Effect of Passive Flow Control Devices on Base Pressure for Mach Numbers Between 0.5 and 1.4

Experimental studies are carried out on an axisymmetric cylindrical base body for six freestream Mach numbers between 0.54 and 1.41. Unsteady pressure is measured on the base surface using high-frequency response Kulite pressure transducers. The effect of passive flow control devices on the mean base pressure and the unsteady characteristics of base pressure have been studied. A blunt base, a conventional cavity device, and three different ventilated cavity devices have been tested along with four different rounded base lip devices. A total of 20 different base geometric modifications are tested at 6 freestream Mach numbers resulting in 120 test cases. The cavity devices improve the base pressure as compared to the blunt base case, particularly for freestream Mach numbers more than 0.98. Among all the cases considered, a maximum increase of 8.6% in the base pressure coefficient is noticed for the normal ventilated cavity device as compared to the blunt base case for freestream Mach number of 1.22. The power spectral density of base pressure fluctuations reveals the dominant peaks on the base surface. The Strouhal number associated with the coherent structures developing in the shear layer varies between 0.2 and 0.27 for the six freestream Mach numbers considered. In the presence of cavity devices, dominant peaks are observed for Strouhal numbers between 1 and 5. The root-mean-square, skewness, kurtosis of the base pressure fluctuations for all the cases are presented. Maximum reduction in base pressure fluctuation is observed for the normal and inclined ventilated cavity device configuration test cases. [DOI: 10.1115/1.4051808]

1 Introduction

Axisymmetric base flows are found in a variety of practical applications such as high-speed projectiles, missiles, aircraft afterbodies, and launch vehicles. The drag produced by the base surface is typically known as the base drag and is known to contribute a significant amount toward the total drag of the body. For the specific case of supersonic missile bodies, it has been reported [1] that the base drag contributes about 50% of the total drag. Based on these data, it can be understood that the estimation of the flight trajectory or the propulsion requirements of a typical missile-like body is impossible unless the base drag is known [2].

Over the past few decades, various studies were conducted to understand the base flow features. Chapman [3], Korst [4], Crocco, and Lees [5], through their experimental studies, have developed semi-empirical methodologies to estimate the base pressure. Deck and Thorngren [6], and Kawai and Fuji [7] have proven the capability of computational methods like large eddy simulation (LES) and ZDES toward simulating the time-resolved features of the dynamic base wake flow. Recently, experimental studies have been carried out using diagnostic tools like particle image velocimetry (PIV), laser Doppler velocimetry to understand the dynamics associated with the recirculation bubble and the shear layer. Janssen and Dutton [8] have investigated the cylindrical blunt base wake at a freestream Mach number of 2.46. They have reported the Strouhal number based on base diameter to be \( St_D = 0.1 \) using high-frequency measurement transducers on the base surface. They have attributed this frequency to the motion of the large structures inside the separation bubble. Depré et al. [9] performed experiments in the afterbody of a launch vehicle configuration. Through spectral analysis of the base pressure measured, they report a well-defined periodicity of the wake, which corresponds to the formation and motion of large scale structures in the wake at a dominant frequency of \( St_D = 0.2 \). Schrijer et al. [10] have conducted time-resolved PIV on a FESTIP base model. They mention a harmonic pulsation of the separated region and ejection of large-scale structures from the separated region. They attribute the characteristic peak of \( St_D = 0.14 \) to the pulsation of the separated region and the broadband spectrum with a peak around \( St_D = 0.4 \) to the undulating motion of the shear layer approaching the reattachment point. Bolgar et al. [11] have carried out studies on a backward-facing step model at subsonic, transonic, and supersonic Mach numbers using PIV and pressure measurements. He reports that the Kelvin–Helmholtz instability and cross pumping motion of the shear layer as dominant features for subsonic freestream Mach numbers and low-frequency pumping motion of the bubble as the dominant features for supersonic freestream Mach number.

