Acoustic analysis of chevron nozzle: A CFD approach

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Abstract. Noise pollution from aircraft is a critical environmental issue, affecting not only wildlife but also human health and comfort, especially for populations living near airports. The recent, researchers have been primarily focused on reducing noise pollution in aircraft systems. Among the major contributors to noise pollution are the aircraft engine and nozzle. To address noise in the nozzle, the chevron nozzle, characterized by a sawtooth pattern at its edge, has been commercialized. Thus, there is a need for dependable Computational Fluid Dynamics (CFD) capabilities to swiftly assess initial designs for noise reduction and analyze problems that involve fluid flows. For noise reduction in aircraft systems, CFD capabilities are essential. This study conducts Finite Element Method (FEM) analysis of the chevron nozzle. Additionally, design optimization is performed utilizing the Taguchi method.

Keyword-: Acoustic analysis, chevron nozzle, CFD, ANSYS, Noise Cancellation.

1 Introduction

Today, commercial engines exhibit far greater power and create considerably less noise compared to the commercial aircraft engines utilized in the 1970s and 1980s. Ongoing efforts are being made to mitigate airplane noise in the vicinity of airports [1]. Aircraft manufacturers are increasingly dedicated to developing engines that effectively mitigate noise in airport areas [2]. During airplane takeoff and landing, engines endure higher loads to generate increased power, resulting in more noise compared to aircraft in flight. Research efforts have predominantly focused on improving the mixing of shear layers in jet engine nozzles while maintaining optimal performance [3]. Aircraft noise ranks as the second most disruptive noise source, following noise generated by rocket launches. Concerns regarding environmental quality are significant among individuals, with noise being identified as the primary source of annoyance. Nozzles play a crucial role in enhancing velocity and providing additional thrust while also regulating the consistent direction of airflow and fuel mixture from the turbine [4-6]. Within the nozzle, the potential energy resulting from the flow following the turbine is transformed into kinetic energy. This kinetic energy generates a difference in velocity between the flow and its surroundings, leading to the production of noise in the jet engine [7]. Hence, it is imperative to minimize the noise emitted by the exhaust of the nozzle. This may be achieved by altering the size of the nozzle and introducing new geometries. The Chevron, characterized by a triangular teeth pattern positioned along the perimeter edge of exhaust nozzles, is currently employed in jet engine designs to effectively reduce jet noise. Chevrons are utilized to mitigate the acoustic intensity emitted by the exhaust [8].

A significant portion of aviation noise stems from aircraft engines, with commercial aircraft commonly utilizing Turbofan engines as gas turbine engines for thrust generation. Turbofan engines typically employ convergent-type nozzles [9-11]. The Chevron convergent nozzle has emerged as a valuable solution for noise reduction in passenger aircraft. Major sources of noise in jet engines include the fan or compressor, turbine, nozzle, and the exhaust jet (jet fluxes) [12]. The given [13]. Jet exhaust noise is generated by the turbulence that occurs when the exhaust gases combine with the surrounding air. This turbulence is induced by the shearing action resulting from the difference in velocity between the

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jet exhaust and the surrounding environment [14]. Several endeavors have been undertaken to comprehend the impact of different geometric features, such as the design of a chevron nozzle, on noise mitigation [15-17]. Friction Stir Processing (FSP) was used in this work to examine how FSP affected the tensile characteristics [18]. Industrial metal development shows pragmatic transformation in metal development [19]. This study examines the acoustic impacts on a chevron nozzle by investigating various modifications in its geometry, such as altering the number and form of chevron teeth. The objective is to identify the most optimal nozzle design that provides superior output compared to other models. SEM and microscopy instruments were used to examine the altered materials [20-25].

2 Methodology

2.1 Parameters and their levels

The Taguchi technique was applied to optimise the tip angle, penetration angle, and number of chevrons. The data has been analysed using Minitab software while simulation was conducted using ANSYS, utilising the settings outlined in Table 1.

