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Summary of “Acoustics of Supersonic Jets: Launch Vehicle and Military Jet Acoustics”

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This paper summarizes a two-part session, “Acoustics of Supersonic Jets: Launch Vehicle and Military Jet Acoustics,” that took place during the 5th Joint Meeting of the Acoustical Society of America and the Acoustical Society of Japan. The sessions were cosponsored by the Physical Acoustics and Noise Technical Committees and consisted of talks by government and academic 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 plumes.

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1. SESSION OVERVIEW

The session for the acoustics of supersonic jets included 22 talks, with a diverse set of topics that addresses a variety of launch vehicle and jet noise problems. Liftoff noise affects the launch structure, payloads, and electronics, whereas jet noise creates a high noise environment for service 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 can be grouped into various subsections, with many talks touching on multiple subsections: launch-pad noise; visualization of jet noise; scale model testing; noise source characterization and modeling; measurements; vibroacoustic methods; and computational aeroacoustics.

A. Launch-pad Noise

There were three talks on launch-pad noise. Karthikeyan Natarajan of the Council of Science and Industrial Research (CSIR)-National Aerospace Laboratories discussed the effects of perforations in a model-scale launch pad. Results using shadowgraphy and microphone measurements indicated that the perforated launch platform reduced the launch-pad noise. Future work will include a study on various sizes of perforations. Hadrien Lambaré from Centre National D'Etudes Spatiales (CNES) discussed the Launchpad for Ariane 6, which is currently under construction. Subscale testing was conducted to determine the necessary water flow rate for sound suppression. Results were shown that supported the conclusion that a flow rate ratio of 5:1 was necessary to achieve the desired payload environment. Clothilde Giacomoni, from ESSSA Group/ NASA Marshall Flight Center (MSFC), presented about horizontal launch vehicle drift during the first seconds of launch and its impact on the acoustic environment. The relationship between plume impingement on the launch pad and the resulting increased noise levels on the launch vehicle was discussed. Overall, all speakers addressed the necessity and importance of the launch pad as a noise source to the launch vehicle.

B. Jet noise visualization

Visualization of jet noise generation was one theme of the talks. In addition to Natarajan’s shadowgraphy work, Yuta Ozawa from Tokyo University of Science described the change in shock cells with nozzle geometry, showing the elimination of shock-cell formation with a converging-diverging nozzle. Schlieren visual images were presented along with a video compilation of the images. Masahito Akamine of the University of Tokyo presented a visualization movie analysis based on acoustic-triggered conditional sampling method, and acoustic phenomena of supersonic jet was discussed in comparison with intensity vectors. He demonstrated how the analyses were complementary in characterizing the jet noise source region.

C. Scale-model testing

Launch vehicle design is heavily influenced by scale-model testing. Wataru Sarae from Japan Aerospace Exploration Agency (JAXA) presented scale-model results using laboratory-scale cold supersonic jets for the Japanese H3 launch vehicle. He presented results showing that in the clustered nozzle configuration, the overall sound pressure level (OASPL) due to the Mach wave radiation was not proportionally increased with the number of exhaust jets. The NASA SP-8072 was therefore considered to be an insufficient model for clustered nozzles. Clothilde Giacomoni of ESSSA Group/NASA MSFC compared the spatial correlation parameters between the scale launch vehicle and the flight vehicle. There was good correlation between the two data sets, showing that scale data can be used with confidence.

D. Noise source characterization and modeling

Acoustical source characterization and modeling of jet noise was also a theme of the session. Two talks described noise source characterizations for the same Mach 1.8 unheated jet described by Akamine. Kent Gee of Brigham Young University (BYU) presented the intensity-based scale jet noise source characterization using the PAGE (phase and amplitude gradient estimator) method. The PAGE method can extend the frequency range up to 40 kHz, a factor of 15 improvement over the traditional intensity method. Aaron Vaughn (BYU) discussed Tam’s two-source jet noise model, where the jet noise radiation is described in terms of fine and large-scale similarity spectra, and examined the spatial comparison between the near and far-field spectra. In the geometric near field, the fit was almost as good as in the far field, helping strengthen the “source” nature of Tam’s model. Two talks dealt with wavepacket modeling of jet noise from military aircraft. Tracianne Neilsen (BYU) discussed wavepacket modeling of high-performance military aircraft noise using Tam’s two-source spectra decomposition. The results show that a self-similar wavepacket behavior emerges not far above the peak-frequency region. Blaine Harker (BYU) discussed a cross-beamforming analysis of high-performance military jet noise and a decomposition of the beamformed cross-spectral matrix into a set of overlapping axial wavepackets. Results indicate that the multi-wavepacket representation is an improvement over single-wavepacket models in that it approximates the radiated levels and the partially coherent nature of the radiated sound field.

