it was noted that whilst agreement was reasonable, there were some important differences including prediction of the peak directivity angle. Meteorological effects will be an important item for predicting noise impacts of launch vehicles (see also Reichman et al.).

Joana Rocha of Carleton University discussed the design of a high-speed aeroacoustic wind tunnel (HSWAT) commissioned by Carleton University specifically for aircraft cabin noise modelling. The noise that propagates to the interior of an aircraft cabin is primarily due to the jet engines and turbulent boundary layer flow, and this chamber will be used to facilitate experimental studies of turbulent boundary layer (TBL) induced surface pressure fluctuations. The facility is one of the few in the world capable of reaching Mach 0.8. CFD analysis was used throughout to validate the design of the chamber elements, including the expansion angle and the length of transition channel for the tunnel. Comparison of preliminary experimental results with existing data and models indicate that improvements are still necessary and ongoing.

William Doebler and Alexandra Loubeau, both of NASA Langley Research Center, presented work related to the important issue of sonic booms. In 2011, NASA conducted a time and labor-intensive flight test to study community response and perception of low amplitude sonic booms – the so-called waveforms and sonic boom perception and response (WSPR) experiment. Such a test will not be possible in the future, which makes the ability to accurately predict such noise critical as we move closer to the goal of supersonic cross-country flight. Doebler discussed the NASA PCBoom code which is used to predict the Stevens Mark VII Perceived Level from real aircraft trajectories and the WSPR data. Results indicate that further work is still necessary. In particular, PCBoom does not capture the variability in the data set well. In a related study, Loubeau explained that there is not one internationally agreed upon sonic boom metric, and that NASA's goal is to develop one and provide data to enable a change in noise standards for sonic booms. There are 13 commonly used metrics, which vary in terms of factors such as whether they address indoor or outdoor noise levels, mean annoyance level or metrics, but no single clear 'best' metric emerged, and the work is ongoing.

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 papers 1pNS1 and 1pNS2 were not presented, but their abstracts are included here for completeness.

1aNS1. Jet aircraft noise—Past, present, and future issues.[3] Richard L. McKinley (Oak Ridge Inst. for Sci. and Education, 2610 Seventh St., AFRL/711HPW/RHCB, Wright-Patterson AFB, OH 45433-7901, rich3audio@aol.com) and Alan T. Wall (Battlespace Acoust., Air Force Res. Lab., Wright-Patterson AFB, OH)

Aircraft noise has been an issue since for the US Air Force since World-War I. The early days of flight had noise issues that were specific to reciprocating engines and propellers. The advent of the jet engine in the 1940s changed the noise issues and focus dramatically. The jet noise problem was first addressed in the Air Force Research Laboratory (AFRL) by Henning von Gierke and has continued until today with the development of more powerful fifth-generation fighter jet engines. This presentation will focus on the role of AFRL in noise issues with jet aircraft from the early days until now, and how that noise impacted people and communities; the research that fostered noise reductions; noise from current aircraft; the problems and issues that have persisted with jet noise; and some thoughts for future research. [Work Supported by the F-35 Joint Program Office.]

1aNS2. Full-spectrum near-field acoustical holography for fighter jet noise imaging.[4] Alan T. Wall (Battlespace Acoust., Air Force Res. Lab., 2610 Seventh St., Bldg. 441, Wright-Patterson AFB, OH 45433, alan.wall.4@us.af.mil), Kent L. Gee, Kevin M. Leete, Mylan R. Cook (Brigham Young Univ., Provo, UT), and Michael M. James (Blue Ridge Res. and Consulting, Asheville, NC)

The development of acoustic imaging technologies over the previous decade has proven useful for increasing our understanding of the noise generation mechanisms inside the turbulent flows of full-scale tactical aircraft engines. In particular, advancements in nearfield acoustical holography have allowed for jet noise source imaging from measurements made on tied-down aircraft over hard reflecting ground surfaces. These images have been limited in bandwidth due to the spatial resolution and extent of the holography arrays. However, improved aperture extension methods have allowed for representation of the lowest frequencies, and a new tool has been developed to produce accurate sound field images at above-Nyquist frequencies for broadband sources. These two technologies are implemented together to extend the imaging of fighter jet noise near-field toward the full spectrum required for an aircraft noise model. [Work Supported by the F-35 Joint Program Office.]

