3D Numerical Studies on Jets Acoustic Characteristics of Chevron Nozzles for Aerospace Applications

R. Kanmaniraja, R. Freshipali, J. Abdullah, K. Niranjan, K. Balasubramani, V. R. Sanal Kumar

Abstract**—**The present environmental issues have made aircraft jet noise reduction a crucial problem in aero-acoustics research. Acoustic studies reveal that addition of chevrons to the nozzle reduces the sound pressure level reasonably with acceptable reduction in performance. In this paper comprehensive numerical studies on acoustic characteristics of different types of chevron nozzles have been carried out with non-reacting flows for the shape optimization of chevrons in supersonic nozzles for aerospace applications. The numerical studies have been carried out using a validated steady 3D density based, k-ε turbulence model. In this paper chevron with sharp edge, flat edge, round edge and U-type edge are selected for the jet acoustic characterization of supersonic nozzles. We observed that compared to the base model a case with round-shaped chevron nozzle could reduce 4.13% acoustic level with 0.6% thrust loss. We concluded that the prudent selection of the chevron shape will enable an appreciable reduction of the aircraft jet noise without compromising its overall performance. It is evident from the present numerical simulations that k-ε model can predict reasonably well the acoustic level of chevron supersonic nozzles for its shape optimization.

Keywords**—**Supersonic nozzle, Chevron, Acoustic level, Shape Optimization of Chevron Nozzles, Jet noise suppression.

I. Introduction

THE strict noise regulations around major airports due to environmental concern have made jet noise a crucial problem in present day aero-acoustics research. The three main acoustic sources in aircraft are aerodynamics noise, noise from aircraft systems and engine and mechanical noise. Among these noise sources engine noise contribute more noise pollution to environment. Although high bypass-ratio turbofans do have considerable fan noise, the majority of engine noise is due to the jet noise coming out from the exhaust nozzle. Although many studies have been carried out during the last few decades a complete understanding of the jet noise mechanisms is still a daunting task [1]-[20]. It is well known that the high velocity jet leaving back of the engine has inherent shear layer instability and rolls up into ring vortices. This later breaks down into turbulence sources of jet noise at the exit of nozzle. There are many methods reported in the literature to reduce the jet engine noise without compromising other design parameters of propulsive system. Among these, the popular methods are variable area jet nozzle using the shape memory alloy (SMA) actuators, fan flow deflectors and chevrons nozzles [1].

Fig. 1 Chevron nozzle flight test with Honeywell's Falcon 20 test plane: A close-up view of engine and nozzle (Adopted from [2])

Zaman et al. [2] reported that 'Chevrons', a sawtooth pattern on the trailing edge of exhaust nozzles, are being implemented on modern jet engine nozzles that help reduce noise from the ensuing jet (see Fig. 1). It has been known from past experimental studies with laboratory-scale jets that small protrusions at the nozzle lip, called 'tabs', would suppress 'screech' tones. In the 1980's and 1990's the tabs were explored extensively for mixing enhancement in jets. These studies advanced the understanding of the flow mechanisms and suggested that the technique might have a potential for reduction of 'turbulent mixing noise' that is the dominant component of jet noise for most aircraft. These are succinctly reported by Zaman et al. [2].

Literature review reveals that the noise reduction nozzles are of great interests to the aerospace industry, such as the serrated (or chevron) nozzle [1] The comprehensives experimental studies of Saiyed et al. [3], [4] at NASA reveal that the chevron modification to the round nozzle can bring as much as 3 dB reduction in peak noise during take-off with less

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than 0.5 % thrust loss during cruise. For high frequencies and large angles to the jet, the use of chevrons may also lead to about to 2 dB noise increase. This naturally leads to the chevron design optimization problem in which eddy resolving numerical simulations and acoustic modeling techniques for jet noise prediction play an important potential role. Hao Xia [5] carried out numerical study of chevron jet noise using parallel flow solver. Author performed hybrid large-eddy type simulations for chevron nozzle jet flows at Mach 0.9 and Re ~ 10^5. Many researchers carried out studies on chevron nozzles for various applications. Fan Shi Kong, Heuy Dong Kim, Yingzi Jin and Toshiaki Setoguchi [6] reported a new kind of nozzle with chevrons was installed inside the supersonic ejector-diffuser system.