Studies have been carried out on the use of both active and passive flow control devices toward base flow applications. Regarding the active flow control studies, Bearman [12] has shown the efficacy of base bleed for a two-dimensional blunt base at subsonic freestream Mach number. He has shown that the base drag reduces by 33% along with the disappearance of the vortex street pattern. Kim et al. [13] through LES showed that a distributed forcing through blowing and suction along the span of the blunt base results in a significant drag reduction for a two-dimensional base. Boucina et al. [14] have used dielectric barrier discharge actuators on Ahmed body, a simplified car geometry and have reported a drag reduction of about 8% by suppressing the base separation bubble. All of these active flow control devices require an external source of energy and hence pose limitations toward practical applications [15]. On the contrary, passive devices do not require an external energy source and hence are more popular as compared to active flow control devices.
A variety of passive devices have been used previously to alter the base wake dynamics. These devices are divided into two categories based on their function. The first one, which alters the near wake directly through their interference. The second category is the one where the geometry upstream of the base is modified and which alters the wake characteristics. The devices falling in the first category are cavity, ventilated cavity, rear-mounted disk, splitter plate, etc. Kruiswyk and Dutton [16] have studied the first category are cavity, ventilated cavity, rear-mounted disk, which alters the wake characteristics. The devices falling in the second category is categorized based on their function. The first one, which alters the near base wake dynamics. These devices are divided into two categories such as rounded base lip and base cavity for a boat-tailed blunt base and the four cavity devices. All these geometries were varied to obtain different Mach numbers in the test section. The centrally mounted stig extends through the length of the nozzle all the way upstream of the settling chamber where it takes an L shape bend. This center stig is a pipeline and has a separate pressure regulating valve, which is used during nozzle flow studies. In the present scenario, the center stig is used only for supporting the cylinder base in the test section. The base cylindrical model is mounted at the end of the central stig as shown in Fig. 1. In Fig. 1, the tunnel test section is shown open. In this figure, the outer nozzle wall, tunnel central sting, axisymmetric after-body, and the passive device are marked. The freestream flow in the test section develops around the tunnel central sting. The after-body model is mounted on the tunnel central sting thereby eliminating the support system interference effects. This feature of the tunnel is particularly useful in conducting nozzle afterbody and base flow studies. The tunnel has been extensively calibrated [24] and the results indicate good mean flow uniformity of the freestream flow in the test section. The flow uniformity in the radial direction is determined using a pitot rake mounted on the tunnel central sting. The variation of the flow Mach number along the radial direction is within 2% of the mean value of the corresponding Mach number. To check the flow uniformity along the streamwise direction, a cylindrical afterbody with pressure taps is used. The flow variation along the streamwise direction is within 1.5% of the mean value of the corresponding Mach number. More details regarding the tunnel can be obtained from reference [24].

For the present experimental study, the axisymmetric base flow model is tested for six different Mach numbers 0.54, 0.88, 0.98, 1.06, 1.22, and 1.41. To achieve these Mach numbers, the stagnation pressure is varied approximately between 1.01 bar and 1.56 bar. The Reynolds number (ReD) based on cylinder base diameter (D) corresponding to the six freestream Mach numbers (M∞) are mentioned in Table 1. The model blockage is negligible in the present experimental setup for all the test Mach numbers since an axisymmetric flow is developing around the cylinder model.

Recently, Tripathi et al. [23] have used base geometry modifications such as rounded base lip and base cavity for a boat-tailed afterbody nozzle configuration. They report a significant increase in base pressure for both nozzle jet on and jet off conditions. This study has motivated us to further investigate the effect of these devices on a simple base geometry. In the present work, different passive devices or base geometry modifications have been employed on a simple axisymmetric cylinder model to check their influence on the base pressure in the transonic Mach number regime. The passive control devices are conventional base cavity and three different ventilated base cavity wherein the ventilation holes are (a) normal (b) inclined and (c) both normal and inclined to the freestream flow direction. All the above-mentioned geometries were tested with four different rounded base lip devices (i.e., blunt lip plus three rounded lip devices). In total, 20 different geometries are possible by using four rounded base lip devices on the blunt base and the four cavity devices. All these geometries were tested for six freestream Mach numbers between 0.54 and 1.41. That is a total of 120 different test cases are presented in this paper. In the open literature, to the authors’ knowledge, few studies have devoted themselves toward axisymmetric base flows at transonic Mach numbers. In this regard, the present base pressure data should add substantial value to the existing literature. The effect of the above-mentioned passive devices on the unsteady characteristics of the base pressure has also been reported.

2 Experimental Details

All the experiments are conducted at the Base Flow Facility of National Aerospace Laboratories, CSIR, Bangalore. The tunnel test section is axisymmetric and features an axially movable nozzle along with a central stig (refer to Fig. 1). Through the axial movement of the nozzle, the nozzle throat area and its area ratio are varied to obtain different Mach numbers in the test section. The centrally mounted stig extends through the length of the nozzle all the way upstream of the settling chamber where it takes an L shape bend. This central stig is a pipeline and has a separate pressure regulating valve, which is used during nozzle flow studies. In the present scenario, the central stig is used only for supporting the cylinder base in the test section. The base cylindrical model is mounted at the end of the central stig as shown in Fig. 1. In Fig. 1, the tunnel test section is shown open. In this figure, the outer nozzle wall, tunnel central stig, axisymmetric after-body, and the passive device are marked. The freestream flow in the test section develops around the tunnel central stig. The after-body model is mounted on the tunnel central stig thereby eliminating the support system interference effects. This feature of the tunnel is particularly useful in conducting nozzle afterbody and base flow studies. The tunnel has been extensively calibrated [24] and the results indicate good mean flow uniformity of the freestream flow in the test section. The flow uniformity in the radial direction is determined using a pitot rake mounted on the tunnel central sting. The variation of the flow Mach number along the radial direction is within 2% of the mean value of the corresponding Mach number. To check the flow uniformity along the streamwise direction, a cylindrical afterbody with pressure taps is used. The flow variation along the streamwise direction is within 1.5% of the mean value of the corresponding Mach number. More details regarding the tunnel can be obtained from reference [24].

