1 Introduction

There is a growing need to significantly reduce the noise generated by high-performance, supersonic military aircraft. The noise generated during take-off and landing on aircraft carriers has direct impact on shipboard health and safety. Noise complaints are increasing; as communities move closer to military bases, there are changes due to base closures or realignment. Furthermore, U.S. and international noise regulations and policies will have an impact on operations and training unless effective steps are taken to reduce the noise.

1.1 Technical Background. There is a significant amount of literature dealing with noise reduction in civilian, subsonic aircraft. Some of the techniques found effective in that regime could possibly be applied for noise reduction in supersonic military jets. Many of these techniques use flow modifiers such as mechanical chevrons to enhance the mixing of the jet with the surroundings to reduce the jet noise. A distinct difference between current civilian aircraft engines and military aircraft engines is that military engines tend to have low bypass ratios and high velocities and noise tends to be dominated by jet noise, especially shock-associated noise. This is because during flight near the ground or by an aircraft carrier such as during take-off or landing, the exhaust from the engines tends to be nonideally expanded. Hence, the current research is focused on these flow conditions.

Although there are still fundamental questions about the source and mechanisms of noise in supersonic jets, significant progress has been made over the past few decades [1–10]. From previous studies, it is known that the noise generated by an imperfectly expanded supersonic jet consists of discrete and high amplitude screech tones, broadband shock-associated noise (BSBN) components, and mixing noise. The first two sources are related to the shock waves that are present in high-speed jet flow. While the mixing noise dominates in the downstream direction, the shock-associated noise elevates the overall noise level in the upstream direction. The screech tones are thought to arise due to a feedback loop involving the large scale flow structures shed from the nozzle lip, their interactions with the shock cell structure producing acoustic waves, and the upwind propagating acoustic waves inducing more large-scale structures at the nozzle lip.

Large eddy simulations (LES) have gained prominence as a tool to investigate the flow-field and noise from supersonic jets [11–23]. Typically, the near-field is computed using LES, and the far-field noise is estimated using the information from LES along with Lighthill’s acoustic analogy [24], or the Flowcs Williams–Hawkins method [25] or the Kirchhoff method.

1.2 Combined Experimental/Numerical Approach. The technical approach employed is to design and fabricate nozzles representative of those used in military engines, conduct experiments and acquire data, compare this information to validate numerical simulations, and then use both experiments and simulations together to understand the sources of the jet noise and investigate specific methods to reduce it.

For this application, experimental measurement and numerical simulation are particularly complementary. Measurement of pressure fluctuations within the jet itself is impossible by any nonintrusive technique. Since the introduction of any probe will introduce new shocks into the jet and since shocks contribute substantially to noise generation, the introduction of pressure probes is quite a substantial intrusion. One can employ measurement techniques to learn a great deal about the acoustical behavior outside the jet, but what can be measured inside the jet is limited. Within the jet, capturing the shock structures with numerical simulations requires very high grid densities. The numerical cost scales with the number of computational cells, so this makes it prohibitively expensive to cover a large domain. The present project, therefore, employs simulations to learn about the noise generation within the jet but limits in the domain simulated. Within the jet, we can make good nonintrusive measurements of velocity with particle image velocimetry (PIV), allowing for well-founded validation so one can have great confidence in the combined approach. A number of cases are run experimentally, and selected cases are examined in greater detail with validated LES.

Laboratory experiments are being conducted at the University of Cincinnati in Cincinnati, OH and numerical simulations at the Naval Research Laboratory in Washington, DC. Design help and overall guidance to ensure relevance to field implementation in the future is being provided by the General Electric Global Research (Niskayuna, NY).
1.3 Scope of Research. This paper reports the progress to date on a project aimed at characterizing the source of the noise from military aircraft jets and investigating several of the promising techniques to reduce it. The baseline nozzle and part of the chevron results were reported at last year’s ASME Turbo Expo [24]. This paper completes the chevron examination and explores two additional techniques, namely, fluidic injection in which blowing from microjets replaces chevrons, and fluidically enhanced chevrons in which microjets blow in addition to chevrons.