Literature review further reveals that the nozzle with chevrons was widely used in the aerospace science and aircraft engine, because it has many advantages such as jet noise reduction, infrared signature control and improvement of conventional converging-diverging nozzle or convergent nozzle [7]. Gregory A. Blaisdell et al. [8] also observe that the conventional nozzle features were improved as a result of installing the chevrons. Note that the chevron nozzles have the flexibility in controlling acoustic and thrust performance. Admittedly, the previous studies reveal that the potential of chevron nozzles (or serration) for aircraft engines noise reduction is promising owing to the fact that the jet noise continues to be the dominant noise component, especially during take-off. Acoustic studies reveal that addition of chevrons to the nozzle reduces the sound pressure level reasonably with acceptable reduction in performance.

Although many studies were carried out by the earlier investigators the understanding of the fundamental mechanisms responsible for the acoustic benefit and the influence of various geometric parameters of chevrons are not clear. Parameters such as, the number of chevron lobes, the lobe length and the level of penetration of the chevrons into the flow have been investigated over a variety of flow conditions. Although experiments are necessary and provide useful data for validating the computations, they are expensive and can supply relatively limited amount of information. Hence it is desirable rather inevitable to have reliable CFD capabilities to quickly evaluate preliminary designs for noise reduction. In this paper comprehensive numerical studies on acoustic characteristics of different types of chevron nozzles have been carried out with non-reacting flows for the shape optimization of chevrons in supersonic nozzles for aerospace applications, which are discussed in the subsequent sessions.

II. NUMERICAL METHODOLOGY

The numerical studies have been carried out using a validated steady 3D density based implicit, standard, k-epsilon turbulence model using standard wall functions. This model uses a control-volume based technique to convert the governing equations to algebraic equations. The viscosity is determined from the Sutherland formula. The nozzle geometric variables and material properties are known *a priori*. Initial wall temperature and inlet temperature are specified. At the exit, far field boundary condition is prescribed. At the solid walls no-slip boundary condition is imposed. The Courant-Friedrichs-Lewy number is chosen as 0.5 in all of the computations. The turbulent kinetic energy and the specific dissipation rate are taken as 0.8. Ideal gas was selected as the working fluid. Fig. 2 shows the base model of the nozzle.

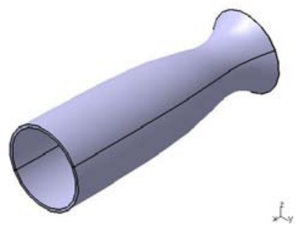
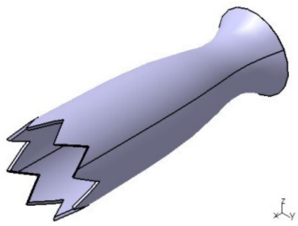
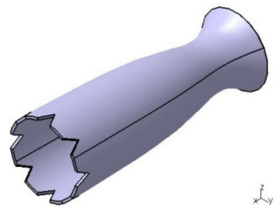


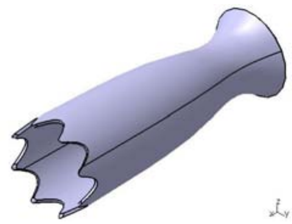
Fig. 2 Base model of the CD nozzle (A_e/A_t = 2.68)



