Acoustic Characterization of High-Speed Jet Using Air Tab

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Abstract: - Jet noise production is a complex phenomenon characterized by the distribution of noise sources along the jet. High-frequency noise components primarily emanate from regions near the nozzle exit, while low-frequency noise is generated farther downstream, around the end of the potential core. This spatial distribution necessitates measurements taken at significant distances from the noise source to accurately characterize jet noise. One method to control and study this noise involves the use of air tabs, which are active control devices placed at the exit plane of the nozzle, oriented perpendicular to the flow. In this study, the flow from a Conical Convergent-Divergent nozzle to the atmosphere under perfectly expanded conditions was simulated using the Fluent software package. Various air tab inlet pressures were tested to observe their effects on the flow and noise characteristics. Virtual receivers were strategically placed at distances of 10d, 30d, and 50d from the nozzle exit, where 'd' represents the nozzle diameter. These receivers were positioned at angles ranging from 0° to 130° in 20° increments to capture a comprehensive set of data on the jet noise. The analysis focused on different air tab inlet pressures, particularly noting the behavior at an inlet pressure of 449,234.52 Pa (1.6 times the initial pressure, Po). It was found that this specific pressure setting resulted in a more pronounced characteristic decay of the jet flow properties compared to other cases. However, when conducting a spectral analysis of the pressure at the receivers, an increase in the Sound Pressure Level (SPL) was observed. Specifically, the SPL increased by approximately 6 dB compared to a free jet, and this increase in SPL correlated with higher air tab inlet pressures. This finding indicates that while air tabs can effectively modify the flow characteristics and potentially reduce certain types of noise, they may also introduce higher noise levels under specific conditions. The use of air tabs at the studied pressure resulted in a significant change in the flow structure, which in turn affected the noise distribution and levels. The increase in SPL suggests that the control mechanism introduced additional turbulence or altered the jet dynamics in a way that amplified the noise. In summary, the study demonstrates that the integration of air tabs at the nozzle exit can influence the jet flow and noise characteristics significantly. While certain configurations may enhance thrust and modify noise profiles favorably, they can also lead to increased noise levels in other scenarios. This underscores the need for careful optimization and consideration of trade-offs when designing and implementing noise control strategies in supersonic jets. The findings provide valuable insights for future research and development aimed at mitigating jet noise while maintaining or improving aerodynamic performance.

Keywords: - High-speed jet, Aeroacoustics, Air tabs.

1. INTRODUCTION

Supersonic jet noise has been extensively researched for the past five decades, focusing on the behavior of jets in supersonic flight. Initial studies centered on the "method of characteristics" applied to converging-diverging nozzles, which, when fully expanded, are free from shocks, with noise primarily arising from turbulent mixing and Mach wave radiation [1,2]. However, when these jets are imperfectly expanded, they exhibit a shock-expansion structure leading to broadband shock-associated noise (BBSN) and discrete screech tones. While smooth nozzle contours optimize performance, practical applications, such as those in modern supersonic jet engines, often use conical sections to allow for varying areas throughout different flight conditions and to reduce overall size, weight, and cost. These practical nozzles, which typically have sharp throats, can generate strong internal shocks that negatively impact performance and increase noise.

Research by Migdal and Landis [3], Darwell and Badham [4], and Migdal and Kossen [5] indicated that conical nozzles might form shocks near the centerline due to the intersection of Mach lines from flow overturning. Their studies suggested that modifying the throat's curvature could mitigate or eliminate these shocks, and a conical divergent section could be added to achieve a shock-free flow, resulting in a simpler design than previous methods. This modification could potentially improve jet thrust [6], but the impact on supersonic jet noise components remains uncertain. Limited acoustic data exists for practical nozzle geometries, and while the influence of nozzle contour on thrust is understood, its effect on noise components is less clear.

Tam and Tanna [7], and Norum and Seiner [8], investigated shock noise from both convergent and convergent-divergent nozzles. Convergent nozzles, at supersonic velocities, are always under-expanded, leading to a continuous increase in shock noise with rising Mach numbers. In contrast, convergent-divergent nozzles show a reduction in shock noise around the nozzle design condition. Seiner and Norum [9] also examined the BBSN of a nozzle similar to that of an F-15, finding higher shock noise across all conditions compared to a smoothly contoured nozzle designed to be shock-free at the design condition. Flow and acoustic measurements by Kuo, Munday [10], and Bridges [11,12] highlighted that practical nozzle geometries exhibit additional complexities, such as double shock structures, shock noise across various operating conditions, and distinct screech characteristics compared to ideal nozzles.