2 Experimental Approach

Models representing practical military aircraft engine exhaust nozzles have been constructed for several design Mach numbers, \( M_d \), where \( M_d \) is a function only of area ratio. These nozzles have a conic contraction section, a sharp throat, and a conic expansion section. These conical convergent-divergent (C-D) nozzles are a reasonable approximation to the faceted nozzles on military aircraft since there is no significant circumferential flow within the nozzle. Unless otherwise noted, all cases presented in this paper have a design Mach number of \( M_d = 1.50 \). The \( M_d = 1.5 \) nozzle is shown in Fig. 1. For this nozzle, the inflow diameter \( D_i \) is 3.124 in., the throat diameter \( D_t \) is 2.640 in. [79], or 47 exit diameters from the nozzle exit. Twelve chevrons extend 0.6 in. between the chevrons approximating the gap that would be left by the inner curves of the chevrons being tangent to the nozzle inner surface. There is a small gap between the chevrons approximating the gap that would be left by the opening of the seals of the actual variable-geometry nozzle.

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The nozzle lip is very thin, with a thickness of 0.020 in. (0.51 mm). This particular nozzle geometry is chosen to be representative of practical engine exhaust nozzles.

2.1 Flow Control Arrangements. A chevron cap has been machined to fit over the outside of the nozzle such that the inner contour of the chevron matches the inner contour of the nozzle at the exit. Twelve chevrons extend 0.6 in. (15.24 mm) from the nozzle trailing edge with a half angle of 35 deg. The inner and outer curves of the chevrons are circular arcs, with the inner arc being tangent to the nozzle inner surface. There is a small gap between the chevrons approximating the gap that would be left by the opening of the seals of the actual variable-geometry nozzle.

The chevron geometry is shown in Fig. 2. For the fluidic injection cases with and without chevrons, a toroidal plenum is fitted around the model with 12 0.125 in. (3.18 mm) i.d. tubes extending to inject one microjet just past the tip of each chevron at an angle of 60 deg to the main jet. This arrangement follows Alkislar et al. [27]. The jets are maintained at a pressure ratio of 3 for the experiments and 4 for the LES. A cross section view of the fluidically enhanced chevron geometry is in Fig. 3. The fluidic injection geometry is the same but with the chevron cap removed.

2.2 Instrumentation. The high-gradient features in the flow are visualized by the shadowgraph technique. An Oriel 66056 arc lamp is used for illumination. A pair of 12 in. (305 mm) parabolic first-surface mirrors with a 72 in. (1.829 m) focal length are employed to collimate the light before the model and then to refocus the beam after. The image is captured with a LaVision imager intense cross-correlation charge-coupled device (CCD) camera with 1376×1040 pixel resolution and 12-bit intensity resolution. This gives a spatial resolution on the order of 0.01 in. (0.25 mm) or 0.004 throat diameters. A 28–300 mm zoom lens is mounted to the camera, which allows optimization of the field of view. The aperture is left completely open, and the exposure is controlled by mounting neutral density filters. Averaging 100 images eliminates the turbulence and gives a clear view of the shock and Prandtl-Meyer waves.

Detailed flow-field mapping is performed by PIV. The PIV system is built by LaVision, and the entire PIV suite (laser and cameras) is mounted on a traverse, which allows the system to be translated undisturbed to any streamwise location, allowing many fields of view to be measured without the loss of time in changing setups and without the uncertainties, which come from repeated adjustment of components. The flow is seeded with olive oil droplets with diameters on the order of 1 \( \mu m \). A 500 mJ New Wave Research neodymium doped yttrium aluminum garnet (Nd:YAG) double-pulse laser is passed through sheet-forming optics to illuminate the seed, and the images are captured by a pair of LaVision CCD cameras with 1376×1040 pixel resolution and 12-bit intensity resolution.

The model is mounted in the University of Cincinnati Acoustic Test Facility (UC-ATF), which is a 24×25×11 ft\(^3\) (7.3×7.6×3.4 m\(^3\)) test chamber that has been acoustically treated to be anechoic down to 500 Hz. Eight quarter-inch microphones are arrayed along an arc at angles ranging from \( \psi = 35 \) deg to 150 deg. \( \psi \) is measured from the upstream direction. The microphones are placed at 135 in. (3.43 m) or 47 exit diameters from the nozzle exit. The facility was described in detail by Callender et al. [58].

Fig. 1 The nozzle geometry for the baseline nozzle, with \( M_d = 1.50 \).

Fig. 2 Geometry of the chevron cap, which fits over the nozzle.

