Introduction to the special issue on supersonic jet noise

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JASA EDITORIAL

Introduction to the special issue on supersonic jet noise[a)]

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ABSTRACT:
This editorial's goals are (1) to highlight a few key developments in supersonic jet and launch vehicle noise research over the past several decades while describing some of the critical modern requirements facing government and industry organizations and (2) to summarize the contributions of the articles in this Supersonic Jet Noise special issue in the context of these developments and requirements.
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I. INTRODUCTION

The program of the 159th Meeting of the Acoustical Society of America (ASA), held in Baltimore, MD in 2010, included special sessions related to supersonic jet and launch vehicle noise. Although jet noise sessions at ASA Meetings had been common in the 1950s and 1960s, aeroacoustics research had mostly moved to other scientific communities, and it had been decades since one had been held. Returning an emphasis to the ASA was a deliberate effort to unify researchers interested in different aspects of jet noise, including its generation, radiation, propagation, reception, and reduction of impact.

Since that 2010 gathering, additional sessions have been held essentially annually (e.g., Gee *et al.*, 2017b; Gee *et al.*, 2017a; Lubert *et al.*, 2018) and have brought together government, academic, and industry researchers from around the world—the United States, South Korea, Japan, Saudi Arabia, India, United Kingdom, France, Spain, and Italy. [These sessions were supplemented by an Acoustics Today article (Gee *et al.*, 2013) on jet noise from tactical aircraft.] More importantly, however, these sessions have begun to reconnect research communities ("jet noise" and "rocket noise") that had held common aims in the 1950s and 1960s but notably drifted apart in the 1970s, perhaps as new research and development into rocket noise waned after the Apollo program. As mentioned, these sessions have also brought together people who approach supersonic jet noise from different backgrounds—from the fluid dynamicist to the acoustician whose interest and expertise intersect within the field of aeroacoustics.

Motivations for studying supersonic jet noise have differed by community. Regarding aircraft-related supersonic jet noise research, the principal reason has been jet noise reduction (JNR) of high-thrust, low-bypass ratio engines. For aircraft maintainers and ground personnel, noise-induced hearing loss is a persistent, pervasive, and costly problem. For communities, JNR is desired to minimize disturbance and annoyance. However, finding practical JNR solutions has been challenging, particularly for military applications because of the need to maximize engine thrust for tactical advantages. In the area of space launch vehicles, the study of highly heated, supersonic rocket plumes is motivated by several aspects of launch noise, from vibroacoustic loading of payloads, the vehicle, and launch pad structures, to far-field noise radiation and associated environmental impacts.

Despite different motivations for studying supersonic jets, the exhausts from laboratory-scale nozzles, aircraft engines, liquid-fuel rocket engines, and solid-fueled rocket motors have similarities and ought to share some noise-generation commonalities. Although they may involve a range of Mach numbers, temperatures, and fuel compositions, the jets generate turbulence with length scales that change with distance and which convect supersonically downstream. Potential cores, supersonic and subsonic mixing layers, shear layers, and shock cells can all play into jet structure and possibly noise radiation. Speaking of noise radiation, Mach wave generation is an important noise source that differs from subsonic jets. Mach wave radiation appears to be responsible for the most intense noise radiation from supersonic jet engines and rockets. Because of the possible similarities and overlap in noise radiation mechanisms, it makes sense to seek improved physical understanding of, and models for, a broader set of supersonic jets. A proper understanding of the effects of, e.g., velocity,

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pressure ratio, temperature, nonideal expansion, and installation effects for real engines over a more universal range of conditions can only help improve potential for JNR, now and in the future.

The call for papers for this special issue was announced in 2019 at the supersonic jet and launch vehicle noise sessions and at a JNR workshop held at the 178th ASA meeting in San Diego (Wall, 2019). In addition to this editorial, the issue consists of 19 regular research articles, a historical review of supersonic jet noise research conducted at NASA, a review article about supersonic jet noise from launch vehicles, and a letter to the editor about historical supersonic jet noise research. The author demographics were diverse, coming from North and South America, Europe, Asia, and Australia, and participating from industry (Cascade Technologies and Blue Ridge Research and Consulting), government [NASA, the United States Air Force Research Laboratory (AFRL) the French aerospace lab ONERA, France's National Centre for Space Studies (CNES), and the Japan Aerospace Exploration Agency (JAXA)], and many universities.

The special issue coverage is also diverse: among the 22 articles are discussed a wide variety of topics from numerical modeling to laboratory-scale measurements, with six articles specifically describing full-scale experiments and analyses. Five articles also discuss launch vehicle noise. To help identify common topics throughout the issue, a word cloud generated from all 22 publications (appropriately in the shape of an F-22) is shown in Fig. 1. It is noteworthy that, despite the topics being in the call for papers, this issue did not produce articles whose focus was far-field propagation, reception, or perception of supersonic jet noise aside from Mobley *et al*. (2021). This may point to a dearth of important research related to the broad challenge of assessing true impacts from supersonic jet noise reduction for existing and future tactical aircraft, possible commercial supersonic aircraft, and the escalating challenge of increased launch vehicle noise.

The remainder of this introductory paper to the special issue describes different themes for supersonic jet noise research that are then used to loosely categorize the publications. These categories include historical background, modern jet noise requirements, methods to represent or characterize jet noise, sources of jet noise, nonlinearity, and jet noise reduction. The introduction to the special issue concludes with a forward-looking perspective on supersonic jet noise from aircraft engines and rockets. As guest editors, we thank the JASA publication staff for their dedication and competence, the authors for their excellent contributions, and the readers, for their interest in learning about this important challenge and ongoing research activities.