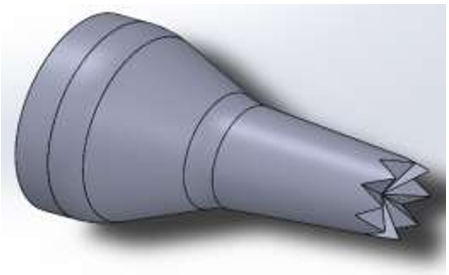
Table 1: Parameters considered and their levels

Parameters	Levels		
Tip angle, ^{o}C	55	60	65
Penetration angle, ^{o}C	4	5	6
Number of chevrons	7	9	11

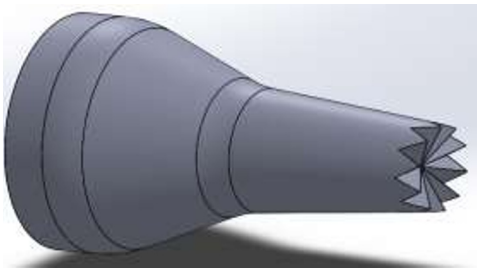
The L9 orthogonal array had been chosen, and according to Table 1, nine simulations were carried out conducted. The table outlines experimental parameters for a study in aerodynamics, fluid dynamics, or similar fields. The parameters include tip angle, penetration angle, and number of chevrons, systematically varied to understand their impact on outcomes.

2.2 FEM Modelling of chevron nozzle

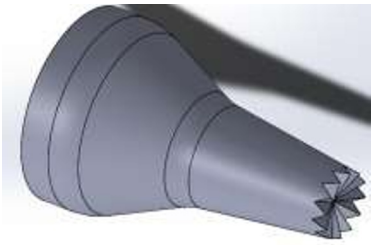
In recent times, scholars have primarily concentrated on mitigating noise pollution in aircraft systems, particularly targeting the aircraft engine and nozzle as significant contributors. To address this concern, the chevron nozzle has gained attention, featuring a sawtooth design at its terminal edge, aiming to diminish noise levels. The incorporation of triangular cutouts along the trailing edge of the nozzle effectively reduces the overall width of the jet plume, contributing to noise reduction efforts [26-28]. Chevron enhances mixing to the desired degree and minimizes jet noise. The primary source of noise remains that of the sound produced by jet engines, particularly during the plane's departure phase." Considerable work has been devoted to the advancement of effective passive flow control methods to reduce jet noise. Nine computer-aided design (CAD) models had been created and constructed using the information provided in Fig. 1.



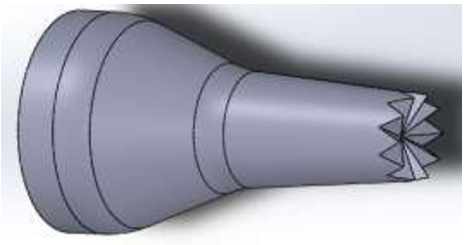
(a) CFD domain 1



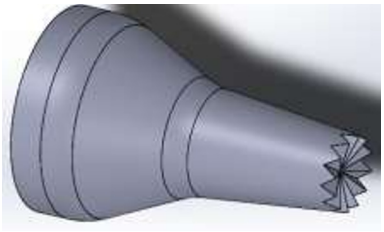
(b) CFD domain 2



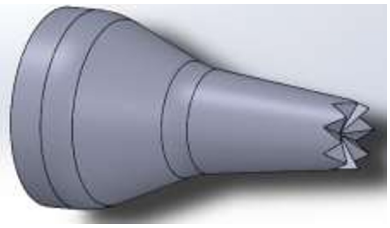
(c) CFD domain 3



(d) CFD domain 4



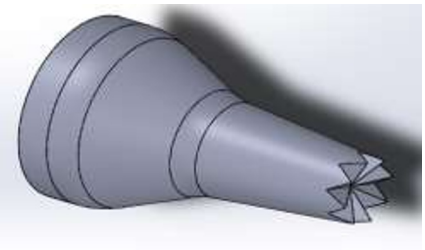
(e) CFD domain 5



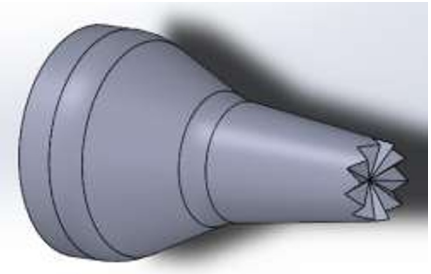
(f) CFD domain 6



(g) CFD domain 7



(h) CFD domain 8



(i) CFD domain 9

Fig. 1: Nine CFD domain of chevron nozzle

2.3 Meshing

An inferior mesh can lead to both imprecise simulation outcomes and potential solver errors caused by instability. The instability is commonly attributed to cells of substandard quality or those that are obtained illegally. Objective is to minimise this occurrence as much as possible. Ensuring simulation accuracy requires careful consideration of creating a high-quality mesh, which is a crucial aspect in Fig. 2.

