On the effect of geometric parameters of chevron nozzle on generation of streamwise vortices in high subsonic jets

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Abstract

Chevron nozzle is gaining popularity as a noise control device for jet noise reduction. Though it is the only noise control technique currently in use for commercial airliners, complete design methodology of chevrons is not available. In the present work, attempt is made to understand the effect of various geometric parameters of a chevron nozzle on the jet flow using commercial RANS based CFD solvers. Enhancement in mixing, which affects the acoustic signature of the jet, can be attributed to the strength of the streamwise vortices produced by chevrons. Hence major emphasis is given on analyzing the streamwise vortices formed in the jet flow from chevron nozzle. Various geometric parameters like different number of chevrons, their length and tip angles are employed on a 30 mm diameter nozzle producing M=0.8 jet for further investigation.

1. Introduction

Chevron nozzles are considered a better control technique for high speed jet noise reduction due to relatively low thrust penalty compared to other passive noise control techniques. Chevrons are simply saw-tooth like cut-outs at the nozzle lip. It creates a pair of streamwise vortices which form lobbed jet and disrupt formation of large scale structures in shear layer [1]. Lobbing of jet increases its perimeter and hence mixing with the surrounding [2]. Enhanced mixing shifts noise source location upstream and reduces propagation of prominent low frequency noise in downstream direction [3]. With higher vortex strength a chevron nozzle is expected to be more effective as a noise reducing device as suggested by Bridges and Brown [4]. However, they estimated the circulation (Γ) from geometric correlation applied to the shape of chevron. In the present work attempt is made to assess the vortex strength using numerical simulations for a variety of chevrons with different geometric features.

2. Chevron Configurations

Simple triangular chevrons are used for present parametric study. Geometry of a chevron nozzle is defined by parameters such as number of chevrons (N), length of chevron (L), tip angle (β) and penetration angle (a). Fig. 1 represents the simple schematic of the chevron geometry with its shape defining parameters. Base of the individual chevron (b) can be calculated as,

\[ b = \frac{\pi D}{N} \]

Relation between tip angle, base and length of chevron can be represented as

\[ \tan\left(\frac{\beta}{2}\right) = \frac{b}{2L} \]

By combining and rearranging these equations, it gives

\[ \left(\frac{L}{b}\right) \times \tan\left(\frac{\beta}{2}\right) \times N = \frac{\pi}{2} \]

This relation suggests these basic parameters governing the geometry of chevron are interdependent and changing individual parameter without changing the other is not possible. Hence, chevron configurations are selected very carefully such that effect of individual parameter can be deduced from that.

Fig 1. Schematic of chevrons
A typical chevron looks similar to a turnabout delta wing; hence it can be assumed that inclination (penetration) and tip angles are akin to angles of attack and sweep, respectively. Combination of angle of attack and the leading edge sweep of a delta wing are known to be a deterministic aspect for the vortex strength. It is obvious that increase in penetration angle will result in stronger vortex for a given shape of chevron similar to increase in angle of attack of delta wing. So, taking cue from this analogy the present study is undertaken only to investigate effects of the number of chevrons and the tip angle on formation of vortex and circulation which is its strength. A 100 mm long conical nozzle having 6° included angle and 30 mm diameter (D) at the exit plane is selected to which chevrons are fitted with constant inclined angle of 4°. Details of chevron configurations are given in Table 1. A nozzle is designated as, for example, N8β60 which has 8 chevrons with the tip angle of 60°.

3. Numerical Model

Aim of this study is primarily to examine effects of different geometric parameters on evolution of streamwise vortices produced by chevrons in jet flow and not to generate high fidelity results. Therefore, numerical simulations were carried out using commercial solver, ANSYS-CFX. Along with grid independence test few inbuilt RANS turbulence models were also tested and results were compared with existing experimental results [2]. Results obtained with K-ω SST turbulence model showed good match, so it was used in the present investigation. To reduce computational time, flow over only one chevron petal is simulated for each configuration as they repeat azimuthally. Fig. 2 shows a representation of flow domain including a petal of chevron with mesh used for simulation. The domain used for simulation has length of 5D and width of 3D. Thickness of the nozzle wall and chevron is taken as 1mm. Fine grid is provided inside nozzle for boundary layer and behind chevron along the lip line to capture streamwise vortices. All the results in the present study are obtained for M=0.8 jet producing the jet velocity (U) of 257 m/s at atmospheric conditions.

<table>
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<th>Name</th>
<th>N</th>
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<th>L (mm)</th>
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</table>

Table 1. Chevron configurations with geometric parameters

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**Fig 2. Computational domain for individual chevron (Dimensions are in mm)**
4. Numerical Results

Each chevron produces pair of contra rotating stream-wise vortices of equal magnitude, hence characteristics of only one of them is used for all further comparison as they are identical. Vorticity (ω) at vortex core and strength of vortex are key parameters for vortex characterization. These parameters are calculated for all planes normal to the jet with an interval of 0.1D along the jet axis. Here, nozzle lip (base of chevron) is taken as reference for axial distance for all configurations (x=0) and results are represented from the location next to tip of the chevron. The vortex strength was estimated from calculation of circulation (Γ) which characterizes lobbing of jet and entrainment. The circulation was calculated by taking area integral of the vorticity distributed under the contour having ω=0.1ω\text{max}.

![Normalized Vorticity vs Distance from Nozzle Exit Plane](image1)

**Fig 3: Core vorticity decay along jet**

Fig. 3 shows the peak vorticity (ω\text{max}) in one of the vortices springing from all the seven nozzles. Initially, the peak vorticity seems to vary with the length of chevron and thereafter it decays rapidly along jet vanishing within just x/D=2.5 and more so for the nozzle having larger number of chevrons as they produce smaller scale vortices which dissipate faster under viscous effects.

![Circulation vs Distance from Nozzle Exit Plane](image2)

**Fig 4: Circulation of individual chevron along jet**

A plot of circulation shown in Fig. 4 illustrates an interesting phenomenon that the vortex strength grows initially and reaches its peak at certain distance from the nozzle before decaying further downstream. Thus, the maximum vortex strength does not correspond to the maximum vorticity and it is surprising to note that the vortex gains its maximum strength where the core vorticity is substantially diminished. Strength of vortex also decays faster for large number of chevron due to its smaller size. This sustainability of the vortex can also affect the overall mixing of the jet and needs to be investigated further.
Fig. 5 shows the net circulation obtained by summing up the absolute magnitude of all the vortices. What emerges is that there is change in the distribution of net circulation in the initially region of growth, however, the trend remains similar in the region of decay. The peak net circulation is observed to be higher for N12β42 configuration despite the individual vortex generated by N8β60 being stronger. Since the net vortex strength of a jet depends on the combination of individual vortex strength and the number of chevrons who generate those vortices, a systematic study is needed to optimize this combination for effective noise suppression using chevron nozzle.

5. Concluding Remarks

In deciding the maximum net vortex strength in the jet from a chevron nozzle for effective noise suppression, it is not necessary to design a chevron which generates the strongest individual vortex but it is important to arrive at a combination of number of chevrons and the individual vortex strength which yields the maximum net vortex strength. Also the length, up to which these vortices are sustained, needs to be considered for its effect on overall mixing enhancement.

References