II. HISTORICAL BACKGROUND

Studies of supersonic jet noise phenomena, modeling, measurement, and control have a rich history, from the 1950s through today. Although much of the jet aeroacoustics research has come from the community connected to the American Institute of Aeronautics and Astronautics, many early descriptions of supersonic jet noise came from ASA publications, such as those by Franken (1958), Mull (1959), and Ribner (1959). Additionally, several publications from this early era of supersonic jet noise research, including those by Franken, Ribner, and Ffowcs Williams (1963),

FIG. 1. (Color online) Word cloud from the special issue articles.

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made explicit efforts to connect supersonic jet flows across different regimes, from laboratory-scale cold jets, to turbojets, to rockets. As an example of the early literature and efforts at scaling, Franken (1958) made analytical arguments as to the acoustic efficiency of different jets, along with ranges for available data, from air jets to large rockets. His figure, reproduced here as Fig. 2, suggests a theoretical limit of 1% for radiation efficiency of a supersonic jet. The idea of radiation efficiency is discussed in this special issue by Lubert *et al.* (2022) and Mathews *et al.* (2021) in the context of launch vehicles (for which the radiation efficiency is believed to be about 0.5%) and by Prasad and Morris (2021) in the context of Mach wave noise reduction.

Three of the special issue articles have a historical bent. Collectively, they serve as a reminder of the wealth of jet noise studies that have been performed and that, often, new approaches have a related, historical foundation. First, Henderson and Huff (2021) describe decades-worth of research into jet noise and JNR at NASA. With 241 references and 29 figures, they provide a comprehensive review of numerous nozzle designs and other technologies that were built and tested, many of them at full scale. Many of the suppressor nozzles resulted in unacceptable thrust losses and were discarded. The program transitioned to focus on increasing bypass ratios and enhanced mixing for subsonic engines. For supersonic engines, JNR technologies were more challenging and continue to be investigated today, primarily motivated by the reinvigoration of supersonic transport.

The other review article (Lubert *et al.*, 2022) describes what has been learned, and in some cases forgotten, about rocket noise in the five decades since the release of NASA SP-8072 (Eldred, 1971) with its empirical methods for calculating rocket noise radiation. Reviewed are the physics associated with noise radiated from undeflected and impinging plumes, including noise source origin, the radiated noise spectrum, and directivity. In addition, noise mitigation and modeling are discussed. Ties to other jet experiments and models are made, helping to hopefully point to future

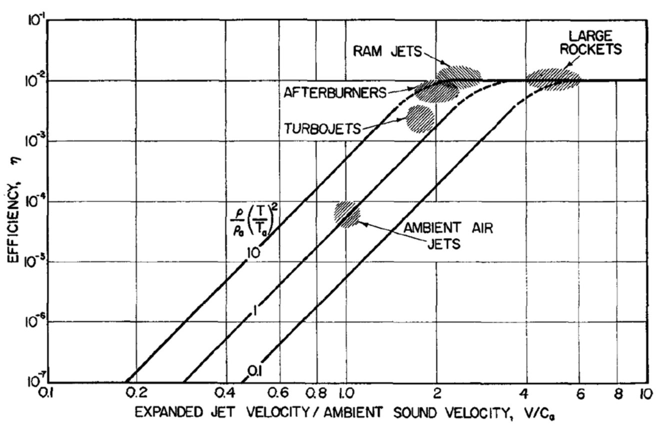

FIG. 2. A reproduction of Fig. 11 from Franken (1958), showing the acoustic efficiency, η, of different jets in terms of an ambient Mach number. Curves represent different ambient and jet densities and temperatures, with a theoretical limit on efficiency of 0.01 (1%).

research directions that overcome the considerable limitations of the SP-8072-based prediction methods.

The final "historical" study is by Gee (2021) who, while working on a section for Lubert *et al.* (2022), discovered that an oft-used axial sound power distribution curve for rockets in NASA SP-8072 was different than a supposedly identical curve in a contemporaneous jet noise paper. The inconsistency was traced to two different plots in the original report that described an experiment to decompose the radiated sound power from a supersonic jet along its axis. The correct plot appears to have been the one adopted by the jet noise community, indicating that rocket noise researchers have been using an erroneous result for decades when implementing SP-8072 models. This has caused them to mistakenly ascribe much of the radiated power from the jet to the subsonic, rather than supersonic, flow. One lesson from this short study is the importance of occasionally returning to original source documents to understand their methods, assumptions, and results on a deeper level. A second lesson, or perhaps cautionary tale, is that this critical error certainly would have not gone undetected for over a half-century had the jet and rocket noise communities seen more overlap.

III. MODERN REQUIREMENTS

Requirements for jet noise research and reduction differ for aircraft and launch vehicles. However, the day-night level (DNL) has been specified by Federal Aviation Administration (FAA) Order 1050.1 °F to be the standard metric for community noise impact analysis from both aircraft and launch vehicles. On the other hand, the Order also indicates that other supplemental metrics can be used as appropriate. There has been very little research done into whether DNL—which entirely eliminates the low-frequency, rumbly component of rocket noise—or other metrics are appropriate for determining the actual acoustical impact footprint for rockets on communities and the environment. It is likely that the increased launch tempos of space vehicles due to space transport commercialization and the shifting of military defense programs into the space arena (exemplified by the 2019 creation of the United States Space Force) will lead to an invigoration of public interest (and hopefully research programs) targeting noise impacts from rocket launches and landings. In addition, while DNL might be a fitting metric to describe the long-term average of noise impacts from regular flight schedules at civilian airfields, it largely misses the irregularity inherent in military flight training campaigns and in rocket flight schedules. To date, environmental impact statements (EIS) and environmental assessments (EA) continue to rely on overall and A-weighted level-based measures.