1aNS3. Localization of directional noise sources from high-performance military aircraft through subarray beamforming analysis.[5] David F. Van Komen, Tracianne B. Neilsen, Blaine M. Harker, Kent L. Gee, S. Hales Swift (Phys. and Astronomy, Brigham Young Univ., N283 Eyring Sci. Ctr., Provo, UT 84602, david.vankomen@gmail.com), Micah Downing, Michael M. James (Blue Ridge Res. and Consulting, Asheville, NC), and Alan T. Wall (Battlespace Acoust. Branch, Air Force Res. Lab., Wright-Patterson AFB, OH)

High-performance military aircraft noise is created by multiple sound generation mechanisms that need to be understood to guide noise reduction efforts and for adequate sound field predictions. Phased-array methods can be used to produce frequency-dependent equivalent acoustic source models. The Hybrid (beamforming) method [Padois et al., J. Sound Vib. 333 (2014)] is applied to an acoustical measurement along a 71-microphone ground-based array, spanning 32 m, placed in the vicinity of a high-performance military aircraft as the engine was operated at different powers. Application of the Hybrid method to the full-array creates an overall equivalent source model that is sufficient for predicting overall field radiation but fails to separate the different noise sources. Applying the Hybrid method to subarrays separates broadband shock-associated noise from the main radiation lobes of turbulent mixing noise. Results show that the subarray-based equivalent source distributions for the different types of noise originate from overlapping source locations. Further analysis of the subarray-based equivalent noise sources using coherence and directionality from the unwrapped phase of the cross-spectral source reconstructions identifies overlapping, frequency-dependent source regions with characteristics unique to broadband shock-associated noise and turbulent mixing noise. [Work supported by an Air Force Research Laboratory SBIR and the F-35 Joint Program Office.]

1aNS4. Beamforming of crackle-related events in supersonic jet noise.[6] Aaron Vaughn, S. Hales Swift, Kent L. Gee (Brigham Young Univ., C110 ESC, Provo, UT 84602, aaron.burton.vaughn@gmail.com), Micah Downing, Michael M. James (Blue Ridge Res. and Consulting, Asheville, NC), and Alan T. Wall (Air Force Res. Lab., Wright-Patterson AFB, OH)

Crackle is an annoying component of supersonic jet noise. In the far field, crackle is related to the presence of acoustic shocks that develop due to nonlinear propagation; however, the intermittent source events that drive crackle generation are not well understood. This study investigates the apparent source locations of events related to crackle, which could include high amplitude or steepened, shock-like waveforms. The measured data were obtained through ground-array measurements near a high-performance military aircraft, which was run at different engine powers. The apparent source regions corresponding to different event triggers, such as pressure amplitude, derivative amplitude, and spectral characteristics, are compared. The crackle-related event beamforming is also compared against the results of time-averaged, frequency-domain source localization. [Funded by an AFRL SBIR and supported by the F-35 Joint Program Office.]

1aNS5. Comparing two inverse array methods for source reconstructions of noise radiated from a high-performance jet aircraft.[7] Jacob A. Ward, Kevin M. Leete, Kent L. Gee, David F. Van Komen, Tracianne B. Neilsen (Phys., Brigham Young Univ., N243 ESC, Provo, UT 84602, jacob.ward@live.com), Alan T. Wall (Battlespace Acoust. Branch, Air Force Res. Lab., Wright-Patterson AFB, OH), Micah Downing, and Michael M. James (Blue Ridge Res. and Consulting, Asheville, NC)

Because direct flow measurements of tactical aircraft jet engines are not currently possible, acoustic source characteristics are instead inferred from array processing. This paper compares two array processing methods using the same array data from a high-performance military aircraft. Hybrid beamforming (HBF) and multisource statistically optimized near-field acoustical holography (M-SONAH) have both been used previously for frequency-dependent jet noise source characterization, but are compared here for the same input data. A 71-element linear array of equally spaced microphones was placed approximately parallel to the shear layer covering a distance of 32 m. Complex pressures obtained from this array served as the input to both methods. Favorable agreement in terms of maximum source location, source shape, and source extent was seen between the two methods' respective results. While the methods continue to have their relative strengths and reasons for use, this favorable agreement indicates that an improved understanding of military jet noise sources has been achieved. [Work supported by an AFRL SBIR and the F-35 Joint Program Office.]

