IMPACT OF MECHANICAL CHEVRONS ON SUPERSONIC JET FLOW AND NOISE

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ABSTRACT
In this paper, we present observations on the impact of mechanical chevrons on modifying the flow field and noise emanated by supersonic jet flows. These observations are derived from both a monotonically integrated large-eddy simulation (MILES) approach to simulate the near fields of supersonic jet flows and laboratory experiments. The nozzle geometries used in this research are representative of practical engine nozzles. A finite element flow solver using unstructured grids allows us to model the nozzle geometry accurately and the MILES approach directly computes the large-scale turbulent flow structures. The emphasis of the work is on “off-design” or non-ideally expanded flow conditions. LES for several total pressure ratios under non-ideally expanded flow conditions were simulated and compared to experimental data. The agreement between the predictions and the measurements on the flow field and near-field acoustics is good. After this initial step on validating the computational methodology, the impact of mechanical chevrons on modifying the flow field and hence the near-field acoustics is being investigated. This paper presents the results to date and further details will be presented at the meeting.

1 INTRODUCTION
There is a growing need to reduce significantly 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 issues. Noise complaints are increasing, as communities move closer to military bases or when there are changes due to base closures and 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 aircrafts. Some of the techniques found effective there could possibly be applied for noise reduction in supersonic jets. Many of these techniques use flow modifiers such as mechanical chevrons to enhance the mixing of the jet with the surroundings and 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 their 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 tend to be non-ideally (under/over) expanded. Hence, our 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 [for example, 1-10]. From the previous studies, it is known that the noise generated by an imperfectly expanded supersonic jet flow consists of discrete and high amplitude screech tones, broadband shock-associated components and mixing noise. The first two types of noise are related to the shock waves that are present in the 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, their interactions with the shock-cell structure and flow disturbances at or near the nozzle lip.

1.2 Numerical Simulations
Numerical simulations can, in principle, play a significant role in the test and evaluation of various noise reduction concepts. However, for the results of these simulations to be credible, they need to be first compared and evaluated against relevant experimental data. This should include geometries and flow conditions that are representative of realistic engine configurations and operating conditions. Furthermore, for the problem at hand, the simulations will need to accurately capture shock waves, unsteady large-scale flow structures and their interactions while dealing with realistic configurations and operating conditions. This is a very challenging task.

In spite of advances in computers and computing, Direct Numerical Simulations (DNS) of supersonic flows from realistic nozzles over the length and time scales of interest is not practical. Hence, Large Eddy Simulations (LES) have gained prominence as a tool to investigate the flow field and noise from supersonic jets [11-21]. Typically, the near field is computed using LES and the far-field noise is estimated using the information from the LES along with Lighthill's acoustic analogy [22] or the Ffowcs-Williams-Hawkins method [23].

1.3 Scope of Research
In this paper, we report the progress to date on a project aimed at characterizing the source of the noise from military aircraft jets and investigating several promising techniques to reduce it. We have adopted a combined computational and experimental approach to address this problem. Laboratory experiments are being conducted at the University of Cincinnati and numerical simulations at the Naval Research Laboratory. Design help and overall guidance to ensure relevance to field implementation in the future is being provided by the General Electric Global Research. The specific focus in this paper is on discussing the observations from a large-eddy simulation approach to simulate the near fields of non-ideally expanded supersonic jet flows from nozzles with and without mechanical chevrons. We also present comparisons of some of the results of the simulations to experimental data.

2 COMPUTATIONAL APPROACH
The unsteady three-dimensional inviscid, compressible flow equations are solved with a finite element flow code FEFLO using unstructured tetrahedral grids [24]. This code is capable of accurately representing complicated geometries, such as the nozzle geometries 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) [25]. The finite element 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 and positivity-preserving [26] and has previously been used to simulate supersonic jet noise [27].

2.1 Computational Domain and Boundary Conditions:
The nozzle geometry used in the simulations is shown in Fig. 1. The diameter at the nozzle inflow is 3.124", the throat diameter is 2.640", and nozzle exit diameter is 2.868". The nozzle tip is very thin with a thickness of 0.024". The design Mach number for this nozzle is 1.5. This particular nozzle geometry was chosen to be representative of practical engine nozzles.

Fig. 1 The nozzle geometry used in the simulations.

The computational domain is outlined in Fig. 2. 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 tip is very thin, the cell size near the nozzle exit is further reduced to accommodate the tip thickness. However, only one element is used around the tip to
avoid a time-step size that is too small. The cell size inside the nozzle geometry increases from 0.025" to 0.15" 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, to 5D in the upstream direction and to 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 millions grid points and 65 millions 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. The slip boundary condition is used for all solid surfaces.