E. Computation of jet noise

Three talks focused on computation of jet noise using different techniques. Oliver Schmidt from California Institute of Technology presented the modeling of supersonic turbulent jet noise by large-scale coherent structures (wavepackets). Building on prior one-way Euler equation analyses, he showed that a singular value decomposition of transfer functions of the governing operator – a “resolvent analysis” – allowed for the computation of optimal forcing functions and responses. Connections were made between the resolvent analysis and the two-source model in that few wavepackets were needed to represent the downstream radiation but many were needed to represent the sideline radiation. Hiroaki Nakano from Tokyo University of Science presented large-eddy simulations (LES) of acoustic waves generated from hot and cold supersonic jets. Results confirmed that the hot jet produced a shorter potential core length, increase of the emitted angle of Mach wave radiation, and greater OASPL compared to the cold jet. Daisuke Kato from the University of Tokyo applied implicit LES using a high-resolution shock capturing scheme to model the supersonic impinging jet that Akamine *et al.* studied experimentally. Qualitative properties of the acoustic field were discussed.

F. Full-scale measurements

Measurements of full-scale rocket motors and military jets were described. Brent Reichman (BYU) presented far-field acoustical measurements of the QM-2 solid rocket motor static firing at Orbital ATK. He demonstrated similar levels as prior measurements of the QM-1, but also the presence of significantly stronger acoustic shocks, suggesting the role of atmospheric effects in the nonlinear propagation. Kevin Leete (BYU) used a vertical array of microphones near a jet plume to obtain the azimuthal coherences of the sound field and determined the upper and lower limits of the coherence length. These results were compared against acoustical holography predictions and demonstrated that the nature of the azimuthal coherence rapidly changed at about twice the peak frequency. Alan Wall from the Air Force Research Laboratory presented two topics on measurements. The first was the near-field array measurements of the F-35 aircraft at Edwards Air Force Base; the data were used to exact source properties. The second presentation was the noise measurements of the F-35C on an aircraft carrier flight deck to determine the sound exposure of aircraft personnel. Brent Reichman (BYU) presented the nonlinear characteristics of the F-35 flyover waveforms. This included the sound pressure level, average steepening factor, and skewness of the first time derivative of the pressure. Won-Suk Ohm of Yonsei University discussed the Morfey-Howell Q/S as a single-point nonlinearity indicator in jet and rocket noise, showed how it had been applied to prior jet noise measurements, and addressed theoretical criticisms to validate its use in analyzing data.

G. Vibroacoustic methods

Janice Houston (MSFC, NASA) presented the Exploration Flight Test 1 (EFT-1) Orion Multi-Purpose Crew Vehicle data and results of the time equivalent duration as a function of position along the vehicle. Lessons learned about data processing were shared with special consideration regarding the data acquisition system and slot card/channelization. Seiji Tsutsumi (JAXA) presented the development of aero-vibro methods for predicting the acoustic environment inside the payload fairing at liftoff. The hybrid methodology used the output of a LES as the input to a modal analysis using finite-element method (FEM), with results up to 20 kHz. It was pointed out that the modal damping ratio in the FEM analysis was very sensitive to the result, and further study was required to increase the accuracy of prediction.

2. SESSION ABSTRACTS

Included are session abstracts from both the morning and afternoon sessions. Abtracts have been edited slightly in some cases for clarity or grammar. Note that 5pEA9 was misplaced in the Meeting Program and was presented in place of 2aPA2, which was withdrawn.

2aPA1. Influence of launch platform cut-outs on flow and acoustic behavior of rocket exhaust.[1] Karthikeyan Natarajan and Lakshmi Venkatakrishnan (Experimental AeroDynam. Div., CSIR-National Aerosp. Labs., EAD, PB 1779, Old Airport Rd., Bangalore 560017, India, nkarthikeyan@nal.res.in)

A launch vehicle experiences intense acoustic loading in the initial phase of its lift-off which affects the launch vehicle structure, sensitive payloads, and electronics on board. There is immense interest in alleviation of acoustic loads resulting in reduced need for strengthening of the vehicle structure. The effect of jet blast deflector shape on the acoustic loading has been extensively investigated, both computationally and experimentally, by simulating jet(s) impinging on a flat plate. However, contributions from the launch vehicle environment, such as the launch platform, are often ignored. The motivation for this study is that the flow over the launch platform is likely to be significantly influenced by the cut-outs made in the platform for the nozzles. As the nozzles emerge out from the cut-outs during lift-off, the jet exhaust grows and interacts with the launch platform, contributing to the overall acoustic loads experienced by the vehicle. This paper presents an experimental investigation of rocket exhaust interaction with the launch platform using single and twin jets impinging on a flat plate with cut-outs. The measurements include high speed shadowgraphy and microphone measurements in the near and far-field to enable flow and acoustic characterization.

