Preliminary aeroacoustic measurements of conditioned jet flow from a circular nozzle

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Abstract. The present study deals with the design, development, and fabrication of a nozzle with flow conditioning assembly and using it to study jet flow acoustics. The flow is conditioned by several means before the nozzle exits and the conditioned flow is allowed to exit the nozzle as jet. This conditioned jet flow produces aerodynamically generated noise and the same is measured using an microphone. The microphone is placed perpendicular to the jet axis and the measurements are recorded for various regimes. The results will be discussed based on the acoustic spectra and the jet decay characteristics.

1. Introduction

Noise is generated due to any turbulent fluid motion or due to the action of aerodynamic forces on surfaces. This kind of noise is studied under the branch of aeroacoustics. Aeroacoustics analogy proposed by Sir James Lighthill in the 1950s can be denoted as the most practical aeroacoustics analysis. The governing equations of aeroacoustics are based on a coerced form of the equation of fluid motion and the classical form of the wave equation. Aeroacoustics can be considered as a novice branch of acoustics, where the earliest origins can be traced in Lighthill’s 1950s publications that are associated with the study of noise generation with the jet engine. The branch of aeroacoustics has been under scrutiny for over 7 decades, over which a considerable range of analysis strategies have been evolved. Due to the aid of new and advanced technology, the validation of the numerical simulations/Computational Fluid Dynamics simulations performed earlier can be done with accuracy. Though CFD analysis of the generated noise does have its perks, but the real factor of conducting an actual experiment cannot be neglected.

The experiments conducted under this report are representatives of how the generation of noise varies based on Mach of the flow. This also identifies the dissimilarity in the noise generated at the subsonic, sonic and supersonic regimes, thus establishing a factual correspondence between the flow pressure and noise generated. Finally, the aim of the experiment, that is to the study the fluctuating compressible and incompressible flow, through a flow conditioning assembly through various grids and honeycomb structures will be completed with fulfilling results. These observations may be later validated with simulations afterward.

The experimentation conducted in the field of aeroacoustics for jet flows can be traced back to the early 1950s, when in 1952, Sir James Lighthill published one of the first theories for fluid acoustics [1], discussing the conversion of energy based on the fluctuation of the momentum of the flow. He developed a theory on sound radiated from a body, by forming equations established on the equations of motion of a gas. He carried on with his research [2] and evolved equations specifically for sound...
generated aerodynamically, observing the effects of turbulent airflows on the generated sound. He noted that their high Mach numbers may present less turbulence, owing to loss of energy in the mixing region. Almost two decades later, Philip and Thomas [3] predicted the mean velocity, temperature, and relevant turbulent properties through the jet flow for axisymmetric single and dual-flow exhaust nozzles. They observed the changes in the turbulent behavior of jet by varying the acoustic or the mean flow data. They adapted a prediction method by assuming that the small-scale turbulent jet structure produces the dominant jet noises in the mixing region and the movement of the noise to the far-field observer is changed by the surrounding jet fluid, in this case, air. They presented a theoretical model to observe the aerodynamic and acoustic characteristics of jet nozzles.

Seiner [4] compiled all the advances that were presented until 1984, explaining the near-field acoustic characteristics of the performance of tactical fighters and second-generation space vehicles. He also elucidated that the physical interpretation of noise generation by the fundamental mechanism is easier when studied for large scale coherent structures. He studied eddy Mach wave radiation, jet screech, broadband shock noise, and the jet mixing noise. He explained the relationship between these noises and the large-scale coherent structures linked to the generation of jet plumes. One year later Seiner and Ponton [5] conducted a study of flow, shock-free and shock containing high jet plumes at an exit Mach of 0.9 to 2.5. They studied aeroacoustics of flow for high Reynolds’s number for supersonic, axisymmetric jets, also observing for an under the expanded convergent nozzle. Centered on Lighthill’s acoustic analogy, Khavaran et al [6] computed supersonic jet mixing noise for a convergent-divergent, axisymmetric nozzle. They calculated the turbulent mixing noise produced due to the nozzle. They established a CFD based solution for correlation between source strength and time delay for jet flow. They established the source strength by using PARC code with k-ε turbulence model and concluded with the predictions being reasonable with the already present experimental data. Two years later, FS Alvi [7] used a diamond-shaped nozzle for superior mixing and to study noise characteristics without significant thrust losses. They explained that the far-field characteristics of a diamond jet are similar to that of an axisymmetric jet, establishing that the role of streamwise vorticity is insignificant on the overall mixing and noise generation of supersonic jet. He employed an Instantaneous Schlieren Image depicting Mach wave radiation. They concluded that the global growth rate of the shear layer is determined by shear layer characterizing parameters such as velocity ratio, density ratio, and the convective Mach number. They also construed that the effect of streamwise vorticity on ideally expanded supersonic jets is very low on the aerodynamic and noise fields of the jet.