Once a mature flow-field is established, the time-step size is kept constant and data is 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 is saved after every twenty time steps. These points essentially serve as non-intrusive 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 and validation simulations has been presented elsewhere [28]. The focus of this paper is on the results, especially those with and without mechanical chevrons.

3 RESULTS AND DISCUSSION
The Nozzle Pressure Ratio, NPR (the ratio between the inlet total pressure to the ambient pressure) at the design condition is roughly 3.7 for the nozzle discussed in this paper. The unsteady flow field for a range of NPR values between 2.5 to 5.0 with an increment of 0.5, along with the design condition, has been simulated. NPR=2.5, 3.0 and 3.5 are cases of over-expanded flow and 4.0, 4.5 and 5.0 are cases of under-expanded flows. Representative cases with the addition of chevrons to the nozzle are also being conducted. The emphasis of this paper is on the impact of the chevrons on the flow field and near-field noise.

3.1 Dynamics of Non-ideally Expanded Jets
Static pressure distributions are used in Fig. 3 to show the overall features of the flow field for several cases. It can be seen that the shock-cell spacing increases as the total pressure ratio increases. The darker shades of gray represent high pressure levels while the brighter shades represent low levels.

As expected, the pressure at the nozzle exit is lower than the ambient pressure for over-expanded jet cases.
(NPR=2.5, 3.0 and 3.5), and is greater than the ambient pressure for all under-expanded jet cases (NPR=4.0, 4.5 and 5.0). The flow field for the case with NPR of 3.7 is particularly interesting. Since this is nominally the “ideally-expanded” or “design” condition, one would have expected the flow to be practically free of any shock cells or expansion waves. However, the flow field is similar to those from the non-ideally expanded flow conditions. Some waves might have been expected since the NPR is only an estimate of pressure ratio needed for the flow to be “ideally-expanded”. However, the waves for this flow condition are not insignificant. Experiments at UC also verified that the flow emanated screech and broadband shock associated noise. A closer examination of the flow field from the computations shows that waves are originating from within the nozzle, where there is sharp contraction at the nozzle throat. What these results imply is that the flow field from nozzles that are representative of practical engine nozzles are unlikely to be shock-free even at the nominally “design condition.” Further experiments (including shadowgraphs) have verified this observation.

The instantaneous pressure distribution for the case with NPR = 4.0 is shown in Fig. 4. This instantaneous flow-field shows the local pressure fluctuations generated by the large-scale turbulent flow structures. It is in the interaction between these flow structures and the shock cells that is the source of some of the noise generated and is the subject of further studies.

3.2 Centerline Pressure and Shock-Cell Spacing:
Detailed results from experiments [29] have previously been presented for NPR = 3.5 and 4.0. Hence, the discussion is focused on these two representative non-ideally expanded conditions. Figure 5 presents the centerline pressure distributions from the simulations, along with those measured by a conical Pitot pressure probe [29] for the NPR values of 3.5. Considering the uncertainties in both the measurements and the computations, the shock-cell spacing and magnitude are both in good agreement between the computations and experimental results. A comparison of the computed centerline pressures for the cases of NPR 3.5 and 4.0 is shown in Fig. 6. These results show that in the under-expanded jet case (NPR=4.0), the shock-cell spacing is larger and the centerline pressure oscillations last longer than in the over-expanded jet case. The under-expanded jet mixes more gradually with the surroundings and has a longer potential core length. All these observations are consistent with those from experiments corresponding to these two cases.

3.3 Near-Field Sound Pressure Levels:
The near-field sound pressure level (SPL) spectra has been computed at various locations within the flow field. Typical spectra from the LES at a near-field location (x = 2.2D and y = 1.0D) for the case of NPR = 3.5 is compared in Figure 7 to that obtained from the experiments at UC [28].

A screech tone is observed in both the experiments and the simulations, and both the intensity and frequency are
in general agreement between the numerical predictions and the measurements. There are differences in the overall amplitude, especially in the frequency range lower than the screech frequency. The causes for this difference is under further investigation but reflects the state-of-the-art in near-field comparisons of supersonic jet noise. An interesting and more revealing way of comparing the results from the simulations to those from experiments is to compare the SPL distributions at a particular frequency (e.g., screech) across the flow field rather than at a specific location. This has been done and the results for the case of NPR = 3.5 are shown in Fig. 8. Since it is difficult to measure sound pressure levels near the jet axis experimentally, the data near and around the centerline is not available from the measurements. On the other hand, because the fine grid is restricted to a region with a small radius, the direct overlap between the data from the simulations and the measurements is rather small. However, this turns out to be revealing because the similarities and differences between the features in the two data are highlighted. The transition between the two data as shown in the figure is almost flawless. This good agreement shows that LES and measurements can play complementary roles in the investigation of the noise sources and near-field acoustics of supersonic jet flows.