1aNS6. Meteorological effects on long-range nonlinear propagation of jet noise from a static, high-performance military aircraft.[8] Brent O. Reichman, Kent L. Gee (Brigham Young Univ., N243 ESC, Provo, UT 84602, kentgee@byu.edu), and Alan T. Wall (Battlespace Acoust., Air Force Res. Lab., Wright-Patterson AFB, OH)

The impact of nonlinearity on the propagation of noise from military jet aircraft has been fairly well documented, but only within a few hundred meters from the aircraft. This paper describes analysis of nonlinear propagation for morning static runups of F-35 aircraft at greater distances, out to 1220 m near the direction of maximum radiation and at heights ranging from 0 m up to 30.5 m. A comparison of overall levels with distance and height reveals evidence of significant atmospheric refraction effects, and a general trend of decreasing level with height. Examination of nonlinearity metrics reveals opposite behavior, however. At these distances, nonlinear propagation effects are often strongest in waveforms with lower sound levels, which is counterintuitive. One important finding, however, is that acoustic shock strength can vary greatly from runup to runup, even for seemingly small changes in atmospheric conditions. This analysis demonstrates the need for further research into long-range nonlinear propagation of jet noise through realistic atmospheric conditions. [Work Supported by the F-35 Joint Program Office.]

1aNS7. Large-eddy simulation of supersonic jet noise emanating from an F404 nozzle at model scale.[9] Junhui Liu and Ravi Ramamurti (Naval Res. Lab., 4555 Overlook Ave. SW, Washington, DC 20375, junhui.liu@nrl.navy.mil)

Large-eddy simulations of supersonic jet noise emanating from an F404 nozzle at the model scale have been carried out using the JENRE flow solver. A wall-model method that was previously validated for a high subsonic flow over a flat plate is used to model the boundary layer effect inside the nozzle. The nozzle geometry is a faceted bi-conic convergent-divergent nozzle with a design Mach number equal to 1.65 and the nozzle-exit diameter equal to 5.07 inches. Both mildly and highly overexpanded conditions are tested for heated jets. The time averaged flow field, turbulence intensities, and the far-field noise are compared with available experimental data. The effects of both the boundary-layer thickness and turbulence intensity at the nozzle exit are investigated to assess their impact on jet noise generation and the noise source characteristics.

1aNS8. Sensitivity of acoustic predictions on the mesh size of large-eddy simulation of supersonic jet.[10] Inman Jang, Won-Suk Ohm (School of Mech. Eng., Yonsei Univ., 50, Yonsei-ro, Seodaemun-gu, Seoul 03722, South Korea, ohm@yonsei.ac.kr), H. S. Joo (Dept. of Mech. and Aerosp. Eng., Seoul National Univ., Seoul, South Korea), S.-J. Shin (Dept. of Mech. and Aerosp. Eng., Inst. of Adv. Aerosp. Technol., Seoul National Univ., Seoul, South Korea), and J. W. Park (Agency for Defense Development, Daejeon, South Korea)

Intense noise produced by the supersonic jet plume from a rocket can cause damage to its structural system and even a failure during launch. In order to predict the acoustic loading by rocket jet noise, large-eddy simulation (LES) is commonly employed for analysis of the jet flow field that is subsequently used as a source condition for predicting the acoustic field. Although desirable from the accuracy standpoint, LES of a supersonic jet is often burdened by an overwhelming computational cost in both runtime and memory. In this talk, we discuss the sensitivity of acoustic predictions on the spatial resolution of LES, and propose a guideline for reducing the mesh requirement. Here, the flow field of a supersonic jet is calculated using a hybrid RANS/LES scheme on meshes of different sizes, and is fed into the Helmholtz-Kirchhoff integral for prediction of the acoustic farfield. Changes in overall sound pressure level (OASPL) and directivity of the Mach radiation are monitored as the LES mesh varies in size. The study suggests that (a) the accuracy of the acoustic prediction is not much affected by the use of a coarser mesh to a certain extent and (b) the resulting improvement in computation speed and economy thus outweighs the loss of details in LES, given the prediction of acoustic loading as the ultimate goal. (This work was conducted at High-Speed Vehicle Research Center of KAIST with the support of the Defense Acquisition Program Administration and the Agency for Defense Development under Contract UD170018CD.)