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![Fig. 1 Picture of the tunnel with the axisymmetric afterbody base flow model mounted on the central stig of the tunnel. A NIVC passive device is connected at the end of the axisymmetric afterbody base flow model. (a) Schematic of the exploded view of the axisymmetric cylindrical afterbody and blunt base (B). (b) Conventional and ventilated cavity devices. (c) Rounded base lip devices.](image-url)
2.1 Model Details. As shown in Fig. 1, the axisymmetric cylindrical afterbody base flow model is mounted on the tunnel central sting. The base diameter of the cylinder afterbody ($D$) is 127 mm. A schematic of the exploded view of the axisymmetric cylindrical afterbody model is shown in Fig. 2(a). It consists of a cylindrical afterbody, a blunt base (B), and an interchangeable base lip device (R0). In this study, we have used various passive devices such as cavity (C), normal ventilated cavity (NVC), inclined ventilated cavity (IVC), and normal-inclined ventilated cavity (NIVC) as shown in Fig. 2(b). Similarly, we have used various interchangeable rounded base lip devices as shown in Fig. 2(c). The cylindrical base model is designed in a way that different geometric base configurations can be attached at the cylinder afterbody end as shown in the Fig. 2(a).

In Fig. 2(b), four different cavities are shown. For all the cavity configurations, the ratio of cavity thickness to the base diameter is 0.075 and the ratio of cavity depth to the base diameter is 0.3. The first one shown in Fig. 2(b) is the conventional cavity and is represented as “C.” The other configurations shown are the ventilated cavities. The configuration wherein the ventilation hole axis is

<table>
<thead>
<tr>
<th>Freestream Mach number</th>
<th>0.54</th>
<th>0.88</th>
<th>0.98</th>
<th>1.06</th>
<th>1.22</th>
<th>1.41</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reynolds number based on diameter ($\times 10^6$)</td>
<td>1.37</td>
<td>2.02</td>
<td>2.18</td>
<td>2.23</td>
<td>2.27</td>
<td>2.42</td>
</tr>
<tr>
<td>Corresponding $P_0$ (bar)</td>
<td>1.01</td>
<td>1.18</td>
<td>1.26</td>
<td>1.30</td>
<td>1.38</td>
<td>1.56</td>
</tr>
</tbody>
</table>
parallel to the base surface and perpendicular to the streamwise direction is referred to as NVC. This device has 12 ventilation holes that are equally spaced along the circumferential direction. The axis of the ventilation holes is at a distance of 15 mm downstream of the base surface. The diameter of the normal ventilation hole is 11.6 mm. The configuration wherein the ventilation holes’ axis is inclined to the base surface is referred to as IVC and is represented as “IVC.” The inclination angle of these holes to the freestream direction is 20 deg as shown in Fig. 2(b). The number of ventilation holes on this device is also 12. The axis of the inclined ventilation holes is at a distance of 12 mm downstream of the base surface. The diameter of the inclined ventilation hole is 11.6 mm, which is similar to the NVC configuration. The ratio of ventilation hole area to the base surface area is 0.1 for both the NVC and IVC cases. The configuration normal–inclined ventilated cavity is represented as “NIVC” and the ventilation holes are placed normal as well as inclined to the freestream direction. The total number of holes on the NIVC configuration are 24 (12 normal holes and 12 inclined holes). The normal and inclined ventilation holes are placed alternately as shown in the Fig. 2(b). Similar to NVC and IVC configurations, the diameter of the ventilation hole for NIVC too is 11.6 mm. Further, the normal and inclined ventilation hole axes are at 15 mm and 12 mm respectively from the base surface. The ventilation hole area ratio to the base surface area is 0.2 for the NIVC device. Based on this, it can be understood that the ventilation hole area considered for the present studies is sufficient to alter the base wake flow features.

In Fig. 2(c), the rounded base lip devices are shown. For all the previously-mentioned blunt and cavity geometries, the base has been mounted with four different rounded base lip devices. The geometry wherein the base lip is blunt is represented as R0. The other rounded base lip geometries are represented as R1, R2, and R3 and have a base lip radius \( r_{lip}/R \) of 0.05, 0.1, and 0.15, respectively. In the text, the geometries have been referred with their corresponding acronym. For example, the BR0 configuration would refer to the blunt base (B) body with the R0 base lip device. The NVCR1 configuration would refer to a NVC body with an R1 base lip device.

### 2.2 Instrumentation Details

Unsteady pressure is measured at five radial locations on the base surface using Kulite sensors. These pressure ports are 11.7 mm apart from each other. The radial locations of the ports are \( r = 0R, 0.18R, 0.37R, 0.55R, \) and 0.74R. These kulite locations have been named as K1, K2, K3, K4, and K5, respectively, in this article (see Fig. 2a(i)). The port at the base surface center is named K1 and the port close to the periphery is named K5. For these five ports, real-time pressure data were acquired using XCQ-093 Kulite pressure transducers, which can measure pressure values up to \( 1.7 \times 10^5 \) Pa. The natural frequency of the sensor without screen is 240 kHz. The M-type protective screen limits the frequency of these transducers to 50 kHz. The transducer data are acquired using a truly simultaneous acquisition card NI 4495 DC series with a 24-bit resolution at 50 kHz. These pressure ports are 11.7 mm apart from each other. The radial locations of the ports are \( r = 0R, 0.18R, 0.37R, 0.55R, \) and 0.74R. These kulite locations have been named as K1, K2, K3, K4, and K5, respectively, in this article (see Fig. 2a(i)). The port at the base surface center is named K1 and the port close to the periphery is named K5. For these five ports, real-time pressure data were acquired using XCQ-093 Kulite pressure transducers, which can measure pressure values up to \( 1.7 \times 10^5 \) Pa. The natural frequency of the sensor without screen is 240 kHz. The M-type protective screen limits the frequency of these transducers to 50 kHz. The transducer data are acquired using a truly simultaneous acquisition card NI 4495 DC series with a 24-bit resolution at 50 kHz. Each sensor is powered by a DC power supply of 9 V, and the output signal from the transducer is passed through an amplifier and a signal conditioner. The dominant frequencies for typical base flows are \( \leq 20 \) kHz. Hence, a low-pass filter of 20 kHz is applied postacquisition during data processing. For each transducer channel, 100 records of 4096 were acquired yielding a total of 409,600 data points per channel per tunnel run. For spectral analysis, a 4096-point narrow band fast-Fourier transform is performed using Welch’s algorithm and later averaged for 100 records with Hanning window. A frequency resolution of 12.2 Hz is obtained for this analysis.