For aircraft engines, the progress of jet noise research and JNR technology development is motivated by the need to reduce noise exposures to personnel working in the vicinity of high-power engine runs; to reduce impacts on communities such as annoyance, sleep disturbance, and disruption of learning in schools; to improve the experience of visitors to national parks, wildlife refuges, and historic sites; and to protect wildlife (FICAN, 2018). The specific responses to these needs by civil transport and military organizations differ based on their distinct missions.

FAA regulations have evolved over the decades to enforce ever more stringent noise limits (stages) on aircraft noise output (14 CFR Part 36; CFR, 2021). The technology for increased fuel efficiency, such as increasing the bypass ratio to 10 or higher, has largely had a positive effect on noise reduction. Jet noise outputs of modern high-bypass engines have dropped to levels comparable to the noise generated by the airframe in flight, such that further JNR alone has negligible effect on the total aircraft noise output without the simultaneous reduction of airframe noise.

After the cancellation of the supersonic transport industry and a two-decade hiatus, NASA has been leading the effort to develop low-boom technologies that will result in a renewal of FAA approvals for commercial supersonic flight (e.g., see Carr *et al.*, 2020). The jet engines that power supersonic aircraft will require higher-thrust engines than their subsonic counterparts, with bypass ratios on the order of 3 or lower. This requirement brings the research needs of civilian transport in closer alignment with those of high-performance military aircraft.

United States Department of Defense (DoD) requirements do not include specific aircraft noise limits. The need for high-performance maneuvers in the execution of tactical missions leads to light-weight airframes and high specific thrust engines with bypass ratios of less than 1. In contrast to the trends in civilian aircraft noise reduction, jet noise emissions from fourth and fifth generation fighter aircraft have remained relatively constant since the 1980s. Some of the loudest work environments in the DoD are those of the "shooter" and final engine checker on an aircraft carrier, where noise levels of aircraft operating at full afterburner can momentarily exceed 150 dB prior to catapult launch.

Hearing loss and tinnitus are in the top three on the list of disabilities for which military veterans receive compensation by the United States Veterans Administration (VA), and yearly compensation costs are in the billions. (It should be noted that VA compensation statistics do not reflect the division of hearing disabilities across exposures to jet noise, other aircraft noise sources, impulse noise from ballistic weapons, and genetic predisposition to hearing loss, as such numbers are not tracked.) High-amplitude noise environments in the DoD have motivated the development of improved hearing protection devices, including active noise reduction, but human tissue conduction limits the effective attenuation of even the highest performing devices to 40–50 dB. In addition, such devices (usually consisting of combined earplugs and earmuffs mounted in a padded helmet) are rarely in operational use due to their expense and the limits they place on crew communications, so true attenuations typically plateau around 30 dB.

Although JNR technologies may not frequently be implemented on tactical fighter engines, the DoD does take extensive measures to characterize aircraft noise outputs, workplace environment exposures, and environmental impacts. For example, Mobley *et al.* (2021) demonstrated a measurement array and spatial interpolation method to characterize the noise exposure to ground crew personnel working in the vicinity of a fighter aircraft during ground engine run-ups. The locations of interest were too close to the airframe and too far forward of the main jet plume for the jet noise to be measured and modeled in isolation. Therefore, the microphone array was designed to capture installation effects including inlet noise and scattering from the airframe at specific crew worksites. Then, a nearest-neighbor interpolation with bilinear smoothing was performed as a straightforward way to quantify noise exposure metrics across the ground crew work area. This was proposed as the method of preference for future ground crew exposure data collection and modeling in accordance with DoD standards.

Public acceptance of noise from DoD mission training and military readiness exercises varies widely, from feelings of patriotism for the "sound of freedom" to protests against squadron basing and litigations against military airfields. Since higher bypass ratios are not a feasible solution for tactical aircraft engines, the focus of JNR is on nozzle designs that disrupt the most energetic flow noise sources while making little to no impact on the thrust performance.

IV. METHODS TO CHARACTERIZE JET NOISE

The special issue papers cover a wide range of topics, and each one emphasizes multiple overlapping methodologies, which makes it difficult to define strict categorical boundaries in which to segregate the papers. In this section, we attempt to emphasize papers that focus on methods to represent jet noise sources and propagation with the aim of creating tools for improved understanding. The papers here are grouped loosely into experimental, computational, and empirical techniques. In contrast, Sec. V focuses on papers that emphasize the results of such techniques—ones that demonstrate physical models and data that improve our understanding of jet noise sources and propagation.

A. Experimental

Physical sampling of jet flows and acoustic pressure waves can provide the most direct information about source generation and radiation. For example, JNR effectiveness is most reliably assessed during pre-treatment/post-treatment comparisons collected in controlled experiments with full-scale engines on test stands (ANSI S12.76; ANSI, 2017), installed engines, and aircraft in flight (ANSI S12.75; ANSI, 2012; Aujogue *et al.*, 2021). However, full-scale data collection with sufficient statistical confidence in measured level reductions is prohibitively costly during developmental stages, and is typically only feasible as a final assessment of a mature JNR technology ready for installation. In addition, some types of data commonly collected during laboratory-scale experiments cannot yet be feasibly obtained from the hot fast flows of operational jet engines and rockets.

