Defence Science Journal, Vol. 70, No. 1, January 2020, pp. 18-22, DOI : 10.14429/dsj.70.13612

Rolling Moment of Slender Body at High Incidence for Air-to-Air Missile/Rocket Applications

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ABSTRACT

Measurements of moments were carried out on a slender body having a pointed forebody at lower velocities. The slender body had an ogive nose shape and an overall length to diameter ratio of 16. The angle of incidence was varied from low to moderate angles of attack in the pitch plane. The main objective of the present investigation was to measure the rolling moments on the slender body with and without the control technique. The side force was reduced using a rectangular cross-sectioned ringplaced suitably on the body, however, the slender body was found to experience rolling moments which may be catastrophic.

Keywords: Asymmetric vortex; Side force; Rolling moment; Rings

NOMENCLATURE

α	Angle of attack
C_m	Pitching moment
C_n	Yawing moment
C_l	Rolling moment
D	Base diameter of the body
X	Axial distance measured from the tip of the body

1. INTRODUCTION

The study of the side force over a slender body at high angles of attack has been under consideration since the 1950s[1-11]. Slender bodies with a pointed nose subjected to fly at high incidence experience a large side force and yawing moment. The key reason for such a large side force is the presence of an asymmetric pair of vortices on the leeward side of the slender body. It is expected that due to the geometric imperfection of the nose tip, one of the vortices established at the nose lifts earlier while the other remains attached to the body. Due to this, the vortices appear to be asymmetric in different cross-flow planes. A typical asymmetric vortex in a cross-plane is as shown in Fig. 1(a).

It is an established fact that in the case of a long slender body, a multi-vortex system is observed as shown in Fig. 1(b). This leads to the change in the asymmetric pattern along the length of the body. The establishment of the multi-vortex pattern will not only affect the forces but will also affect the moments significantly. The side force and yawing moment depend upon several factors such as Reynolds number, nose geometry, slenderness ratio, angle of incidence (α), roll orientation (Ø). Keener[1], *et al.* performed experiments over a wide range of nose shapes and observed that the use of conical nose shapes may yield a side force which can be 1.5 time the normal force. This clearly indicated the complexity of the flow. Lamont & Hunt[2] did extensive experiments on the slender body using pressure measurements only. Effect of nose shapes, Reynolds number and roll orientation on the forces was obtained which indicated that the side force is significantly affected by these parameters. Zilliac[3], *et al.* observed that the side force was affected even by a very small perturbation at the tip. Moreover, the side force was also observed to exhibit a “bistable-state” at different roll angles. Gendel[4], *et al.* conducted a numerical investigation on the ogive nosed slender body, mounted on a torsion spring. The study made at a diameter Reynolds number of 30000 and Mach 0.2 at angles of attack of 40° and 50° respectively indicated that the body if elastically mounted results in high amplitude periodic pitching and yawing moments. Lua[5], *et al.* showed that the use of circular trips and helical grooves help in reducing the side force.

Kumar & Prasad[6-8] conducted experiments and computations on an ogive nosed slender body and showed that only the initial portion of the body was responsible for the generation of the large side force of the body at high angles of attack. Use of a rectangular cross-sectioned rings place at different locations was found to reduce the side force drastically. However, the changes in the moments due to the rings were not reported. The use of a particular device may eliminate the side force but may have a non-zero yawing moment. Secondly, the presence of asymmetric vortices may induce rolling moment on the body that itself will change the roll angle (Ø) of the body. The roll moment is expected to be very small in comparison to the

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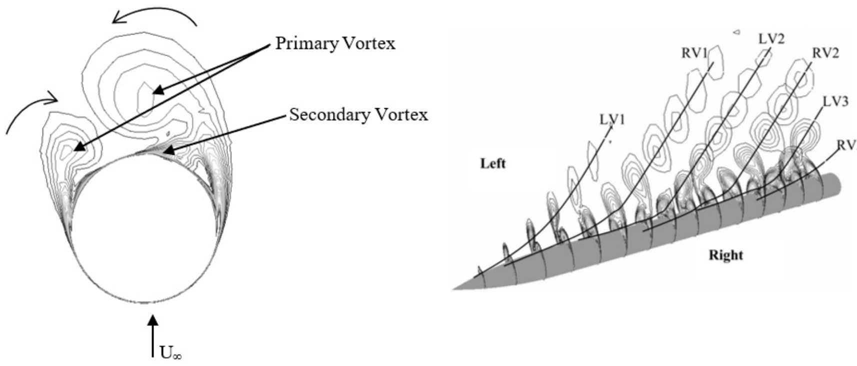
Received : 14 September 2018, Revised : 04 September 2019
Accepted : 27 December 2019, Online published : 10 February 2020



(a) (b)