The uncertainty in the pressure measurement is estimated using a statistical approach based on repeatability tests is 1% of the measured value. The transducers for unsteady pressure measurements were calibrated statically, and the uncertainty obtained from calibration is within \( \pm 1.5 \% \) of the transducer measuring range. The uncertainty obtained from calibration is higher than the uncertainty from repeatability tests. Hence, the uncertainty based on calibration is used in the analysis of results. The uncertainty in the measurement of the Mach number is \( \pm 0.02 \) [23].

### 3 Results and Discussion

In this section, the characteristics of the base pressure are discussed. A statistical analysis of the unsteady pressure signal for the different passive devices at six freestream Mach numbers is carried out. The statistical quantities presented are the mean of the base pressure fluctuations.

#### 3.1 Coefficient of Mean Base Pressure

The variation of the base pressure coefficient \( (C_{pb}) \) along the radial direction for blunt base configuration BR0 at six different Mach numbers is shown in Fig. 3(a). The pressure coefficient \( (C_{pb}) \) is defined as \( \frac{P_b - P_{\infty}}{q_{\infty}} \), where \( P_b \) is the base pressure, \( P_{\infty} \) is the freestream static pressure, and \( q_{\infty} \) is the freestream dynamic pressure. The uncertainty in the \( C_{pb} \) for the six freestream Mach numbers has been listed in Table 2. For a given Mach number, the base pressure is relatively constant on the blunt base surface. A maximum variation of about 4% is observed between the five radial ports across all the freestream Mach numbers \( (M_{\infty}) \). The variation of the average of \( C_{pb} \) with the freestream Mach number is shown in Fig. 3(b). The base pressure coefficient behavior with \( M_{\infty} \) is shown in Fig. 3(b). The base pressure coefficient data available in
open literature have also been shown. It can be seen that the present experimental data compare reasonably well with the existing literature data. Herrin and Dutton [29] and Merz et al. [25] base pressure data are support interference free. In the subsonic Mach number range, the present data compare well with the Merz et al. [25] data. In the supersonic Mach number range, the present data compare well with Chow [30]. It needs to be noted that for supersonic Mach numbers, tested \( C_{pb} \) values available in literature show differences. Chang [2] has shown that for supersonic free-stream Mach number, a wide region of measured base pressure values exists for a cone cylinder model. For Mach number 1.5, he has shown that the experimental base pressure coefficient values are in the range of \(-0.184 \pm 0.05\). The present experimental data fall within this range of experimental values presented in Fig. 3(b) for supersonic freestream Mach numbers.

### 3.1.1 Effect of Passive Devices on Mean Base Pressure.
Regarding the uniformity of the pressure on the base surface in the presence of passive control devices rounded base lip, cavity and ventilated cavity devices. The maximum variation in base pressure along the radial direction is about 4% of the corresponding mean value. In Fig. 4, the effect of the passive devices on the base pressure at the K1 center kulite port is presented. The figure shows the percentage increase in base pressure to the blunt base configuration (BR0) for each of the freestream Mach numbers in the form of a bar chart. For the blunt configuration, three bars are shown while for the cavity configurations four bars are plotted. This is because the values are compared with the BR0 configuration. The uncertainty band of 1.5% is marked with a dotted line in the figure.

Before going into the details of how much each of the passive devices alters the base pressure, it is imperative to look into how these devices affect the base wake flow field. The base pressure and the development of wake downstream are dependent on factors such as the boundary layer upstream of the base lip and the shear layer growth downstream of the base lip. To improve the base pressure, the following flow elements need to be altered according to Ref. [1]: (1) boundary layer upstream of the base lip.

<table>
<thead>
<tr>
<th>Mach number</th>
<th>( C_{pb} ) uncertainty band</th>
<th>( P_{RMS}/q' ) uncertainty band</th>
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<tbody>
<tr>
<td>0.54</td>
<td>± 0.0087</td>
<td>±0.0053</td>
</tr>
<tr>
<td>0.88</td>
<td>±0.0067</td>
<td>±0.0019</td>
</tr>
<tr>
<td>0.98</td>
<td>±0.007</td>
<td>±0.0017</td>
</tr>
<tr>
<td>1.06</td>
<td>±0.0056</td>
<td>±0.0014</td>
</tr>
<tr>
<td>1.22</td>
<td>±0.0036</td>
<td>±0.0009</td>
</tr>
<tr>
<td>1.41</td>
<td>±0.0025</td>
<td>±0.0007</td>
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</table>

Fig. 4 Percentage difference in base pressure of center kulite (K1) with respect to the corresponding blunt base configuration (BR0) for all Mach numbers: (a) \( M_\infty = 0.54 \), (b) \( M_\infty = 0.88 \), (c) \( M_\infty = 0.98 \), (d) \( M_\infty = 1.06 \), (e) \( M_\infty = 1.22 \), and (f) \( M_\infty = 1.41 \).
which essentially feeds in the vorticity into the free shear layer (FSL) of the recirculation bubble; (2) the FSL development in the local base wake field; (3) flow entrainment in FSL from the recirculation bubble and outer flow; and (4) recompression of the FSL, marking the end of separation flow.

