Comparative Study of Different Configurations of Chevrons for Noise Reduction of Exhaust Nozzles

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***Abstract*- A regular problem faced by the aeronautical industry is high noise emission as it causes discomfort to both humans and animals. A major source of aircraft noise is jet noise, particularly during take-off and landing. Exhaust conditions may become under-expanded, as an aircraft climbs to cruise altitude. 'Turbofan engines are considerably quieter than turbojets though higher bypass ratio, further reduction in noise is still desirable for the aircraft.**

Hence, chevrons are designed to reduce the acoustic power levels to a maximum while maintaining performance and keeping thrust loss to a minimum. This paper mainly focuses on the geometry of the chevron nozzles that are cut out into triangle and round shapes. The geometries are further analysed to obtain the comparison parameters from which the most effective chevron is attained.

Keywords— Acoustic Noise, CFD, Chevrons, Jet Noise Reduction, Turbulence Model.

I. INTRODUCTION

In the modern world, airplanes are a major source of noise pollution due to the jet noise of their engines. The Federal Aviation Administration (FAA) has come up with several noise standards to mitigate the consequences. NASA has been working on noise reduction technologies since 1950s – initially had a breakthrough on a technology called 'tabs' which were proven to reduce the screech noise that the engines produce. This noise-reducing technology further developed on commercial jet engines is now called chevrons. Chevrons are a sawtooth-like pattern seen on the trailing edges of turbofan engine nozzles. As the hot air through the engine's core and the cold air from the engine fan mixes, the trail edge patterns smoothen the mixing and reduces the turbulence which creates noise inside and outside the cabin [7]. The breakdown of the large turbulence to a small-scale turbulence reduces the low-frequency noise leading to an overall reduction in a sound pressure level.

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The penetration in the chevron in linked to decrease in noise but at the cost of performance. The penetration increase, increases the entire projected area of the engine corelating to the performance losses. Experimentally 0.25% of the performance is decreased by installing the chevrons [8]. Chevrons appear to be a simple solution, but the design is a result of years of experimentation by NASA and other companies. NASA expects to reduce 20–30 dB below the limits by 2026–2031. The aim of our study is to augment the existing efforts to understand the noise reduction behaviour of chevron nozzles, experimentally.

II. LITERATURE REVIEW

[1] Nevis Jenifer, Selva Preethi discussed that jet noise is produced by the mixing of shear layers of the jet plume - the free, fan, and primary streams. Considerable research has undergone to ease the mixing of the jet plumes without significantly hurting the performance. Numerical analysis of chevron nozzles with various configurations for noise reduction is investigated to find out the acoustic power level and is then compared to the baseline nozzle.

[2] B. Callender, E. Gutmark discussed that chevrons nozzles are of reducing engine exhaust noise with agreeable performance, minimum thrust loss penalty, and weight reduction compared to other technologies that it has evolved from like tabbed nozzles per multi-lobed mixed. NASA's study in Gkenn Research Centre in 2000 identified the reductions in jet-effective perceived noise level with minimal loss of nozzle thrust.

[3] Sasi Kumar M, Abirami K, Sandhiya K, Vijay G, and Vishnu Varthan discussed the various parameters of chervrons such as the number of chevron lobes, the lobe length and the level of penetration of the chevrons into the flow examined over a variety of flow conditions. Although the implications and results of chevron performance can be validated experimentally, it is an expensive option. Hence it is viable to evaluate our efforts in CFD for our early designs for noise reduction.

[4] Sadanandan R, Dheeraj R, Aswin B, Akshay Kumar K, Arjun Radhakrishnan proposed to analyze different types of nozzles for performance evaluation and seek to provide a better outcome than chevron nozzle. Different nozzles are designed in CATIA V5R20 and analyzed in ANSYS CFD for acoustic performance.

III. PROBLEM STATEMENT

Jet noise is a major problem around airports, which can be resolved using present-day aero-acoustics research. The three major acoustic sources in aircraft are aerodynamic noise,

noise produced by aircraft systems and the engine and, involuntary noises. The noise produced by the gases exiting the exhaust nozzle of a jet engine is the significant contributor to the overall noise. Introducing chevrons minimizes the noise production during takeoff but includes penalties in thrust throughout the entire mission, presenting the challenge of decreasing noise while limiting the thrust penalty.