5pEA9. Acoustical design of the ELA4 launch pad for the Ariane 6 launcher.[2] Hadrien Lambaré (CNES, CNES Direction des lanceurs 52 rue Jacques Hillairet, Paris 75612, France, hadrien.lambare@cnes.fr)

A new launch pad, ELA4, will be built in Kourou (French Guyana) for the future launcher Ariane 6. As the A64 version of the launcher will be more powerful at lift-off than Ariane 5, the exhaust ducts and the water injection systems have to be carefully designed, in order to be as effective as possible, and to reduce the acoustics on the payloads and the launcher. This has been done using the experience acquired with the Ariane 5 and VEGA launch pads, as well as the understanding of the complex phenomena obtained by research activities. The general design has been validated and optimized by subscale test campaigns at the MARTEL test bench. Numerous configurations and parameters have been tested, including the geometry of the ducts and the launch table, the altitude of the launcher, the position and the mass flow rate and the spray type of the water injection systems. [This work has been done in collaboration between ESA, CNES, ASL, ONERA and PPRIME.]

2aPA3. Impact of drift on the vehicle liftoff acoustic environments. [3] Clothilde Giacomoni (All Points Logistics, LLC, M.S. ER42, Bldg. 4203, Huntsville, AL 35812, clothilde.b.giacomoni@nasa.gov) and R. Jeremy Kenny (Marshall Flight Ctr., NASA, Huntsville, AL)

During liftoff, a vehicle can drift due to wind, nozzle gimbaling, fly-away maneuver, etc. This drift can cause the exhaust plumes to impinge on the deck and cause the noise levels experienced by the vehicle to increase. A small increase in the plume impingement can have a dramatic effect on the noise levels when the vehicle is only a few nozzle diameters from the deck. As the vehicle lifts off the deck the increase in noise levels lessens as the plume impingement increases. Several scale-model acoustic tests have been undertaken at Marshall Space Flight Center, which had test cases that were used to define the relationship between drift and the noise levels experienced by the vehicle.

2aPA4. Analysis of nozzle geometry effect on supersonic jet noise using Schlieren.[4] Yuta Ozawa (Tokyo Univ. of Sci., Niijuku 6-3-1, Katsushika-ku, Tokyo 125-8585, Japan, ozawa@flab.isas.jaxa.jp), Akira Oyama (ISAS/JAXA, Sagamihara-shi, Kanagawa, Japan), Masayuki Anyoji (Kyusyu Univ., Kasuga-shi, Fukuoka, Japan), Akira Oyama (ISAS/JAXA, Sagamihara-shi, Kanagawa, Japan), Hiroya Mamori, Naoya Fukushima, Makoto Yamamoto, and Kozo Fujii (Tokyo Univ. of Sci., Katsushika-ku, Tokyo, Japan)

Strong acoustic waves emitted from rocket plumes may cause damage to fragile rocket payloads. Therefore, it is important to predict the noise’s acoustic directivity and reduce its intensity level. In this study, we conduct experiments of supersonic jet flows and investigate an influence of the nozzle geometry on acoustic waves by means of Schlieren method and microphone measurement. Three different nozzles are examined: a conical nozzle, a convergent-divergent nozzle (referred as C-D nozzle), and a tab-C-D nozzle. Tabs are equipped in the nozzle inside and additional turbulence is generated in the tab-C-D nozzle case. The Schlieren visualization shows that the strong shock trains are observed in the potential core of the jet for the conical nozzle case, while the shock waves are relatively weak since the nozzles are in the nearly ideal expanded condition in the C-D nozzle and tab-C-D cases. The distribution of near field OASPL (over all sound pressure level) obtained by microphone measurement shows strong directivity in the downstream direction for all the cases. This directivity seems to be due to the Mach wave radiation. Moreover, conical nozzle cases have strong acoustic intensity level caused by shock-associated noise.

2aPA5. Visualization movie analysis of acoustic phenomena of a supersonic jet and its comparison with intensity vectors.[5] Masahito Akamine, Koji Okamoto (Graduate School of Frontier Sci., Univ. of Tokyo, Kashiwanoha 5-1-5, Okamoto lab., Dept. of Adv. Energy, Graduate

School of Frontier Sci., Kashiwa, Chiba 277-8561, Japan, akamine@thermo.t.u-tokyo.ac.jp), Kent L. Gee, Tracianne B. Neilsen (Dept. of Phys. and Astronomy, Brigham Young Univ., Provo, UT), Susumu Teramoto, Takeo Okunuki (Graduate School of Eng., Univ. of Tokyo, Bunkyo-ku, Tokyo, Japan), and Seiji Tsutsumi (Japan Aerosp. Exploration Agency, Sagamihara, Kanagawa, Japan)

The authors have studied the acoustic wave from an unheated, Mach 1.8 ideally expanded jet by using the acoustic intensity vector measurement and analysis of high-speed schlieren visualization movies (for example, the Fourier transform and wavelet-based conditional sampling). Both these techniques reveal the characteristics of the acoustic wave, such as the propagation direction and location of a source region. These techniques have their own advantages: the quantitative data can be obtained by using the acoustic intensity vector measurement, whereas the acoustic field, including a close region to the jet, can be visualized with high spatial resolution by using the Schlieren movie analysis. Therefore, their comparison is a meaningful approach to understand the acoustic phenomenon. This presentation compares these two techniques, describes the physical insight gained, and considers the advantage and disadvantage of each measurement technique.