The characterization of the supersonic jet is very difficult due to the presence of the shock cells. In the laboratory, mostly conical convergent-divergent nozzles are used instead of conventional contour nozzles due to the simplicity of their manufacturing and design. Munday [5] describes that the CCD nozzle while operating in design conditions produces double diamond shock waves, but they produce the same shock-cell size, broadband shock-associated noise peak frequency, and screech frequency as traditional convergent-divergent nozzles when operated at off-design conditions.

Numerical simulation plays a major role in predicting jet noise. Liu, J., Kailasanath [4] also analyzed the flow and acoustic properties of the CCD nozzle both numerically and experimentally and found that Pressure distributions and near-field noise intensities obtained from the simulations show very good agreement with those obtained from the experimental measurements. For imperfectly expanded jets the potential core may extend up to 12d from the nozzle exit. The near-field intensities of pressure fluctuations show wavy structures for cases in which screech tones are observed.

Ching-Wen Kuo et.al [2] made the acoustic measurement on the scaled model of military nozzles for both heated and unheated jets and found that Various scales of heated jets operating at the same condition show good agreement within a maximum 2 dB deviation. This deviation is due to the small-scale nozzles used in conducting experiments showing that the internal nozzle surface is slightly rougher at this scale level in comparison with the moderate-scale nozzle. In addition, the lip thickness is not exactly reproduced, due to the limitations of the rapid prototyping technique and the brittleness of the material used. Therefore, the thickness of the boundary layer at the exit plane of the nozzle may not scale perfectly.

2. Methodology

2.1 Designing of CCD Nozzle

The CCD nozzle was designed for exit Mach no 1.3 and exit diameter 10mm based on that by using th*e* area and Mach no relation the geometry of the nozzle is tabulated.

Table 1. Title of the table

Diameter of Convergent section	14.05mm
Diameter of Throat	9.68mm
Diameter of Exit	10 mm
Length of the Convergent section	24 mm
Length of the Divergent section	4.58mm
Total length of the nozzle	29.58 mm

2.2 Designing of Airtab

Airtab inlet diameter can be calculated as the Area of the nozzle exit =78.53mm2 Maximum of 12% of blockage is allowed

$$0.012*78.53 = 9.4236mm^2$$

here 2 airtabs are used so the blockage area of one airtab is 4.7118 mm^2. Let us consider the secondary fluid from the one airtab can be penetrated up to 4mm

$$L*D = 4.7118 \quad D=4.7118/4 = 1.1mm$$

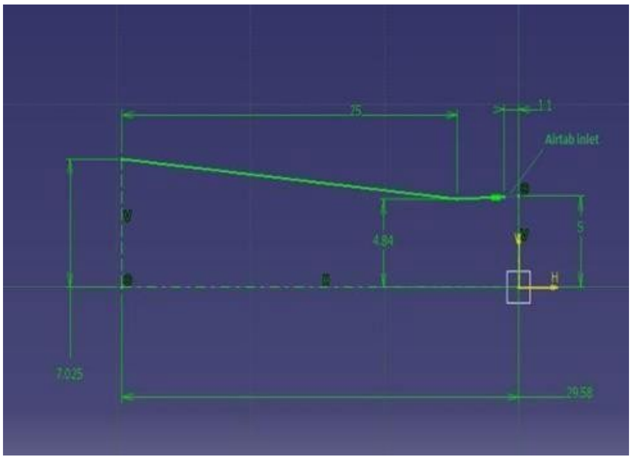

Figure 1. Nozzle dimensions with airtab

2.3 Meshing

Meshing was done by fluent-Gambit which is a powerful 2d meshing tool by using Gambit the structured grid was created very easily. The number of nodes and number of elements are tabulated below:

Table 2. Mesh details

Part	No. of Nodes	No. of element
Inlet	15	14
Wall	64	60
Opening 1	292	290
Opening 2	1002	1000
Opening 3	305	304
Interior	153255	152420