1aNS9. Improvement of aero-vibro acoustic simulation technique for prediction of acoustic loading at lift-off.[11] 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)

Aero-vibro acoustic simulation for the prediction of harmful acoustic loading at lift-off of launch vehicle is developed. In this simulation technique, high-fidelity large-eddy simulation with computational aeroacoutics based on full-Euler equations is employed for computing jet aeroacoustics and their propagation to the outside of payload fairing. Acoustic field inside the payload fairing is computed by the coupled vibro-acoustic simulation based on finite element method. A simplified fairing model is used for the validation of the present method. An impact hammer test and acoustic vibration test using a loudspeaker in an anechoic chamber are conducted for validating the structural model. Then, the accuracy of this method is validated by using the acoustic vibration test result with a subscale rocket engine.

1aNS10. Spectral analysis of jet turbulence and radiated sound.[12] Oliver T. Schmidt (MAE, Univ. of California, San Diego, 1200 E California Blvd., MC 104-44, Pasadena, CA 91125, oschmidt@caltech.edu), Tim Colonius (MCE, California Inst. of Technol., Pasadena, CA), Aaron Towne (CTR, Stanford Univ., Pasadena, CA), Georgios Rigas (MCE, California Inst. of Technol., Pasadena, CA), and Guillaume A. Bre`s (Cascade Technologies Inc., Palo Alto, CA)

Informed by LES data and resolvent analysis of the mean flow, we examine the structure of turbulence in jets in the subsonic, transonic, and supersonic regimes. Spectral (frequency-space) proper orthogonal decomposition is used to extract energy spectra and decompose the flow into energy-ranked coherent structures. We demonstrate that two distinct mechanisms, which can be distinguished by their characteristic frequency scaling and spatial support, lead to the formation of wavepackets—coherent structures that are known for their acoustic importance in the aft-angle radiation of high subsonic and supersonic jets. We compare these characteristics to acoustic source features extracted from hologram sound pressure measurements in a recent publication. The evidence strongly suggests that both mechanisms are active in full-scale jets and comprise the experimentally educed sources of sound.

1aNS11. Launch vehicle acoustic measurements for community noise model development and validation.[13] Alexandria R. Salton, Michael M. James (Blue Ridge Res. and Consulting, 29 N Market St., Ste. 700, Asheville, NC 28801, Alex.Salton@blueridgeresearch. com), Matthew F. Calton (Blue Ridge Res. and Consulting, Provo, UT), Kent L. Gee, Reese D. Rasband, Daniel J. Novakovich, and Brent O. Reichman (Phys. and Astronomy, Brigham Young Univ., Provo, UT)

A measurement campaign is being conducted under ACRP Project 02-81 to compile a database of high-fidelity modern rocket propulsion noise measurements for facilitating community noise model development and validation. As part of this measurement campaign, acoustic measurements of the Orbital ATK Antares rocket, launched as part of NASA's eighth cargo resupply mission (OA-8E) to the International Space Station, were collected. The OA-8E acoustic measurement test plan was based on guidelines from the community noise measurement protocol being developed under the same effort. Pressure measurements were collected from 46 microphones at 19 unique geographic locations ranging from 0.2 to 19.1 km of the launch pad. The acoustic measurements and the resultant initial data products related to the OA-8E Antares launch will be presented. Comparisons of the multiple recording systems and microphone heights/orientations will be discussed in relation to their relevance in informing equipment recommendations and site layout related to the protocol design.

1aNS12. Experimental study of acoustic reduction technique for H3 launch vehicle.[14] Wataru Sarae, Keita Terashima (JAXA, 2-1-1 Sengen, Ibaraki, Tsukuba 305-8505, Japan, sarae.wataru@jaxa.jp), Seiji Tsutsumi (JAXA, Sagamihara, Kanagawa, Japan), Masao Takegoshi (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. Last year the results of the first campaign of the HARE, which aims at understanding the effects of elevation, the shape of ML, were presented. This year, the results of the second campaign which aims at studying the effects of acoustic reduction techniques such as acoustic shields and water injection will be presented.