3.4 Flow Modification due to Chevrons:

Figure 9 shows the near-field static pressure distribution in two planes. One plane crosses two opposite chevron tips and the other crosses two opposite chevron trough. It can be seen that chevrons create large disturbances in the near field region. The frequencies of such disturbances appear to be high. The flow near the chevron tips converges slightly towards the jet center due to the inward tip surfaces, and the flow near the chevron troughs shows slight expansion with high-frequency waves that emanate from there.

Figure 9. Static pressure distributions in two planes. Plane crossing two opposite chevron tips (top figure) and plane crossing two opposite chevron troughs (bottom figure).

Figure 10 shows the static pressure distribution and Figure 11, the velocity vector field in the yz-plane at \( x = 0.1D \), which is located at the half way point between the chevron trough and tip. Counter-rotating streamwise vortices are seen around the chevron lobes, creating local high-pressure and low-pressure regions circumferentially near the edge of the jet potential core. The streamwise vortices carry high-speed jet fluid out of the potential core and produce high-speed pockets in the low-speed flow surrounding the jet, but they are gradually dissipating in the axial direction, as shown in Figure 11. In order to reveal the details of the local flow field more clearly, the velocity vectors over a smaller segment of the cross-section is presented in Figure 12. Even here, not every available data point is shown because doing that would make the picture too cluttered hiding the finer details.
Figure 11. The velocity vector field at $x = 0.1D$, corresponding to the pressure field shown in Figure 10.

Figure 12. An inset showing further details over a smaller segment of the velocity vector field shown in Fig. 11.

3.5 Comparison of the flow field and noise with and without chevrons:
Figure 13 shows the comparisons of the static pressure and the streamwise velocity between the chevron nozzle and the base nozzle. It can be seen that chevrons cause the shock cells to move closer to the nozzle and reduce the spacing between them. In addition, they induce more spread of the jet flow and decrease the strength of the shock cells. These phenomena have been also observed in the experimental measurements. The SPL predicted by the simulations with chevrons has been compared to those predicted for the base-line case without chevrons at a series of locations. One such comparison at the near-field location ($x = 10.8 \text{D}, y = 2.2\text{D}$) is shown in Figure 14.

As shown in this figure (and other data not presented), the screech tone is absent in the simulations with chevrons. Also, there is an overall reduction in the sound pressure levels at other frequencies. More detailed comparisons with experiments as well as further analysis of the impact of the chevrons on the near-field noise are currently underway and will be reported later.

Figure 13. Impact of chevrons on the static pressure distribution (top) and streamwise velocity distribution (bottom). In each figure, the upper half is from the simulation with chevrons and the lower half is from the base case simulations.

Figure 14. Comparison of the SPL at $x = 10.8\text{D}, y = 2.2\text{D}$ predicted by the simulations for the base-line case (green) with those predicted at the same location for the case with mechanical chevrons (red).

4 Concluding Remarks
Monotonically Integrated Large-eddy simulations (MILES) of the imperfectly expanded jet flows from a convergent-divergent nozzle with and without chevrons have been
carried out. Total pressure ratios from over-expanded to under-expanded jet conditions have been simulated. The shock cell spacing and the length of the potential core increase as the nozzle pressure ratio increases. The general features of the flow field and the differences observed between under- and over-expanded jets are in good agreement with experimental observations.

Unexpectedly, weak shock cells are observed at the nominal “design” condition. Results from the simulations have identified the cause for these waves to be the sharp contraction at the nozzle throat, which was introduced to make the nozzle representative of realistic engine nozzles. Hence, these studies suggest that the flow fields from realistic engine nozzles are not likely to be shock-free under any operating condition. This lends further importance to the study of non-ideally expanded jet flows.

Pressure distributions and the near-field noise intensities from the simulations show very good agreement with those obtained from the experimental measurements. This good agreement shows that LES and measurements can play complementary roles in the investigation of the noise generation from supersonic jet flows.

Current results show that chevrons cause the shock cells to move closer to the nozzle and reduce the spacing between them. In addition, they induce more spread of the jet flow and decrease the strength of the shock cells. Current results indicate that the screech tone is absent in the simulations with chevrons. A general reduction in the sound pressure level is also observed. Detailed comparisons with experiments as well as more details on the impact of the chevrons on the flow field and near-field noise will be presented later.

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6 REFERENCES