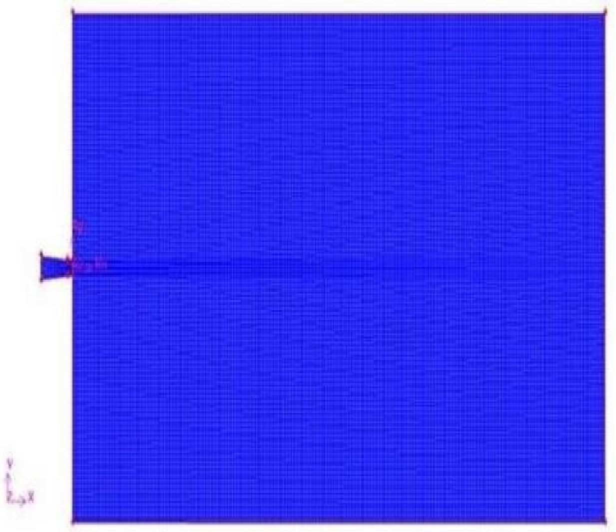

Figure 2. Meshed model

Table 3. Conditions are given in fluent

<table>
<tr><td>Model</td><td colspan="3">Energy: On
Viscous: Realizable k-e, Standard wall function
Acoustics: Ffowcs- William &Hawkings</td></tr>
<tr><td>Material</td><td colspan="3">Fluid: Air (Ideal Gas) Solid: Aluminium</td></tr>
<tr><td rowspan="8">Boundary Conditions</td><td>Inlet</td><td colspan="2">Type: Pressure Inlet
Total Gauge Pressure: 280771.575 Pa
Initial Gauge Pressure 101325 Pa</td></tr>
<tr><td>Opening</td><td colspan="2">Type: Pressure Outlet
Gauge Pressure: 101325 Pa</td></tr>
<tr><td rowspan="5">Tab Inlet</td><td colspan="2">Type: Pressure Inlet</td></tr>
<tr><td>1P0</td><td>280771.575 Pa</td></tr>
<tr><td>1.2 P0</td><td>336925.89 Pa</td></tr>
<tr><td>1.4 P0</td><td>393080.205 Pa</td></tr>
<tr><td>1.6 P0</td><td>449234.52 Pa</td></tr>
</table>

2.4 Pre-Processing and Solving

Pre-processing and solving were done by a fluent solver because in fluent the FW-H model is available. FW-H model is an effective one to determine the sound pressure level at various locations by placing the virtual receivers. Another advantage of fluent is that Fast-Fourier Transform is embedded in it. The conditions given as fluent are tabulated in Table 3.

In the acoustics Model the wall is generally considered as the source and the virtual Receivers are placed depending on our wish to place the Receiver, Positions are to be entered in coordinates. I kept the 24 receivers, 8 receivers are kept at 10d, and other 8 receivers are kept at 30d, and the remaining 8 receivers are kept at 50d from the nozzle exit from 0 deg to 130 deg.

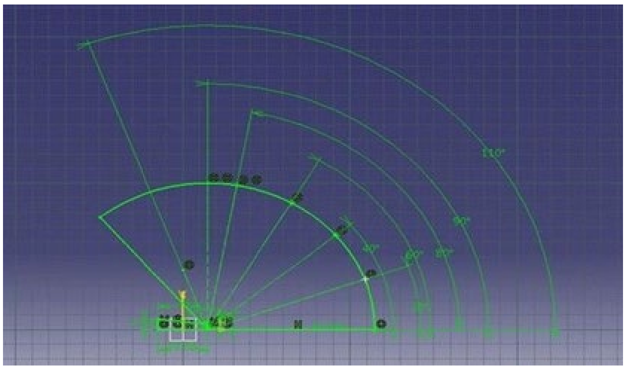

Figure 3. Position of receiver

2.5 Grid Independence Study

The simulation results depend on the grid if you make the grid finer and finer at one point the results don't vary with the grid size, for numerical simulation the grid must be independent of grid size. For the grid independence study, I took the 3 mesh types which were tabulated below.

Table 4. Grid independence study mesh details

Mesh type	No of nodes	Elements
GRID-1	153255	152420
GRID-2	70241	69821
GRID-3	60478	58751

The plot shows that for mesh types 1 and 2 the variation is very low, so the results are going to be independent of the grid size so for the safer side I choose grid - 1 for further analysis.

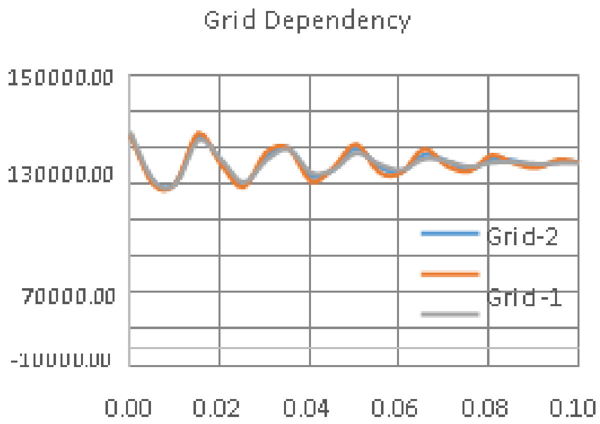

Figure 4. Grid Independency Study

3. RESULTS AND DISCUSSIONS

3.1. Comparisons Of Mach Plot Along Centre Line

In High-Speed Jet flows the measurements are taken along the centerline because the boundary layer effects are negligible, so the study of jet characteristics is simple, and it gives the behavior of the jet when it expands to the ambient conditions.