In the presence of cavity and ventilated cavity, all the above flow elements in the above paragraph are altered. The freestream flow on the cavity wall results in a thicker base lip boundary layer. The cavity devices at the end of the base surface alter the near wake structure. The flow within the walls of the cavity results in an increased dead air region. This affects the shear layer mass and momentum transfer from the base surface. The low pressure associated with these vortices has a reduced influence on the base surface, which results in improved base pressure. The above statements are hypothetical and require a detailed investigation in the near-wake region in the presence of a cavity. In the case of the ventilated cavity, the ventilation holes act as bleed and can be realized to maximize the effects of the base bleeding concept. It is well known that the base recirculation bubble is sensitive to the mass and momentum of the bleed air into the base [1,2]. Considering the above facts, it is understood that the geometric parameters of the cavity need to be optimized according to the local base flow conditions to realize an improvement in the base pressure.

The changes in base pressure with respect to the BR0 case are presented in Fig. 4. The following observations can be made from these results:

(1) Passive devices are more effective for $M_\infty$ more than 0.98. This should be because of the local pressure gradient created downstream of the cavity and the amount of vorticity being fed in the recirculation bubble shear layer. The dynamics associated with these features can be understood using non-intrusive techniques like PIV. The changes in the

![Fig. 5 Radial variation of the RMS of base pressure fluctuations normalized using freestream dynamic pressure of the blunt base device (BR0) at six Mach numbers](image)

![Fig. 6 Percentage difference in RMS of the base pressure fluctuations of the center (K1) port with respect to the corresponding blunt base configuration (BR0) for all Mach numbers: (a) $M_\infty = 0.54$, (b) $M_\infty = 0.88$, (c) $M_\infty = 0.98$, (d) $M_\infty = 1.06$, (e) $M_\infty = 1.22$, and (f) $M_\infty = 1.41)](image)
wake field development for different Mach numbers can reveal the efficacy of the passive devices for Mach numbers more than 0.98.

(2) From the experimental study, it was observed that in general, the cavity devices increase the base pressure for all the cases as compared to the BR0 case. Especially based on the results presented in Fig. 4, the maximum increase in base pressure is observed for the NVCR1 at $M_\infty = 1.22$ by 8.6%.

(3) Among the ventilated cavities, the NVC and NIVC configurations perform better than the IVC configuration in improving the base pressure considering all the test cases. This would imply a normal ventilation hole to the cavity surface is better as compared to an inclined ventilation hole.

(4) The rounded base lip devices show both an increase and a decrease as compared to the base configurations, i.e., BR0, CR0, NVCR0, IVC0, and NIVCR0. Based on the results obtained, it is seen that the change in base pressure as compared to the blunt base case (BR0) does not follow a particular pattern. In the blunt base case (BR0), the separation point is fixed at the sharp base lip corner. For the rounded base lip case, the separation point is not fixed and is placed on the rounded base lip, which is determined by the local flow conditions such as the incoming boundary layer, interaction between the FSL and recirculation bubble, etc. The initial conditions of FSL development are altered with the rounded base lip device. The uncertainty in the location of separation point for different test conditions in the presence of R1, R2, and R3 rounded base lip devices should be the reason behind the no apparent pattern in the base pressure results in Fig. 4.

### 3.2 Root-Mean-Square, Skewness, and Kurtosis of the Base Pressure Fluctuations.

In this study, RMS is defined as the ratio of the RMS of the base pressure fluctuations to the dynamic pressure. The radial variation of the RMS of base pressure fluctuations for the blunt base case (BR0) is shown in Fig. 5 for six freestream Mach numbers. The uncertainty in $P_{RMS}/q_\infty$ for the six cases is listed in Table 2. It is consistently noticed that the RMS of base pressure fluctuations at the K1 port, i.e., at the base center, is the least of the five ports. The maximum RMS of base pressure fluctuations is observed at the K4 port ($r = 0.55R$) for the BR0 configuration. For a blunt base configuration, this inter-radial maximum of base pressure fluctuation has been reported by Janssen and Dutton [21] before. For a blunt base configuration at freestream Mach number 2.46, Janssen and Dutton [21] mention that maximum base pressure fluctuation occurs at $r = 0.62R$. For the cavity configurations, the maximum pressure fluctuation is observed at the K5 port, the port close to the base periphery. From Fig. 5, it can be noticed that the RMS of fluctuations reduces with...
increasing freestream Mach number. This behavior of RMS with freestream Mach number is also reported in the very recent literature by Bolgar et al. [11].