Still, full-scale data collection opportunities do arise (Aujogue *et al.*, 2021; Henderson and Huff, 2021; Lubert *et al.*, 2022; Mathews *et al.*, 2021; Mobley *et al.*, 2021; Vaughn *et al.*, 2021), and these datasets provide rich opportunities for the investigation of multiple measurement and analysis techniques. Moderately sized experiments occasionally occur, (e.g., McLaughlin, 2019), but overall there seems to be a significant gap in the literature between the full-scale and the laboratory-scale datasets.

Small-scale mockups of free-field jet and rocket plumes are by far the most readily available datasets and represent a relatively inexpensive approach to test and evaluation of promising JNR technologies. The inclusion of scaled-down models of rocket launch pads, impingement surfaces like jet blast deflectors and rocket flame trenches, and physical objects that shield/scatter acoustic waves are sometimes included to represent the acoustics environments in which jets and rockets operate. However, it is an ongoing challenge to determine whether the JNR effects are scalable–that is, whether quantified noise reductions due to treatments of a smaller jet or other engineering controls applied to scaled mock-ups of an environment will result in the same noise reduction at full-scale.

Sampling of physical jet flows includes point measurements of multiple quantities of interest such as bulk convection velocity and dynamic velocity fluctuations, turbulent kinetic energy, and temperature. Many JNR solutions have benefitted from targeting spatially correlated/coherent flow features, which can be obtained from multi-point data collection techniques like schlieren photography and particle image velocimetry (PIV). The hydrodynamic and acoustic fields can similarly be represented, and their spatial coherence features leveraged for JNR evaluations, with phased-array acoustic imaging techniques like beamforming and near-field acoustical holography. In this special issue, Breen and Ahuja (2021) used both beamforming and schlieren photography to create images of noise source distributions in shock-containing jets. Gryazev *et al.* (2021) validated their computational aeroacoustics (CAA) predictions of broadband shock-associated noise (BBSAN) in highly underexpanded jets against PIV images as part of a larger work effort to generate a new database of computational models for highly supersonic jets that mirror a series of experimental data collections in the Supersonic Jet Facility at Monash University, Australia.

Microphone arrays placed in flow, such as in the hydrodynamic near field of a jet or flush-mounted in a wind tunnel, are subject to noise contamination from flow over the microphone or turbulent boundary layer fluctuations. Denoising techniques are often implemented on the cross correlation or cross-coherence matrices, which take advantage of strong acoustic correlations over short microphone separation distances. Aujogue *et al.* (2021) implemented a denoising method on a flush-mounted microphone array that collected data on the side of a fuselage during flight. Prior but uncertain knowledge of the noise correlation based on background noise measurements was coupled with Bayesian factor analysis to intelligently remove correlated noise contamination from the turbulent boundary layer. The denoised cross correlation matrix was then used to better quantify BBSAN from the jet engines during real world flight conditions in preparation for the future application of acoustic imaging of the engine noise.

B. Computational

With the emergence of increasingly powerful computers and efficient models, it is possible to represent the entire time-resolved compressible flow field and the acoustic field with computational fluid dynamics (CFD) simulations. Large-eddy simulation (LES) is a high-fidelity method commonly yielding results that are accurate when compared against experimental data (Bodony and Lele, 2006; Brès and Lele, 2019). However, the computational cost of doing so with sufficient fidelity for full-scale heated jets and rockets is still largely prohibitive. Compared to LES, Reynolds-Averaged Navier-Stokes (RANS) methods are typically lower cost (producing simulations within hours), and are therefore presently preferred to LES as a tool to aid jet engine design.

A full CAA simulation of the three-dimensional acoustic field for the purposes of modeling acoustic propagation to the far-field requires exceptionally large grids to cover the spatial extent of the field, resulting in high computational cost. Therefore, it is often desirable to limit the CAA computational space to the near field, after which acoustic propagation may be computed from the bounding surface surrounding the jet flow field (e.g., the Kirchhoff surface) with efficient techniques that use solutions of linearized propagation equations such as the Ffowcs-Williams and Hawkings (FWH) equation, the Lighthill equation, or other CAA methods. Resolvent analysis employs a reduced-order modal decomposition of the simulated hydrodynamic near field as a coherent source representation. The resolvent modes become a forcing term (the sources) to the full linearized Navier-Stokes equations, which are used to propagate the sound to the far field. In general, methods that do not require time-resolved information on the Kirchhoff surface bounding the jet are especially efficient.

In this special issue, Patel and Miller (2021) used the field variables output from steady RANS CFD models as arguments in decomposed Navier-Stokes equations for nozzle parameter sensitivity analyses. Adam *et al.* (2021) used RANS to investigate vortical and acoustic near-fields of three-steam jets, and used LES to validate the RANS-based models. They also used the LES to represent the source on a surface boundary between the rotational and irrotational fields.

Gryazev *et al.* (2021) simulated the BBSAN components of high-area-ratio underexpanded jets using both LES and RANS methods. They were simulated at the same conditions as those in a university laboratory and validated against measured PIV data, where the formation of a Mach disk was captured. Then, the reduced-order model from the

RANS solutions became the inputs to the Morris and Miller (2010) BBSAN model. The predicted noise levels were also compared against the experimental data and the NASA sJet model. An accuracy of 1–2 dB in the Strouhal number region of interest was shown.