1pNS1. An investigation of the interactions between impulsively started and steady supersonic jets.[15] Karthikeyan Natarajan (Experimental AeroDynam. Div., CSIR-National Aerosp. Labs., EAD, PB 1779, Old Airport Rd., Bangalore 560017, India, nkarthikeyan@nal.res.in), Suriyanarayanan P, Lakshmi Venkatakrishnan (Experimental AeroDynam. Div., CSIR-National Aerosp. Labs., Bangalore, Karnataka, India), and Sankaran Sathiyavageeswaran (Satish Dhawan Space Ctr., Indian Space Res. Organization, India, Sriharikota, Andhra Pradesh, India)

The ignition of the solid rocket booster strap-on and the following IOP wave have a severe influence on the dynamic as well as the acoustic loads experienced by a launch vehicle during lift-off. The jet from the strap-on interacts with the core jet and its established flow over the jet blast deflector, influencing the acoustic field experienced by the launch vehicle. The existing literature provides very little understanding of such interactions. This work investigates the interaction between the jet from SRB and the core, by simulating them with an impulsively started supersonic jet in close proximity to another established jet. While the flow for the core nozzle was allowed directly from the settling chamber, a novel approach using a quick opening valve was used for initiating the flow through the strap-on nozzle. The evolution of a strong shock wave emanating from the strap-on nozzle and the ensuing vortex ring, their interaction with the core jet flow, etc., was captured using schlieren. The results document the fluid dynamic interactions such as the evolution of a strong shock wave emanating from the strap-on nozzle and the ensuing vortex ring, their interaction with the core jet flow, etc., using flow visualizations and acoustic measurements.

1pNS2. Flow and acoustics of an isothermal supersonic 2:1 rectangular jet with an adjacent surface.[16] Ephraim Gutmark, Florian Baier, and Aatresh Karnam (Aerosp. Eng., Univ. of Cincinnati, Rhodes Hall 799, Cincinnati, OH 45221-0070, ephraim.gutmark@uc. edu)

In integrated airframe/propulsion system configurations, additional noise sources can be created from the interactions between the jet flow and the adjacent airframe surfaces. Another situation of surfaces of close proximity occur during takeoff and landing when the ground is close enough to cause the jet-surface interference. The impact of a plate oriented parallel to the axis of a 2:1 rectangular supersonic jet (De = 20.65mm) at the minor axis side is studied. Plate offset (h) distances of h = 0, 1, 2, and 3 equivalent diameters from the nozzle lip to the surface are included. The impact of the plate is studied at nozzle pressure ratios (NPRs) of 2.5–4.5 when the design Mach number is 3.67, at a temperature ratio of TR = 1.1. Mean and turbulent flow field data are acquired using streamwise particle image velocimetry (PIV). Trends of shock cell spacing, potential core length, and shear layer development are analyzed. Near and far field data are taken and correlated with the flow field details. The offset from the nozzle is shown to vary flow and acoustic properties and impact screech tones.

1pNS3. Laser optical measurement of acoustic phenomena in the near field of a supersonic jet using 2-D position sensitive detector.[17] Koji Okamoto, Kazuya Fukatsu, Masahito Akamine (Dept. of Adv. Energy, Graduate School of Frontier Sci., The Univ. of Tokyo, 5-1-5, Kashiwanoha, Kashiwa, Chiba 277-8561, Japan, k-okamoto@edu.k.u-tokyo.ac.jp), and Susumu Teramoto (Dept. of Aeronautics and Astronautics, Graduate School of Eng., The Univ. of Tokyo, Bunkyo, Tokyo, Japan)

Acoustic measurement close to noise sources is significant to understand the generation mechanisms of jet noise. Microphones are generally used for the acoustic measurement, but they may disturb the flow and acoustic fields when they are used in the near field of a jet. In this study, an optical measurement method using a laser and 2-D position sensitive detector (PSD) is proposed for the acoustic measurement in the near field. In this method, 2-D PSD detects the angle and direction of the refraction of the laser path by acoustic wave passing, so that the propagating direction, as well as the acoustic intensity, is expected to be measured by this method. To discuss its validity, this method was applied to the acoustic measurement of a correctly expanded supersonic jet. In this experiment, microphone measurement was also carried out simultaneously, and cross correlation between the signals of these two measurements is discussed. Also, the measured spectra and propagating directions for different frequencies are compared with those of the acoustic intensity vector measurement.