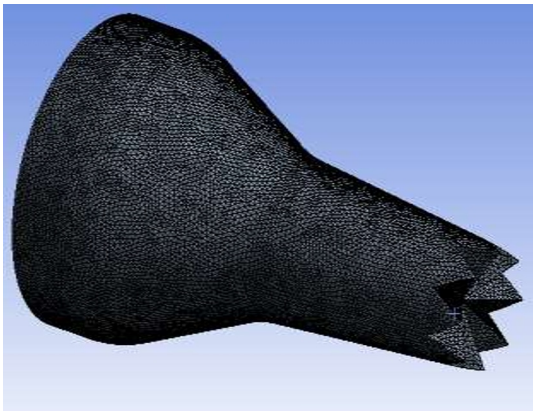


Fig. 2: Mesh model

2.4 Boundary condition

A boundary condition constitutes a specification of the value that a solution must have in a certain region of space, and it does not depend on time. The initial condition refers to a specific criterion that a solution must satisfy at a single moment in time. The inputs of the simulation model are defined by the boundary conditions. The fluid's entry or exit from the model is determined by several factors, such as velocity and volumetric flow rate. The exchange of energy among the model or its surroundings is determined by factors such as film coefficient and heat flow. In this study, the terms "inlet," "outlet," and "wall" are designated as boundary conditions by in Fig. 3.

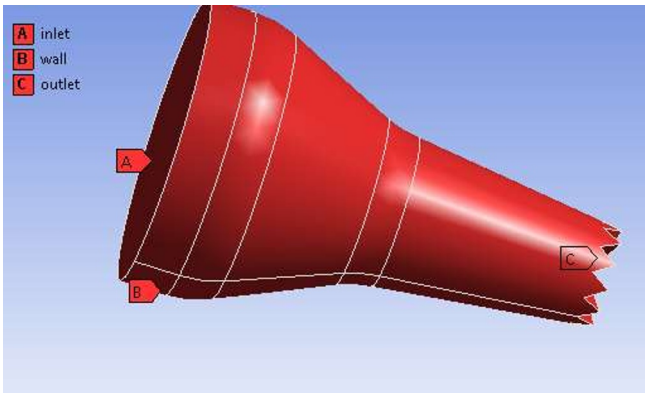


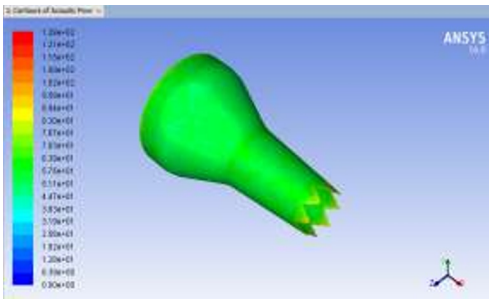
Fig. 3: Boundary condition

The fluid arrives in the form of air with a perfect gas structure. Simulations have been conducted for jets, utilising a stagnation temperature of 600K. The inflow pressure is 1,555,000 Pa and the output pressure is 24,500 Pa. The boundary conditions are specified for a specific condition, and the computations are performed for a maximum of 10000 iterations or until the solution reaches convergence. Pressure, Mach number, and acoustic contours are determined for different nozzle designs.

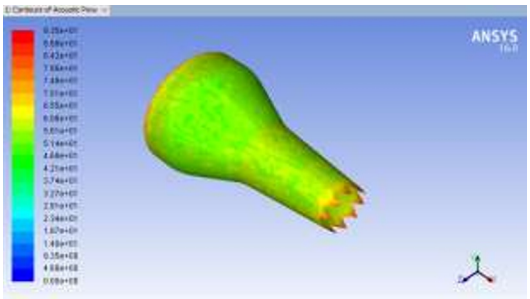
3 Results and Discussion

The study examines the Acoustic Power Level contours across different models of jet engine nozzles, focusing on the distribution of acoustic power and its variations. The results show that the acoustic power level varies near the nozzle's end due to merging hot and cold air streams and strong vortices. The study also examines the impact of serrated designs on jet engine nozzles, specifically chevrons, on noise reduction. The objective of the analysis is to determine which of models 1 through 4 has the greatest reduction in acoustic power levels.