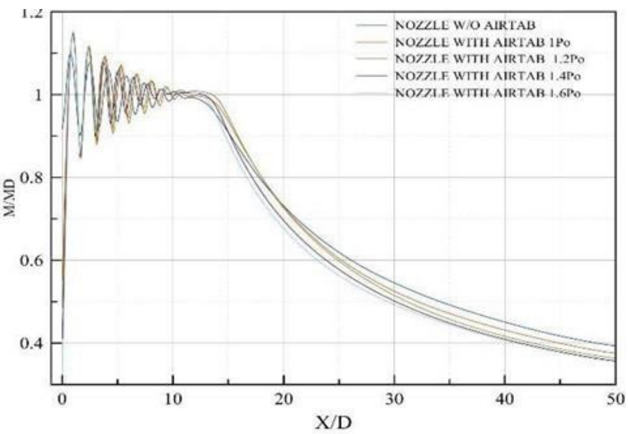

Figure 5. Mach No distribution along the Centre line

The plot shows for the nozzle without air tab there are fluctuations in the Mach this is because the CCD nozzle cannot operate at shock-free conditions so there is a formation of weak shock waves. For the nozzle with an air tab, the exit Mach decreases because as the air tab inlet pressure increases it adds additional pressure to the nozzle and makes the nozzle work like an under-expanded nozzle for the under-expanded nozzle the exit shock is so strong and reduces the exit Mach to subsonic. The potential core length of the Nozzle without a tab is up to 12d while up to 10d there are fluctuations in the Mach no. In the Nozzle with air tab 1P0 the potential core is slightly increased than in the nozzle without Airtab but for Airtab 1.6P0 the potential core is decreased slightly it indicates that in this condition the secondary flow penetrated up to the core region of the primary flow.

3.2. Comparison of Pressure Plot Along Single Line

There are two pressure plots that are generally concerned they are static pressure and total pressure these plot gives the idea about the strength of the shockwaves and expansion waves and what position they occurred.

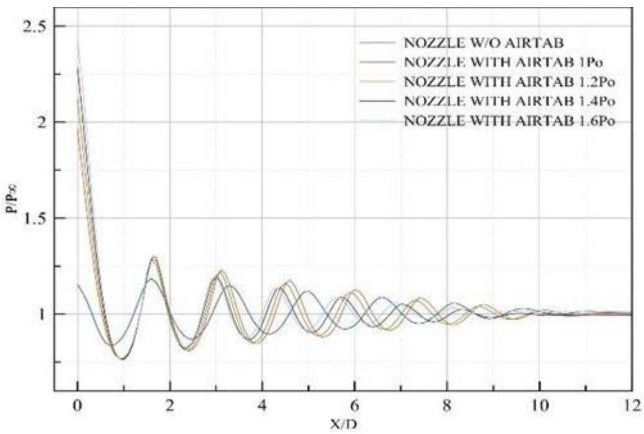

Figure 6. Static Pressure distribution along the center line

From the plot, there are five shock cells are formed for the nozzle without an air tab the static pressure fluctuations are small showing that there is a formation of weak shocks and expansion fans.

Nozzle with air tabs the static pressure at the exit is higher because of the formation of the strong shock wave at the exit after that the expansions are formed and decrease the static pressure as move along downstream the shock cell length is reduced and the shock cell number also increased for the nozzle with air tabs.

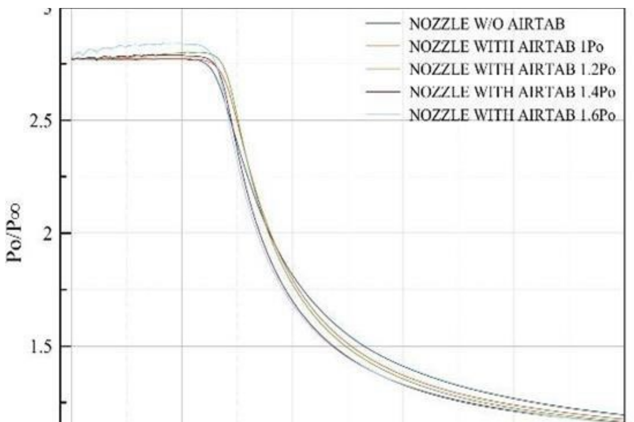

Figure 7. Total pressure distribution along the centreline

From the plot, the total pressure is maintained at more than 12d for the nozzle with airtab 1P0, 1.2P0 but when the airtab inlet increases beyond 1.2P0 the total pressure starts to earlier then the nozzle with airtab 1P0 and 1.2P0, it shows that the secondary flow is starting to disturb the primary flow after that the decay for the nozzle with airtab 1.6P0 start to decay faster than the nozzle without airtab that means the mixing is more efficient.