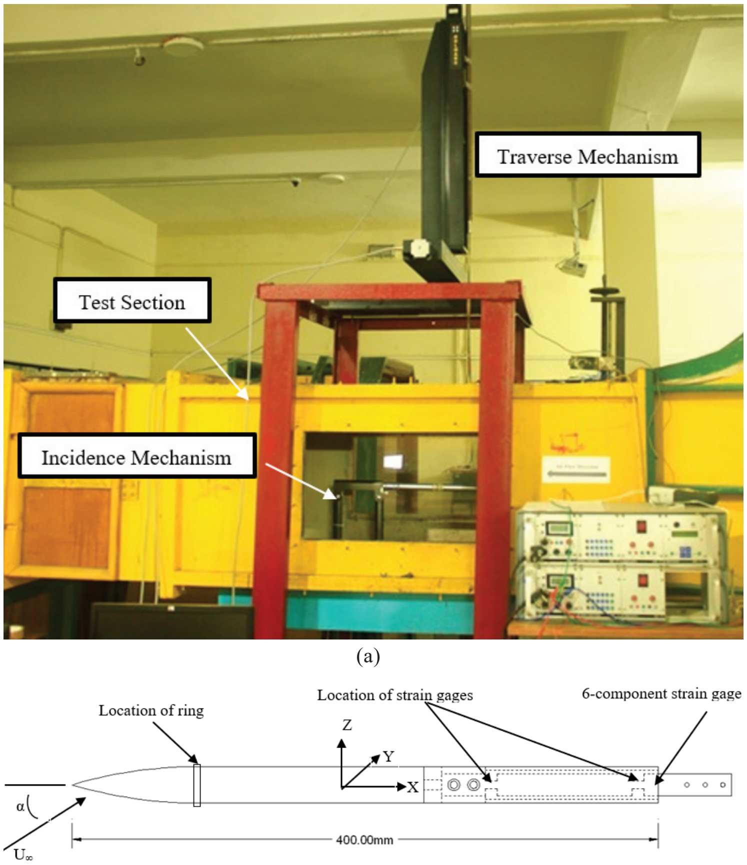
Figure 1. (a) Asymmetric vortex in a cross plane at high angles of attack and (b) Multi vortex system at high angles of attack[6].

pitch and yaw moments, however, it will be adequate to change the orientation of the body. The change in the orientation may significantly affect the vehicle aerodynamics as the change in the roll orientation will lead to the variation in the direction and magnitude of the side force[1-5]. Aerospace vehicles during manoeuvers often experience low speeds and high angles of attack, hence it becomes imperative to investigate the rolling moment on the pointed nosed forebody at different angles of attack. Apart from this, such investigations at low speeds will help in understanding the existing flow physics and develop control techniques that could be more efficient. To the best of author's knowledge, such measurements of rolling moment on slender body have not been reported earlier.

2. EXPERIMENTAL SETUP

The experiments were performed in the low-speed tunnel (Fig. 2(a)) available in the Department of Space Engineering and Rocketry at Birla Institute of Technology, Mesra, Ranchi. The wind tunnel is an open circuit, suction type, having a test section size of 600 mm x 600 mm and a speed ranging from 0 to 35 m/s. The speed of the wind tunnel was varied with the help of variable frequency drive. The turbulent intensity of the wind tunnel was found to be better than 0.3% which was measured using the Hotwire anemometer. The boundary layer in the test section was found to be of the order of around 20 mm. The length to diameter ratio was 16 which was similar to the model used[3,5]. The fineness ratio of the nose was kept as 3.5. The overall length of the model was around 400 mm and had a base diameter of 25 mm. The semi-apex angle of the nose was kept as 16.25°. The test model was made up of aluminum. The surface roughness of the model was found to be less than 4 μm which was ascertained using a Scanning Electron Microscope available at the Central Facility of Birla Institute of Technology, Mesra, Ranchi[10]. A computer-controlled model positioning system was used to change the angle of attack. The mechanism had an accuracy of 0.1°. The angle of attack of the model was ascertained using a highly sensitive accelerometer that was suitably placed on the incidence mechanism. The angle of attack was varied from 0° to 50° in the pitch plane (X-Z). The forces and moments were measured using an internal strain gage balance which was suitably placed inside the test model (Fig. 2(b)). The strain gage balance had a diameter of 10 mm and overall length of 204 mm. The strain gage balance was capable of measuring the axial force of 1 kg, Normal force of 2 kg, side force of 1 kg, pitching moment of 100 kg-mm, yawing moment of 50 kg-mm, and rolling moment of 50 kg-mm from the balance center.