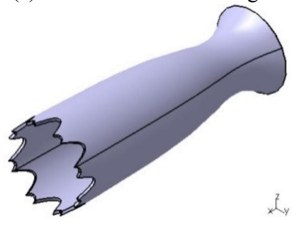
(a) Chevron with sharp edge



(b) Chevron with flat edge



(c) Chevron with round edge

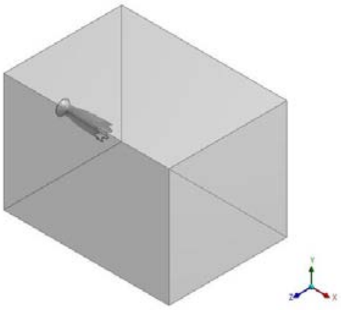


(d) Chevron with U-type edge

Figs. 3 (a)-(d) The 3D physical models of different types of Chevron nozzles

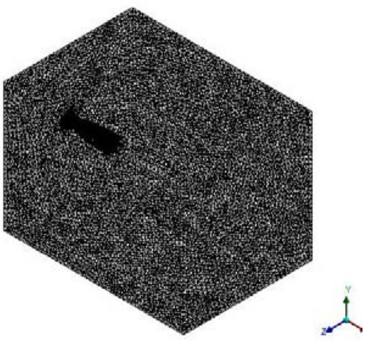
The base model was designed with an area ratio (A_e/A_t) of 2.6814 with an exit Mach number of 2.6 at the given inlet conditions. The coordinate points for the divergent portion of the nozzle were selected based on a typical shock-free convergent-divergent (CD) nozzle. Figs. 3 (a)-(d) show four different types of idealized chevron nozzles selected for the parametric analytical studies. In all the cases the number of chevron selected was 8.

An unstructured grid with tri angular elements was used for all the cases. Grid system (~240000 elements) in the computational domain is selected after detailed grid refinement exercises. Fig. 4 shows the chevron nozzle with round edge in the computational domain.



(a)3D model in the computational domain

(b) 3D grid system in the computational domain



(c) Model with wireframe meshes (corresponding to Fig. 4 (b))

Figs. 4 (a)-(c) Chevron nozzle with round edge in the computational domain

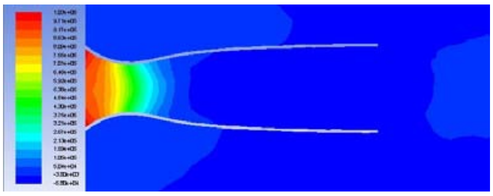
III. Results and Discussion

In this paper comprehensive numerical studies on acoustic characteristics of four different types of chevron nozzles have been carried out with non-reacting flows and compared each other and also with the base model for the shape optimization.

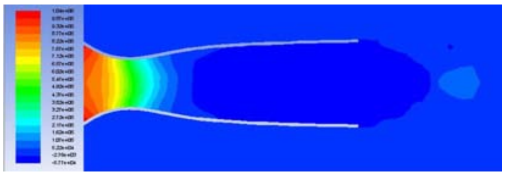
Due to the lack of well established correlation between jet noise and the chevron shape and its penetration distance it was difficult for choosing types of chevron for parametric studies. However, authors made an attempt to idealize the shapes of various chevron nozzles using empirical techniques for throwing light for its shape optimization. In this paper chevron with sharp edge, flat edge, round edge and U-type edge are selected for the jet acoustic characterization and comparison with the base model. Note that the 2d analyses for the aforesaid four types of chevron with different dimensions having one chevron were carried out by the earlier investigators and found that chevron with round edge exhibit less acoustic level [20]. In this 3d analyses an inlet Mach number of 0.35 is imposed in all the cases having 8 chevrons for a realistic estimation of the jet noise reduction.

Numerical prediction of static pressure, velocity, turbulence and acoustic levels of all the four cases are compared with the base model. Figs. 5 (a)-(e) show the static pressure contours of the base model and the four different types of chevron nozzles. Figs. 6 (a)-(e), 7 (a)-(e), and 8 (a)-(e) show the corresponding velocity, turbulence kinetic energy and the acoustic levels respectively. Fig. 9 shows the comparison of the turbulent intensity variations at the tip of the nozzles in the radial direction. Fig. 10 shows the corresponding acoustic power level. Fig. 11 shows the comparison of the exit radial Mach number of all the nozzles considered in this paper. It is apparent from the Figs. 5-11 that a nozzle with round edge shows an appreciable sound reduction of the supersonic jet on the order of 4.13% while comparing with the base model with 0.6% thrust loss. While comparing with other chevron nozzles we observed that chevron with flat edge shows higher acoustic level than the base model and the other three cases. It indicates that chevron with flat edge will defeat the very purpose of its objective for jet noise reduction. Through the exit Mach number comparisons we concluded that chevron with flat edge leads to adverse results and recommended that it must be expunged from further analysis. It is evident that a slight difference in the chevron geometry makes a large difference in the noise benefit as well as the thrust penalty. Therefore prudent selection of chevron geometry is a meaningful objective for the jet noise reduction without scuttling the vehicle performance. Analyses further reveal that some penetration by the chevrons is necessary to achieve good noise benefit. On the other hand, it is also clear from the parametric analytical studies that that too aggressive penetration would reverse the benefit due to increased high-frequency noise. Chevron penetration was identified as the primary factor controlling the trade-off between low-frequency reduction and high-frequency increases [9], [10]. Thus, for a given number of chevrons with a particular geometry, there should be an optimum penetration. Perhaps, this should translate to an optimum ratio between the peaks of streamwise vorticity generated by the chevrons and the azimuthal vorticity, as reported by Callendar et al. [9], [10].