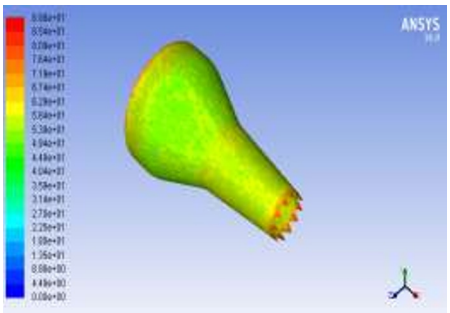
3.1 Acoustic Power Level contours



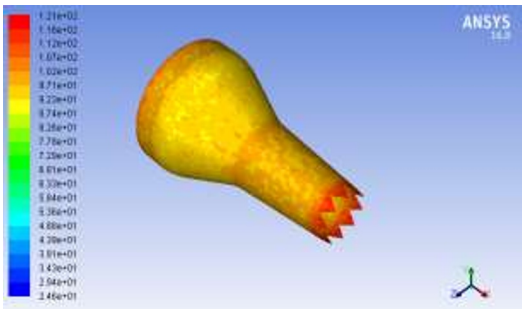
(a) Acoustic power level contour for model 1



(b) Acoustic power level contour for model 2



(c) Acoustic Power Level contour for model 3



(d) Acoustic power level contour for model 4

Fig. 4: Acoustic power level contours

The noise distribution produced via diverse designs or configurations is depicted within the acoustic power level contours for model 1 to 4, which are frequently utilized in engineering to assess the efficacy of noise reduction/removal strategies. The contour map of each model suggests areas with unique sound intensities, emphasising places with the best and lowest concentrations of noise. By the evaluation of those contours, scientists can examine the effectiveness of noise reduction in various designs and determine which characteristics result in decreased noise levels in Fig. 4. This comparative analysis of models with design optimisation, are helpful particularly in conditions where noise reduction is essential for regulatory and environmental compliance, which include jet engines. The acoustic power level contours depicted for model 1 to 4 offer precious insights into the noise distribution generated across various models with unique designs or configurations, serving as a factor in engineering for comparing the efficacy of noise reduction strategies. Those contour maps present a visible instance of regions with high sound intensities, correctly highlighting places characterised through both the highest and lowest concentrations of noise. Via cautious analysis of these contours, scientists and engineers can figure styles and inclinations, enabling them to assess the effectiveness of noise reduction techniques across models with different designs. By figuring out which traits make contributions to reduced noise ranges, researchers can improve the design optimization procedure, refine it and bring about solutions to produce improved noise mitigation controls.

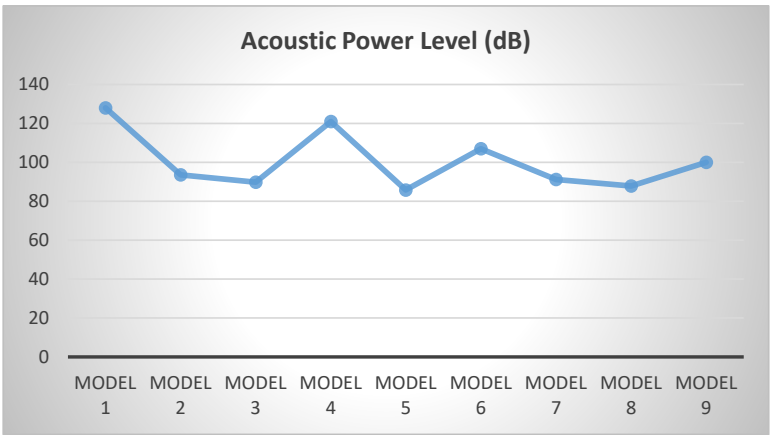


Fig. 5: Acoustic power level

The acoustic power level serves as a essential metric for quantifying the extent of noise generated in various engineering applications, and its importance is underscored by means of the accompanying figures that depict the results of analysis conducted on various models. In these figures, it is inferred that the acoustic level has a tendency to be extra near the nozzle's top, that may be due to air streams and the presence of robust vortices. For example, Fig. 5 offers a comparative analysis across special models, revealing that model 1 exhibits better acoustic power levels as compared to model 5. One great layout function influencing noise technology and mitigation is the incorporation of chevrons, which refers to the serrated patterns located on the rear margins of certain jet engine nozzles. These chevrons play a pivotal function in shaping the airflow dynamics through facilitating the interaction between the hot air entering from the engine center and the cold air passing through the engine fan. The contoured edges of these chevrons serve to reduce turbulence in the exhaust flow, consequently leading to a reduction in noise emissions. The findings of an acoustic power level through this experiment, demonstrates that the strategic utility of chevrons efficiently contributes to noise level reduction. Overall, the insights from research provide valuable information for engineers and researchers seeking to optimize acoustic performance in diverse engineering structures, ranging from jet engines to ventilation systems, thereby enhancing each operational efficiency.