In Fig. 6, the effect of the passive devices on the RMS of the base pressure fluctuations at the K1 center port is presented. The uncertainty in RMS has been marked using a dotted line in the figure. The figure shows the percentage increase in base pressure fluctuations to the blunt base configuration (BR0) for each of the freestream Mach numbers in the form of a bar chart. Based on the results at the K1 port, the passive cavity devices are effective in reducing the RMS of base pressure fluctuations for Mach numbers between 0.54 and 1.06. For the supersonic Mach numbers of 1.22, the RMS values are increasing in the presence of passive devices. For Mach number 1.41, the change in RMS is within 10% of the BR0 case. For all the cases studied, the skewness values of base pressure fluctuations are higher at the inner port (K1) location and lesser at the outer port (K5) location. In Fig. 8, the effect of the passive devices on the skewness of the base pressure fluctuations at the center (K1) port location for all Mach numbers: (a) $M_\infty = 0.54$, (b) $M_\infty = 0.88$, (c) $M_\infty = 0.98$, (d) $M_\infty = 1.06$, (e) $M_\infty = 1.22$, and (f) $M_\infty = 1.41$

3.3 Power Spectral Density. The normalized PSD of the base pressure fluctuations for the BR0 case at two freestream Mach numbers 0.54 and 1.41 is presented in Fig. 9, one case corresponding to each of the subsonic and supersonic Mach numbers. For each Mach number, the variation in the PSD is shown along the radial direction for these two cases. Each of the spectra has been shifted in Y-direction by one unit to improve the legibility. The spectra $G(f)$ have been premultiplied with frequency $f$ and normalized with the square of the standard deviation of base pressure fluctuations ($\sigma^2$). Along with the frequencies, the corresponding Strouhal numbers are also marked on the X-axis of these
The freestream velocity, $U_\infty$ and base diameter, $D$ of the cylinder afterbody have been considered to calculate these Strouhal number, $St_D = fD/U_\infty$. From Figs. 9(a) and 9(b), it can be noticed that the PSD of the innermost ports on the base surface i.e., at K1 and K2 and that of outermost ports on the base surface, i.e., at K4 and K5 are quite similar.

For $M_\infty = 0.54$ (Fig. 9(a)), at innermost pressure ports, a small peak is noticed at 769 Hz followed by a dominant peak at 2026 Hz. Also, a broad frequency range from 2.5 kHz to 6 kHz has significant energy corresponding to pressure fluctuations. The outermost pressure ports display a dominant peak at 976 Hz. Further other small peaks are seen at 378 Hz, 1672 Hz and a broad frequency range from 3.5 kHz to 8 kHz. The PSD at the K3 port location displays the peaks corresponding to both the innermost and outermost ports.

For $M_\infty = 1.41$ (Fig. 9(b)), at innermost ports a broadband in the PSD centered around 230Hz is seen. This is followed by a dominant peak observed at 732 Hz. For outermost ports also broadband in PSD is seen centered around 230Hz. This is followed by twin dominant peaks at 732 Hz and 854 Hz. The PSD at the K3 port location displays the behavior corresponding to both the innermost and outermost ports. It can be noted that the frequencies corresponding to the dominant peaks at the inner ports are also present at outermost port locations. The outermost ports show an additional frequency of 854 Hz, which should correspond to a flow phenomenon dominant at the periphery of the base surface, predictably to coherent structures developing from the base lip of the shear layer. For all the freestream Mach numbers except for $M_\infty = 0.54$, the dominant peaks at innermost ports are the same as those at outermost ports. This can be seen in Fig. 10 where the PSD for all the six Mach numbers is shown for K1 and K5 ports.

From Figs. 10(a) and 10(b), two main observations are listed. The first one is concerning the developing coherent structures in the shear layer from the base lip. From literature [8,10], it is understood that the pulsing motion of the base recirculation bubble and the coherent structure motion in the shear layer are the dominant unsteady features of the base flows. It can be easily
inferred that the recirculation bubble pulsing motion should be felt over the entire base region. The effect of coherent structure dynamics in the shear layer should be more dominant at the outermost pressure ports than the innermost pressure ports because of the proximity, i.e., the frequency peak related to coherent structure motion is easily noticeable at the K5 port than at the K1 port. Further, in literature [6,10], it is mentioned that the Strouhal number corresponding to coherent structure motion in shear layer is about 0.2 for the blunt base configuration. Based on these details, for the BR0 model, it can be found that the frequency associated with the coherent structures developing in the shear layer for $M_\infty = 0.54$ is 378 Hz ($St_D = 0.263$), $M_\infty = 0.88$ is 488 Hz ($St_D = 0.217$), $M_\infty = 0.98$ is 537 Hz ($St_D = 0.218$), $M_\infty = 1.06$ is 549 Hz ($St_D = 0.209$), $M_\infty = 1.22$ is 793 Hz ($St_D = 0.27$) and $M_\infty = 1.41$ is 854 Hz ($St_D = 0.262$). These frequencies associated with coherent structures have been marked on the figure for the K5 port. Kawai and Fujii [7] from computational studies on a blunt base cylinder model have found that the coherent structure motion in shear layer Strouhal number for $M_\infty = 0.52$ to be 0.28, which closely corresponds to the present value of the BR0 model.

