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Visualization of Mixing and Acoustic Characteristics of Elliptical Throat Jet with Passive Control

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Keywords：Jet noise, mixing promotion, Supersonic Jet, Screech Frequency.

ABSTRACT

This paper deals about the effect of aspect ratio and related acoustic properties of jet issuing from non circular throat jets. The experimental program investigates the elliptical throat jet of aspect ratio of 2, 3 and 4 with passive control. The series of experiments conducted on both controlled and uncontrolled jet at NPR4 to find the core length and jet decay. The results are evaluated in perfectly expanded conditions, the results reveals that as the aspect ratio increases, the shear layer growth decrease. This leads to the axis switching at downstream. At perfectly expanded it is noticed that, due to the change in aspect ratio the shock cell structure sees appreciable change. At the aspect ratio of 2:1, the shock is oblique and it is replaced by normal shock at the aspect ratio of 3 and 4 jets. The variation of aspect ratio increases the amplitude of screech frequency. Implementation of passive control at the major axis of exit modifies the shock cell structure and which alters the amplitudes of screech tone frequency for aspect ratio of 2, 3 and 4 jets.

INTRODUCTION

This paper presents the novel study of non circular jet entrainment at different elliptical throat aspect ratio with the crosswire passive control. There are several pieces of research available for the supersonic jet with elliptical exit. However, the works on the elliptical throat are very limited. This paper aims to explore the aspect ratio importance in the throat area and their significance. We have taken the elliptical throat with aspect ratio ranges from 2, 3 and 4. Elliptical jet is chosen for its superior quality and high mixing properties.

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Study of the controlled jet has a huge scope than the study of the uncontrolled jet in aero acoustic fields. The passive control techniques are already explored by several pioneers. However, still a lot of advancement are taking place in capturing the results of jet with active and passive controls since it has a great value in both aerodynamics and acoustics.

Early researchers noticed that implementation of passive control at the end of the jet gives enhanced mixing capabilities. The tabs are small device placed in flow direction to generate the vortices in transverse direction. In early times few studies have focused on passive control jet like triangular [1, 2], rectangular [3, 4, 5, 6, 19], square [7, 19] and many more profiles. Small aspect ratio has huge importance in recent days [8] since it provides high mixing and adequate axis switching. Hussain and Hussain [14] done experiments on aspect ratio effect from 2 to 8, they observed that, for controlling deforming of jet aspect ratio is an important parameter. They reported jet bifurcation change when the aspect ratio of the jet changes. They also found axis switching is witnessed subjected to the change of aspect ratio of the nozzle. One of recent study recognized that the deformation of vortical structures is identical to elliptical ring [9, 10]. The ring is unstably inherent due to its azimuthal variation of the nozzle. They prove that, due to non uniform self induction mechanism the passive control ring deforms to provide a dual axis switching. Switching mechanism has dominant a role in mixing efficiency compared to circular and planar jets. Gutmark et.al [2] have studied non circular jets using PLIF (Planar laser induced fluorescence) technique. They carried out experiments on the effect of sharp corners on the mixing and combustion. Further, they also relatively studied the behavior of the vertical structures and concluded the role of aspect ratio in jet mixing. Bradbury and khadem [11] were the first one to study the effect of passive control on a low speed circular jet. They found that, when two tabs are placed diametrically opposite gives the better alteration in jet than other types of configurations. They also saw that, the jet is divided into two high speed regions 1 and 2 behind tabs. There are several literatures to state based on passive control, one of notable works is done by Abya and Brown [12], and they carried experiment on mixing enhancement in subsonic and supersonic circular jets with tabs at nozzle lip. They conducted the experiments of jet flow in both heated and unheated conditions. They finally revealed that, when tabs are placed diametrically opposite gives better mixing than the tabs in another position. Rathakrishnan [13] recently carried out a study on passive control to increase the efficiency of convergent-divergent nozzle. They introduced the rectangular tabs on major and minor axis of the elliptical jet. They found that the tabs along the minor axis gives shore core length than the tab along the major axis, this occurs due to the shock cell growth. The shock cell strength is higher in major axis than minor axis. Vijayaraja [19] conducted an experiment on passive control using shifted tabs. They concluded at higher NPR 5 to 8, the amplitude of centerline pitot pressure is considerably less than uncontrolled jet. They proved shifted tabs gives higher mixing than regular tabs. Manigandan [20] calibrated the effect of crosswire in elliptical jet. They presented the effects of crosswire along major and minor axis. They confirm that, the crosswire along the minor axis gives better mixing promotion than major axis. From all above literatures, it is identified that, when the passive control are placed on the minor axis gives the enhanced results than major axis. Further, manigandan [21] carried out experiments on acoustic characteristics of elliptical jet and circular jet. They reported, elliptical jet performs better than a circular jet. Moreover, we also understood that, the tabs are reducing the core length of the jet [22-26]. The literature undoubtedly shows that the researchers are interested in studying the effect of aspect ratio for supersonic elliptic jets issuing from elliptic slots. Also, the reported supersonic jet Mach numbers which is analogous to perfectly expanded flow. Hence the study of elliptical throat jet of different aspect ratio issuing from convergent-divergent nozzles would be of immense value in the field of high speed flow dynamics. In the present study, an effort has been made to study the flow field characteristics of elliptic jets issuing from convergent-divergent elliptic nozzles of aspect ratio 2, 3 and 4 of Mach number 2 and constant nozzle pressure ratio under the influence of local nozzle heating process. The results of the present study were compared with the available literature.

