Experimental Analysis of Acoustic Performance of Porous Ducts using a Small-scale Shock tube

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Abstract. A Shock tube is a device often used to recreate the shock phenomena by several methods. The present work is a preliminary study to analyse the efficiency of baffles in suppressing the noise generated from the shock associated jet ejected from the duct exit. The experiment was performed at a shock Mach number of 1.27 using a diaphragm based, small scale, open ended shock tube. Parametric study conducted by varying the baffle dimensions such as outer diameter, hole diameter and porosity reveals that the baffles with hole diameter less than half of the baffle diameter and with a greater porosity is a cost effective and efficient noise suppressor for shock associated jets.

1. Introduction

In the present fast-paced lifestyle of the people, supersonic air travel could make their lives much easier. Commercially operated supersonic transport Concorde aircraft was retired nearly two decades ago due to several factors, of which one of the main reasons was the environmental hazards caused by the sonic boom. For several decades, suppression of noise generated due to the motion of high-speed vehicles have been a critical concern for aerospace engineers.

The results of the work performed by Mariano et.al on testing acoustic properties of facings with perforations using a shock tube proved that open area ratio had more influence on the attenuation than hole diameter and the shock tube could be effectively used for acquiring data concerned with the absorption characteristics of acoustic materials at a very high sound amplitude [1]. A.Sasoh et.al investigated the effects of pseudo-perforated walls in attenuating the weak shock waves in ducts and the study indicated that an incident shock wave attenuates and eventually turns into a sound wave as it travels along the pseudo-perforated wall and sufficiently long pseudo-perforation section could effectively suppress the sonic boom in the tunnel [2]. It was found that the strength of an impulse wave and aeroacoustics parameters should be measured at a distance greater than four times the duct diameter, downstream of the duct exit from the study conducted by H.D.Kim et.al [3].

Later, K.Seto analyzed the aerodynamic and aeroacoustic performance of the slotted tubes and the perforated tubes by varying their dimensions. The results indicated that the tubes with smaller perforation angle and the tubes with Slot length ratio (S/D) of unity showed the greatest noise reduction properties [4]. Lower thrust loss and higher noise reduction capability of the forward slanted perforated tubes were revealed from the experimental study carried out by M.T.I Khan et.al to compare the aeroacoustic performance of perforated tubes with different angles of perforations [5]. Similar results were indicated from the work by Islam khan et.al and was found that the oblique perforated tube with a
smaller angle of perforation or a forward slanted perforation (O-type) showed superior performance in reducing noise level at a high-pressure ratio with minimum jet thrust loss [6].

The present work focuses on analyzing the effect of perforation diameter and porosity of the baffle in reducing the sound generated by the shock associated jet ejected from the duct exit using a small-scale open-ended shock tube.

2. Experimentation methodology

2.1. Shock tube setup

Shock tube is a device used to replicate blast wave or produce plane propagating shock usually in a laboratory scale. The design and material selection of the shock tube components were based on the reference setup taken from Anugya et al. [7]. The length of the high-pressure region or the driver and the lower pressure region or the driven section was chosen to be 1m and 1.5m respectively so that the length ratio remains between the minimum and maximum ratio values obtained from the optimum and minimal tailoring conditions according to equation 1 and equation 2 respectively.

\[
\left( \frac{L_{DT}}{L_D} \right)_{\text{opt}} = \frac{(\frac{y+1}{2} u_3-a_4+V_R)(u_3+V_R)(1-\left(\frac{y-1}{2}\right)u_3^{1+y})}{(u_3+V_R)(1+\frac{V_R}{V_f})a_4}
\]

\[
\left( \frac{L_{DT}}{L_D} \right)_{\text{max}} = \frac{2(u_3+V_R)(1-\left(\frac{y-1}{2}\right)u_3^{1+y})}{(1+\frac{V_R}{V_f})a_4}
\]

Where,
\( \gamma = \gamma_4 = 1.4 \) and \( V_R \), the speed of the Reflected Shock Wave.

Here \( u_3 \) and \( a_4 \) are calculated using equation 3 and 4 [8].

\[
u_3 = \frac{2a_4}{\gamma_4-1} \left[ 1 - \left( \frac{P_3}{P_4} \right)^{\frac{\gamma_4-1}{\gamma_4}} \right]
\]

\[
a_4 = (\gamma R_4 T_4)^{\frac{1}{2}}
\]

A PN10 grade High-Density Polyethylene (HDPE) pipe of a constant cross-sectional area with 50mm and 40mm as outer and inner diameter respectively was used for the fabrication of the driver and driven section of the shock tube. A three-layered combination of Aluminium foil-tracing paper-Aluminium foil was used as the diaphragm which on rupturing causes the propagating shock to attain a speed of Mach 1.27 [8].

