Jet mixing enhancement of a supersonic twin jet nozzle using rectangular tabs

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Abstract. Computational study on the development of mean flow and mixing capability of a rectangular tab placed at the exit of a Mach 1.6 single and twin jet nozzles has been presented. Placing two identical conical nozzles side by side separated by a distance of 1.5 times exit diameters makes the twin jet configuration. The mitigation technique for twin jet cross coupling effects by rectangular tabs for the enhancement of aerodynamic and acoustic characteristics is validating. The results are relevant to situations wherever shock cell structures, potential core length, jet mixing related noise are of concern. Centre line pressure decay characteristics shows that there is an abrupt reduction in the core length and suppression of shock cell structure at off design conditions. The results are in good agreement with the experimental results.

1. Introduction

In the past two decades, there is an increased demand of supersonic and hypersonic vehicles in the field of military and space applications. A lot of researches are going on these areas like jet mixing enhancement, noise reduction methods, augmentation of thrust levels etc. All these parameters are highly depending on the interactions of exhaust plume from the nozzle with the ambient air and the structural components around the immediate vicinity. Since the jet is a typical type of shear layer, a large number of investigations on both subsonic and supersonic jet flows have been studied on the basis of free shear layer theories from the beginning of the aerospace industry itself.

An experimental study on the characteristics of transition of a free laminar shear layer to turbulent shear layer and its instability was studied by the jet mixing of two different velocity flows through a splitter plate arrangement and showed that the instabilities of this free shear layer is high at very high Reynolds’s numbers [1,2]. The instability waves then spread, roll up and forming vortices and leads to the formation of turbulence in the downstream. For supersonic jet as the convective velocity increases the turbulence structure becomes unstable and the development rate of these shear layer along with the vertical structures depends on the compressibility effect, exit Mach number and temperature [3]. The entrainment of ambient fluid particles results in the fast decomposition of jet during the generation of vortices.

From the above discussions it is clear that the behaviour of a jet whether subsonic or supersonic relay on the growth of free shear layer and the subsequent flow structure. In the case of subsonic flows and at design expansion of supersonic flow the presence of jet flow structure is the main source of acoustic radiations other than any other sources [4]. The investigations of Tam [5], Plaschko [6] and
McLaughlin [7] showed the relation between instability waves caused by the turbulent structures and the acoustic wave. In the noise spectrum the peak frequency is in resonant with the peak frequency of instability acoustic waves. At imperfect expansion, the subsonic and supersonic shock cell structure at the core has a periodically oscillating form and the oscillations of these waves are the sources of broadband shock associated noise and screech tones. The effect of temperature on broadband associated noise from a CD nozzle at imperfect expansion and the characteristics of these noises were studied by Tam and Tanna [8]. An experimental study on screech tones was carried out by Benoit and his colleagues [9]. Screech tones are very high intensity discrete frequency waves in the noise spectrum. Its intensity depends on the Mach number, temperature and expansion rate. Tam [10] carried out a very good review on the supersonic jet noise. Mubarak and Tide conducted experimental and numerical study on the supersonic exhaust jet structure emanating from a conical, bell and double parabolic nozzles at various nozzle pressure ratios [11,12]. They showed that there is not that much influence of nozzle profiles on exhaust shock cell structures.

All the above discussions so far highlighted the role of turbulent structure generated by the shear layer vortices and shock waves in the noise generation. Therefore, it is important to control this type of noise which hampers the performance of aircrafts and rockets. The structural failure of F-15 and B-1B aircrafts are due to the intense acoustic loading generated by the shock associated noise. Experimental investigations on twin jet nozzles carried out at NASA Langley Research Centre by Seiner, Ponton and Manning [13] showed that the fatigue failure of twin jet nozzles used in aircrafts was due to the screech tone resonance. This screech tone was generated by the intense pressure fluctuations associated with the large-scale shock cell structures of each jet. These aircrafts had very closely placed twin jet dynamics. To understand the aero-acoustic phenomenon, associated with twin jet assembly a significant number of studies are carried out at the end of last century.

In 1958, Greatrex and Brown proposed the twin jet configuration for the reduction of jet noise. [14] In their study they found that when two parallel and co-planar jets placed sufficiently far apart, the jet resulted in less noise than a single jet, this phenomenon known as the acoustic shielding. Later a number of studies had been done by various scientists on this acoustic shielding and provide the actual mechanism behind the acoustic shielding [15]. Later on, 2012 at NASA Glenn Research centre, Richard and Brenda carried out a number of aero-acoustic experimental tests on twin jets. They studied the acoustic shielding ability of twin jet configurations over subsonic and over-expanded supersonic conditions and found that a maximum of 3Db reduction in overall sound pressure level along the jet noise direction but there is an increase of noise perpendicular to the plane containing the jet [16]. When the jets emitting from the twin nozzles, at first the thin shear layer near the nozzle exit area entrains the surrounding fluid then it thickens and its width increases due to the further entrainment at the free shear boundaries and at the jet core. Then the two independent jets interact each other at the middle plane and at the downstream it developed as a single flow [17, 18]. The generation of acoustic waves due to the mutual interaction of the independent jets depends on the nozzle spacing, Mach number and pressure ratio [19].