Fig. 3 Fluidic injection geometry (cross section view), 0.125 in. i.d. tubes.
The unsteady three-dimensional inviscid compressible flow equations are solved with a finite element flow code FEFLO using unstructured tetrahedral grids [29]. This code is capable of accurately representing complicated geometries such as the nozzle geometry used in this work. No explicit subgrid scale model is used, and the modeling of subgrid scales is implicitly provided by the embedded flux limiter. The present simulations are in the framework of monotonically integrated large eddy simulations (MILES) [30]. The finite element (FEM) version of flux-corrected transport (FCT) algorithm (FEM-FCT) is used for the spatial discretization, and a second order Taylor–Galerkin scheme is used for the time integration. FCT is ideal for simulating the shock containing flows because it is high-order, conservative, monotone, positivity-preserving [31], and has previously been used to simulate supersonic jet noise [32].

3 Computational Approach

The nozzle geometry used in the simulations is shown in Fig. 1. The computational domain is outlined in Fig. 4. Fine grids are clustered around both the nozzle and the jet wake. The area with the fine grid is divided into two regions. The inner region is the most refined area, which covers the core of the jet flow to capture the energy-containing turbulence scales. This region has a cell size of 0.0345D (D is the exit diameter), and its length extends to 24D downstream in the axial direction. The radius of this region is 1.4D near the nozzle exit, and it gradually increases to 1.9D at the end of the region. Since the nozzle lip is very thin, the cell size near the nozzle exit is further reduced to accommodate the lip thickness. However, only one element is used around the lip to avoid a time-step size that is too small. The cell size inside the nozzle geometry increases from 0.025 in. (0.635 mm) to 0.15 in. (3.81 mm) as it approaches the inflow boundary. Since the propagation of sound waves in the frequency range of interest allows a little coarser cell size, the cell size in the outer region increases to 0.065D. This region extends to 3D in the radial direction, 5D in the upstream direction, and 24D downstream. Very coarse cell sizes are used in the far-field and near outflow boundaries to avoid wave reflections from these boundaries. The overall domain size is 15D in the radial direction, 17D in the upstream direction of the nozzle exit, and 47D downstream. The mesh has roughly 11 × 10^6 grid points and 65 × 10^6 tetrahedral elements.

Characteristic boundary conditions are applied to both the far-field and outflow boundaries (with pressure relaxation). The total pressure is kept constant at the inlet of the nozzle. A slip boundary condition is used for all solid surfaces.

Once a mature flow-field is established, the time-step size is kept constant and the data are collected at small time intervals. Since the number of grid points is large, it is not realistic to save all the data at all points with a small time interval. Instead, the data at points on a Cartesian mesh are saved after every 20 time steps. These points essentially serve as nonintrusive numerical probes in the flow-field. The distances between the neighboring probes are 0.2D in both the axial and radial directions. More details on the methodology and verification at validation studies have already been presented elsewhere [33]. This paper extends the investigation to include noise reduction techniques, namely, mechanical chevrons and fluidic injection.

4 Results and Discussion

The flow through the nozzle is characterized by the fully expanded Mach number, Mj, which is a function only of the nozzle pressure ratio (NPR) between the nozzle’s total pressure and the ambient static pressure. The nozzle is at its design condition when Mj = Md. The off-design operation of these nozzles is of particular interest, so overexpanded conditions Mj = 1.22, 1.36, and 1.47 and underexpanded conditions Mj = 1.56, 1.64, and 1.71 will be examined. All cases are unheated. All conditions are tested on the baseline, chevron, fluidic, and fluidically enhanced chevron configurations. Selected cases are presented below. The emphasis of this paper is on the acoustic emissions.

4.1 Dynamics of Jets From Practical Military Nozzles

Mach contours from LES are shown in Fig. 5. This figure illustrates the features typical of jets from practical military nozzles. The sharp throat generates a shock wave inside the nozzle. For the range of design Mach numbers explored in this project (Md = 1.3 – 1.65), this throat wave always forms a Mach disk, which sheds a slip line that can be observed leaving the nozzle. The diameter of the internal Mach disk and the slip line are dependent on Md.

Depending on the nozzle length and the Md, the outward wave from the Mach disk may reflect inside the nozzle or may emerge from the nozzle and reflect from the shear layer outside the nozzle, as it does for the Md = 1.5 nozzle shown in Fig. 5. The reflected wave sets up a shock diamond independent of the shock diamonds shed from the nozzle lip, producing a double-diamond pattern, which coalesces into a single diamond pattern after two or three
reflections.