All the experimental and theoretical results were summarised by Christopher Tam [8] until the year 1997. He concluded by comparing the inferences of different publications, drawing from them a base for future studies to carry on from. He summarised the Acoustic Analogy Theory and its variations, the Source Convention effect, the effect of Refraction of sound waves, the large turbulence structures model, Mach wave radiation and the similarity spectra for sound waves for jet flows. He also paved the way for the requirement of new technological advances in the computational aeroacoustics field, predicting the fact that direct numerical simulations will be able to calculate large turbulence structures in jet flows.

One year later Kinzie et al [9] studied the comparison between simulated heated and cold jet conditions and on favorable aero-acoustic properties. At comparable conditions, they inferred that less noise is radiated by the elliptic jet than the round jet. They observed strong evidence of Mach wave radiation, on adding helium to the jet flow at 1.5 Mach. Again, in the year 2001, Seiner et al [10] presented a 2-D and a stereo PIV visualization of the turbulence characteristics for nozzle operating at Mach 0.85. They also elucidated the measurement of turbulence and statistical convergence of turbulent moment required further investigation. In the same year, Simonich et al [11] presented a far-field acoustics database along with pressure and temperature surveys for high subsonic, turbulent jet. They observed that as the size of the scaled model increased, the spectral peaks for screech and other noises shifted to lower frequencies and increase in the mixing noise. Thus, they established the scaling
effect of high subsonic jets, paving the path to relate small-sized experiments to actual real-time situations.

Afterward, Scott Munro and Krishna Ahuja [12], studied the sound generated due to high aspect ratio jets, particularly in the range from 100 to 3000. They explained the relation between the aspect ratios and the frequencies generated at Screech and the mixing length. They also elucidated the co-dependency between jet noise and jet velocity, as well as between jet dimensions and slot dimensions. In 2005, KM Khritov et al [13] used traditional aeroacoustics methods to predict the generation of turbulent jet noise including far-field microphones and by studying classical aeroacoustics methods. They inspected various experimental, computational and theoretical analyses of jet flow. They elucidated the possibilities and limitations of classical aeroacoustics methods. Three years after, P Jordan and Yves Gervais [14] conducted experiments where they traced the principal movements of the flow in the field from the start. They practiced theoretical, experimental and numerical simulations to study and explain the source flow mechanism in free shear flows. In 2011, Ali Uzun and M Yousuff Hussaini [15] used computational aeroacoustics to study the noise generated by a round nozzle jet. They conducted experiments to capture the physical processes that lead to noise generation in a jet flow. They studied the turbulent and laminar conditions for inflow through the nozzle inlet. They elucidated the influence of nozzle inflow conditions on the jet flow field, far-field noise and the mixing length of the flow.

Through the years, the aeroacoustics field has witnessed a quite major leaps with some minor setbacks. These setbacks can be attributed to scaling issues, lack of computation data or just unexplored viewpoints for simulations and experiments. Thus, it is important to keep in mind that the field still requires much more exposure and attention.

2. Methodology
To fulfill the needs of the experiment a flow conditioning assembly was required which could condition the flow in such a way that there would be minimum sound emission and disturbances in the flow.

![Figure 1. (a), (b), (c), (d) Pipe and coupler dimensions for flow conditioning assembly.](image-url)
A threading of length 30 mm was made inside and outside the couplers and pipes as per need, to fix the whole assembly tightly. The whole assembly was made of brass, to provide strength to the structure at high-pressure conditions. It also prevented the leakage of air from any point of the assembly. The reason for making different ducts and pipes was to place different flow conditioners like grids and honeycomb meshes anywhere in the required assembly.

![Diagram](image)

**Figure 2.** Complete joined setup of flow conditioning assembly without the nozzle and the nozzle coupler.

A flow conditioning assembly made up of brass couplers and ducts with honeycomb structure and grids (as given in figure 2), was joined with the components listed below, is being used to produce the jet flow of various Mach numbers

1. Compressor X2
   - Horse Power: 20hp
   - Rpm: 1150
   - Max W/Pr.: 30 kgf/cm²
   - Disp. Vol: 1535 lpm

2. Plenum Chamber

3. Pressure Gauges and Regulators

The assembly was connected to the compressor to produce a nozzle exit speed operating at the three regimes, namely subsonic, sonic and supersonic. The nozzles required to produce the respective jet flows of required Mach were carefully designed by accurately calculating the inlet and outlet dimensions based on the inlet pressure provided by the compressor.