2aPA6. Results of scale model acoustic tests using supersonic cold jets for H3 launch vehicle.[6] Wataru Sarae, Atsushi Sawada, Keita Terashima (JAXA, 2-1-1 Sengen, Ibaraki, Tsukuba 305-8505, Japan, sarae.wataru@jaxa.jp), Takanori Haga, Seiji Tsutsumi (JAXA, Kanagawa, Japan), Tatsuya Ishii (JAXA, Tokyo, Japan), and Tetsuo Hiraiwa (JAXA, Miyagi, Japan)

Acoustic test using Mach 2 cold jet was conducted for the H3 launch vehicle currently being developed in Japan. Effect of the clustered engines and the newly built movable launcher on the lift-off acoustics was investigated. The overall acoustic level taken by the far-field microphones did not show proportional increase in the number of engines, especially for the angles corresponding to the Mach wave radiation from the free jets. The observation here disagrees with the empirical prediction model, NASA SP-8072. Computational fluid dynamics was also employed to analyze the acoustic mechanism of clustered engines.

2aPA7. Comparison of spatial correlation parameters between full and model scale launch vehicles.[7] Clothilde Giacomoni (All Points Logistics, LLC, M.S. ER42, Bldg. 4203, Huntsville, AL 35812, clothilde.b.giacomoni@nasa.gov) and R. Jeremy Kenny (Marshall Flight Ctr., NASA, Huntsville, AL)

The current vibro-acoustic analysis tools require specific spatial correlation parameters as input to define the liftoff acoustic environment experienced by the launch vehicle. Until recently, these parameters have not been very well defined. A comprehensive set of spatial correlation data were obtained during a scale model acoustic test conducted in 2014. From these spatial correlation data, several parameters were calculated: the decay coefficient, the diffuse to propagating ratio, and the angle of incidence. Spatial correlation data were also collected on the EFT-1 flight of the Delta IV vehicle which launched on December 5, 2014. A comparison of the spatial correlation parameters from full-scale and model-scale data will be presented.

2aPA8. Intensity-based laboratory-scale jet noise source characterization using the phase and amplitude gradient estimator method.[8] Kent L. Gee, Tracianne B. Neilsen, Eric B. Whiting, Darren K. Torrie (Dept. of Phys. and Astronomy, Brigham Young Univ., N243 ESC, Provo, UT 84602, kentgee@byu.edu), Masahito Akamine, Koji Okamoto (Graduate School of Frontier Sci., Univ. of Tokyo, Kashiwa, Chiba, Japan), Susumu Teramoto (Graduate School of Eng., Univ. of

Tokyo, Bunkyo-ku, Japan), and Seiji Tsutsumi (Japan Aerosp. Exploration Agency, Sagamihara, Kanagawa, Japan)

A new method for the calculation of vector acoustic intensity from pressure microphone measurements has been applied to the aeroacoustic source characterization of an unheated, Mach 1.8 laboratory-scale jet. Because of the ability to unwrap the phase of the transfer functions between microphone pairs in the measurement of a broadband source, physically meaningful near-field intensity vectors are calculated up to the maximum analysis frequency of 32 kHz. This result improves upon the bandwidth of the traditional cross-spectral intensity calculation method by nearly an order of magnitude. The new intensity method is used to obtain a detailed description of the sound energy flow near the jet. The resulting intensity vectors have been used in a ray-tracing technique to identify the dominant source region over a broad range of frequencies. Additional aeroacoustics analyses provide insight into the frequency-dependent characteristics of jet noise radiation, including the nature of the hydrodynamic field and the sharp transition between the Mach wave and sideline radiation.

2aPA9. Spatial variation in similarity spectra decompositions of a Mach 1.8 laboratory-scale jet.[9] Aaron B. Vaughn, Tracianne B. Neilsen, Kent L. Gee (Phys. and Astronomy, Brigham Young Univ., Brigham Young University, C-110 ESC, Provo, UT 84602, aaron.burton.vaughn@gmail.com), Koji Okamoto, and Masahito Akamine (Adv. Energy, Univ. of Tokyo, Kashiwa, Japan)

The primary source of noise from supersonic jets is turbulent mixing noise. Tam et al. [AIAA Paper 96-1716 (1996)] proposed similarity spectra for a two-source model of turbulent mixing noise corresponding to noise from omnidirectional fine-scale turbulence structures and directional largescale turbulent structures. These empirical similarity spectra have been compared with reasonable success to the spectra of both military and laboratory-scale jets. Most applications have looked at the variation in angle: fine-scale similarity spectra match at the sideline of the jet nozzle, large-scale spectra agree in the maximum radiation lobe, and a combination of the two spectra is needed in between. A similarity spectra decomposition of noise from an ideally expanded, Mach 1.8 laboratory-scale jet allows for a spatial comparison between the near and far-field spectra. The sound from the convergent-divergent nozzle was collected at the Hypersonic and High-Enthalpy Wind Tunnel at Kashiwa Campus of the University of Tokyo at a variety of near, mid, and far field locations. Comparison of similarity spectra decompositions over distance yield insights into the sound propagation from this supersonic jet. In addition, results from a preliminary wavenumber eduction technique to build a wavepacket-based equivalent source model of the large-scale turbulent mixing noise. [Work supported by Office of Naval Research grant.]