IV. OBJECTIVES

- To design a chevron nozzle using geometric parameters such as number of lobes and level of penetration of the lobe which are established to be the top parameters in designing a chevron.
- To perform computational fluid dynamic analysis for the designed chevron to understand the interaction of the fluid with surfaces of the exhaust nozzle and cowling of the engine.
- To study the acoustic power level, pressure variations, velocity magnitude and thrust reduction to determine the performance of the chevron nozzle.
- To compare the obtained results for the most effective chevron design with least thrust penalty incurred.

V. METHODOLOGY

Designing chevron nozzle and engine cowling using CATIA V5R21

The design of the chevrons on the engine cowling and nozzle exhaust is done using CATIA V5R21. It enables the creation of 3D parts from 2D sketches wherein the dimensions of design are scaled down for our project.

Generating mesh of the designed model using ANSYS Version 18.1

To obtain accurate results in ANSYS Version 18.1, the design is then discretized using the process of meshing to break up the model into several elements, to replicate and predict real-world environments.

Refining the generated mesh by carrying out Grid Independency Test

Grid independency test is employed to improve the results with the standard CFD procedure beginning with a rough mesh and progressively refine it until the fluctuations observed within the results are reduced.

Imposing the boundary conditions on the model in ANSYS Fluent Version 18.1

Computational fluid dynamic analysis is performed on the design model for the interaction of the fluid with surfaces of the engine cowling and exhaust nozzle defined by boundary conditions to analyze the design.

A comparative study among the obtained results

The design of chevron models of different configurations is each analyzed for their acoustic power level, static pressure contours and velocity magnitude to compare and obtain the design with the minimal noise level and least reduction in performance.

VI. DESIGN PROCESS

Preliminary Baseline Design

The main objective of the preliminary analysis is to compare acoustic levels of the aircraft engine nozzle in the presence and absence of chevron. Doing so identifies a notable reduction in acoustic levels in the presence of chevron caused by the breakdown of the large-scale turbulence into a small scale. The dimensions for the engine cowling diameter are taken from GEnx website [5] with a scale factor 0.03 and for the exhaust nozzle and chevron design, are taken from “Parametric Testing of Chevrons on Single Flow Hot Jets” by NASA. [6]

Table 6.1 - Engine Cowling Dimensions

Engine Cowling	GEnx Engine Dimensions	Scaled-down Dimensions
Engine Cowling Length	4673.33 mm	140.2 mm
Engine Cowling Diameter	2800 mm	84 mm

Table 6.2 - Engine Nozzle Dimensions

Exhaust Nozzle	Dimensions
Engine Nozzle Length	80 mm
Engine Nozzle Diameter	70 mm
Engine Nozzle Taper Ratio	0.7

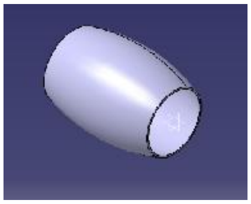

Fig 6.1 (a) Cowling of the engine

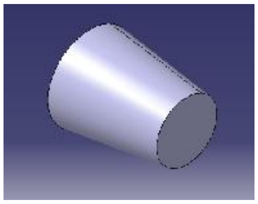

Fig 6.1 (b) Exhaust Nozzle of the engine

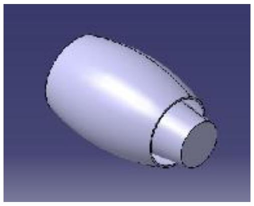

Fig 6.1 (c) Assembled nozzle with cowling

Design Configuration 1 – Triangle Pattern

The subsequent design to be developed was a chevron with triangle cut-outs on the exhaust nozzle and cowling of the engine. The dimension of the chevron penetration is 9mm with 20 lobes at the exhaust nozzle and engine cowling.

