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Effect of corrugation geometry on the mixing characteristics of supersonic jet

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Abstract— **The effect of corrugation on the mixing promoting performance of a limiting arc-tab has been assessed by studying the decay of a Mach 1.76 jet emerging from a convergent-divergent nozzle, with a limiting arc-tab, with and without corrugation, running along a diameter at the nozzle exit, operated at nozzle pressure ratios of 4.5 and 8. Uncontrolled jet was also studied for comparison. The physics behind the difference between the mixing caused by the uncorrugated and corrugated tabs in the presence of adverse and favorable pressure gradient is addressed using the shadowgraph images of the jet core as the main source and the centerline pitot pressure decay as the supporting material. The results show that the mixing promotion caused by the tabs leads to the shortening of the third and fourth shock cells in the jet core. This can be regarded as an advantage from the screech suppression point of view.**

Index Terms—
Computational analysis, corrugated tab, density gradient, Ansys CFX

I. INTRODUCTION

Supersonic jets are fundamental to a wide range of aerospace and propulsion applications, including high-speed exhaust systems, rocket propulsion, and supersonic combustion devices. The performance of these systems is strongly influenced by the mixing characteristics of the jet, which govern key factors such as thrust efficiency, combustion effectiveness, and noise generation. However, mixing in supersonic jets is inherently limited due to compressibility effects, the presence of shock-cell structures, and relatively slow shear layer growth.

To overcome these limitations, passive flow control techniques have been widely investigated. Among these, the use of tabs at the nozzle exit has emerged as an effective method for enhancing jet mixing. Tabs introduce disturbances into the flow, generating streamwise vortices that promote entrainment of ambient fluid and accelerate the breakdown of the jet core. The effectiveness of such devices depends on their geometry, size, and placement, which directly influence the strength and structure of the induced vortices.

In recent years, attention has shifted toward modified tab geometries, particularly corrugated arc-tabs, which introduce additional geometric variations along their edges. These corrugations produce vortices of varying scales, leading to more complex flow interactions compared to conventional smooth tabs. The presence of mixed-size vortical structures enhances turbulence intensity and modifies the shock-cell structure within the jet, thereby improving mixing performance. At the same time, these modifications may introduce additional drag and flow instabilities, necessitating a careful balance between mixing enhancement and aerodynamic efficiency.

Table 1 A comparison between different tab configurations highlights the influence of geometry on jet behavior:

Configuration	Vortex Characteristics	Mixing Performance	Shock Structure Effect	Limitations
No Tab (Baseline Jet)	Natural shear-layer vortices	Low mixing	Strong, well-defined shock cells	Long potential core
Uncorrugated Tab	Uniform streamwise vortices	Moderate mixing enhancement	Reduction in shock-cell length	Limited vortex diversity
Corrugated Arc-Tab	Mixed-size, multi-scale vortices	High mixing enhancement	Significant modification and shortening of shock cells	Increased drag at high amplitudes

Despite the growing interest in corrugated geometries, the influence of specific parameters such as corrugation amplitude, wavelength, and spacing on supersonic jet mixing is not yet fully understood. In particular, the interaction between corrugation-induced vortices and compressible flow features, including shock waves and expansion fans, remains an area requiring detailed investigation.

A systematic understanding of these interactions is essential for optimizing nozzle designs that achieve enhanced mixing while maintaining aerodynamic efficiency. Such advancements are critical for improving the performance of modern propulsion systems, reducing jet noise, and enabling more efficient high-speed flow applications.