2aPA10. Far-field acoustical measurements during QM-2 solid rocket motor static firing.[10] Brent O. Reichman, Tracianne B. Neilsen, (Brigham Young Univ., 453 E 1980 N, #B, Provo, UT 84604, brent.reichman@byu. edu), Won-Suk Ohm (Yonsei Univ., Seoul, South Korea), Blaine M. Harker and Kent L. Gee (Brigham Young Univ., Provo, UT)

The five-segment Space Launch System solid rocket motor was recently tested at Orbital ATK. Far-field acoustical measurements were performed at angles between 80 and 120 relative to the rocket exhaust at a distance of roughly 2500 m from the rocket, approximately 800 nozzle diameters. The angular aperture allows for evaluating spatial variation in acoustic properties and a comparison with similar tests in the past, including the 2015 test of the same rocket motor. Although terrain variations introduce uncertainty, an approximate 10 dB change in level is seen throughout the aperture, consistent with previous studies. In addition, at low frequencies a high degree of correlation is seen. Near the peak radiation direction high levels of derivative skewness indicate significant shock content and crackle. This dataset also presents the opportunity to test a new method for processing acoustic vector intensity [Thomas et al., JASA 137, 3366-3376 (2015)]. Comparison with the traditional method shows an increase in usable bandwidth of more than an order of magnitude.

2pPA1. Liftoff and time equivalent duration data evaluation of exploration flight test 1 Orion multi-purpose crew vehicle.[11] Janice Houston (Fluid Dynam., NASA Marshall Space Flight Ctr., Bldg. 4203, Huntsville, AL 35812, janice.d.houston@nasa.gov)

The liftoff phase induces high acoustic loading over a broad frequency range for a launch vehicle. These external acoustic environments are used in the prediction of the internal vibration responses of the vehicle and components. There arises the question about time equivalent (Teq) duration of the liftoff phase and similarity to other launch vehicles. Vibroacoustic engineers require the fatigue-weighted time duration values for qualification testing inputs. In order to determine the Teq for the Space Launch System, NASA’s newest launch vehicle, the external microphone data from the Exploration Flight Test 1 (EFT-1) flight of the Orion Multi-Purpose Crew Vehicle (MPCV) was evaluated. During that evaluation, a trend was observed in the data, and the origin of that trend is discussed in this paper. Finally, the Teq values for the EFT-1 Orion MPCV are presented.

2pPA2. Development of aero-vibro acoustics methods for predicting acoustic environment inside payload fairing at lift-off.[12] Seiji Tsutsumi, Shinichi Maruyama (JEDI Ctr., JAXA, 3-1-1 Yoshinodai, Chuuou, Sagamihara, Kanagawa 252-5210, Japan, tsutsumi.seiji@jaxa.jp), Wataru Sarae, Keita Terashima (JAXA, Tsukuba, Japan), Tetsuo Hiraiwa (JAXA, Kakuda, Japan), and Tatsuya Ishii (JAXA, Chofu, Japan)

Prediction of harmful acoustic loading to payloads inside launcher fairing due to intense acoustic wave generated from propulsion systems at lift-off is an important design issue. Aero-vibro acoustics method developed in this study for predicting the acoustic loading consists of four elements. Hydrodynamics of the jet flow-field that generates the aeroacoustic wave is computed by the high-fidelity large-eddy simulation. Computational aeroacoustics based on the full Euler equations is conducted to simulate propagating acoustic wave from the jet to the payload fairing. Then, finite element method is applied to simulate the structural vibration that radiates acoustic wave inside the fairing. Finally, acoustic behavior inside the payload fairing is also computed by the finite element method. An overview of the methods and recent work for validation and verification will be presented.

2pPA3. Large eddy simulations of acoustic waves generated from hot and cold supersonic jets at Mach 2.0.[13] Hiroaki Nakano (Mech. Eng., Tokyo Univ. of Sci., 6-3-1,Nijuku, Katsushika, Tokyo 125-8585, Japan, nakano@flab.isas.jaxa.jp), Taku Nonomura, Akira Oyama (Inst. of Space and Astronautics Sci., JAXA, Sagamihara, Japan), Hiroya Mamori, Naoya Fukushima, and Makoto Yamamoto (Mech. Eng., Tokyo Univ. of Sci., Katsushika, Japan)

Strong acoustic waves are generated from the rocket plumes in the supersonic jet condition. The acoustic waves are significantly affected by temperature of jets. In this study, we perform large eddy simulations of the acoustic waves generated from the hot and cold jets. The temperature ratio of chamber to ambient air is set to be 4.0 and 1.0 for the hot and cold jets, respectively. Mach waves are radiated from the region close to the nozzle exit. In the hot jet case, we confirmed that the shorter potential core length, the larger angle of Mach waves, and the higher sound pressure level, as compared with those in the cold jet case.