There are 4 nozzles as given below:

- **Nozzle 1:** A convergent nozzle for producing jet flow speeds up to Mach1. This same nozzle has been used to produce M=0.8 (as given in figure 3).
- **Nozzle 2:** A CD nozzle for producing jet flow speeds up to Mach 1.5 (as given in figure 4).
- **Nozzle 3:** A CD nozzle for producing jet flow speeds up to Mach 2 (as given in figure 5).
- **Nozzle 4:** A CD nozzle for producing jet flow speeds up to Mach 2.5 (as given in figure 6).
The data acquisition setup consisting of the equipment listed below is used for acquiring the acoustic data of the jet flow.

1. Free-Field Microphone - Gives Audio signals in microvolts
2. Pre-amplifier - Amplifies the signal to a readable voltage
3. Signal Conditioner - Coverts AC signal to DC signal and acts as a filter
4. DAQ - Converts electrical signals to computer recognized language

3. Results and discussion

NPR (Nozzle Pressure Ratio) can be demarcated as the ratio of the static pressure at the settling chamber to the ambient pressure outside the nozzle. Experiments were conducted for the before mentioned nozzles by changing the pressure from the storage tank via a control valve before the settling chamber, thus increasing the NPR. It was observed that as the NPR increases, the length of the shock cell increases and the screech frequency increases. Over expanded flow condition testifies that the nozzle exit pressure is lower than the ambient pressure and vice versa for under expanded nozzles. The overall broadband frequency length increases as the NPR increases. Results of the visualization were observed, pointing towards the variation in the frequency of the shock cell depending on the value of the NPR and the Nozzle. The observations in the following visualizations are centered on under expanded conditions. As the flow conditions move towards the correctly expanded stages, the intensity of the shock cell will decrease.
The initial conditions in the noise level, that is the ambient noise observed during the test had an amplitude of 58.8 dBA. The blue line depicts the sound that can be perceived by the microphone while the red line shows the sound waves that are audible by the human ear.

In figure 7, a very faded set of shock cells can be observed depicting the low strength of the shocks produced at a low NPR, i.e. NPR=2 for a Convergent Nozzle. The intensity of the shocks is decreasing as it moves away from the nozzle. In figure 8, we can observe that the screech tone can be studied at approximately 7500 Hz at about 62 dB. The Over All Sound Pressure Level (OASPL) is 87.2.

As seen in figure 9 and Figure 10, as the NPR increases to 3, the intensity of the shock cells increases, thus making the expansion fans more visible than at NPR = 2 and the frequency of the screech increases to about 80 dB. The length of the shock cell also increases.

Figure 11 and figure 12 demonstrate a further increase in the length of the shock cell and an increase in the screech tone to 85 dB. The increase in the OASPL value was also observed. The increase in the OASPL value is low for lower NPR, but as the NPR increases, the OASPL value also increases. The strength of the expansion wave also increases.
Figure 11. Shadowgraph of Convergent Nozzle for NPR 4.

Figure 12. Frequency vs Noise level for NPR 2 at Mach 1.5.

Figure 13. Shadowgraph of Mach 1.5 Nozzle for NPR 2.

Figure 14. Frequency vs Noise level for NPR 2 at Mach 1.5.

Figure 15. Shadowgraph of Mach 1.5 Nozzle for NPR 3.

Figure 16. Frequency vs Noise level for NPR 3 at Mach 1.5.
Figure 17. Shadowgraph of Mach 2 Nozzle for NPR 2.

Figure 18. Frequency vs Noise level for NPR 3 at Mach 2.

Figure 19. Shadowgraph of Mach 2 Nozzle for NPR 3.

Figure 20. Frequency vs Noise level for NPR 3 at Mach 2.

Figure 21. Shadowgraph of Mach 2 Nozzle for NPR 4.

Figure 22. Frequency vs Noise level for NPR 4 at Mach 2.
4. Conclusion
Observing the pattern of the shock cells depending on the NPR, the length of the shock cell increases as the NPR increases. The intensity of the shock cell also increases, until the NPR is the correctly expanded condition, at that point no shock cells are formed. It is also observed that though the human ear might not be able to perceive the beginning sound levels, for all jet flows, it is very well matching the screech sound level with the readings given by the microphone. The Over All Sound Pressure Level varies according to the Nozzle Pressure Ratio, i.e. as the NPR increases the OASPL also surges. Expansion shock waves are visualized at the shock cells, creating a set of pseudo shocks as the flow moves away from the nozzle. The sound level of the screech tone also increases as the NPR increases. The Mach 2.5 Nozzle at NPR 3 is the only over-expanded case where a set of shock cells formed due to oblique shock waves is seen. The preliminary study of the flow through the various nozzles was conducted successfully giving satisfactory and verified results when compared with the previously known observations.

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