EXPERIMENTAL SETUP

Experiments are conducted using the high speed jet facility at Jeppiaar Engineering College, Chennai, India. Figure 1 shows the test setup. This facility enclosed by cylindrical settling chamber which is connected to high pressure storage tank. The desired nozzle pressure ratio is arrived by adjusting the chamber pressure. The jet is oriented horizontally and there is no impingement to produce free jet entrainment for this study. The system is connected to a high pressure reservoir that stores nearly 50psi for practical runtime of 2hours.

Fig. 1. Open Supersonic Jet facility

The pressure is controlled by the control valve. The air flows into stagnation chamber, where pressure is calibrated. The nozzle pressure ratio is achieved by controlling settling chamber pressure.

Experimental model

The experimental model is tested for the Mach number of 1.5 at different aspect ratio 2, 3, and 4. The model shown in figure 2 is made of brass fabricated by electrical discharge Machining technique. The diameter of the throat is 8±0.1mm, the inlet and outlet diameter of nozzle found to be 13±0.1mm and 11±0.1mm. The nozzle is designed in such a way that it varies for aspect ratio 2, 3, and 4, whose respective diameters are 8, 10, and 12mm respectively. The figure 2 shows one of the test models, elliptical throat nozzle whose aspect ratio is 4 with circular exit. The cross wire is used as the passive control; it is made of brass, of thickness 2mm and 11.1mm long. The Mach number of the exit plane is 1.5. The jet study is not screech free since the range of screech jet is 1.5 to 1.8 Mach [13]. The Reynolds numbers for the design nozzle are 6.5 × 105 and 15.5 × 105, respectively, for nozzle pressure ratios (NPRs) of 4. A probe is inserted at the exit of the nozzle where the flow is supersonic. Hence the total pitot pressure is measured behind the shock at the probe.

Instrumentation

The pressure variation along X/D is measured using the 16 channel pressure system which ranges 0-2.1Mpa. The software coding is integrated to the transducer to import the data simultaneously from the 16 channel pressure system. The accuracy of calibration pressure to be 0.2% full scale. The jet field pressure measurement is carried out by the Pitot tube, whose inner diameter and the outer diameter is 0.4mm and 0.6mm mounted on the automatically operated three dimensional transverse mechanisms. Resolution of the transverse mechanism is 0.1mm.