1pNS4. Experimental investigation of the impacts of total temperature non-uniformities on the flow and acoustic fields of a heated supersonic jet.[18] Kyle A. Daniel (Aerosp. and Ocean Eng., Virginia Tech, 460 Old Turner St., Blacksburg, VA 24060, kyled1@vt.edu), David Mayo (Mech. Eng., Virginia Tech, Blacksburg,

VA), Kevin T. Lowe (Aerosp. and Ocean Eng., Virginia Tech, Blacksburg, VA), and Wing Ng (Mech. Eng., Virginia Tech, Blacksburg, VA)

In recent years, the noise produced by tactical aircraft has become a growing concern due to stricter community noise standards and the negative health effects it has on flight support personnel. This study proposes the examination of a new novel noise reduction method involving thermal non-uniformities in heated supersonic jets. Thermal non-uniformities have the advantage of increasing turbulent mixing in jets without the use of additional hardware and can most likely be implemented in afterburning engines with minimal modification. In the course of this study a thermally non-uniform Mach 1.5 heated jet with a centered and offset thermal non-uniformities will be examined. It will be shown that thermal non-uniformities reduce the far-field radiated noise up to ~2dB at peak frequencies and have a measurable impact on the directivity of radiated noise, including a narrowing of the Mach wave emission angle and a non-uniform azimuthal directivity. These changes in the acoustic field are directly related to global changes in the turbulence development observed in the jet. These effects include a shortened potential core, increased shear layer thickness, and a decreased mean flow in regions of peak Reynolds shear stress. These effects are captured by stereoscopic PIV and near and far-field microphone measurements.

1pNS5. Visualization of acoustic phenomena of imperfectly expanded supersonic jets using acoustic-triggered conditional sampling analysis.[19] Yuya Sekiguchi, Koji Okamoto (Graduate School of Frontier Sci., Univ. of Tokyo, Kashiwanoha 5-1-5, Kashiwa, Chiba 277-8561, Japan, 9601548985@edu.k.u-tokyo.ac.jp), and Susumu Teramoto (Graduate School of Eng., Univ. of Tokyo, Bunkyo, Tokyo, Japan)

For rockets and supersonic aircrafts, acoustic waves from an exhaust jet cause problems of vibration and noise. To reduce the influence of acoustic waves effectively, it is important to reveal characteristics of acoustic phenomena, such as source locations and the relation between the flow and acoustic phenomena. For this purpose, the authors carried out visualization of acoustic field of a correctly expanded supersonic jet in the previous studies, and proposed the acoustic-triggered conditional sampling analysis to obtain acoustic information from high speed Schlieren movies. This method is also expected to be applied to other jet acoustic phenomena. In this study, this method is applied to imperfectly expanded supersonic jets and the relation between the flow and acoustic phenomena will be discussed.

1pNS6. Design and evaluation of a high-speed aeroacoustic wind tunnel.[20] Joana Rocha (Dept. of Mech. and Aerosp. Eng., Carleton Univ., 1125 Colonel By Dr., Mackenzie Building, ME 3135, Ottawa, ON K1S 5B6, Canada, Joana.Rocha@carleton.ca)

The high-speed aeroacoustic wind tunnel (HSAWT) at Carleton University is a new facility commissioned with the purpose of facilitating experimental studies of turbulent boundary layer (TBL) induced surface pressure fluctuations. This research is primarily intended for applications related to aircraft cabin noise generation from structures exposed to high-speed flow. This open-jet, blowdown wind tunnel is a unique facility in Canada and one of a few aeroacoustic wind tunnels in the world capable of achieving speeds up to Mach 0.8. Flow is delivered from a nozzle with dimensions of 6.1 cm × 15 cm to a test section enclosed within an anechoic chamber with internal dimensions of 1.9 m × 0.88 m × 1.95 m. This study details the complete design methodology for all major wind tunnel components, including the numerical simulations performed in the validation of the designed components. Results of preliminary test section flow characterization and chamber background noise measurements are discussed. Finally, experimental results of the TBL surface pressure fluctuation spectral behavior developed over a flat test section plate are compared with established data and empirical models available in literature.