Since the expansion section of these nozzles is conical, the flow leaving the nozzles cannot be a parallel flow. This means that even if the nozzle is operated with a perfect pressure match across the exiting shear layer, there will still be turning of the flow. This will produce a shock wave even at the design condition. The details of the baseline flow have been more fully discussed elsewhere.

Validation of LES for this configuration has been presented in Ref.

4.2 Flow Modification Due to Chevrons. The application of chevrons produces a large convolution of the shear layer. Chevrons force negative radial velocity behind the lobes and induce positive radial velocity between the lobes. This convolution persists several diameters downstream of the exit. Figure 6 shows the character of the convolution. The potential core of the jet is reduced in diameter, and the sonic surface is also convoluted and made radially smaller. The radially smaller supersonic region reduces the shock cell spacing, which, in turn, shifts the peak frequencies.

The shift in shock cell size can be readily observed in the averaged shadowgraph images in Fig. 7. Each pair has the baseline nozzle on the upper half and the chevron nozzle on the lower half. The shift in the shock cell size is most apparent in the lower half of the images, where the additional shock structures introduced by the chevrons are less pronounced. At the higher values of $M_j$, it becomes more difficult to discriminate the comparable lines in the image.

In examining the baseline images (the upper half of each composite image), it can be seen that the angle of the outer edge of the jet changes. For the most overexpanded case, the jet contracts so the edge turns radially inward. This implies a radially inward component of velocity at the edge, and so the local velocity vector at the edge of the jet points inward. For increasing values of $M_j$ as moving through perfect expansion and into underexpansion, one can see the edge of the jet moving outward, implying an outward pointing velocity vector at the edge of the jet, but as the velocity vector changes direction, the angle of the chevrons remains unchanged. This implies a change in the effective penetration of the chevrons. At the lowest values of $M_j$, the chevrons barely penetrate into the flow, and the flow is relatively undisturbed by the chevrons. As $M_j$ increases, they penetrate more and more deeply into the undisturbed flow so their influence becomes more pronounced.

The shadowgraph technique is line integrating, so what is seen on the chevron images is the superposition of the flow between chevrons, the flow from the chevron tips, and all points in between. Two bright lines can be seen emerging from the edge of the nozzle beginning with the case of $M_j = 1.47$. One inclines outward and the other inclines inward. These are indications of the edge of the jet as it flows between the chevrons and from the chevron tip, respectively. These become more and more separated as $M_j$ increases because the effective penetration grows and the chevrons produce greater and greater convolution of the jet shear layer.

LES data can be plotted in arbitrary planes within the flow, avoiding the complication of line integration. The chevron tip and valley planes are plotted separately in Fig. 8. Like in Fig. 7, the images are composites with baseline on the top and chevrons on the bottom. The lower half of the upper image is a plane bisecting the valley between two chevrons, while the lower half of the...
Injection tube pressure ratio was 4. Velocities are normal to the main jet at the tips of the chevrons. The mass flow in this case is the same for all values of \( M_j \) and ranges from 1.1% of the main jet to 60 deg to the main jet at an angle of 60 deg. The mass flow in this case is the same here. Both effects are greatest at the largest \( M_j \) and are negligible at the lowest value of \( M_j \). This is due to both the reduction in effective penetration at low \( M_j \) and the reduction in shear velocity.

### 4.3 Acoustic Influence of Fluidic Injection

Chevrons have shown their value as a jet noise reduction tool in a number of applications, but they have a distinct disadvantage in that they impose a small thrust loss, which must be carried throughout the flight, even in parts of the flight when noise production is of reduced importance. An alternative approach is to induce streamwise vortices into the shear layer by fluidic injection or microjet blowing. The blowing has a cost in terms of bleed air, but it has the advantage that it can be turned on for noise sensitive portions of the flight and turned off the rest of the time, reducing the performance impact on the overall flight.

Figure 11 shows the far-field spectra for a configuration with fluidic injection at \( M_j = 1.56 \), Injection tube pressure ratio was 4. Velocities are normalized by \( U_j \). The top half is fluidic injection; the bottom half is chevrons.