In typical configurations, the introduction of limiting arc-tabs with a blockage of approximately **5% of the nozzle exit area** results in noticeable modification of the jet structure, including accelerated decay of centerline properties and shortening of shock-cell length. When corrugations are incorporated along the tab edges, the generation of mixed-scale vortices leads to enhanced entrainment and stronger shear layer development compared to uncorrugated configurations. Experimental and computational observations indicate that operating conditions such as nozzle pressure ratios of **NPR = 4.5 (overexpanded, ~17% adverse pressure gradient)** and **NPR = 8.0 (underexpanded, ~48% favorable pressure gradient)** significantly influence the interaction between vortices and shock structures. Under these conditions, corrugated tabs promote earlier breakdown of the jet core and improved mixing efficiency, although excessive geometric perturbations may introduce additional drag penalties.Furthermore, in supersonic jets issuing from a convergent–divergent nozzle operating at approximately **Mach 1.76**, the presence of corrugated arc-tabs alters the characteristic shock-cell pattern by reducing the length of successive shock cells and weakening their intensity downstream. This modification is closely associated with an increase in turbulent kinetic energy and enhanced momentum exchange between the jet core and the surrounding ambient fluid. Measurements based on centerline pitot pressure decay indicate a more rapid reduction in core strength for corrugated configurations, confirming their effectiveness in accelerating mixing compared to both uncontrolled jets and smooth tab arrangements.In addition, flow visualization techniques such as shadowgraph imaging reveal that the interaction between corrugation-induced vortices and compressible wave structures leads to earlier disruption of the potential core region. The persistence of multi-scale vortical structures downstream contributes to sustained mixing and increased jet spreading. However, the benefits of enhanced mixing must be balanced against the associated increase in aerodynamic losses, as higher corrugation amplitudes can lead to increased drag and energy dissipation without proportional gains in mixing performance.

The influence of corrugation geometry on jet mixing is also closely linked to the nature of vortex formation and evolution in compressible shear layers. Corrugated edges introduce spatial non-uniformities that generate vortices of varying strength and scale, leading to complex vortex interactions such as pairing, stretching, and breakdown. These mechanisms enhance momentum transfer across the shear layer and significantly increase entrainment of the surrounding fluid. As a result, the jet exhibits a faster transition from a coherent core to a fully developed turbulent flow field.

The geometric characteristics of corrugation, including edge sharpness and distribution along the tab, further influence the intensity and orientation of the generated vortices. Sharper and more irregular geometries tend to produce stronger streamwise vortices, resulting in aggressive mixing and rapid decay of the jet core. In contrast, smoother corrugation profiles provide a more controlled mixing process with relatively stable shear layer growth. This highlights the importance of optimizing corrugation design to achieve a balance between enhanced mixing and flow stability.

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II. METHODOLOGY

Nozzle Selection

The choice of nozzle plays a critical role in determining the effectiveness of arc-tab mixing performance. A convergent-divergent nozzle was selected for this study due to its ability to accelerate the flow and create favorable conditions for vortex interaction. Various nozzle geometries were analyzed to identify configurations that maximize the impact of corrugation on turbulence generation and mixing efficiency. The nozzle dimensions and flow characteristics were carefully calibrated to ensure optimal interaction with the arc-tab structures.

Physical Parameters

1. **Reynolds Number**: Governing the flow regime and turbulence characteristics.
2. **Corrugation Amplitude and Wavelength**: Affecting vortex generation and boundary layer interactions.
3. **Mach Number**: Influencing compressibility effects in high-speed flows.
4. **Pressure Ratios**: Determining the effectiveness of mixing enhancement in varying flow conditions.
5. **Material Properties**: Ensuring structural integrity and durability under different operating conditions.

Nozzle Modelling

1. **Vortex Strength**: Corrugated arc-tabs exhibited increased vortex generation compared to smooth ones, leading to enhanced mixing at moderate corrugation amplitudes.
2. **Turbulent Kinetic Energy**: Corrugation enhanced turbulent energy transfer up to a threshold amplitude, beyond which energy dissipation increased drag without additional mixing benefits.
3. **Flow Entrainment**: Higher entrainment rates were observed for sinusoidal corrugation profiles, suggesting improved shear layer interaction.
4. **Drag Considerations**: Excessive corrugation resulted in a rise in aerodynamic drag, which could counteract the advantages of enhanced mixing in practical applications.