The second observation from Fig. 10 is concerning the differences in spectra between subsonic and supersonic freestream Mach number. For supersonic freestream Mach numbers, a gradual increase in the base pressure fluctuation energy is noticed with broadband from Strouhal number of 0.03–0.1. This low-frequency broadband at supersonic freestream conditions might correspond to one of the dynamical features of the base wake such as the pumping of recirculation bubble or the intermittent upstream boundary layer thickening or thinning which influences the expansion at the base lip. At subsonic freestream Mach numbers, at corresponding frequencies, the increase in base pressure fluctuation energy is negligible. In Fig. 10, it can be observed that for subsonic freestream Mach numbers, a broadband energy distribution is seen between frequencies 2.5 kHz and 8 kHz, and the corresponding Strouhal numbers are between 1 and 5. This is particularly predominant for $M_\infty = 0.54$. With the increase of freestream Mach number, the energy in this broad range of frequencies is reduced. This might be due to the dominance of Kelvin–Helmholtz instabilities for subsonic conditions, as suggested by Bolgar et al. [11]. The absence of Kelvin–Helmholtz instabilities at supersonic freestream conditions is also shown in Simon et al. [31].

3.4 Effect of Passive Devices on Power Spectral Density. The effect of the conventional cavity (C) and ventilated cavity devices (NVC, IVC, NIVC) with the sharp base lip device R0, on the PSD is shown in Figs. 11–13 corresponding to freestream Mach numbers of 0.54, 0.88, and 1.41, respectively. The spectra are shown only for the K1 and K5 pressure ports. The spectra $G(f)$ in these plots have been premultiplied with frequency $f$ and normalized with the square of standard deviation value of the blunt base ($\sigma_{b,m}$) configuration. This has been done to bring out the effects of the different cavities on base pressure fluctuations as compared to the blunt base configuration (BR0). The Strouhal number and frequency are both marked on the X-axis of the figure. The following inferences can be drawn from the PSD plot shown in the Figs. 11–13.

1. In the presence of a cavity, multiple dominant peaks are observed at high frequencies between 2 kHz and 8 kHz ($St_D$ between 1 and 5). Kruiswyk and Dutton [16] have conducted studies on two-dimensional cavities at subsonic speeds and have mentioned the differences between the blunt and cavity base flow are subtle. In a blunt base case, the forming vortices see a solid base wall at the trailing edge plane and a solid–fluid interaction is observed. In the cavity case, forming vortices see a compliant fluid boundary at the trailing edge plane and a fluid–fluid interaction is observed. Kruiswyk and Dutton [16] through tuft experiments report that the air at the entrance of the cavity is in a state of unsteady pulsating motion. Because of the fluid–fluid interaction in the cavity case, it can be assumed that the recirculation vortices inside the cavity enhance the turbulent mixing followed by the development of shear layer instabilities. Detailed flow measurement in the cavity region is essential to throw some light on the dynamic processes involved near cavity entrance and prove the hypothesis mentioned above.

2. It is noticed that with the increase of freestream Mach number from subsonic to supersonic, the number of high-frequency dominant peaks as well as the energy associated with these peaks is reduced (Figs. 11–13). This observation is similar to the broadband distribution observed for blunt base configuration in the frequency range of 2.5–8 kHz ($St_D$ between 1 and 5) as presented in Fig. 10. The energy associated with this broadband frequency is reduced with increasing Mach number even in the blunt base case.

3. It is noticed that the ventilated cavity configurations show similar spectral behavior as the conventional cavity
Fig. 12 Normalized PSD of the pressure fluctuations at center and periphery port for various passive control devices using the sharp lip devices (R0) at $M_* = 0.88$: (a) center port (K1) and (b) periphery port (K5)

Fig. 13 Normalized PSD of the pressure fluctuations at center and periphery port for various passive control devices using the sharp lip devices (R0) at $M_* = 1.41$: (a) center port (K1) and (b) periphery port (K5)

Fig. 14 Normalized PSD of the pressure fluctuations at center and periphery port for blunt base (B) device using various lip devices (R0–R3) at $M_* = 0.54$: (a) center port (K1) and (b) periphery port (K5)
configuration (Figs. 11–13). This indicates that the ventilation hardly affects the flow features corresponding to dominant peaks on the base surface as compared to the conventional cavity. It needs to be noted that the ratio of ventilation holes area to the base surface area considered in the present study is large enough and is quite close to the optimal value as discussed in the model details section of the paper.

(4) The influence of coherent structure motion in the shear layer on the base pressure fluctuations at the periphery K5 port is reduced in the presence of the cavity. It can be noticed from figures that the energy associated with the coherent structure motion frequency noticed at K5 port for blunt base BR0 configuration ($S_M = 0.263$ for $M_x = 0.54$, $S_M = 0.217$ for $M_x = 0.88$, $S_M = 0.262$ for $M_x = 1.41$) is reduced for the cavity device configurations (Figs. 11(b), 12(b), and 13(b)). This further confirms that the coherent structure motion in the shear layer has a reduced influence in cavity device configurations.