3.3. Comparison of Turbulent Kinetic Energy Along the Centreline

Turbulence kinetic energy (TKE) is the mean kinetic energy per unit mass associated with eddies in turbulent flow. Physically, the turbulence kinetic energy is characterized by measured root-mean-square (RMS) velocity fluctuations.

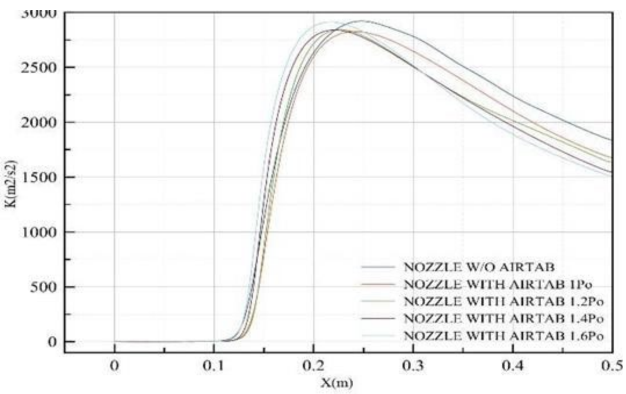

Figure 8. Turbulent kinetic energy along the center line

From the plot, the maximum turbulent kinetic energy is the same for both the Nozzle without airtab and the Nozzle with airtab1.6P0. For the nozzle with airtab 1P0 and 1.2P0 the turbulent kinetic is starts to rise after the nozzle without airtab but for the nozzle with airtab 1.6P0, the turbulent kinetic energy [13] starts to increase than the other cases it shows that the formation of the vortices is starts at lesser distance after reaching maximum value and then it decays faster.

3.4. Spectral Analysis of Pressure at The Receivers

The following plots show the Sound spectrum/ Spectral Analysis of Pressure at the receivers present at the distance of 10d for 0°,90°, and 130°. Here the spectral analysis was done concerning the 1/3 octave band instead of frequency because the jet noise is highly disturbed so the frequency is highly complex the frequency analysis consumes more time and it's difficult for that reason 1/3 octave band is used.

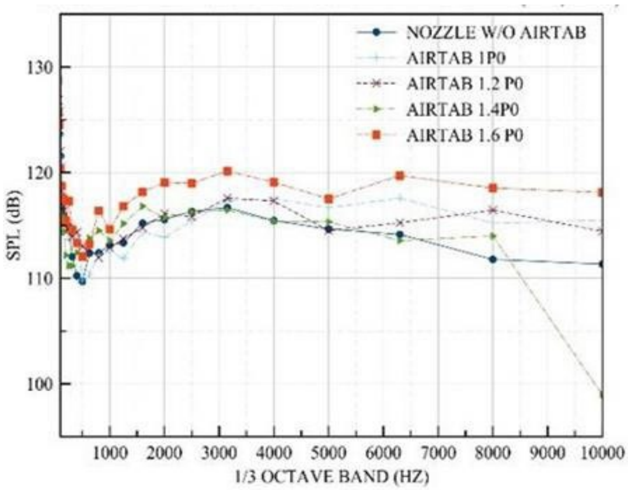

Figure 9. Spectral analysis of pressure at receiver 1 (10D,0°)

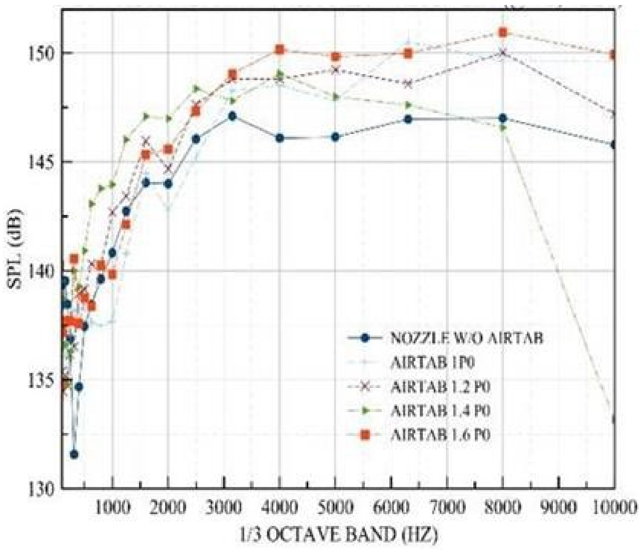

Figure 10. Spectral analysis of pressure at receiver 6 (10D,90°)