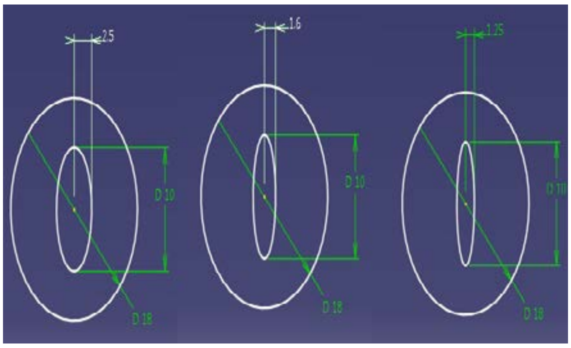

Fig. 2. Test model with elliptical throat of Aspect Ratio a) AR2 b) AR3 c) AR

The sensing probe is kept normal to the jet axis. To avoid the errors in Pitot tube 250 samples per second measurement is done [13]. Axis switching is captured using the Ansys-ICEM for computational visualization.

RESULTS AND DISCUSSION

Centerline Pitot Pressure Decay

Identification of quantifying core length, characteristic decay is one of serious difficulties in supersonic jets. The pitot pressure decay is a reliable method to measure the characteristics of jet mixing, indicating the mixing of the fluid mass entrained at the jet boundary with the mass inside the jet. Faster decay leads to rich jet mixing with the entrained fluid mass. When those terms are calibrated experimentally we face a lot of challenges associated with the analysis of experimental data to measure far field decay using pitot tube. This is because the tests are calibrated in the presence of atmospheric environment. The variation of pitot pressure along the jet axis with non dimensional axial distance, called as centerline pitot pressure decay. It is directly related to the measurement of jet mixing and mass of fluid issuing out from the exit of the nozzle. Faster decay of pressure represents the faster mixing of the jet. To investigate the mixing characteristics of the jet issuing convergent divergent nozzle of throat aspect ratio of 2, 3 and 4, the pitot pressure is calibrated in jet axis up to 25D from the nozzle exit at NPR4. The nozzle pressure ratio of the system is constant for all the three aspect ratios. The center line pressure decay of controlled and uncontrolled jets of all aspect ratio is brought in figures 3-5. It is every amazing to visualize the graphs shows an oscillatory nature, this occurs due to the shock cell structure in jet core and crosswire control. The core length is measured based on the oscillation of the pressure ratio to axial distance. The end of the oscillation in curves depicts the end of supersonic core length, after that flow attains the lower Mach number where the decay takes place. Supersonic core length is defined as the axial distance from the exit of the nozzle to the characteristic decay of jet [14]. The oscillation also reveals the length of the shock cell. The length of the shock cell is calibrated based on the minimum and maximum peak of the oscillation. The distance between the minimum and maximum pressure peak in the core is called as shock cell length. The figure 3-5 presents the difference of the decay of jet for uncontrolled and controlled for all three types of configurations.

At Aspect ratio 2, the controlled and uncontrolled jet profile looks identical in terms of oscillation. However, the oscillation and the shock cell growth are higher for uncontrolled jet. The core length for the aspect ratio extends up to X/D=5.5 for controlled jet and for uncontrolled jet it extends up to X/D=9.