2pPA4. Quantitative evaluation of the acoustic waves generated by a supersonic impinging jet.[14] Daisuke Kato (Aeronautics and Astronautics, Univ. of Tokyo, Yoshinodai, Sagamihara, Kanagawa 2520206, Japan, dkato@flab.isas.jaxa.jp), Taku Nonomura, and Akira Oyama (Japan Aerosp. Exploration Agency, Sagamihara, Japan)

Strong acoustic waves are generated when rockets launch. The accurate prediction of these acoustic waves is important for the design of the rocket launch site because the acoustic waves may possibly damage the payload. However, it is difficult for numerical simulations to predict accurately because the numerical simulation overestimates the strength of acoustic wave by several decibels compared to that observed in the experiment. The objective the present study is to obtain the knowledge for quantitative evaluation of the acoustic waves generated from supersonic impinging jet. According to the free-jet studies, the reason for difference between numerical simulations and experiments in acoustic field is considered to be turbulence intensity in nozzle exit. Thus, the flow inside the nozzle is calculated, and together with the turbulent disturbance, is added to the boundary layer. In the numerical simulation, three-dimensional compressible Navier-Stokes equations are solved with the high resolution shock capturing scheme (WCNS).

2pPA5. Modeling the generation of supersonic turbulent jet noise by large-scale coherent structures.[15] Oliver T. Schmidt, Tim Colonius (MCE, California Inst. of Technol., 1200 E California Blvd., MC 104-44, Pasadena, CA 91125, oschmidt@caltech.edu), and Guillaume A. Brés (Cascade Technologies, Inc., Palo Alto, CA)

Large-scale coherent structures, or wavepackets, are a salient feature of turbulent jets, and the main source of jet mixing noise at aft angles. They are extracted from a high-fidelity Mach 1.5 LES database as spectral POD mode estimates. These most energetic wavepackets obtained via POD and their acoustic far-field radiation patterns are compared to solution to the one-way Euler (OWE) equations recently introduced by Towne & Colonius (AIAA Paper 2013-2171, 2013; AIAA Paper 2014-2903, 2014). Within the OWE framework, the linearized Euler equations are modified such that all upstream propagating acoustic wave components are removed from the solution. The resulting spatial initial value problem can be solved in a stable and computationally efficient manner by downstream marching the solution. Additionally, the scenario of stochastic forcing of wavepackets by the surrounding turbulence is considered in a resolvent analysis. The resolvent analysis allows for the computation of optimal forcing distributions and corresponding responses. It is based on a singular value decomposition of the transfer function of the governing linear operator. The results of the both methods, OWE and resolvent analysis, are compared to the most energetic POD modes with a special focus on far-field radiation patterns and computational efficiency.

2pPA6. Self-similarity of level-based wavepacket modeling of high-performance military aircraft noise.[16] Tracianne B. Neilsen, Kent L. Gee, Blaine M. Harker (Brigham Young Univ., N311 ESC, Provo, UT 84602, tbn@byu.edu), Alan T. Wall (Battlespace Acoust. Branch, Air Force Res. Lab., Wright-Patterson AFB, OH), and Michael M. James (Blue Ridge Res. and Consulting, LLC, Asheville, NC)

Construction of the equivalent acoustic source model for high-performance military aircraft noise presented in this paper begins with a decomposition of sound levels, from ground-based microphones 11.7 m from a highperformance military aircraft, into portions matching the similarity spectra associated with large-scale and fine-scale turbulent mixing noise (LSS and FSS). [Tam et al. AIAA Paper 96-1716 (1996)]. A Fourier transform of the spatial distribution of the decomposed levels yields frequency-dependent wavenumber spectra [Morris, Int. J. Aeroacoust. 8, 301-316 (2009)]. Each LSS-educed wavenumber spectrum corresponds to a wavepacket, consisting of a spatially varying amplitude distribution with a constant axial phase relationship. This wavepacket model produces a directional, coherent sound field. However, the asymmetry in the LSS-educed wavenumber spectra may indicate that a nonuniform phase relationship is a more physical choice that could be correlated to the axial variation in convective speed. The FSS component is modeled with a line of incoherent monopoles whose amplitude distribution is related to the FSS-educed wavenumber spectrum. While this level-based model is limited, the addition of the FSS-related source yields a better match to the noise environment of a high-performance military aircraft than is found using a single coherent wavepacket. [Work supported by ONR.]