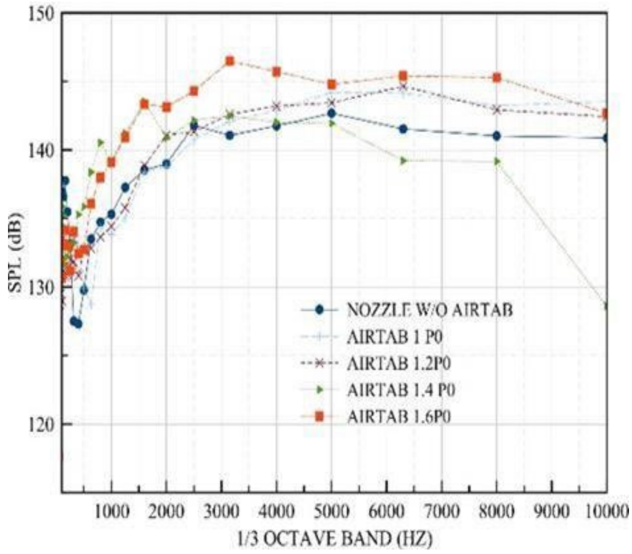

Figure 11. Spectral analysis of pressure at receiver 8 (10D,130°)

The spectral analysis of pressure at 0° shows the noise associated mainly with the presence of the shock waves because the turbulent mixing noise is only dominant from 11° so the SPL of Nozzle with air tab [14] 1.6 P0 is more due to the presence of the strong shock wave when it interacts with the shear layer this type noise occurs.

As the radial distance increases the turbulent mixing noise takes the dominant but it is difficult to differentiate the noise components into noise only due to shock and turbulent mixing these two are commonly called broadband noise. They look like a hump of a camel. As the jet issues, axially the sound propagates in the direction perpendicular to it and the sound pressure is maximum at 90°.

The SPL of the Nozzle with airtab 1.6P0 is higher than the other cases due to it disturbs the flow and increases the turbulence and also the shock strength [15] is high, but the second largest one is Nozzle with airtab 1 P0 this is due to that combination of source of sound either shock or turbulence is more.

For the Nozzle with the air tab 1.4P0 at the higher frequencies the SPL is low this fact is taken into consideration because at the higher frequencies say 1Kz the human ear can hear the 0dB also. While increasing the airtab inlet pressure the Sound pressure level [16] is also increasing instead of decreasing in the near field but in the near field the sound pressure variation with a distance is a complex function of radiation characteristics of the source so further investigation is needed.

The following plots are Spectral analyses of pressure at the Receiver at the axial distance of 30 d for 0°,90°, and 130°.

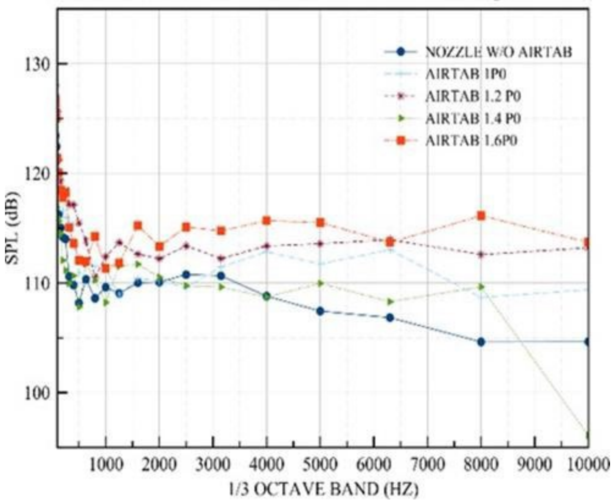

Figure 12. Spectral analysis of pressure at receiver 9 (30D,0°)

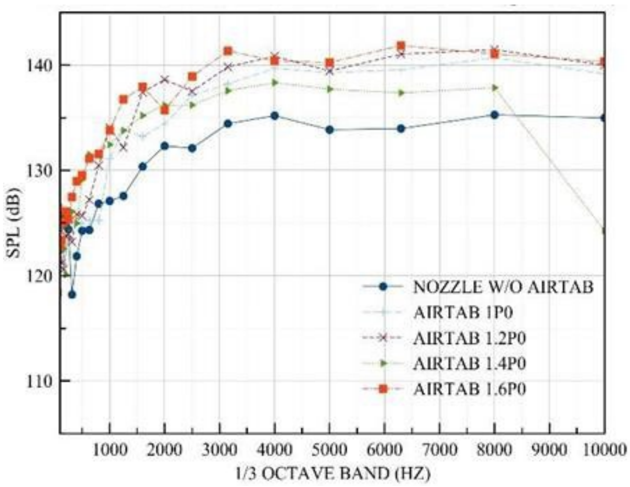

Figure 13. Spectral analysis of pressure at receiver 14(30D,90°)