The strain gage balance was exited using a 3-volt DC power supply. The deviation of the output from the mean was found to be less than 0.25 per cent which was ascertained after repeated measurements. Since the major objective of the present investigation is the measurement of the rolling moment, therefore it is very important that the data to be measured should not have the influence of noise, as the output voltage for the



(a)

(b)

Figure 2. (a) Low-speed wind tunnel and (b) Details of the model for force measurement.

rolling moment will be very low. A low noise DC power source was utilised to excite the strain gage balance. In addition, an ultra-isolation transformer was also used prior to the DC power source to minimise the noise in the power supply. The data was obtained using a signal conditioning module with a low pass filter having a cut off frequency of 10Hz. This was based on the measurements made by Lua[5], *et al.* and Kumar & Prasad[6].

Since the flow appears to be in a quasi-steady state at high angles of attack[6], hence the measurement was made for a time of 5 s with a sampling frequency of 500 samples/second. To reduce the side force, a rectangular cross-sectioned circumferential ring having a width of 2 mm and variable height was used[5-8]. An effort was made to obtain the effect of rings on the rolling moment of the slender body.

3. RESULTS AND DISCUSSIONS

A pointed forebody geometry followed by a cylindrical aft body experiences a side force at higher angles of attack. This side force is mainly due to the formation of asymmetric vortices in the lee side of the body. It has been investigated by many researchers in the past few decades. It has been observed that depending upon the nose shape, the side force starts to increase beyond an angle of attack of around 20° and reaches its maximum value at $\alpha \approx 50°$. It is mainly because the oncoming flow separates at the lower angles of attack and rolls up into a pair of vortical structures. At larger angles of attack, the flow appears to be asymmetric in different cross planes. Moreover, the vortical structures also seem to switch-over which due to the presence of multi-vortex system arranged alternately in the lee side of the body. This leads to the asymmetric pressure distribution along the longitudinal midplane of the body which in turn establishes local side forces that vary in magnitude as well as the direction along the length of the body and further leading to an overall lateral force existing on the body. More details of the flow physics are reported by Kumar & Prasad[6]. Figure 3 shows the comparison of the measured and reported side force which seems to be reasonable agreement.

The present investigation mainly concentrates on the moments that exist on the slender body at higher angles of attack. Figure 4 shows the pitching moment (C_m), yawing moment (C_n) and rolling moment (C_l) that is experienced on the slender body at different angles of attack. All the moments have been calculated from the center of gravity of the body. It is to be noted that the pitching moment increases with the increasing angles of attack. This is because of the lee side vortices which grows stronger with increasing angles of attack. However, an interesting fact was observed in the case of yawing moment where a variation in the magnitude, as well as direction, was observed at higher angles of attack. This variation in yawing moment could be due the presence of multi-vortex system. As reported by Kumar & Prasad[6], with increase in the angle of attack, the number of vortices in the multi-vortex system increases. This will definitely affect the side force as well as the yawing moment of the body. In comparison to the pitching and yawing moment, the rolling moment observed was to be feeble.

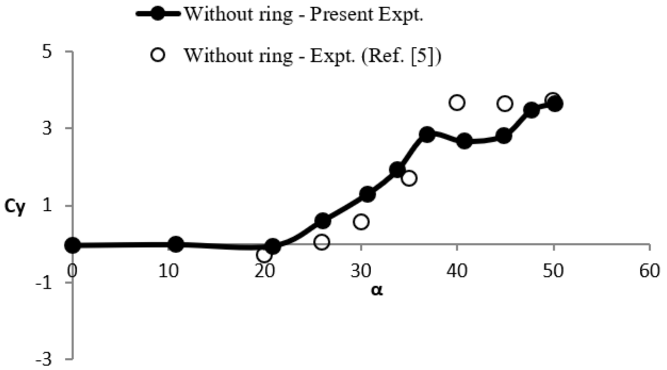


Figure 3. Comparison of measured side force with reported experimental results.

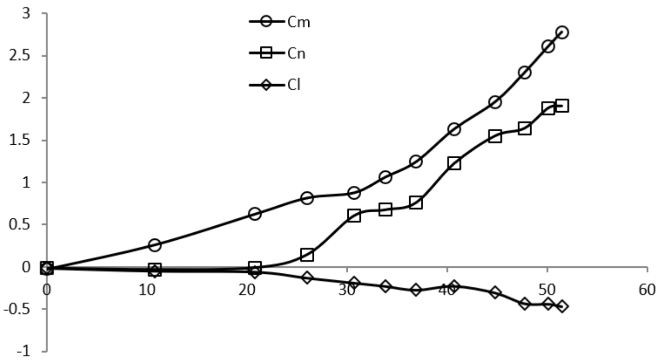


Figure 4. Measured pitching, yawing and rolling moment.