2.2. Baffle Design

The baffles were fabricated using rigid PVC (Polyvinyl chloride) due to its durability, cost efficiency, and ease of fabrication. The dimensions of the baffle were chosen such that the internal diameter(D) of the baffle is equal to the external diameter of the shock tube. For the efficient performance of the baffle, the effective length(L) of the baffle was chosen as 5 times the diameter of the baffle [6].
Four different cases were considered by varying the perforation diameter \( x \) and porosity of the baffle. The perforation angle, which is the angle between the central axis of the hole and central axis of the baffle was maintained constant as 90° for all the cases. The spacing between the centers of holes along the length of the baffle is double the diameter of the hole as shown in Figure 1. The detailed specifications of the baffles considered for the different cases are shown in Table 1. The case 4 baffle was further studied by doubling the spacing between the holes and by reducing the diameter of the baffle.

![Figure 1. Criteria for holes and its spacing in the baffle.](image)

### Table 1. Criteria for holes and its spacing in the baffle

| Case No. | Hole diameter in terms of \( D \) | Actual value (\( x \)) (mm) | No. of holes | Spacing between holes (2\( x \)) (mm) | Porosity In terms of \( D \) Actual value |
|----------|----------------------------------|----------------------------|--------------|--------------------------------------|----------------------------------------|
| 1        | \( D/2 \)                        | 25                        | 36           | 50                                   | 0.409090                               |
| 2        | \( D/4 \)                        | 12.5                      | 76           | 25                                   | 0.215909                               |
| 3        | \( D/8 \)                        | 6.25                      | 152          | 12.5                                 | 0.107954                               |
| 4        | \( D/10 \)                       | 5                         | 194          | 10                                   | 0.088182                               |

2.3. Final Experimental Setup

An air compressor connected to the driver section was used to compress and pressurize the air present in the driver section which causes the diaphragm to rupture. Two microphones (\( m_1 \) & \( m_2 \)) were attached to the driven section, such that they were placed 5cm apart from both the ends of the driven section [7]. The data from the microphones were obtained using a dual-line record splitter and further connected to a recording device. The baffle was fixed at the free end of the duct or the driven section of the shock tube as shown in Figure 2. As the shock propagates along the baffle, it gets dissipated. The sound level meter was used to obtain the maximum sound pressure level value measured over a specific time period and was placed at a distance of 25\( D \) radially from the center of the baffle exit.
3. Results and Discussions
The Sound generated from the shock associated jet ejected from the duct exit of the driven section was analyzed, with and without baffle. The sound level attained by each case was plotted against the non-dimensional parameter corresponding to the diameter of its perforations as depicted in Figure 4. It is evident from the figure that the sound generated has been significantly suppressed in the presence of baffles. It is found that the sound level increased with an increase in the diameter of the perforations.
It was expected that the baffle with greater porosity would alleviate under-expansion and decrease jet noise effectively [5], although the suppression of the generated sound was found maximum for the 5mm hole diameter baffle compared to the other cases in spite of its lesser porosity.

![Figure 4. Change in Sound Level with respect to hole diameter (non-dimensional).](image)

The baffle with 5mm perforation diameter was considered for further analysis by varying the parameters such as the spacing between the perforations and the diameter of the baffle as shown in Table 2. A maximum sound level suppression of 22dBA compared to the noise level attained without the baffle installed was recorded with the case 6 baffle. It is found to be noisier than the unmodified baffle on doubling the spacing between the perforations. Considering the later baffles, the sound level was effectively suppressed with baffles of higher porosity as shown in Figure 6. Considering the overall performance, despite the appreciable performance of the case 6 baffle concerning sound reduction, it could cause a significant loss in the thrust exerted by the jet due to the internal shock reflections caused by the internally inserted part of the baffle which could be a potential obstruction to the approaching shock. It was noticed that the noise reduction was more effective with the hole diameter less than half of the baffle diameter.

| Case No. | Modification                                      | Porosity   |
|---------|--------------------------------------------------|------------|
| 4       | 2x spacing between holes (unmodified)            | 0.088181   |
| 5       | 4x spacing between holes                         | 0.043636   |
| 6       | External diameter equal to the internal diameter of the duct | 0.134548   |
In order to confirm the reliability of the data, the experiment was repeated multiple times with the baffle used for case 4. The sound level obtained from the repeated trials were used to calculate the statistical parameters as shown in Table 3. Quantitative representation of the standard deviation of the obtained results are shown in Figure 7. From Figure 7 and Table 3, it is justified that the data remained within the satisfactory limit.

**Table 3. Statistical analysis of the repeated trials**

| Parameter               | Value  |
|-------------------------|--------|
| Mean                    | 113.62 dBA |
| Median                  | 113.3 dBA |
| Standard Deviation      | 1.3798 |
| Coefficient of Variation| 1.214% |
4. Conclusion

Duct acoustic experiment was performed to analyze the efficiency of baffles in suppressing the sound generated from the shock associated jet ejected from the duct exit using a small-scale shock tube at a shock Mach number of 1.27. The baffles were designed and fabricated with varying perforation diameter and were fixed at the duct exit of the shock tube driven section. It was found that the baffles with diameter of the perforations less than half the baffle diameter showed better performance in reducing the sound level. The sound suppression characteristics of the baffle were reduced as an effect of increasing perforation diameter. It was inferred from the results that porosity had a proportional effect on noise suppression. Thus, the baffles with perforation diameter less than half of the baffle diameter and with a greater porosity is a cost-effective and efficient noise suppressor for shock associated jets.

5. References

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