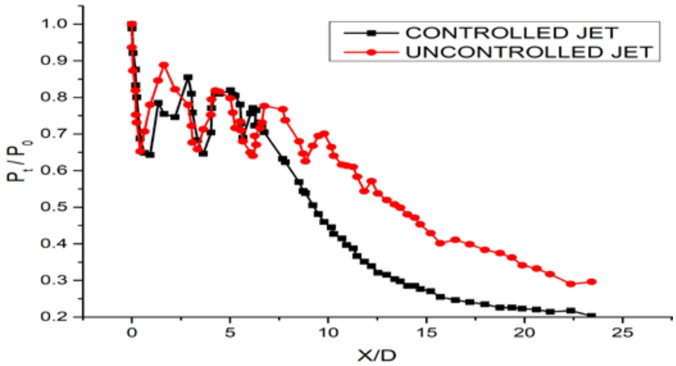

Fig 3. Pressure decay characteristics curve for AR2

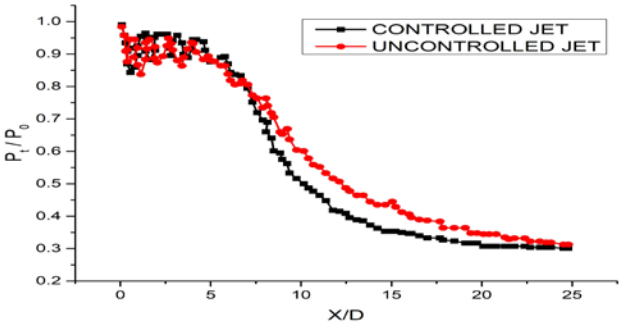

Fig 4. Pressure decay characteristics curve for AR3

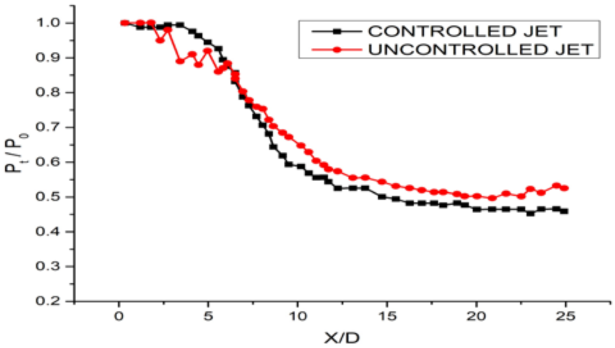

Fig 5. Pressure decay characteristics curve for AR4

Due to the effect of crosswire, extraordinary 48% reduction in the core length is witnessed. At aspect ratio 3, the controlled and uncontrolled profiles come closer to each other than aspect ratio 2. The core length of controlled jet is X/D=5 and for uncontrolled jet X/D=7. Influence of the passive control reduces the core length up to 30%. At aspect ratio 4, the profile curves not identical as seen before, they deviate themselves in all the oscillation. Core length of the controlled jet X/D=4 and uncontrolled jet X/D=5. Few pioneers noticed similar results for different aspect ratio [29, 30]. Furthermore, the oscillation of the curves for the both aspect ratio 3 and 4 looks identical and their respective X/D ratio also very closer than expected.

Meanwhile, the mixing of the AR2 is slower than AR3 and AR4 which is indicated by shorter core length. In other words, the shock oscillation is very weak as the NPR decreases. Similar type of results was noticed by E. Rathakrishnan [29] and K. Vijayaraja [31]. Eventually, the characteristics region of AR4 is inferior to the AR2 and AR2. AR2 jet is faster compared to AR3 and AR4 in all three zones like potential core, jet decay and the expansion. The shorter core of the AR 4 and 6 jets indicate that the near-field mixing of these jets is superior to for the AR 2 jet. In other words, weaker waves in the core of AR4 and AR6 are responsible for the shorter core length. Beyond the core, the AR2 and AR3 jet exhibits rich mixing than AR4. From the above three curves it is clear that the oscillation of the issuing jet is higher in uncontrolled jet than a controlled jet. Due to this, the length of the core will be shorter when the issuing jet is controlled by a passive control like cross wire, tabs. The figure 4 presents the effect of the throat aspect ratio on axis switching. The figure 5 represents that, as the aspect ratio changes the axis switching exhibits linear variation. At the aspect ratio of 2 the axis shifts upstream due to influence of shock cell strength. As the aspect ratio increased further axis switching moves to downstream, since the shear layer growth is marginally affected. The figure 6 shows the axis switching location with respect to the aspect ratio and further it is tabulated in table 1 and compared with the notable work by E. Rathakrishnan [13,22].