In CAA (as well as in any research method), pristine nozzle and flow conditions may mask the effects of installation or scalability. For example, an accurate representation of the nozzle exit boundary layer has a large influence on the accuracy of LES results, and is therefore an area of intense scrutiny. In this special issue, Nonomura *et al.* (2021) demonstrated how pristine initial conditions at the nozzle exit may lead to overestimates of acoustic levels due to an inaccurate representation of the energy released in the transition from laminar to turbulent flow. They investigated some of the fundamental effects of initial conditions in an LES of a transitional jet by varying both shear layer thickness and flow disturbances at the nozzle exit. They showed that shear layer thickness affects the turbulent transition point and the energy of the turbulent fluctuations. They also showed an approximately 5 dB noise increase with an increase in shear layer thickness, but the increase in acoustic levels was less drastic for the supersonic jet than they were for its subsonic counterpart because the energy in the transition is dominated by a spiral mode in the supersonic case and by axisymmetric modes in the subsonic case. Therefore, careful consideration of the initial conditions is required to avoid unrealistic predictions of noise reduction when JNR effects are added.

C. Empirical

Analytical functions and empirical models of jet sources seek to encapsulate dominant acoustic features, such as sound power (source strength), directivity, spectral shape (Tam, 1987; Tam *et al.*, 2008), and spatial coherence into low-order, efficient representations, often with the intent of highlighting the most vulnerable targets for JNR. For example, wavepackets model group wave behaviors as either analytical functions or as the dominant modes from statistical decompositions of the full flow or acoustic fields (Jordan and Colonius, 2013).

Modal decompositions are a popular approach for modeling jet flow and acoustic fields. The techniques of principal component analysis (PCA), proper orthogonal decomposition (POD), partial field decomposition (PFD), Fourier decomposition, etc., are all used to represent jet noise sources or their radiated fields as a small number of dominant modal terms. It is a general rule that most of the flow or acoustic energy can be represented by the first few modes, but an increasing number of terms are required to maintain accuracy as frequency increases or in radiation directions away from peak directivity.

In PCA, where an eigenvalue approach is used to compress as much energy as possible into the fewest number of low-order terms, it is important to understand that the dominant eigenvalues (principal components) of flow fields do not directly cause the dominant principal components of the acoustic field. This is because of the relatively low acoustic efficiency of supersonic jet flows (roughly 0.1%–1%). Flow/acoustic mode coupling must be carefully considered when targeting the principal components of the flow for JNR purposes.

Some studies take advantage of simultaneous flow/acoustic field sampling and cross correlation/cross-coherence analyses to isolate the flow field sources that cause the dominant acoustic energies and vice versa. For example, resolvent analysis employs a singular value decomposition (SVD) of the linear resolvent operator to identify a set of orthogonal forcing functions and rank them according to their energy transfer into radiated noise. Pickering *et al.* (2021) generated a set of low-order resolvent modes as wavepackets from an LES database. These became the source terms to predict noise radiation. They found that one resolvent mode was sufficient to comprise the most energetic azimuthal modes for Strouhal numbers up to 1. They further collapsed the model to a set of coefficients for scaling the optimal modes, and were able to predict peak noise levels within 2 dB.

Chen and Towne (2021) performed an azimuthal Fourier transform on the solution to the FWH equation in the frequency domain to obtain azimuthal modes of the acoustic field that matched the FWH source terms. The resulting method directly obtains the individual azimuthal modes of the acoustic field from the azimuthal modes of the flow field inputs, avoiding the requirement for representing either in three-dimensional space. It was first validated using a monopole problem with an exact solution, and then with LES data of a Mach 1.5 jet.

Kleine *et al.* (2021) used the computationally efficient Parabolized Stability Equations (PSE) to obtain time-domain transfer functions between measured upstream inputs and downstream flow and predict the unsteady fluctuations that couple the fluid dynamic and acoustic fields. The results were reduced order wavepacket models of the dominant noise sources. The transfer functions and the predicted noise levels were validated against an LES. Such a relationship could be exploited for closed-loop control of jet noise emissions.

The emphases of empirical rocket noise models differ somewhat from jet engine noise models in the literature. Rocket noise source models are largely based on Apollo-program era understanding and were documented in NASA SP-8072 (Eldred, 1971). Eldred estimated that radiated sound power was bounded by a radiation efficiency between about 0.1% and 1% of the mechanical power of the rocket engine. [Figure 2 from Franken (1958) suggested those bounds with earlier data for jets ranging in size from turbojets through large rockets.] Although an order-of-magnitude change in efficiency is a 10 dB uncertainty in sound power level, recent measurements have placed the radiation efficiency range for heated, supersonic jets with growing precision toward the historically accepted value of ∼0.5%.

Models that predict the maximum overall sound pressure level (OASPL) from fundamental jet parameters

(Greska, 2008) have shown promise across both turbine engines and rockets. In contrast, while jet engines over a wide range of sizes and powers are characterized by a peak Strouhal number in the regime of 0.2, this is a poor predictor of noise peak frequencies, which are characterized by peak Strouhal numbers nearly an order of magnitude lower. There is also wide variation in rocket directives reported across the literature, with reported disagreements on peak directivity as high as 20°–25°. With modern datasets and more recent discoveries on the dominance of Mach wave radiation in supersonic jet noise sources, the influence of convective Mach number is becoming recognized as the driver for rocket noise directivity (Lubert *et al.*, 2022), yet questions remain.