So, from the discussions on twin jet nozzles, it is clear that the use of twin jets at supersonic and subsonic flows reduces the acoustic radiations significantly. But at off design conditions, like all other nozzles the advantage of noise reduction of twin jet is somewhat questioning. Researchers carried out a number of studies to overcome these unfavourable situations at off design conditions by controlling the jet exiting from the nozzles with active and passive control devices. These controls comprise alteration of nozzle exit shape like chevrons, use of vortex generators, injecting micro jets etc. These methods enhance the jet mixing and reduction of noise.

E. Gutmark and Grinstein [20] carried out an experimental study on flow control over non circulars jets and showed the jet interaction mechanism and vorticity dynamics. A supersonic inlet unstart had been resolved by introducing vortex generators by Valdivia et.al [21]. A significant number of researches had been carried out widely on the control of supersonic jet using micro jets and all the studies showed the jet mixing enhancement. [22,23, 24]
The present paper mainly focuses on the control of jet using the vortex generator in the form of a rectangular tab. The mixing characteristics of a supersonic nozzle with triangular tabs was carried out experimentally by E. Radhakrishnan and Arun Kumar [25] in 2013 and showed that there is a significant reduction of core length for right angled triangle. An experimental study on a supersonic twin jet for the jet mixing enhancement had been carried out by Aquib Khan, Saif A and Rakesh K in 2019 using horizontal and vertical rectangular tabs at the nozzle exit [26]. They showed that the orientation of vortex generators has significant effect on the characteristic pressure decay at the centre line jet.

From above all discussions, it can be summarized that the aero-acoustic characteristics of a supersonic flow depends on the shock cell structures and the interactions. To reduce the noise radiations, use of twin jet is preferred. But the structural issues associated with the twin-engine configurations lead to further mixing of jets exiting from the nozzle. Thus, the objective of this paper is the computational study of controlling the jets from a twin jet nozzle by using rectangular tabs as passive vortex generators at the exit.

2. CFD modelling
The computational study has been carried out by 2D compressible flow modelling in the ANSYS FLUENT 2020 R2 software using RANS equations combined with k-ω SST (Shear Stress Transport) turbulence model. This flow solver gives much accurate solutions for the analysis of CD nozzles, and the results are in good agreement with experimental data [27]. Since the k-ω SST model based on the turbulent kinetic energy and dissipation rates, it is widely used for turbulent flow analysis.

2.1 Nozzle geometry
All the dimensions used in this paper is accordance with the experimental set up used for modelling the supersonic flow by CD nozzle with a rectangular tab [24]. The control volume dimensions are given in Figure 1.

![Figure 1. Nozzle Dimensions](image)

2.1.1. Twin jet geometry with tabs. Two rectangular vortex generators are placed vertically at the exit of each nozzle as shown in Figure 2. The twin jet configuration is obtained by placing two above said nozzles side by side at a distance of 1.5*De (Exit diameter of the nozzle). The dimensions of the tabs are fixed as 3mm in length and 1.5 mm in width as shown in Figure 2.
2.2 Simulation set up
In the fluent solver the setting that have been established are:
- 2D density-based
- Viscous k-ω SST with compressibility effects.
- Air as fluid, ideal gas, viscosity by Sutherland law.
- Boundary conditions have been given as per Table 2 in each case.
- Calculation: Hybrid initialization, Implicit, First order upwind scheme

Stable convergence has been achieved after 5000 to 7000 iterations, as per the flow geometry of each case.

In this paper the aerodynamic and aero-acoustic characteristics by the centre line pressure decay of 3 cases are studied at various nozzle pressure ratios (NPR) as shown in Table 1. Centre line pressure ratio (Static pressure/total pressure) from the nozzle exit plane (x=0 point) up to the downstream point 15 times the nozzle exit diameter is considered for the demonstrate the pressure decay. If the pressure decay is fast and more, the jet mixing also high.

### Table 1. Nozzle conditions

| Case number | Conditions                     | NPR  |
|-------------|--------------------------------|------|
| 1           | Single jet                     | 4.25, 5 and 7 |
| 2           | Twin jet                       | 5    |
| 3           | Twin jet with rectangular tabs | 5    |