Table 6.3 Engine Cowling and Exhaust Nozzle Dimensions

Engine Cowling and Exhaust Nozzle	**Dimensions**
Engine Length	140
Engine Cowling Diameter	84
Exhaust nozzle Length	80
Exhaust nozzle Diameter	70
Exhaust nozzle taper ratio	0.7

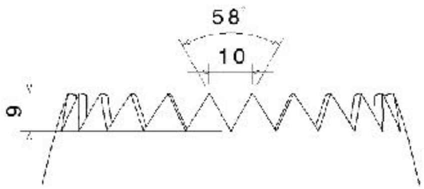

Fig 6.2 Chevron Dimensions for Engine Cowling

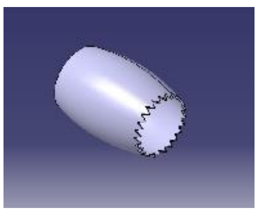

Figure 6.3 (a) Cowling with Triangle Pattern

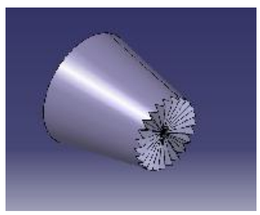

Figure 6.3 (b) Nozzle with Triangle Pattern

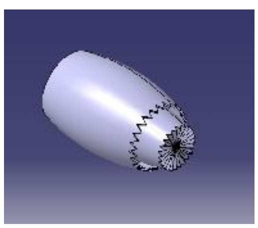

Figure 6.3 (c) Assembled Exhaust Section

Design Configuration 2 – Round Pattern

The following design contains a round pattern on the exhaust nozzle and cowling of the engine. The dimensions of the chevron penetration are 9mm with 20 lobes on the engine exhaust and the cowling.

Table 6.4 Engine Cowling and Exhaust Nozzle Dimensions

Engine Cowling and Exhaust Nozzle	**Dimensions**
Engine Length	140
Engine Cowling Diameter	84
Exhaust nozzle Length	80
Exhaust nozzle Diameter	70
Exhaust nozzle taper ratio	0.7

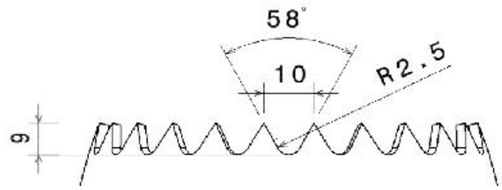

Fig 6.4 Chevron Dimensions for Engine Cowling

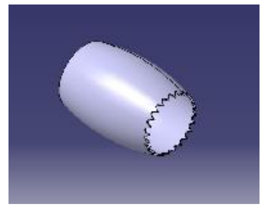

Figure 6.5 (a) Cowling with Round Pattern

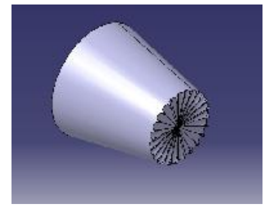

Figure 6.5 (b) Nozzle with Triangle Pattern

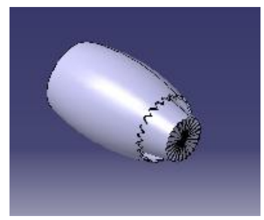

Figure 6.5 (c) Assembled Exhaust Section

Design Configuration 3 – Merged Pattern

The final chevron design is a combination of triangle and round patterns that have been previously utilized. The triangle pattern appears on the cowling of the engine while the round pattern is at exhaust nozzle, with the same penetration and the number of lobes as mentioned earlier.