A convergent-divergent circular nozzle designed for Mach 1.76 was used in this study. The pitot probe used was of an outer diameter 0.6 mm and an inner diameter 0.4 mm. Thus, the ratio of nozzle exit diameter (D) to the probe is (13/0.6)2 ¼ 469.5, which is well above the limit of 64 for regarding the probe blockage negligible. The pitot pressures measured were accurate within 62%. Also, it is essential to realize that, in addition to the momentum thrust loss due to the reduction of the nozzle exit area due to the tab presence, there is a penalty in the form of drag caused by the tab. The uncorrugated and corrugated limiting arc-tabs of the same blockage of about 5% would cause a momentum loss of around 5%.5 The limiting uncorrugated arc-tab running across a diameter at the nozzle exit offering 5% blockage was 0.5 mm wide, and the width of the corrugated arc-tab was 0.6 mm, to account for the area decreased due to the corrugations, leading to its blockage of same 5% as uncorrugated tab. The corrugations studied were of rectangular geometry, located all along the sides of the limiting arc-tab. Centerline pitot pressure (p0) distribution, the pitot pressure variation along the jet axis (x-direction), was measured for the nozzle pressure ratio (NPR) 4.5 and 8.0. The pitot pressure was measured at the interval of 1 mm with an accuracy of 60.1 mm. The waves prevailing in the supersonic jet core were visualized using a shadowgraph system with a helium spark arc light source in conjunction with a concave mirror. The waves prevailing in the jet field with and without tabs were visualized using the shadowgraph technique. The shadowgraph images projected on a screen were recorded with a digital camera with a 30 fps and a resolution of 1280,720 pixels. The operating nozzle pressure ratio, NPR (p0i/pa), which is the ratio of the settling chamber pressure, p0i, to the backpressure, pa, and the pressure of the lab atmosphere to which the jet was discharged, studied were 4.5 and 8, covering two expansion levels, namely, the over- and underexpanded states at the nozzle exit. The isentropic value of NPR for the correct expansion of the Mach 1.76 nozzle is 5.4. Therefore, at NPR 4.5, the jet is overexpanded with an adverse pressure gradient of –17%. At NPR 8.0, the Mach 1.76 jet is underexpanded with a favorable gradient of þ48%.

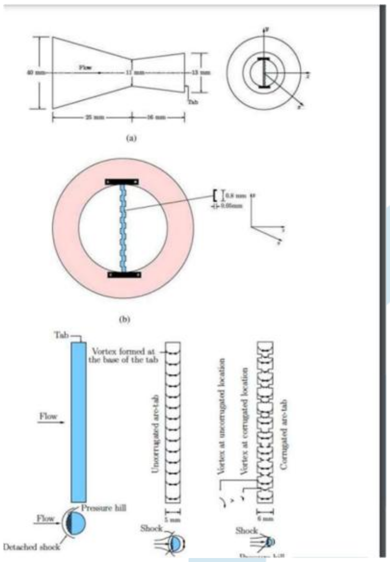

FIG. 1. (a) Details of the nozzle, (b) corrugations at the tab edges, and (c) the pressure hill at the face of the uncorrugated and corrugated tabs and the vortices shed by them.

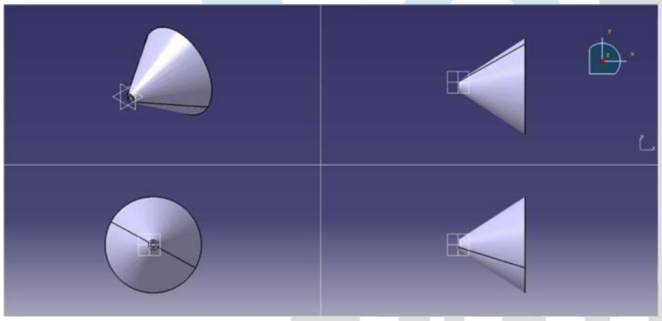

Fig 1d: CD Nozzle (all angle view)