Mathews *et al.* (2021) collected Falcon 9 first-stage launch noise during three launches and compared their measured and modeled values of multiple source metrics. First, their data confirmed a strong connection between convective Mach number and directivity when flight effects are considered. Second, overall sound power level appeared to agree with the historical ∼0.5% radiation efficiency model. Third, the maximum OASPL was well predicted by two separate empirical models. Last, they showed how incorporating more detailed flow characteristics into peak-frequency prediction models improved the model collapse where other datasets failed, and they provided some possible explanations for historical discrepancies. Barrier shielding models for terrain and nonlinear propagation models also showed promise.

V. JET NOISE SOURCES

The focus of this section is on the special issue papers that emphasize an improved physical understanding of jet noise generation mechanisms obtained through the implementation of techniques like the ones discussed in Sec. IV. For subsonic jets, noise sources are often described in the context of fine-scale and large-scale mixing noise. For laboratory-scale supersonic jets, new noise sources are created: Mach waves, BBSAN, and screech. Yet more sources are generated when a jet impinges on a hard surface. Most papers in this issue focus on one or two of these source types at a time. The reader is referred to reviews by Tam (1995), Morris and Viswanathan (2013), and Bailly and Fujii (2016) for further discussions of high-speed jet noise sources and characteristics.

The dominant acoustic energy radiated to the far field of highly heated supersonic jets is almost universally attributed to the supersonic convection of large vortical flow structures (large-scale turbulence), which produce (with high spatial coherence and relative efficiency) directional radiation downstream in the form of Mach waves. The importance of these features lead to many studies targeting the reduction of large-scale turbulent energy, often by slowing their convection velocity or inducing upstream decay of large-scale vortices into smaller vortices (enhanced mixing), as a principal approach to JNR.

BBSAN can be a dominant component of noise radiation in some jet flows as large-scale turbulence interacts with shock cells in the plume. It can be modeled as a series of periodic, spatially distinct sources at the locations of the shock fronts, where the convection velocity of large pressure disturbances passing through these fronts and the shock cell spacing determines the phase relationships (Harper-bourne and Fisher, 1973). BBSAN tends to radiate in the forward direction and is characterized by a distinctive spectral shape (Tam, 1987). The saturation of BBSAN with temperature (Miller, 2015) may explain why BBSAN is not observed in rocket noise (see discussion in Lubert *et al.*, 2022).

Although screech is important in laboratory-scale jets (Raman, 1998, 1999), it does not appear to be an important noise source in tactical jet engines or in rockets. However, screech-like resonances can appear in jet noise with impingement (Edgington-Mitchell, 2019). And, while screech-like phenomena have been discussed in conjunction with impinging rocket noise (Jiang *et al.*, 2019), it is unclear the extent to which these phenomena exist with actual rocket launches because strong tones have not been observed in launch data.

In this special issue, Wong *et al.* (2020) used azimuthal Fourier decomposition of measurements made by a traversable microphone array to model BBSAN as a series of azimuthal modes. They showed that the higher-order azimuthal modes were stronger for BBSAN than was the axisymmetric component. The required number of modes and their relative contributions depend on frequency and observer angle, with higher-order modes increasing in importance with increasing frequency.

In an experimental study of laboratory-scale jets, Breen and Ahuja (2021) used beamforming and schlieren photography to examine how noise source distributions to the sideline and forward region of supersonic jets are affected by changes in pressure ratio and nozzle exit diameter. They represented the jet in three Strouhal number regions. First, the region of low Strouhal number is dominated by fine-scale turbulence mixing noise. Second, a region of high Strouhal number is dominated by spatially distinct broadband sources that appear to be correlated to shock cell locations. The location of these sources, scaled by the jet diameter, appears to be dependent on the Mach number but independent of diameter. Last, in the mid-Strouhal region, the contributions from mixing noise and shock cell noise are roughly equal.

Three papers in the special issue deal with impinging jets (Krothapalli *et al.*, 1999), where the free-field jet is altered by effectively shortening its extent or changing its direction of flow and can result in new sources such as wall jets and impingement noise in the form of tonal feedback resonance loops. In some scenarios, these new sources can drastically increase noise emission levels. Relative contributions of the impingement sources are highly dependent on the geometry of deflecting structures.

Langenais *et al.* (2021) investigated the total noise source composition of a simulated Mach 3.1 hot jet plume entering and being deflected inside a rocket launch flame

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duct. Their use of an LES of the flow field and full two-way Navier Stokes-Euler coupling simulation of the acoustic far field, which accounts for nonlinear propagation and feedback in the flow and aeroacoustic coupling, showed improved agreement with measured data than did a previous FWH acoustic prediction. Radiation from the trench dominates, and the noise is strongly influenced by the flame trench geometry. Transverse acoustic modes in the duct are favored over longitudinal, resulting in broadband peaks around specific frequencies, which then radiate to the far field. Nonlinear distortion effects in the far field are also indicated by calculation of a number of nonlinearity metrics (see Sec. VI).

Stahl *et al.* (2021) investigated how the noise generated by the acoustic feedback loop in an impinging jet (which had been previously modeled by Powell, 1988, and Edgington-Mitchell, 2019) changes with the addition of a second impinging jet adjacent to the first. They employed well-resolved LES of twin under-expanded Mach 1.27 jets. The twin jet scenario exhibits three feedback harmonics represented by axisymmetric and asymmetric POD modes similar to the single jet, but the coupling mechanisms in the dual jet result in azimuthally local instabilities and impingement mechanisms between the jets that increase the amplitude of the lowest harmonic represented by two counter-rotating helical modes. An understanding of multi-jet impingement noise mechanisms is critical for vertical takeoff and landing operations of advanced fighter jets (like the F-35B), and multi-engine launch vehicles.