Table 6.5 Engine Cowling and Exhaust Nozzle Dimensions

Engine Cowling and Exhaust Nozzle	**Dimensions**
Engine Length	140
Engine Cowling Diameter	84
Exhaust nozzle Length	80
Exhaust nozzle Diameter	70
Exhaust nozzle taper ratio	0.7

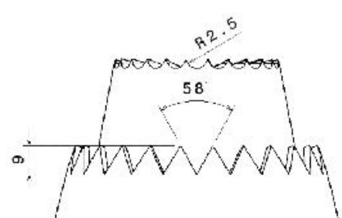

Fig. 6.6 Chevron Dimensions on Merged Configuration

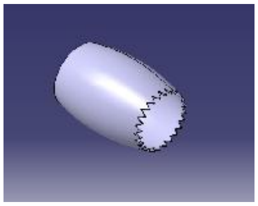

Fig. 6.7 (a) Cowling with Triangle Pattern

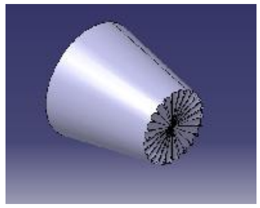

Fig. 6.7 (b) Nozzle with Round Pattern

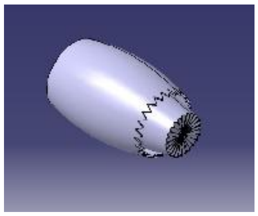

Fig. 6.7 (c) Assembled Exhaust Section

VII. PRE- PROCESSING WITH ANSYS

Meshing is an integral part of the analysis problems. Meshing is a process of dividing a complex geometry into smaller finite elements or grids that can be used as discrete local approximations. The geometry of the design is curved. Tetrahedral elements enclose the curved geometries well. Hence in our model tetrahedral elements are used for all the configurations.

The grid independency test is performed for computing the solutions on a successively finer grid. This eliminates the influence of the number of grids on the analysis. The number of elements is varied by increasing the number of divisions in the edge sizing. The result parameter is plotted again the number of elements. It's noticeable from the graph that it converges after a certain point and this is the selected number of elements for performing the analysis.

Baseline Design

The preliminary design has 33488 nodes and 129210 elements. The grid independency test is performed. The graph is plotted for the number of elements and rate of dissipation of kinetic energy. The graph converges at 129210 elements.

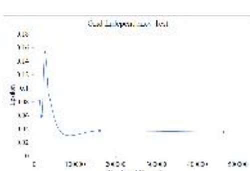

Fig. 7.1 (a) Grid Independency Test for Baseline Chevron

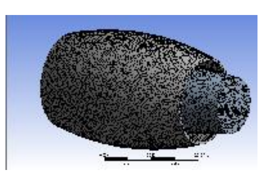

Fig. 7.1 (b) Meshing for Baseline Chevron

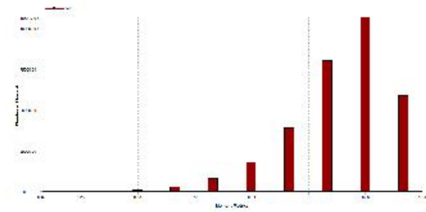

Fig. 7.1 (c) Element Metrics Baseline Chevron

Configuration 1 – Triangle Pattern

The double Triangle chevron design has 182494 nodes and 845369 elements. The grid independency test is performed. The graph is plotted for the number of elements and density. The graph converges at 845369 elements.

Fig. 7.2 (a) Grid Independency Test for Triangle Chevron

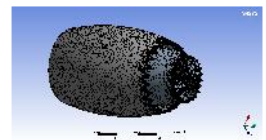

Fig. 7.2 (b) Meshing for Triangle Chevron

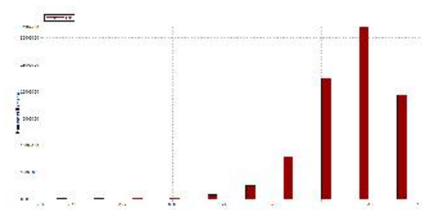

Fig. 7.2 (c) Element Metrics for Triangle Chevron

Configuration 2 – Round Pattern

The double Round chevron design has 85673 nodes and 377673 elements. The grid independency test is performed. The graph is plotted for the number of elements and rate of dissipation of kinetic energy. The graph converges at 377673 elements.