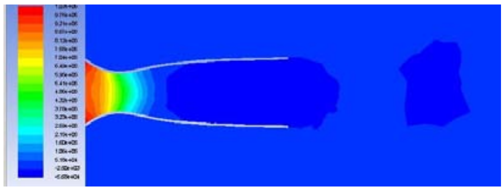
One way of understanding the chevron nozzle flow is in terms of vorticity distributions. It is amply clear that introduction of streamwise vortex pairs is necessary. These vortices appear to have a 'calming effect' reducing the overall turbulence in the shear layers. With the baseline nozzles, the vorticity in the shear layer is primarily composed of the azimuthal component. Such vorticity concentrates into the discrete ring-like (or helical) coherent structures. These structures go through contortions and interactions while propagating downstream. Their dynamics are unsteady and vigorous giving rise to high turbulence intensities. In contrast, the streamwise vortices are part of the steady flow feature and have a 'time-averaged definition'. They persist long distances and do not involve as vigorous dynamics as do the coherent azimuthal structures. Note that the only source of vorticity in the flow is the efflux boundary layer of the nozzle. The chevrons simply redistribute part of it into the streamwise component at the expense of the azimuthal component. Thus, the chevrons arrest the vigorous activity of the azimuthal coherent structures to some extent via introduction of the streamwise vortices. The result often is a reduction in the turbulence intensities that correlates with the noise reduction [1]-[3]. We are corroborating the aforesaid facts through our 3d analyses and presented in Figs. 7-10. Note that until the complex vortex motions can be directly linked to sound generation, the reduced turbulence intensity is the most direct connection to the noise reduction as far as one can comprehend [2]. As endorsed by Calkins et al. [11] the chevron technology has potential for possible spinoffs. Because even a small fraction of a percent of thrust loss is of concern, there have been efforts to develop 'smart chevrons' where the penetration can be reduced during cruise. The chevrons not only reduced jet noise but also broadband shock associated noise at cruise [11]. Note that the higher turbulence near the nozzle exit could increase high-frequency noise; however, understanding of jet noise is still a daunting task. The trends in turbulent kinetic energy profiles were eventually used as guidelines. As comprehended by Zaman et al. [2] the energy in the radiated noise represents only a minute fraction of the turbulence kinetic energy in the flow; thus, there could be pitfalls in such guidelines. In any case, accumulated evidence suggests in our analyses too that this may be a sound choice as turbulence and noise seem to correlate well in these flows. As seen in literature, we also emphasized here that jet noise remains a major component of aircraft noise for moderate to low bypass ratio engines. This study reveals that chevron technology has provided a reasonable relief for jet noise reduction.