2pPA7. Wavepacket source modeling of high-performance military aircraft jet noise from cross-beamforming analysis.[17] Blaine M. Harker, Kent L. Gee, Tracianne B. Neilsen (Dept. Phys. & Astronomy, Brigham Young Univ., N283 ESC, Provo, UT 84602, blaineharker@gmail.com), and Michael M. James (Blue Ridge Res. and Consulting, LLC, Asheville, NC)

Wavepacket models provide a convenient representation of jet noise source phenomena because of the extended, partially correlated nature of the turbulent mixing noise. When treated as an equivalent source model, they are useful to estimate features of both the radiated noise as well as the source characteristics to assist in jet noise reduction efforts. In this study, advanced cross-beamforming techniques are applied to measurements in the vicinity of a high-performance military aircraft. These results are then decomposed into an azimuthally-averaged multi-wavepacket representation of the data, which can then be treated as an equivalent source. Estimates of the field levels and coherence properties using the equivalent source are compared with measurements, and results from the multi-wavepacket model show good agreement with benchmark measurements over a range of frequencies that contribute significantly to the overall radiation. The capabilities and limitations of the model to estimate field properties are quantified with respect to benchmark measurements in the mid and far fields as a function of frequency. Results indicate that the multi-wavepacket representation is an improvement over single-wavepacket models, which do not incorporate spatiotemporal features of the radiation. [Work supported by ONR and USAFRL through ORISE.]

2pPA8. Azimuthal coherence of the sound field in the vicinity of a high performance military aircraft.[18] Kevin M. Leete (Phys. and Astronomy, Brigham Young Univ., Provo, UT 84604, kevinmatthewleete@gmail.com), Alan T. Wall (Battlespace Acoust. Branch, U.S. Air Force Rersearch Lab., Dayton, OH), Kent L. Gee, Tracianne B. Neilsen, Blaine M. Harker (Phys. and Astronomy, Brigham Young Univ., Provo, UT), and Michael M. James (Blue Ridge Res. and Consulting LLC, Asheville, NC)

Mixing noise from a jet engine originates from an extended spatial region downstream of the nozzle and is partially correlated both spatially and temporally. Previously, the coherence properties in the downstream (axial) direction of the sound field of a tethered military aircraft were investigated, resulting in the identification of different spatial regions based on coherence length [B. M. Harker et al., AIAA J. 54, 1551-1566 (2016)]. In this study, a vertical array of microphones to the side of the jet plume is used to obtain the azimuthal coherence of the sound field. Although multipath interference effects and a limited angular aperture make coherence length calculation impossible, information about upper and lower bounds can be extracted. The measured azimuthal coherence as a function of downstream distance and frequency is then compared to that predicted by sound field reconstructions using multisource, statistically optimized near-field acoustical holography (M-SONAH) [A. T. Wall et al., J. Acoust. Soc. Am., 139, 1938-1950 (2016)]. This comparison helps to benchmark the performance of a reduced-order M-SONAH algorithm that employs only axisymmetric cylindrical basis functions to represent the direct and image sound fields. [Work supported by USAFRL through ORISE (2016).]

2pPA9. In defense of the Morfey-Howell Q/S as a single-point nonlinearity indicator: An impedance-based interpretation.[19] Won-Suk Ohm (School of Mech. Eng., Yonsei Univ., 50 Yonsei-ro, Seodaemun-gu, Seoul 120-749, South Korea, ohm@yonsei.ac.kr), Kent L. Gee, and Brent O. Reichman (Dept. of Phys. and Astronomy, Brigham Young Univ., Provo, UT)

Since the Morfey-Howell Q/S was proposed as a nonlinearity indicator for propagation of intense broadband noise [AIAA J. 19, 986-992 (1981)], there has been considerable debate as to its meaning and utility. Perhaps the most contentious argument against Q/S is about its validity as a single-point nonlinearity indicator: the importance of nonlinearity is often judged by observing cumulative effects over some propagation distance, whereas Q/S is based on a pressure waveform at a single location. Studies to address these criticisms have emerged over the years, most recently by Reichman et al. [J. Acoust. Soc. Am. 139, 2505-2513 (2016)] in support of Q/S. In this talk we show that the Burgers equation (from which the Q/S was originally derived) can be recast in terms of specific impedance, linear absorption and dispersion coefficients, and normalized quadspectral (Q/S) and cospectral (C/S) densities. The resulting interpretation is that Q/S and C/S represent the additional absorption and dispersion, introduced by the passage of a fi- nite-amplitude wave to the existing linear absorption and dispersion. In other words, a nonlinear wave process alters the apparent material properties of the medium, the extent of which can be used as a single-point indicator of the relative strength of nonlinearity.

2pPA10. Near-field array measurements of F-35 aircraft noise.[20] Alan T. Wall (Battlespace Acoust. Branch, Air Force Res. Lab., Bldg. 441, Wright-Patterson AFB, OH 45433, alantwall@gmail.com), Kent L. Gee, Tracianne B. Neilsen, Kevin M. Leete (Brigham Young Univ., Provo, UT), Michael M. James (Blue Ridge Res. and Consulting, Asheville, NC), and Richard L. McKinley (Battlespace Acoust. Branch, Air Force Res. Lab., Wright-Patterson Air Force Base, OH)

Noise source measurement and modeling efforts are being conducted for current and future generations of high-performance military aircraft. A near- field microphone array was used in a noise measurement of F-35A and F- 35B aircraft at Edwards Air Force Base in 2013 in order to extract source models. The two aircraft measured were tethered to the ground on a concrete run-up pad. The array consisted of 76 sensors, spanned 32 m, and was placed on the ground approximately 7 m from the jet plume. The engines operated over a full range of power settings from idle through full afterburner. In preparation for the execution of source modeling efforts, these near-field data are explored and compared to far-field data published previously [James et al., AIAA Paper 2015-2375]. [Work supported by USAFRL through F-35 JPO.]