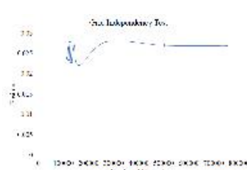

Fig. 7.3 (a) Grid Independency Test for Round Chevron

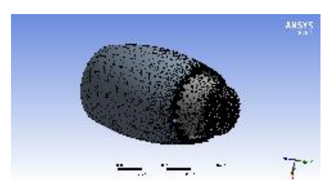

Fig. 7.3 (b) Meshing for Round Chevron

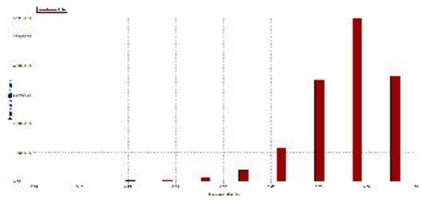

Fig. 7.3 (c) Element Metrics for Round Chevron

Configuration 3 – Merged Pattern

The triangle and round merged chevron design have 295996 nodes and 1417054 elements. The grid independency test is performed. The graph is plotted for the number of elements and total pressure. The graph converges at 1417054 elements.

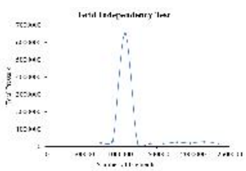

Figure 7.4 (a) Grid Independency Test for Merged Pattern

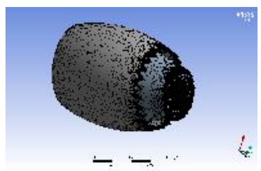

Fig. 7.4 (b) Meshing for Merged Pattern

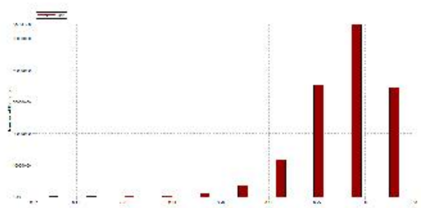

Fig. 7.4 (c) Element Metrics for Merged Chevron

Boundary Conditions

ANSYS-Fluent is a Computational Fluid Dynamics code that will perform the simulation for four different chevron nozzle configurations. Pressure based solver is not suitable for compressible fluids as in pressure-based solvers the acoustic timescale is completely neglected, hence density-based solver is used.

K-epsilon model solves for two variables that are turbulent kinetic energy and the rate of dissipation of kinetic energy. Boundary condition epsilon equation contains a term which cannot be calculated at the wall hence the std wall functions are used along with the realizable k-epsilon model. A control volume-based approach is used in FLUENT. A second-order upwind solution method is used for both turbulent kinetic energy and turbulent dissipation rate since it is more accurate than the first-order method

Table 7.1 Boundary Conditions

Acoustics model	Broadband noise sources with reference acoustic power of 4e-10 w
Material	Air with ideal gas density and Sutherland formula for viscosity
Inlet	Pressure inlet Gauge total pressure - 155000Pa Initial Gauge pressure - 154555Pa Total temperature - 833.3K
Outlet	Pressure outlet Gauge pressure - 7500Pa Backflow total temperature - 300K

VIII. ANALYSIS

Acoustic Analysis

The rate at which sound energy is emitted, reflected, transmitted or received, per unit time is Acoustic Power. From the acoustic studies, it is noticeable that the addition of chevrons to the nozzle reduces the sound level when compared with the baseline design. The CFD analyses are performed for the different geometry chevrons. The results for the analysis are shown in fig 8.1 (a), 8.1(b), 8.1 (c), 8.1(d). It is observable from the results that the acoustic power level of the baseline configuration is considerably high than the models with chevrons on them.