(5) The effect of rounded base lip devices on the base pressure PSD for the blunt base configuration at $M_x = 0.54$ has been shown in Fig. 14 for K1 and K5 ports. The $G(f)$ is normalized with $\sigma_p^2$ for sake of comparison in these figures. It is noticed that the dominant peaks are at the same frequencies for all the rounded base lip configurations and all freestream Mach numbers. Different rounded base lip geometries have no apparent effect on the entire PSDs. The rounded base lip devices R1, R2, and R3 alter the initial growth of the base wake FSL. The present results indicate that these local base lip flow conditions hardly alter the dominant frequencies associated with the base wake flow.

4 Conclusion

Studies on an axisymmetric cylindrical blunt base model have been carried out at six different freestream Mach numbers 0.54, 0.88, 0.98, 1.06, 1.22, and 1.41. The effect of passive flow control devices on the base pressure at these Mach numbers has been brought out. The passive devices are simple geometrical modifications, namely, rounded base lip, conventional cavity, ventilated cavity wherein the ventilation holes are normal and inclined to the streamwise direction. Four rounded base lip devices (R0, R1, R2, and R3) were used separately on the blunt (B), cavity (C), NVC, IVC, and NIVC configurations resulting in 20 different base geometries tested at six freestream Mach numbers. A total of 120 test cases are presented here.

Regarding the coefficient of base pressure, in the subsonic and supersonic regime, a monotonic increase and decrease in the base pressure coefficient are seen. The base pressure coefficient is maximum close to the sonic Mach number. The base pressure for all the freestream Mach numbers shows a near uniform behavior along the radial direction. The cavity devices improve the base pressure as compared to the blunt base configuration particularly for $M_x > 0.98$. The maximum increase in base pressure is 8.6% and observed for the NVC device for freestream Mach number of 1.22. Considering all the 120 test cases, it has been observed that the NVC device has shown a better performance as compared to the cavity, NVC and IVC devices in increasing the base pressure considering all the 120 test cases. It is understood from the studies in literature [16] that the low-pressure region associated with vortices has a reduced influence on the base pressure. Hence, the base pressure is improved in the presence of a cavity. Further, the ventilation holes on the cavity act as bleed devices altering the mass and momentum transfer to the recirculation bubble. Regarding the RMS of base pressure fluctuations, it decreases with the increase of freestream Mach number. In the presence of a cavity device, the fluctuation energy particularly at subsonic freestream Mach numbers reduces at the center of the base surface.

The unsteady characteristics of base pressure are analyzed along the radial direction at five pressure ports using Kulite sensors. Regarding the results obtained for the cylindrical blunt base, the PSD behavior is different at the center and peripheral ports. The dynamics associated with the recirculation bubble is seen at all the pressure ports while the dynamics associated with the coherent structures developing in the shear layer is predominant at ports closer to the base surface periphery. The Strouhal number corresponding to the coherent structures developing in the shear layer for the six freestream Mach numbers considered varies between 0.2 and 0.27. A comparison between the PSDs of all the freestream Mach numbers has brought out differences between the dominant frequencies observed for subsonic and supersonic freestream Mach numbers. From literature [11,31], it is understood that the Kelvin Helmholtz instabilities are dominant at subsonic conditions, which result in broadband. In the present experiments, the broadband at high frequency is noticed in the range of 2–8 kHz, corresponding to the Strouhal number range of 1–5. For supersonic test cases in the present experiments, broadband is noticed at low frequency in the range of 100–300 Hz, the corresponding Strouhal number range is 0.03–0.1. This low-frequency broadband at supersonic freestream conditions might correspond to one of the dynamical features of the base wake as the pumping of recirculation bubble or the intermittent upstream boundary layer thickening or thinning which influences the expansion at base lip. In the presence of cavity devices, a couple of differences are noticed in the PSD as compared to the blunt body case. The first one is concerning the multiple dominant peaks noticed at high frequencies in the range of 2–8 kHz (the corresponding Strouhal number range is 1–5) in the presence of cavity devices. The recirculation bubbles downstream of the cavity see a compliant fluid boundary at the cavity entrance. From the studies of Kruiswyk and Dutton [16], it is understood that the air at the entrance of the cavity is in a state of unsteady pulsating motion. Based on this fact, it is assumed here that the fluid interactions at the cavity entrance enhance the turbulent mixing and hence the shear layer related instabilities. These fluid dynamic interactions at the cavity entrance might be the reason for the dominant peaks at high frequencies. Detailed flow measurement in the cavity region is essential to throw some light on the dynamic processes involved near cavity entrance and prove this hypothesis. The second observation is, the cavity reduces the influence of the coherent structures in the shear layer on the base surface. The rounded base lip devices considered in the study have no apparent effect on the PSD.

Nomenclature

- $C_p$: pressure coefficient
- $C_{pb}$: base pressure coefficient
- $D$: diameter of the base, mm
- $f$: frequency, Hz
- $G(f)$: power spectral density, Pa²/Hz
- $M_x$: freestream Mach number
- $P_b$: static pressure on base surface, Pa
- $P_{b0}$: stagnation pressure, Pa
- $P_{bs}$: freestream static pressure, Pa
- $q_0$: freestream dynamic pressure, Pa
- $R$: radius of the base, mm
- $Re$: Reynolds number
- $r_{lip}$: radius of the base lip, mm
- $S$: Strouhal number
- $\sigma$: standard deviation, Pa
- $\sigma_{nst}$: standard deviation of blunt base configuration, Pa

References