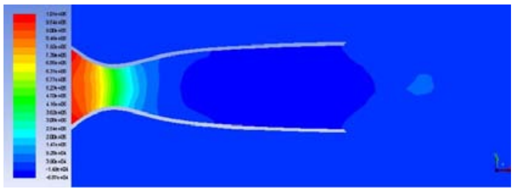
(a) Base model of the CD nozzle



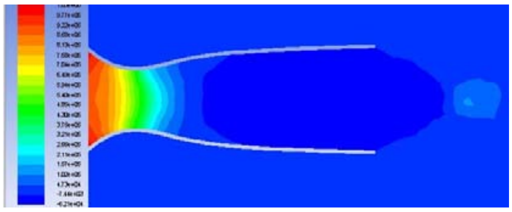
(b) Chevron with sharp edge



(c) Chevron with flat edge

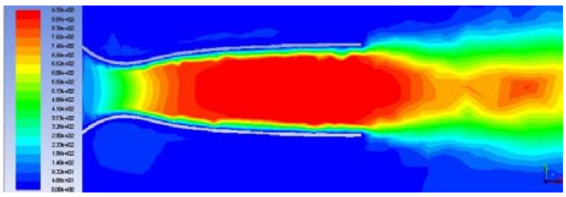


(d) Chevron with round edge



(e) Chevron with U-type edge

Fig. 5 (a)-(e) Static pressure contours of five different cases



(a) Base model of the CD nozzle

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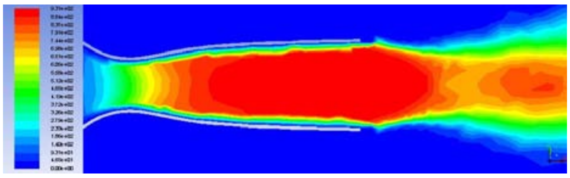
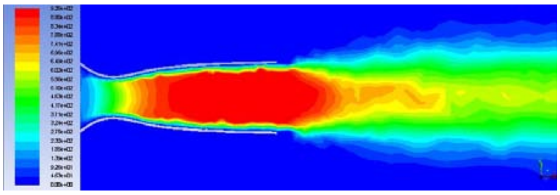
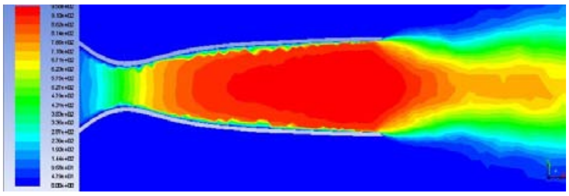


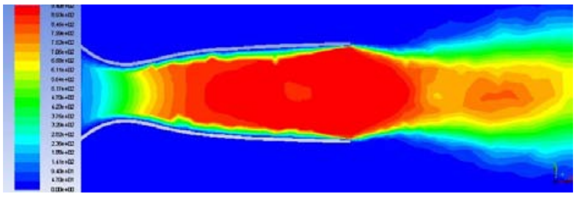
(b) Chevron with sharp edge



(c) Chevron with flat edge

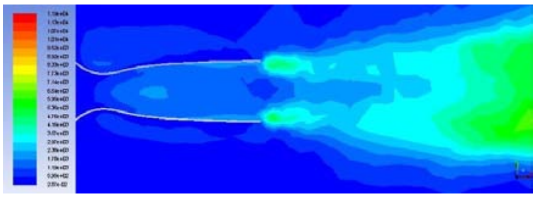


(d) Chevron with round edge

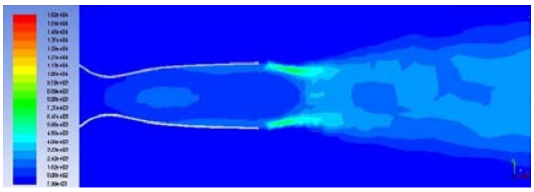


(e) Chevron with U-type edge

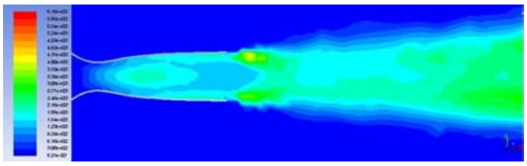
Fig. 6 (a)-(e) Velocity contours of five different cases