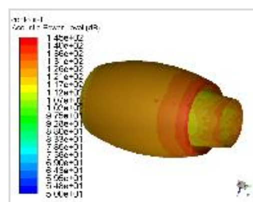

Fig 8.1 (a) Acoustic Power Level Contour for Baseline Chevron

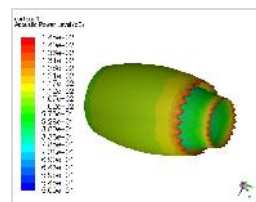

Fig 8.1 (b) Acoustic Power Level Contour for Triangle Chevron

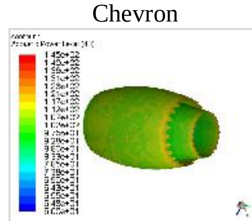

Fig 8.1 (c) Acoustic Power Level Contour for Round Chevron

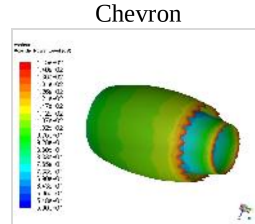

Fig 8.1 (d) Acoustic Power Level Contour for Merged Chevron

Among the results of the acoustic analysis of the chevron models, we can see that the red region i.e., the region with high noise level or the acoustic power level is relatively less for round edge cut chevron model. Hence from the acoustic analysis results, we note that the round configuration is more effective in reducing the noise level at the exhaust of the engine nozzle.

Static Pressure Analysis

The relationship between velocity and pressure for incompressible flow is given by Bernoulli's Law which states that an increase in velocity causes a decrease in static pressure. Expansion of exhaust gases causes the static pressure to decrease at the exit resulting in an increase of the velocity magnitude. Therefore, the amount of the expansion also determines the exit static pressure and indirectly the velocity of the exhaust gases.

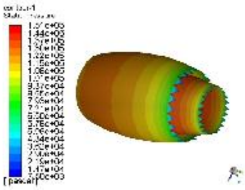

Fig. 8.2 (a) Static Pressure Contour for Triangle Chevron

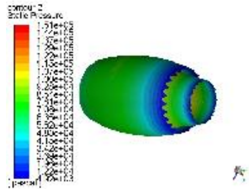

Fig. 8.2 (b) Static Pressure Contour for Round Chevron

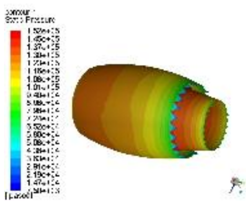

Fig. 8.2 (c) Static Pressure Contour for Merged Chevron

Velocity Magnitude Analysis

Temperature increase at the nozzle exit with a reduction in the area also leads to acceleration of the exhaust gases with an increase in velocity magnitude.

Pre – Processing for Velocity Magnitude

To obtain the exit velocity of the design configurations, an analysis is performed to acquire an isosurface presenting the velocity magnitude. Enclosure is used to study the velocity within the volume of the three-dimensional domain.

The triangle configuration has 37564 nodes and 162084 elements. The grid independency test is performed. The graph is plotted for the number of elements and pressure. The graph converges at 162084 elements.

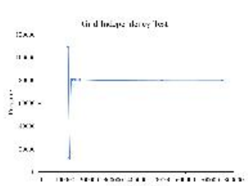

Fig. 8.3 (a) Grid Independency Test for Triangle Chevron

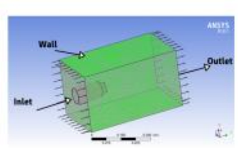

Fig. 8.3 (b) Enclosure for Triangle Chevron

The round configuration as 62925 nodes and 273171 elements. The grid independency test is performed. The graph is plotted for the number of elements and rate of dissipation of kinetic energy. The graph converges at 273171 elements.

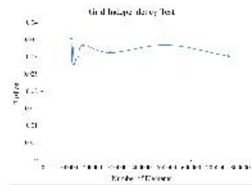

Fig. 8.4 (a) Grid Independency Test for Round Chevron

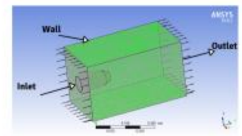

Fig. 8.4 (b) Enclosure for Round Chevron

The merged configuration has 33008 nodes and 143601 elements. The grid independency test is performed. The graph is plotted for the number of elements and acoustic power level. The graph converges at 143601 elements.

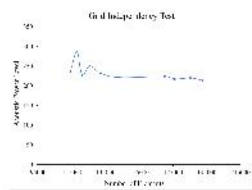

Figure 8.5 (a) Grid Independency Test for Merged Pattern

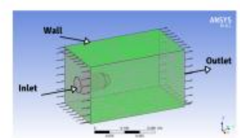

Figure 8.5 (b) Enclosure for Merged Pattern

Analysis for Velocity Magnitude

A turbofan engine can produce more thrust by accelerating the gas to a higher velocity exiting the engine. The chevron penetration geometries raising the overall projected area leads to a reduction in the exit velocity and therefore reduction in performance losses. In order to study the extent of these losses, an isosurface placed in a three-dimensional domain has been utilized to study the velocity contour of the chevron configurations.