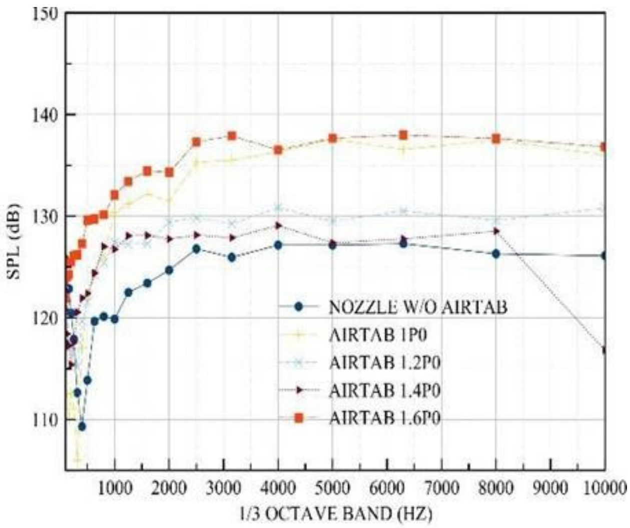

Figure 14. Spectral analysis of pressure at receiver 1(30D,130°)

From the above plots, the spectral analysis of pressure at the axial distance 30d is quite complex because it has a prominent effect on sound due to shock and turbulence. At 0° the SPL of the Nozzle with airtab 1.6P0 raised up to 7 to 10dB but at 40° the SPL raises peak only at low frequencies while at higher frequencies the nozzle with airtab 1.2P0 is in the peak this shows that it has a higher shear stress across the jet fluid and the ambient fluid.

At 90° the Nozzle with airtab 1.2P0 and 1.6P0 nearly have the same SPL at the higher frequencies [17] but at 130° the nozzle with airtab 1Po and 1.6 P0 are similar and the nozzle without airtab and nozzle with airtab 1.4P0 are similar the reason is need to be investigate further.

The following plots are a Spectral analysis of pressure at the Receiver at the axial distance of 50 d (far field) for 0°,90°, and 130°.

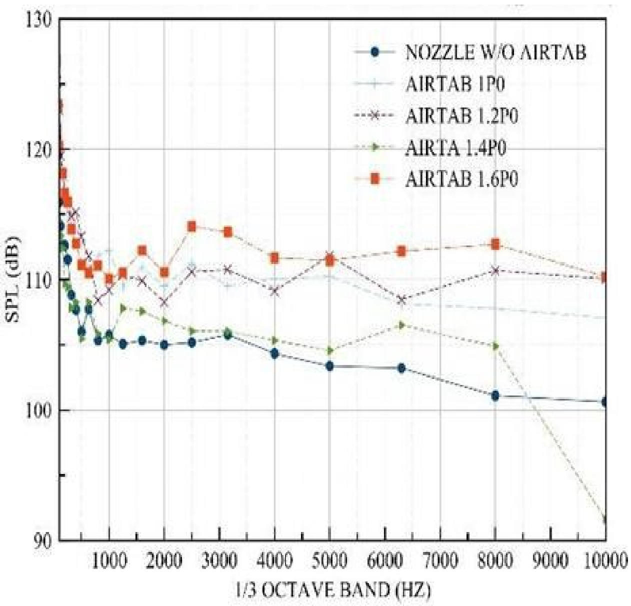

Figure 15. Spectral analysis of pressure at receiver 17 (50D,0°)

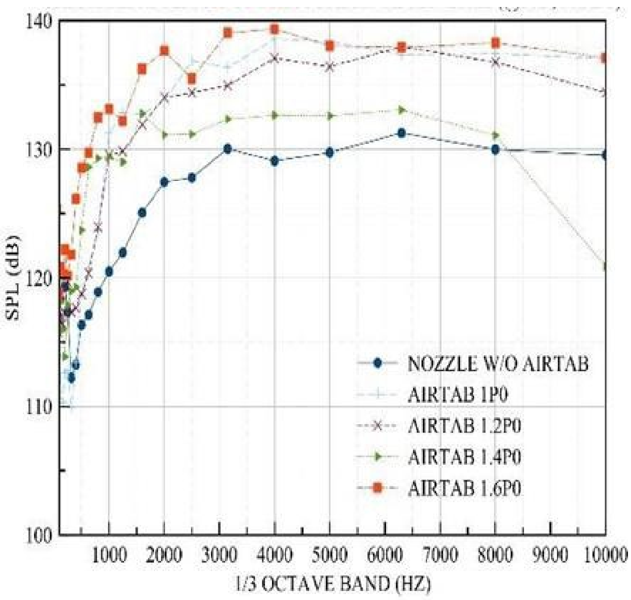

Figure 16. Spectral analysis of pressure at receiver 22(50D,90°)