### 4.4 Acoustic Influence of Fluidic Enhancement of Chevrons

The trends in terms of sensitivity to \( M_j \) are complementary between chevrons and fluidic injection. This suggests that combining the two approaches might be useful. Figure 12 shows spectra for fluidically enhanced chevrons in which the blowing is applied at 60 deg to the main jet at the tips of the chevrons. The mass flows are the same as in the fluidic injection case. Combining the two approaches does show some benefit in reducing the screech at the lower values of \( M_j \) where chevrons are least effective, but for the midvalues near the design condition, blowing increases the BBSN.
and produces a small increase in noise at high frequencies. At aft angles shown in Fig. 12, one can see that for the lower values of $M_j$, there is suppression of the screech tone and small broadband reduction at lower frequencies. For the midvalues of $M_j$, there is some increased noise when blowing is applied to chevrons.

5 Discussion and Conclusions

Three noise reduction technologies have been examined experimentally and numerically as they have been applied to overexpanded, perfectly expanded, and underexpanded supersonic jets from convergent-divergent nozzles representative of those on high-

Fig. 10 (a) Far-field spectra of baseline and chevron configurations for an observer at $\Psi=35$ deg in the upstream quadrant. (b) Far-field spectra of baseline and chevron configurations for an observer at $\Psi=150$ deg in the downstream quadrant.
Chevrons have been shown to reduce or eliminate screech and reduce broadband shock-associated noise and mixing noise. Mixing noise and BBSN are known to be the most strongly generated near the end of the potential core and the end of the shock train, respectively. For the case of $M_j = 1.56$, this happens in the neighborhood of ten diameters. LES computation of pressure spectra is shown in Fig. 13. This plot shows that at $x/D = 10.8$, near the peak source region chevrons produce a significant reduction in near-field pressure fluctuations below 9 kHz. This includes the frequencies at which BBSN peaks are observed in the far-field.

Figure 14 shows the instantaneous contours of pressure from LES $M_j = 1.56$. The effect of chevrons is quite striking. Beyond

- performance military aircraft.
In the region where BBSN production is strongest, the shocks are becoming weak, the pressure fluctuations are dominated by the convecting large-scale structures. The chevrons substantially reduce the size of these structures. Since the BBSN is produced by the interaction between the large scale structures and the shocks, reducing the size of the structures will reduce BBSN production. Chevrons also shift the shock-associated noise peaks to higher frequency by reducing the diameter of the supersonic region and, by this, the length of the shock cells.

Chevrons increase noise at higher frequencies due to an intense small-scale turbulence generation near the nozzle. For the application of chevrons to this baseline nozzle, the lobe of increased noise near the nozzle has previously been shown to be centered at $x/D = 2$ [25]. Figure 13 shows the near-field spectra in this region.

Fig. 12 (a) Far-field spectra of chevron and fluidically enhanced chevron configurations for an observer at $\psi=35$ deg in the upstream quadrant. (b) Far-field spectra of chevron and fluidically enhanced chevron configurations for an observer at $\psi=150$ deg in the downstream quadrant.
This shows that chevrons increase near-field fluctuations above 10 kHz, verifying that the high-frequency penalty imposed by chevrons comes from the near-nozzle region.

Fluidic injection has been found to reduce screech, broadband shock-associated noise, and mixing noise. It also shifts the shock-associated noise peaks to higher frequency and generates increased high-frequency noise as chevrons do. Examination of Fig. 13 reveals that fluidic injection produces the same reduction near x/D = 10 at midfrequencies and the same increase in high frequencies near the nozzle as chevrons. In fact, the spectra for chevrons and for fluidic injection are strikingly similar. The instantaneous pressure contours shown in Fig. 14 are also very similar between chevrons in the upper plot and fluidic injection in the lower plot. Both noise reduction techniques reduce the size of the large-scale structures beyond x/D = 6 and so both reduce BBSN by the same mechanism. The principal difference between chevrons and fluidic injection is that for constant injection mass flow, the effectiveness of fluidic injection increases with decreasing values of Mj, while for chevrons, the trend goes the other way.

The application of blowing at the tips of the chevrons in an effort to enhance chevrons shows modest additional noise reduction in the form of screech suppression but shows some noise increase for a nozzle operating near the design condition.

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Nomenclature

C-D = convergent-divergent
D = exit diameter
De = exit diameter
Dr = inflow diameter
Dt = throat diameter
M0 = design Mach number
Mj = fully expanded Mach number
NPR = nozzle pressure ratio
\( \psi \) = angle from the upstream jet axis

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