1pNS7. Resolvent analysis for jet noise source identification.[21] Ethan M. Pickering, Georgios Rigas, Oliver T. Schmidt, and Tim Colonius (Mech. Eng., California Inst. of Technol., 1200 East California Boulevard, Mail Code MC 104-44, Pasadena, CA 91125, pickering@caltech.edu)

We use resolvent analysis and spectral proper orthogonal decomposition (SPOD) to deduce the acoustic sources for an isothermal Mach 1.5 round jet. Both physics-based resolvent analysis and data-driven SPOD (using a high-fidelity, experimentally-verified, large-eddy simulation (LES) database) provide a basis for predicting the perturbation field. Singular value decomposition of the resolvent operator based upon the LES baseflow provides optimal volumetric forcing modes, or sources, and their associated linear responses. To identify physically relevant resolvent modes, comparisons are made between the highest gain responses and the highest energy SPOD modes computed directly from LES realizations. The prevalence of the associated resolvent forcing modes in the data are then assessed by projecting them onto the full LES nonlinear terms. The resulting distributions are presented and a jet noise model leveraging these forcing statistics is discussed. [This research was supported by a grant from the Office of Naval Research (Grant No. N00014- 16-1-2445). Ethan Pickering was supported by the Department of Defense (DoD) through the National Defense Science & Engineering Graduate Fellowship (NDSEG) Program.]

1pNS8. Fundamental study on the acoustic fields caused by the interference of supersonic jet with a perforated plate.[22] Yo Murata, Kazutoki Iwasa (The Univ. of Tokyo, 7-3-1, Hongo Bunkyo-ku, Tokyo 113-8656, Japan, ymurata@fiv.t.u-tokyo.ac.jp), Tatsuya Ishii (Japan Aerosp. Exploration Agency, Tokyo, Japan), Koji Okamoto (The Univ. of Tokyo, Kashiwa, Chiba, Japan), and SHIGEHIKO KANEKO (The Univ. of Tokyo, Tokyo, Japan)

The supersonic jet contains intensive sound sources. It is known that when this jet collides with the perforated plate, a complicated flow field is formed on the plate and a high-amplitude sound is radiated as compared with the case without the perforated plate. Attention is paid to understanding the sound generating mechanism and proposing the measures to alleviate the sound pressure levels. In this study, two types of fundamental model tests have been carried out with a simple combination of a nozzle and a perforated plate. One is acoustic measurement in an anechoic facility. Test results indicated the amplified sound pressure levels in the forward arc of the nozzle. The aperture geometry suggested certain suppression in sound pressure levels in the arc. The other test is an optical visualization with Schlieren photographs. The photographs tried to account for reflection of high-amplitude sound waves on the plate downstream the nozzle.

1pNS9. Coherence analysis of the simulated sound field of a highly-heated laboratory-scale jet.[23] Kevin M. Leete, Kent L. Gee (Brigham Young Univ., Brigham Young University, Provo, UT 84604, kevinmatthewleete@gmail.com), Junhui Liu (Naval Res. Lab., Washington, DC), Alan T. Wall (Battlespace Acoust. Branch, Air Force Res. Lab., Wright-Patterson AFB, OH), and S. Hales Swift (Brigham Young Univ., Provo, UT)

Large eddy simulations (LES) have successfully reproduced the flow and acoustic fields generated by laboratory-scale jets. However, laboratory-scale test conditions ordinarily do not match those of full-scale military aircraft. Recently, Liu et al. (AIAA 2016–2125) showed that accounting for a variable ratio of specific heats leads to increased accuracy in LES simulations of heated jets. As a step towards modeling operating parameters similar to military aircraft, they produced a simulation of a highly-heated jet with a temperature ratio of seven. This paper shows the levels in the field as well as the axial and azimuthal coherence trends of this simulated jet. Large axial coherence lengths are found in the direction of maximum radiation with decreased coherence towards the sideline. Azimuthally, coherence length scales are greatest in the region of maximum radiation and generally decrease with increasing frequency. Additionally, evidence is seen for multiple self-coherent and mutually-incoherent radiation lobes within the region of maximum radiation. [Work supported by USAFRL through ORISE.]