Akamine *et al.* (2021) conducted experiments to characterize some of the complex behavior of a jet impinging on a deflected surface based on multiple angles of impingement. They showed that an energetic high-angle (upstream) lobe appears for the more aggressive impingement angles of 45° and 22.5°, which seems to originate directly from shock cell boundaries created at the impingement, and may be caused by the passage of large-scale turbulent structures through the shock cells. Both the presence of these shock waves and the high-angle lobe diminish for the shallower 10° impingement angle. The presence of strong upstream lobes during impingement are a potential cause for concern where such waves might be directed towards payloads or launch pad structures during rocket liftoff.

VI. NONLINEARITY

Nonlinear propagation has been shown to be essential for the accurate prediction of far-field noise spectra for high-speed supersonic jets, such as fighter jet aircraft (Gee *et al.*, 2008) and launch vehicles (see discussion in Lubert *et al.*, 2022). This is because nonlinear distortions of high-amplitude propagating waveforms shift significant energy into the higher frequencies. Efforts to quantify this nonlinearity have resulted in different nonlinearity measures or metrics, such as the skewness of the pressure waveform time derivative ("derivative skewness," see Mcinerny, 1996; Reichman *et al.*, 2016a), the Morfey-Howell indicator (Morfey and Howell, 1981; Reichman *et al.*, 2016b), and the Gol'dberg number (see Baars *et al.*, 2016). The derivative skewness is an example of a time-domain metric and the Morfey-Howell indicator, a frequency-domain metric. The Gol'dberg number relates source and field properties and is expressed as the ratio between absorption length to shock-formation distance; it quantifies the relative dominance of nonlinear propagation over absorption. Many studies have also suggested a strong causal relationship between the generation of high-amplitude pressure events (quantified by elevated pressure skewness) and acoustic shocks within or near the source that continue to evolve into stronger acoustic shocks as they propagate nonlinearly into the far field. These acoustic shocks are perceived as "crackle," (Ffowcs Williams *et al.*, 1975) a topic of much recent interest (e.g., see Baars and Tinney, 2014; Murray and Lyons, 2016; Gee *et al.*, 2018).

Increasingly accurate and capable computational solvers are being developed to study acoustic shock generation, interaction, and propagation in the near and far fields. The study by Langenais *et al.* (2021), dealing with nonlinear wave propagation from a supersonic jet LES in a rocket flame trench is an example from this special issue. They examined the nonlinearity through several metrics, including derivative skewness and the Gol'dberg number.

Another example of enhanced computational capability for nonlinear acoustic propagation from high-speed jets was demonstrated by Pineau and Bogey (2021), who described the suitability of the Morfey-Howell indicator to characterize nonlinear distortions of jet noise. They used LES to simulate a Mach 3 cold jet flow and its near field, then propagated to the far field by solving the linearized or the weakly nonlinear Euler equations. Linear and nonlinear predictions of pressure skewness are nearly identical in the direction of maximum radiation, but wave steepening is better characterized by the nonlinear propagation. The Morfey-Howell indicator quantifies the nonlinear transfer of energy across frequencies. Spatial distributions of the Morfey-Howell indicator are in agreement between the LES predictions and a directly measured field.

The presence of acoustical nonlinearities in full-scale measurements was examined by Vaughn *et al.* (2021) in a different context than done previously. They investigated the possibility of irregular shock reflections in ground-based measurements of an installed, full-scale jet engine with afterburner capability. Irregular reflections are nonlinear reflections where shock coalescence occurs. These irregular reflections resulted in more than a doubling of peak pressures at the ground and, consequently, stronger shocks (quantified by the derivative skewness) at the ground than those measured off the ground. The impact of these increased shock strengths and distorted waveform characteristics must be considered in the ongoing discussion of ideal microphone placement on high-amplitude jet noise data collected over ground surfaces, such as in the requirements specified in ANSI (2012, 2017).

VII. SUPERSONIC JET NOISE REDUCTION

The universal question that arises with the presentation of any promising JNR technology is "What about the thrust?" How will the JNR solution affect the performance of the aircraft, and would it be any more effective than a simple reduction of engine power? Any technique that disrupts significant portions of the flow for the purposes of enhanced mixing or the mitigation of large-scale turbulence structures is likely to have some negative impact on performance (Henderson and Huff, 2021), so the JNR solutions that are most likely to be implemented on operational aircraft may be the ones that seek a middle-ground, sacrificing some noise reduction in favor of limiting thrust losses to 2% or less. For some aircraft manufacturers or missions, even a 2% thrust loss is unacceptable.

Adaptive (active) noise reduction techniques may be more practical, such as those that favor noise reduction in the takeoff/landing phases in proximity to the ground and to near-airfield communities, then transition to a higher thrust, higher noise phase during cruise. Adaptive JNR techniques may include the addition of a third stream bypass flow, or fluidic injection from bleed air. Recent studies have suggested that the turbulent dynamics of the outermost shear layer—especially its convection velocity—dominate the sound production in high-speed multi-stream jets (Papamoschou, 2018).

Two papers in this special issue highlighted the efficacy of JNR in a preferred direction through the use of asymmetric third-stream flows. First, Adam *et al.* (2021) used RANS models of a three-stream jet to represent the dominant noise source flow elements on a radiator surface (in the outermost shear layer) of a three-stream jet. On this surface, the convection velocity of the primary turbulent structures is equal to the mean flow velocity of the outer surface of peak stress, which velocity is easily obtained from the RANS data. They used these tools to show that acoustic sources in the vortical field are reduced on the thicker side of an eccentric (asymmetrical) third stream in accordance with the slowing of the mean flow velocity.