### Table 2. Boundary conditions

| Case     | Boundary conditions  | Values                                                      |
|----------|----------------------|-------------------------------------------------------------|
| **Case 1** | Pressure inlet       | 430.63×10⁴pa, 506.625×10⁴pa, 709.275×10⁴pa                  |
|          | Temperature inlet    | 350 K                                                       |
|          | Pressure outlet       | 101.325×10⁴pa                                              |
|          | Temperature outlet    | 300 K                                                       |
|          | Pressure inlet       | 506.63×10³pa                                                |
|          | Temperature inlet    | 400 K                                                       |
| **Case 2** | Pressure outlet       | 101.325×10⁴pa                                              |
|          | Temperature outlet    | 300 K                                                       |
|          | Pressure inlet       | 506.63×10³pa                                                |
|          | Temperature inlet    | 400 K                                                       |
| **Case 3** | Pressure outlet       | 101.325×10⁴pa                                              |
|          | Temperature outlet    | 300 K                                                       |
At first the single jet supersonic nozzle at NPR of 4 is considered for grid independent study. The nozzle domain extends up to 16De downstream of the jet. The design Mach number of each nozzle is 1.6. The NPR is varied from 4 to 7 by setting the outlet pressure as constant, which is the standard ambient pressure at sea level condition and the inlet pressure is varied. In all the simulated cases the centre line pressure decay is measured to find the shock cell suppression and thereby the jet mixing characteristics. Boundary conditions for each simulation is as in Table 2.

### 3. Results

Twin jet supersonic nozzles with vortex generators play an important role in the reduction of acoustic radiation by jet mixing. The present study investigates the role of rectangular tabs placed vertically at the exit of a supersonic twin jet nozzle on the aerodynamic and aero acoustic phenomenon. The following paragraphs describe these effects.

#### 3.1 Single Jet

The pressure contours and velocity contours of a single jet CD nozzle without tab at NPR=4 is shown in figure 3 and 4. Figure 5 indicates the centre line pressure ratio plot of the uncontrolled jet at three different NPR as in Table 1. From these plots it is clear that a train of shock cell is generated downstream of the nozzle. As NPR increases the spacing between shock cell structures also increases.

![Figure 3. Pressure Contour of Single uncontrolled jet](image)

![Figure 4. Velocity Contour of Single uncontrolled jet](image)
From the isentropic relations for the design expansion at $M=1.6$, it is found that NPR is 4.25. Therefore, in figure 5 at the NPR condition the nozzle is at slightly over expanded conditions. An oblique shock wave envelops formed very near to the nozzle lip which converges into a point known as the shock cross over point. As the NPR increases, the nozzle become under expanded and a series of oblique shock waves are formed near the nozzle exit and further downstream there is a formation of Mach disk which in turn cause the deceleration of subsonic values. This is the reason for the minimum value of pressure near the $2De$ location.

3.2 Uncontrolled twin jet nozzle
Figure 6 and 7 shows the pressure and velocity contours of twin jet uncontrolled nozzle at NPR=5. At high NPR the interaction of very closely placed jet is very complicated, they entrain a large amount surrounding fluid near the nozzle exit and this will lead to the fatigue failure near the nozzle exit.
The region of the flow in between the two jets is known as the inter nozzle region. The entrainment of surrounding fluid increases jet spread due to shear layer thickening. Therefore, the region near the nozzle exit of a twin jet is significantly different from single jet. Figure 8 shows the centreline pressure decay of single and twin jet nozzles at NPR 5.

At higher NPRs the variation at the centre line pressure decay of single and twin jet is significant as shown in Figure 8. At these NPR the jet interaction of twin jet is more and that begins from the inter nozzle region itself. Since in the case of a single jet, the fluid can entrain fluid from all directions the centre line pressure decay is faster than that of the twin jet.

3.3 Controlled Twin jet

To reduce the acoustic radiations, we have to again enhance the jet mixing. For that the passive control mechanism of placing the vortex generates in the form of rectangular tab is placed at the exit of each nozzle. The Pressure and velocity contours of the controlled twin jet are shown in Figure 9 and Figure 10.
The presences of vortex generators are offering a 5% blockage to the outgoing stream at the nozzle exit. There is a significant variation of centre line pressure decay of the controlled and uncontrolled jets can be evidently seen from the Figure 9. It is calculated for NPR = 4.25 (for the correct expansion). At 4 the nozzle is at over expansion and the presence of oblique shock envelop is formed near the nozzle lip. But at the corners there some presence of expansion fans because of the sudden change in area at the nozzle exit.

Figure 9. Pressure contours of controlled twin jet with tabs

Figure 10. Velocity contour of controlled twin jet with tabs

Figure 11. CPD of controlled and uncontrolled twin jets at NPR 4.25
The sudden decay of controlled twin jet is due to the formation of higher vortices and the suppression of shock cell structures. The result is in good agreement with the experimental data by Aquib Khan [24] as shown in Figure 12.

![Figure 12. Comparison between experimental with computational analysis](attachment:image.png)

4. Conclusion
The present numerical analysis has brought about some key aspects of the effect of using rectangular tab as vortex generators for controlling the twin jet flow field. It has significant relevance in the supersonic and hypersonic aerodynamics and aero acoustic characteristics. The centre line pressure decay downstream of the nozzle exit is considered as the measure of jet mixing. It was observed that the presence of tabs increases the jet spread which in turn suppresses the shock cell structures. The enhancement in mixing reduces the acoustic radiations. All the above presented studies are in good agreement with the experimental data.

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