4 Design optimization

The Taguchi approach utilises the Signal-to-Noise (S/N) ratio to enhance the performance feature. The S/N ratio may generally be classified into three categories: lower-the-better, higher-the-better, or nominal-the-better.

$\frac{S}{N} = -10Log\left(\frac{1}{n}\sum Y^2\right)$: Lower the better …(1)

$\frac{S}{N} = -10Log\left(\frac{1}{n}\sum \frac{1}{Y^2}\right)$: Higher the better …(2)

$\frac{S}{N} = -10Log\left(\frac{1}{n}\sum \frac{Y^2}{Y^2}\right)$: Nominal the better …(3)

Here, 'n' was the number of times the experiment is repeated, and 'Y' represents the value of the response variable that is assessed. Figure 6 illustrates the impact of a specific parameter and the acoustic power level.

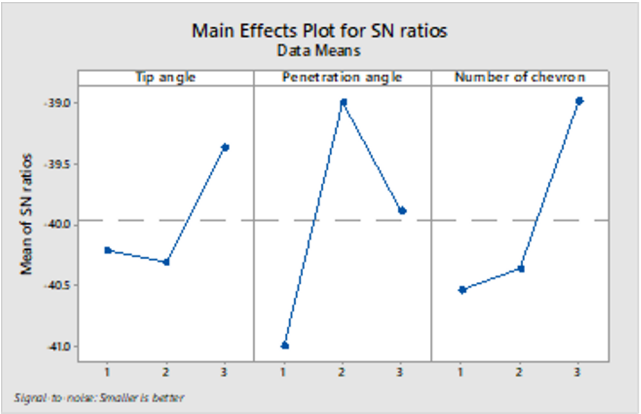


Fig. 6: Effect of selected parameter on level of acoustic

The horizontal axis represents the magnitude of design parameters. Fig. 6 demonstrates that the tip angle, penetration angle, and number of chevrons have an impact on the acoustic power level. Based on the information provided in figure, the ideal settings may be determined as A3B2C3. By combining these settings (A3B2C3), it's inferred that the mixture of a specific tip angle, penetration attitude, and quantity of chevrons results in a improved configuration that achieves the favored acoustic power level. This shows that A3B2C3 represents the most advantageous design parameters for maximizing the acoustic power level primarily based on the statistics offered in Fig. 6. In the context of Fig. 6, variations in the tip angle result in modifications to the acoustic level. It's probable that positive tip angles are extra effective at producing or controlling sound waves, leading to differences in acoustic strength output. The penetration angle represents another parameter that influences the acoustic power level. Fig. 6 indicates that changing the quantity of chevrons has a significant effect at the acoustic energy level. The presence of chevrons may also have an effect on the flow of air or different mediums, leading to changes in sound wave propagation and, therefore, the acoustic power level.

5 Conclusion

Advancements in modern era have yielded considerable reduction in noise levels as compared to engines utilized in early nineties. Recognizing the importance of mitigating plane noise, specially in proximity to airports, plane manufacturers have intensified their efforts and allotted widespread resources on the research associated with the improvement of more silent engines. A remarkable factor highlighted in latest studies is the important position played by jet engine nozzle in noise production, in particular during the time of takeoff and landing stages while engines function under more load. To cope with this issue, considerable research have focused on the efficacy of chevron nozzles in decreasing noise via improving the integration of shear layers and optimizing engine performance. Utilizing advanced computational fluid dynamics (CFD) simulations, which include those carried out with ANSYS CFD software program, researchers have evaluated various chevron nozzle designs for acoustic efficiency. The findings of these studies show that chevron nozzles diminishes noise level in turbofan engines, thereby contributing drastically to the understanding of jet engine noise mitigation measures. It has been found that most of the recent investigations are aimed towards refining and optimizing chevron nozzle designs to attain even greater noise reduction methods. By focussing on the ability of chevron nozzles and offering insights into their acoustic performance, this frame of research is aimed at modelling of nozzels and comparing their acoustic efficiences. The outcomes drawn during the analysis is as follows:

a. Tip angle, penetration angle, and number of chevrons impact noise level. Chevrons effectively reduce acoustic intensity, making them a valuable noise reduction solution.

b. Taguchi method and FEM modeling provide insights into nozzle design acoustic power level contours. Study contributes to understanding jet engine noise and mitigation, promoting a silent, more sustainable future in aviation technology.

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