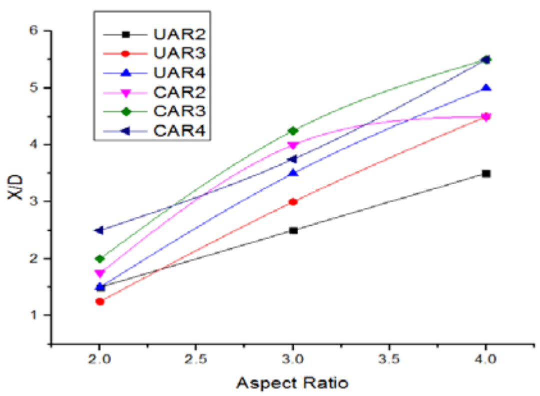

Fig 6. Effect of aspect ratio to potential core length

Screech tone frequency

The screech tone frequency fs can be predicted using shock cell length average LAVG. Tam [16] given them as

$$f_s = \frac{U_{cv} K_1}{2\pi(1 + \frac{U_{cv}}{a_\infty})}$$

K1 is the smallest wave length of the shock cell, Ucv is convection phase velocity, the values are assumed as in literature [16] of 0.7Uj.

The K is predicted by expression

$$K_1 = \frac{2\pi}{L_{avg}}$$

The study of screech tone is must for all kinds of jet since it prevails everywhere. Since the study claim that after 1.8 Mach there will be no screech, however, some literature witnessed the screech after the 1.8 Mach also. Hay and Rose [27] have reported the flight failures due to high fluctuating of pressure near the jet orifice. So the study of screech is equally important to shock cell growth and decay characteristics.

The measurement of jet noise is done by piezoelectric microphone. The microphone has the capacity to calibrate frequency and sound waves. It is positioned at an observer convenient angle of 38 degrees based on literature [17, 18]. In the acoustic far field the sound pressure level and frequency obtained with loudspeaker. The Overall Sound Pressure Level (OASPL) variation with NPR observed by a microphone placed at the intervals of 2D, 5D, 10D, 20D and 25D for the elliptical jets indicated in Figure 6. It is clearly seen in Figure 7-9, SPL decreases with an increase in diameter ratio of jet. However, in few regions we noticed the drop off in the SPL with increases with NPR and we also witnessed one sudden SPL jump due to presence of shock waves. The figure 7-9 shows the acoustic spectrum of all three configurations of controlled jet. For aspect ratio 2 the maximum SPL is 12dB, 15.5dB for aspect ratio 3 and 19.5dB for aspect ratio 4. From the results it is evident that, AR2 reports 48% reduced noise compared to AR4. Further, the aspect ratio of the throat increases, the acoustic characteristics of the nozzle are affected. At a lower aspect ratio the jet noise level is less. From three types of configurations the noise level at aspect ratio 2 is less than AR3 and AR4, so we conclude that the aspect ratio has a direct effect on jet noise. Further, it is seen, the role of cross wire has high importance in reduction of jet noise. When the cross wire is introduced the levels of jet is noise reduced drastically, the passive control crosswire shifts the

SPL levels by decreasing the pressure fluctuations. The same behavior had been noticed by Balakrishnan [28].