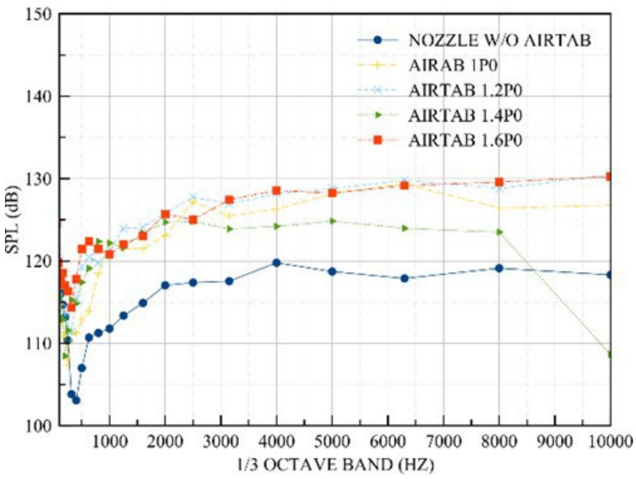

Figure 17. Spectral analysis of pressure at receiver 24 (50D,130°)

The above plots show the Spectral analysis of pressure at the Receiver at the far field at an axial distance of 50d from the nozzle exit for varying angles from 0° to 130°. The spectral analysis at the far field is very important because here only the more humans are working.

In the far-field, the Sound pressure is inversely proportional to the distance. The broadband shocks [18] look like a hump, and the SPL [20] increases as the Frequency increases and reaches the maximum after that then it starts to decrease. The decrease in the profile is due to the adjusted sound not the sound pressure at the receiver. At low frequencies, there are several fluctuations in the SPL because at lower frequencies the sound waves have a large wavelength it tend to scatter, this scatter may increase the acoustic power for that reason the peaks in the lower frequencies are not considered generally the researchers considered the frequency beyond 100-150 Hz.

At 0° the SPL of the Nozzle [19] with airtab 1.6P0 increases by approximately 10dB when compared to the nozzle without airtab and the SPL of the nozzle with airtab 1.4P0 lies close to the nozzle without airtab. At 60° nozzle with airtab 1.4P0 the SPL is lower than the other cases and nozzle with airtab 1.4P0 takes the lead. At 110° nozzle with airtab 1.4P0 has a maximum SPL at higher frequencies. The reason for this may be due to the computational error or some reasons that need to be investigated.

4. CONCLUSIONS

The project work has been carried out with different air inlet pressures and done the spectral analysis of the pressure at the receivers located at the axial distance 10d, 30d, and 50d for varying angles from 0° to 130° and found that for the nozzle with the air tab 1.6P0 the potential core is reduced and mixing is high but the turbulent mixing noise becomes dominant so the SPL is more. The number of shock cells is greater in the nozzle with air tab but the length of the shock cells is minimal. At 10d, 90° the maximum SPL is about 150 dB which is 7dB more than the nozzle without airtab. At 30d, 90° the SPL of the nozzle with airtab 1.6 P0 increases up to 6dB. At the far field at 90° also the SPL of airtab 1.6P0 is increased by about 10dB. This shows that at the near field, the increase in SPL due to the air tab is more due to the influence of strong shock waves and at the far field the increase of SPL is very high due to the influence of turbulence for the nozzle with air tab inlet pressure 1.6P0 it shows it creates more turbulence for reduction in sound it is ineffective. Since the lip thickness is not concerned the ring vortices are weak so the mixing characteristics are different from the nozzles with lip thickness, it needs to be investigated further.

ACKNOWLEDGMENTS

My hearty thanks to the Head of the Institution Dr. S.N. Murugesan for his continuous encouragement and for providing all the facilities to do this project on the college campus. I wish to express my sincere thanks to Dr. Suresh Chandra Khandai Professor and Head of the Aeronautical Engineering Department for allowing me to do this project in the Aeronautical Department.

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NOMENCLATURE				
A	amplitude of oscillation		Fy	component of the resultant pressure force acting on the lower side
a	cylinder diameter		h	height
Cp	pressure coefficient		i	time index during navigation
d	jet diameter		j	space index
D	cylinder diameter			
h	penetration depth		α	angle of attack
V	jet velocity		γ	dummy variable