1pNS10. Acoustic/drag interaction and its impact on future aircraft design.[24] Christopher Jasinski (Mech. Eng., Univ. of Hartford, 54162 Ironwood Rd., South Bend, IN 46635, chrismjasinski@gmail.com)

For several decades, acoustic liner technology has substantially reduced the noise created by commercial jet engines. Conventional placement of the perforate-over-honeycomb liner is in the fore and aft bypass duct of an engine nacelle; however, future aircraft design may incorporate liners on additional surfaces, such as the underside of wings and the fuselage. In order to use liner technology in novel locations, the impact of the porous facesheet and core of the liner on the aerodynamic drag of the craft must be fully understood. Work conducted at the University of Notre Dame has experimentally evaluated this drag, as well as the impact of acoustic fields on the aerodynamic drag produced by acoustic liners. Measurements of several quantities across the full boundary layer profile show this impact is substantial and quantifiable. Such results for several liner facesheets will be presented. Through further testing of the acoustic impedance of various facesheets at the University of Hartford, the goal of striking design balance between acoustic performance and aerodynamic reliability can become more clear. Fluid mechanic, acoustic, and direct aerodynamic measurements for several liner samples will be presented and discussed.

1pNS11. Comparison between predicted and measured Stevens perceived level of sonic booms for community response testing.[25] William Doebler (NASA Langley Res. Ctr., M.S. 462, NASA Langley Res. Ctr., Hampton, VA 23681, william.j.doebler@nasa.gov)

In 2011, NASA conducted a flight test to study community response and perception of low amplitude sonic booms in the Waveforms and Sonic Boom Perception and Response (WSPR) experiment. Several noise monitors were placed in a 1.6 sq. km area to record the booms. In future sonic boom community response flight tests, it will not be practicable to place noise monitors at the locations of every survey respondent. Therefore, noise predictions are necessary. Using NASA's PCBoom code, the Stevens Mark VII Perceived Level (PL) was predicted at each noise monitor locations using the real aircraft trajectories and weather balloon data taken during the WSPR test. These predictions are then compared to the measured PL values. This comparison will inform the methodology for estimating noise exposure in future flight tests.

1pNS12. Updated evaluation of sonic boom noise metrics.[26] Alexandra Loubeau (Structural Acoust. Branch, NASA Langley Res. Ctr.,MS 463,Hampton, VA 23681, a.loubeau@nasa.gov), Sara R. Wilson (Systems Eng. and Eng. Methods Branch, NASA Langley Res. Ctr., Hampton, VA), and Jonathan Rathsam (Structural Acoust. Branch, NASA Langley Res. Ctr., Hampton, VA)

There is no internationally agreed-upon standard noise metric that can be used to quantify sonic boom levels from overflight of supersonic aircraft. Several laboratory studies have investigated perception of sonic booms in outdoor environments, as well as in indoor environments, where transmission loss alters the spectral content and level of the sonic boom and additional factors such as secondary rattle noise and vibration affect perception. Each study has previously been evaluated separately for performance of noise metrics, and the results do not clearly indicate a preferred metric. Meta-analyses have also been performed to evaluate the performance of metrics across five of these studies. An additional sixth study of human response that incorporates rattle noise resulting from sonic booms at representative levels was recently conducted and has been added to the meta-analysis. The analysis considered thirteen metrics with three meta-analysis methodologies: individual subject ratings for indoor studies, mean ratings for indoor studies, and mean ratings for both indoor and outdoor studies. Considering both indoor and outdoor studies, this latest analysis confirmed previous results on the five metrics with highest correlation (r2) across studies: PL, BSEL, DSEL, ESEL, and ISBAP (Indoor Sonic Boom Annoyance Predictor).

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