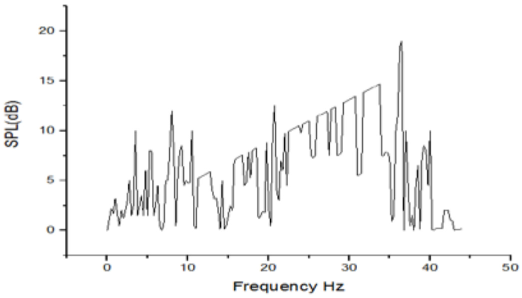

Fig 7. Far field acoustic characteristics of the elliptic throat of AR2

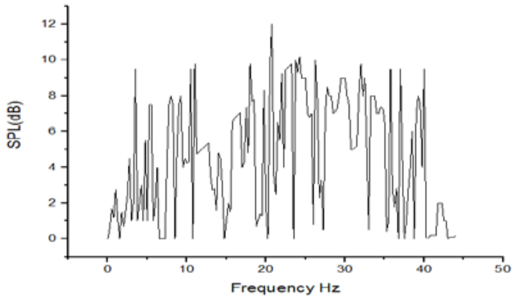

Fig 8. Far field acoustic characteristics of the elliptic throat of AR3

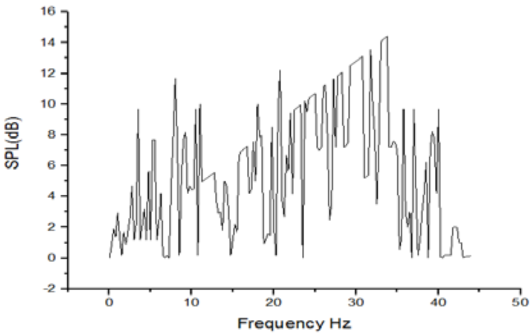

Figure 9. Far field acoustic characteristics of the elliptic throat of AR4

Visualization

The visualization of axis switching and core length is done numerically using isosurface contour. CFX is used to find the jet axis switching computationally. Figure 7 to 9 represents the core length of controlled and uncontrolled jet. From the figures we can conclude, the core length of the uncontrolled jet is high compared to controlled jet. The shock waves present in major and minor axis of controlled and uncontrolled jet is presented. Because of azimuthal symmetry, the wave's present in the core region is asymmetric in shape. Therefore, we can witness an asymmetric type of shock in the jet. When the cross wire is introduced, the shock waves are weakened, so that the length of the core is reduced significantly than uncontrolled jet. The figure 7-9 also depicts shock cell structure is weaker in controlled jet than uncontrolled jet. Figure 10-14 gives the axis switching contour from 0.1D to 25D along the jet axis and it also represents the stages of the shifting of contours at different axial distance. The jet transforms itself into several shapes based on the strength of the shock cell. At the run 1 there is no axis switching, hence the shape remains elliptical. As the run continues, the axis swifts its location upstream and downstream based on the shock cell development. At the final run, the shape is climaxed to cylindrical at the decay point, where the pressure is lost almost 95%.