2pPA11. Noise measurements of the F-35C on an aircraft carrier flight deck.[21] Nourhan K. Abouzahra, Alan T. Wall, Richard L. McKinley, Billy J. Swayne (Air Force Res. Lab., 2610 Seventh St. Bldg. 441, Wright-Patterson AFB, OH 45433, nourhan.abouzahra.ctr@us.af.mil), Michael J. Smith, and Allan C. Aubert (NAVAIR, Patuxent River Naval Air Station, MD)

In 2015, scientists from the Air Force Research Laboratory (AFRL) in collaboration with other teams performed noise measurements of the F-35C aircraft aboard a Nimitz-class carrier. The purpose of the measurements was to quantify the crewmembers' exposure to noise. The measurements were taken using hand-held noise recorder systems, and the recording engineers shadowed actual locations of crew. The near-field noise levels caused by aircraft are reported in the areas experienced by crew on board aircraft carriers. High noise levels can interfere with communications and may pose a risk for hearing loss. These data represent a unique measurement; the previous measurement of aircraft noise from catapult launches and wire arrestments aboard a carrier occurred more than 15 years ago.

2pPA12.[22] **Nonlinear characteristics of F-35 flyover waveforms.** Brent O. Reichman, Kent L. Gee, Tracianne B. Neilsen (Brigham Young Univ., 453 E 1980 N, #B, Provo, UT 84604, brent.reichman@byu.edu), and Sally A. McInerny (Univ. of Louisiana at Lafayette, Lafayette, LA)

Metrics indicating the presence of acoustic shocks are calculated from noise measurements of F-35 aircraft during flyover operations. The sound pressure level, average steepening factor, and skewness of the first time derivative of the pressure waveform are calculated for the A and B variants of the aircraft. Other metrics more specific to flyover measurements are also shown. Comparisons of nonlinear indicators are made between engine thrust conditions, aircraft type, microphone height, microphone size, and sampling rate. Nonlinear indicators are also compared against other full-scale military aircraft. Comparisons are made with similar conditions during ground run-up operations.

REFERENCES

[1] J. Acoust. Soc. Am. **140**, 3042 (2016); http://doi.org/10.1121/1.4969446.
[2] J. Acoust. Soc. Am. **140**, 3422 (2016); http://doi.org/10.1121/1.4971011.
[3] J. Acoust. Soc. Am. **140**, 3042 (2016); http://doi.org/10.1121/1.4969448.
[4] J. Acoust. Soc. Am. **140**, 3043 (2016); http://doi.org/10.1121/1.4969449.
[5] J. Acoust. Soc. Am. **140**, 3043 (2016); http://doi.org/10.1121/1.4969450.
[6] J. Acoust. Soc. Am. **140**, 3043 (2016); http://doi.org/10.1121/1.4969451.
[7] J. Acoust. Soc. Am. **140**, 3043 (2016); http://doi.org/10.1121/1.4969452.
[8] J. Acoust. Soc. Am. **140**, 3044 (2016); http://doi.org/10.1121/1.4969453.
[9] J. Acoust. Soc. Am. **140**, 3044 (2016); http://doi.org/10.1121/1.4969454.
[10] J. Acoust. Soc. Am. **140**, 3044 (2016); http://doi.org/10.1121/1.4969455.
[11] J. Acoust. Soc. Am. **140**, 3096 (2016); http://doi.org/10.1121/1.4969653.
[12] J. Acoust. Soc. Am. **140**, 3096 (2016); http://doi.org/10.1121/1.4969654.
[13] J. Acoust. Soc. Am. **140**, 3097 (2016); http://doi.org/10.1121/1.4969655.
[14] J. Acoust. Soc. Am. **140**, 3097 (2016); http://doi.org/10.1121/1.4969656.
[15] J. Acoust. Soc. Am. **140**, 3097 (2016); http://doi.org/10.1121/1.4969657
[16] J. Acoust. Soc. Am. **140**, 3097 (2016); http://doi.org/10.1121/1.4969658.
[17] J. Acoust. Soc. Am. **140**, 3097 (2016); http://doi.org/10.1121/1.4969659.
[18] J. Acoust. Soc. Am. **140**, 3098 (2016); http://doi.org/10.1121/1.4969660.
[19] J. Acoust. Soc. Am. **140**, 3098 (2016); http://doi.org/10.1121/1.4969661.
[20] J. Acoust. Soc. Am. **140**, 3098 (2016); http://doi.org/10.1121/1.4969662.
[21] J. Acoust. Soc. Am. **140**, 3098 (2016); http://doi.org/10.1121/1.4969663.
[22] J. Acoust. Soc. Am. **140**, 3098 (2016); http://doi.org/10.1121/1.4969664.