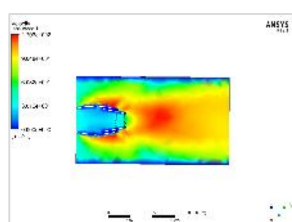

Fig. 8.6 (a) Velocity Contour for Triangle Chevron

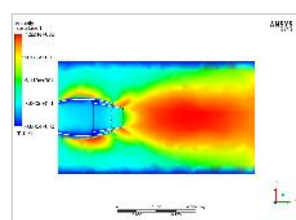

Fig. 8.6 (b) Velocity Contour for Round Chevron

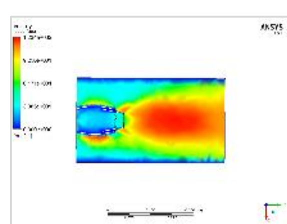

Fig. 8.6 (c) Velocity Contour for Merged Chevron

From the velocity isosurface contour analysis the maximum exit velocity is 120.6 m/s, 122.4m/s, 123.4m/s for triangle, round and merged pattern respectively.

IX. RESULTS AND CONCLUSION

Study of Acoustics

At 150dB it has proven that the eardrum ruptures, in our study we have noticed that the maximum decibel level is for baseline nozzle and the minimum decibel level is for round configuration. There is a decrease of 20dB.

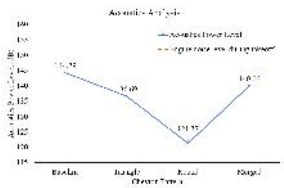

Fig 9.1 Acoustics Power Level Comparison for the Chevrons

Study of Jet Plume

When the nozzle exit pressure relative to the static pressure is almost equal to one, the design condition will be achieved during which the jet plume will be at its peak value. In our study, we have noticed that the round and triangle configuration is at the closest value to the design condition. Therefore, having maximized the thrust.

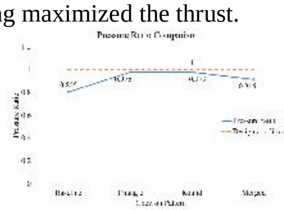

Fig 9.2 Pressure Ratio Comparison for the Chevrons

Study of Velocity Magnitude

From the values of the maximum velocity magnitude, a graph is plot in **Fig. 9.3**, we infer that the merged pattern has the maximum exit velocity. However, the velocities obtained for the three configurations are close and comparable, the variation in the velocity magnitude is not more than 1 m/s between round and merged configuration.

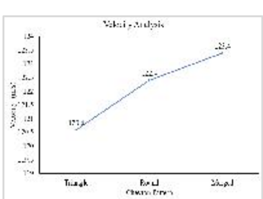

Fig. 9.3 Velocity Comparison for the Chevrons

Conclusion

From the acoustics study, we can conclude the round configuration having the lowest decibel value compared to other configurations. From the design condition study, taking pressure ratios between exit static pressure and ambient pressure, we conclude Round and Triangle having the closest value to the design parameter.

From the velocity isosurface contour study, the velocity magnitude of all three configurations is quiet in the same range i.e., 120m/s. We can thereby conclude that round configuration is the best chevron design in terms of geometry, aerodynamics and performance.

X. FUTURE SCOPE

- Static structural analysis to be carried out by varying the loads that an aircraft engine will experience during its operation.
- Dynamic analysis for the inertial and damping loads that an aircraft engine will experience.
- CFX analysis to be conducted for a wide range of fluid flow parameters at various flying altitude.
- Aeroacoustics study for noise reduction considering shock waves that will be obtained at higher Mach numbers.
- Replicating the real-life conditions with a nozzle acoustic test rig in order to obtain practical values and validation to the analysed results.

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