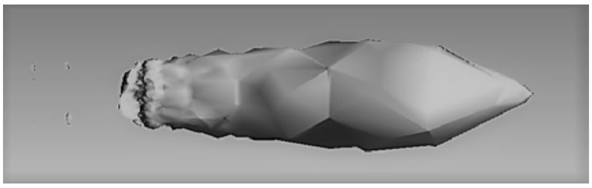

Fig 10. Core length of the elliptical throat Uncontrolled jet AR2

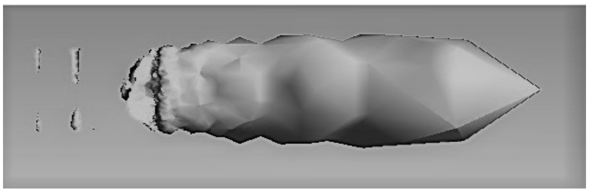

Fig 11. Core length of the elliptical throat controlled jet AR2

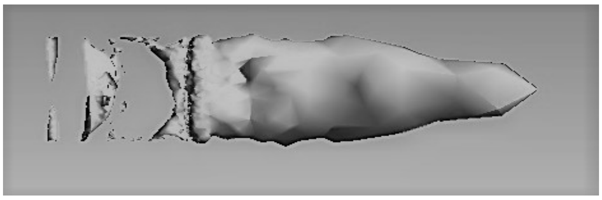

Fig12. Core length of the elliptical throat controlled jet AR3

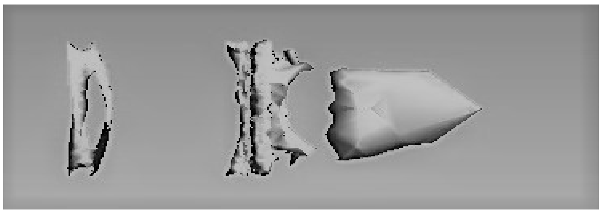

Fig 13. Core length of the elliptical throat Controlled jet AR4

Table 1. Comparative study of literature review

Nozzle pressure ratio (NPR)	Triangular tab (E.Rathakrishnan) X/Deq [22]				Controlled Jet [13]		Variable Aspect ratio Jet	
	Minor Axis core length	Major Axis core length	Fully expanded minor axis	Fully expanded major axis	Elliptic jet core length	Circular jet core length	Cont rolled jet AR2/AR3/AR4	Uncon Trolled jet AR2/AR3/AR4
4	1.7	3.7	7.3	11.5	3.5	5	5.5/5/4	9/7/5

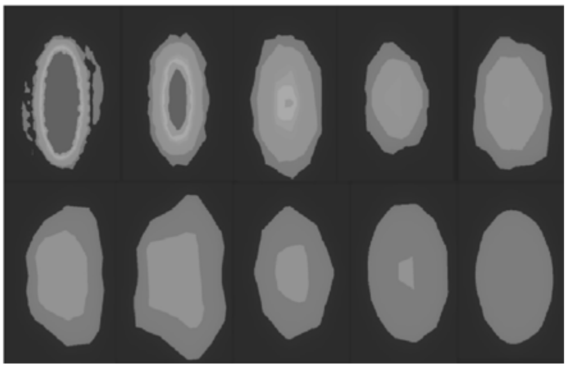

Fig 14. Axis switching contours from 0.1D to 25D

CONCLUSION

The present study shows the effect of the throat aspect ratio on mixing and acoustic characteristics of free jet with passive control. The crosswire is introduced to increase the mixing promotion of the jet due to azhimuthal asymmetry. The study reveals that the aspect ratio has strong influence on potential core length and decay of the jet. The crosswire is introduced to control the jet, due to this passive control the jet is divided into two high speed regions which ends in jet bifurcation. Due to the influence of the passive control crosswire massive reduction of core length 48%, 30% and 21% is witnessed for AR2, AR3 and AR4. The small throat aspect ratio has huge scale vertical structures close to the exit of the issuing jet, however there is no such incident seen in other two types of configurations. Centerline pitot pressure oscillation is higher in uncontrolled jet than controlled jet due to the growth of shock cell structure. At under expansion, the shock cell structure development takes place as aspect ratio changes. For the aspect ratio 2 it was seen that the oblique shock was replaced by normal shock. Due to this change over, shock gives a strong influence in effect of noise field. The screech frequency in the elliptical throat jet increases as the aspect ratio of the throat changes. When the crosswire is introduced at the exit of the issuing jet, the development of shock cell occurs due to which the screech frequency and screech magnitude drops rapidly. This rapid dropping mainly occurs due to weakening of the shock cell structure. As the throat aspect ratio goes higher values the screech frequency is dropping. Finally this paper brings to conclusion that, aspect ratio parameter and passive control strongly governing the screech frequency and shock development process in the supersonic jet.

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NOMENCLATURE

a_∞ Speed of Sound

D Diameter of exit

fs Screech tone frequency

k1 Fundamental wavelength of the shock cell system

Lavg Measured average shock-cell length

Ucv Convection phase velocity of the large-scale instability waves of the flow

Uj Equivalent jet velocity based on equivalent Mach number

X Co-ordinate perpendicular to the exit plane

NPR Nozzle pressure ratio