Second, Scupski *et al.* (2022) conducted two JNR experiments on a jet with a rectangular nozzle operated in an overexpanded shock-containing configuration, with an emphasis on noise reduction along the major axis (corresponding to the sideline of a jet aircraft). The first technique was the addition of fluidic inserts injecting air into the diverging section of the nozzle, where JNR effectiveness was quantified through a comparison to a baseline jet with an identical core flow. Noise reductions up to 3 dB were achieved in the sideline direction with some of the fluidic insert configurations. The second technique was the addition of fluid shields onto the sides and bottom of a dual flow jet to reduce the noise in those directions. JNR effectiveness was quantified through a comparison to a baseline on an equal thrust-per-unit-area basis. They found that the fluid shields provided improved JNR over the fluidic inserts for the jet in this experiment.

Prasad and Morris (2021) investigated noise reduction by fluidic inserts in high-temperature jets. They performed LES on a military-style nozzle at temperature ratios up to 7 (afterburner-like conditions), and decomposed the flow field into hydrodynamic, acoustic, and thermal components to show how fluidic inserts reduce the radiation efficiency of the Mach wave noise sources. They also showed that the effectiveness of the fluidic inserts improved with increasing jet exhaust temperature, and that conservative thrust losses were less than 2%, making it a viable candidate for JNR on full-scale jet engines.

Whereas Prasad and Morris investigated Mach wave noise reduction mechanisms, Patel and Miller (2021) focused on fine-scale mixing noise and BBSAN. Using statistical RANS models, they quantified the sensitivities of these two types of noise sources to nozzle design parameters for a method-of-characteristics nozzle, a biconic nozzle, and a faceted nozzle. This allowed them to show which noise components were most sensitive to changes in nozzle pressure ratio, total temperature ratio, area ratio, and the nozzle exit boundary layer profile. They were also able to show the upstream movement of dominant noise source locations and quantify the noise reduction as a result of fluid injection.

VIII. OUTLOOK

This special issue on supersonic jet noise, along with ASA meeting special sessions, summary articles, and an Acoustics Today magazine feature, has contributed to progressing noise characterization and reduction efforts. It has bridged gaps across academia, industry, and government and across the jet and (much smaller) rocket noise communities and has encouraged new research applications and collaborations.

Regarding launch vehicle noise characterization, modeling, and reduction, the review article by Lubert *et al.* (2022) highlights the need for physics-based models for noise generation of undeflected and impinging rocket plumes. Extrapolation of laboratory-scale jets and model-scale rockets to vehicle-scale phenomena needs to be accompanied by the collection of, and comparison with, high-fidelity near- and far-field data. As launch cadence continues to increase globally, researchers, engineers, and policy makers need an improved understanding of all aspects of acoustics in order to optimally design vehicles, payloads, and launch operations. There has been much learned by the aircraft-focused supersonic jet noise community in the past several decades, and there are many opportunities to apply those lessons and increasingly advanced analysis tools to identify and solve challenges created by rocket noise.

For aircraft engine noise reduction, the goals of JNR have been more focused as the challenges associated with warfighter health and community annoyance and disturbance have been better constrained. However, while the physics of supersonic jets and their noise radiation is becoming increasingly understood through full-scale measurements and interrogation of computational databases produced by high-fidelity modeling, reducing noise without sacrificing performance remains a fundamental challenge. As articles in this issue are addressing, multistream jets with a more gradual coupling of the shear layer to the surrounding atmosphere or adaptive JNR technologies that achieve a reduction in acoustic radiation efficiency are required.

Although there will always be different reasons for studying and reducing jet noise from aircraft engines and rockets, both communities will benefit from improved scaling of noise characteristics over a broad range of heated, supersonic jets. As a more complete understanding of the similarities and differences between jets of different scales, nozzle designs, velocities, temperatures, and both jet and convective Mach numbers emerges, targeted research can be conducted more effectively at the requisite scale and fidelity using the necessary computational and experimental tools.

In addition to the concentrated efforts on jet noise source reduction, more propagation and receiver-related studies are required. Regardless of the source, the most effective noise control strategies have always benefitted from a holistic look at source, propagation, and receiver. It may be that a focused effort on reducing noise metrics that are better linked to human perception than overall and A-weighted levels could lead to more impactful JNR strategies. Unfortunately, there have been few opportunities for sustained research progress into the propagation and receiver facets of JNR. This has been especially true for launch vehicle noise, mostly because launch cadence was slow enough that launches were a novelty, not a disturbance. However, the lack of sustained, sufficient funding into fundamental and targeted research and development in all areas of jet noise research has been a deterrent to pursuing optimal noise reduction solutions. Funding challenges create both inefficiency and ineffectiveness as knowledgeable researchers leave the field for other opportunities and new researchers are forced to start over and relearn lessons of the past.

Hopefully, as this special issue and other initiatives foster improved connections across researchers from varied jet noise disciplines, greater opportunities will exist to take advantage of these connections. To end on an analogy—as jet aeroacoustics is famous for its analogies—the relative efficiency of the directional, focused Mach wave radiation in supersonic jet noise comes from temporally coherent, spatially coherent, high-speed motion. Directional, focused progress in supersonic jet noise research requires the same conditions—opportunities for academicians, practitioners, and policy makers to act swiftly, coherently, and continuously—to enable greater collaboration, not competition, in solving present and future challenges in jet noise reduction.

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