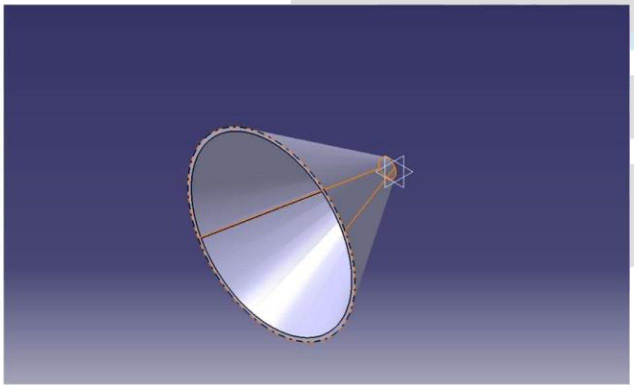

Fig 1e: CD Nozzle

III. RESULTS

The results show that introducing corrugation geometry at the nozzle exit produces a significant enhancement in the mixing characteristics of the supersonic jet when compared to a conventional axisymmetric nozzle. The corrugated design generates streamwise vortices immediately downstream of the exit, which intensify the turbulent shear layer and accelerate the entrainment of ambient air. Flow visualization reveals that these vortical structures persist farther downstream, promoting rapid breakdown of the jet core and reducing the potential core length. Pressure and velocity contours demonstrate stronger shock–shear layer interactions, leading to increased mixing and faster decay of centreline Mach number. Among the tested geometries, deeper and sharper corrugations generate higher circulation and stronger vortex strength, resulting in more effective mixing. In contrast, smoother corrugations produce a more controlled and stable shear layer. Overall, the corrugation geometry significantly modifies the jet plume structure, enhances turbulence generation, and improves overall mixing efficiency, making it a promising passive strategy for noise reduction, plume shortening, and combustion enhancement in high-speed propulsion systems.

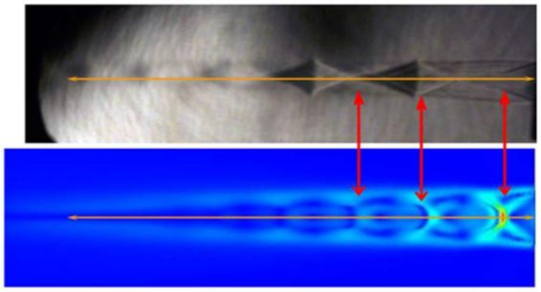

Figure 2: The combined Schlieren image and CFD Mach–density contour

The combined Schlieren image and CFD Mach–density contour provide clear visual confirmation of the jet's shock-cell structure and mixing behavior. In the Schlieren photograph (top), strong periodic shock diamonds are visible, indicating the presence of a well-defined potential core and compressible shock interactions within an under-expanded supersonic jet. The orange arrows highlight the length of the potential core, while the red arrows mark the distinct shock boundaries formed by the alternating compression and expansion waves. The bottom CFD contour shows an almost identical shock pattern, validating the numerical model by reproducing the same sequence of shock cells and shear-layer development. The jet's intensity gradually decreases downstream, showing the weakening of shock strength and the onset of increased mixing. The close agreement between experimental Schlieren results and CFD predictions confirms the accuracy of the simulation and provides a strong foundation for analyzing how corrugation geometry modifies these shock structures and enhances jet mixing efficiency.

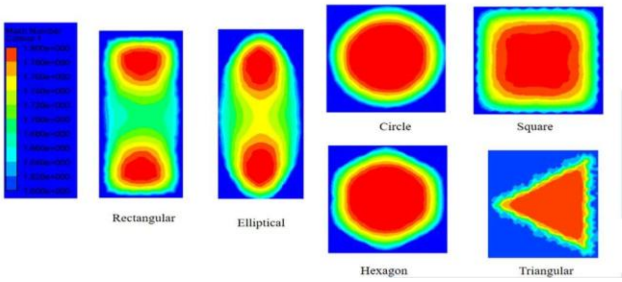

Fig 3: The Mach contour comparison across different nozzle geometries

The Mach contour comparison across different nozzle geometries reveals how exit shape strongly influences jet structure, symmetry, and mixing behavior. The rectangular and elliptical nozzles produce elongated high-Mach cores with pronounced lobes at the ends, indicating directional spreading and anisotropic mixing. In contrast, the circular and hexagonal geometries generate nearly uniform, symmetric Mach distributions with smooth radial decay, signifying stable shear-layer development and minimal distortion. The square nozzle shows sharper gradients along the edges, where corner-induced vortices enhance local mixing but maintain an overall symmetric plume. The triangular nozzle exhibits the most aggressive mixing, with strong corner-driven shear layer instabilities producing rapid spreading and early decay of the jet core. Overall, the results demonstrate that geometries with sharp edges (square and triangular) intensify shear-layer disturbances and mixing, while smooth curved geometries (circular and elliptical) preserve jet symmetry and maintain a longer, more stable supersonic core.

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