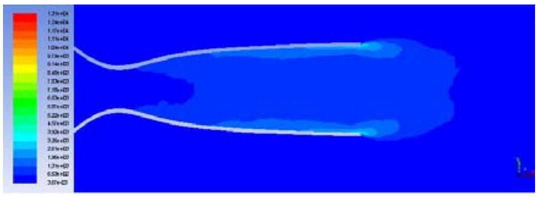
(a) Base model of the CD nozzle



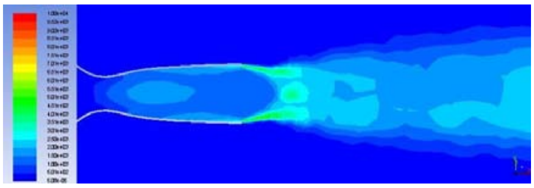
(b) Chevron with sharp edge



(c) Chevron with flat edge



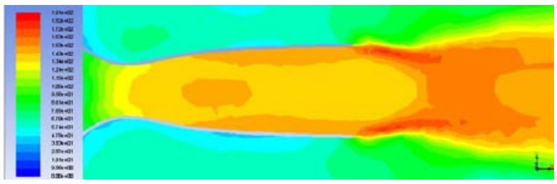
(d) Chevron with round edge



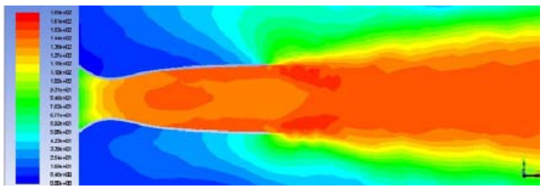
(e) Chevron with U-type edge

Fig. 7 (a)-(e) Turbulent kinetic energy of five different cases

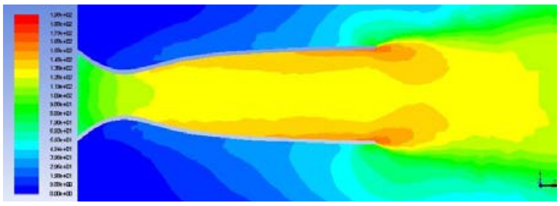
(a) Base model of the CD nozzle



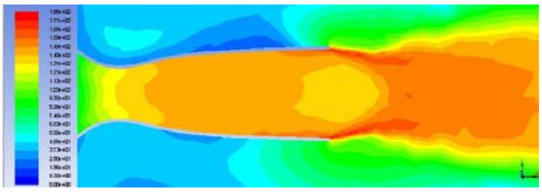
(b) Chevron with sharp edge



(c) Chevron with flat edge



(d) Chevron with round edge



(e) Chevron with U-type edge

Fig. 8 (a)-(e) Acoustic power level contours of five different cases

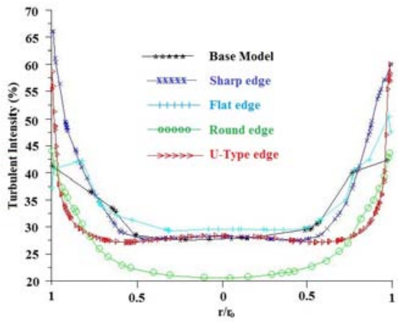


Fig. 9 Comparison of the radial turbulent intensity at the tip of the base model with the various nozzles with chevron

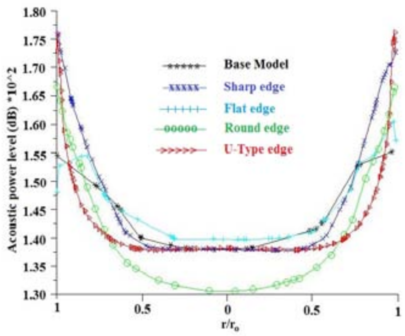


Fig. 10 Comparison of the acoustic power level at the tip of the base model with the various nozzles with chevron

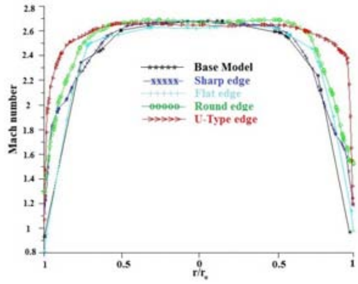


Fig. 11 Comparison of the exit radial Mach number at the tip of the base model with the various nozzles with chevron

IV. Conclusion

We concluded that the shape optimizations of chevron nozzle have a potential for reduction of turbulent mixing noise further, which is believed to be the dominant component of jet noise for most aircraft. It is emphasized that jet noise remains a major component of engine noise. The Chevron technology has provided a modest relief for jet noise reduction in aerospace applications. As the result of analysis, comparison was carried with baseline CD nozzle and four different types of chevrons. Finally we concluded that the chevron with round edge is the best choice for the sound reduction, of the acoustic power level of the base model of the nozzle, on the order of 6 dB. We also concluded that the prudent selection of chevron will enable the designer to reduce the sound level ~5%.

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