Several methods have been reported in the past to alleviate the side force at higher angles of attack. A rectangular cross-sectioned circular ring having a height of 5 per cent of the local diameter placed at X/D = 3.5 on the body was found to reduce the side force at higher angles of attack by a considerable amount[5,6]. However, its impact on the existing moment was not reported. Figure 5 shows the variation in the pitching moment at different angles of attack. At lower angles of attack, no significant variation in the pitching moment was observed. At large angles of attack, the pitching moment varied, however, it was not very significant. Surprisingly, a major variation in the yawing moment was observed with the use of circular rings at large angles of attack (Fig. 6). The yawing moment was lesser in $\alpha < 40°$, however, a significant increase in the yawing moment was observed at $\alpha > 40°$. This clearly indicates that a control technique could reduce the side force of the slender body at a high angle of attack by a considerable amount, but it

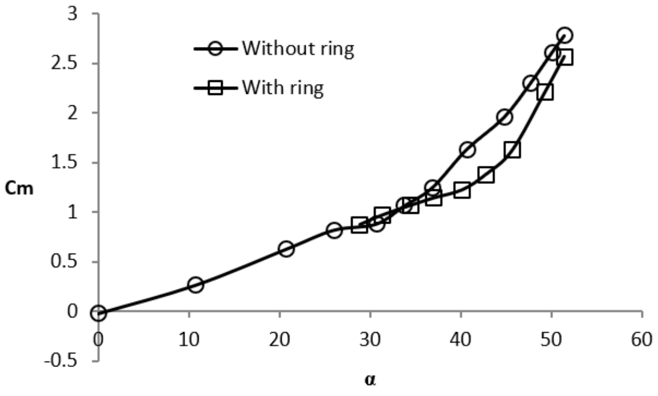


Figure 5. Measured pitching moment for with and without ring.

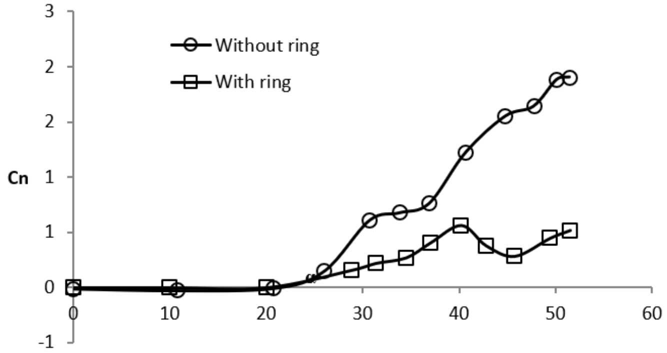


Figure 6. Measured yawing moment for with and without ring.

may induce a non-zero yawing moment which could be risky for the vehicle. Therefore, the control techniques should ensure that there exists a negligible side force as well as a negligible yawing moment on the body.

Another important aspect to be considered is the rolling moment of the body. Since the generation of the side force of the slender body at higher angles of attack remained a major concern of the researchers, the rolling moment was completely ignored. To best of our knowledge, the experimental investigation of the rolling moment on the slender body has not been reported. The onset of the asymmetric vortex will induce a rolling moment which could be very small in comparison to the other moments, however, even a small rolling moment will be enough to rotate the body about its axis. The rotation of the body will change the roll orientation that may lead to a major change in the body aerodynamics. Henceforth, it becomes imperative to investigate the rolling moment of the body at different angles of attack. Figure 7 shows the variation in the rolling moment at different angles of attack. For the case of a slender body without any control technique, it is observed that the rolling moment increases with the increase in the angles of attack. At lower angles of attack (α < 20°), the vortices are almost symmetric in the cross-plane and hence primary separation zone are also symmetric that leads to a very small/negligible rolling moment. At higher angles of attack, the onset of asymmetric vortices creates a force imbalance about the center of the body which tends to roll the body. It was observed that the use of ring did not significantly change the magnitude and direction of the rolling moment.

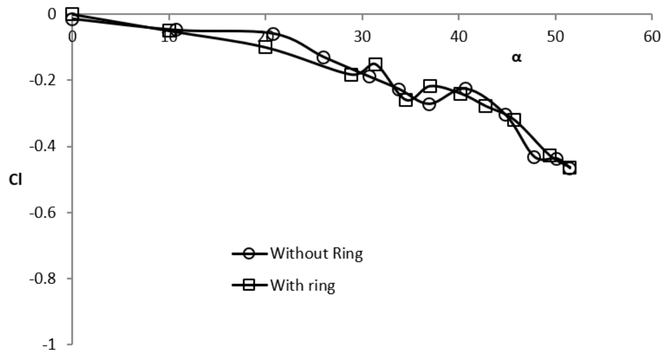


Figure 7. Measured rolling moment for with and without ring.

Investigations were made by Kumar & Prasad[7] to observe the effect of height of ring at X/D = 3.5. It was found that a ring height of around 2.5% - 3% placed at X/D = 3, was suitable to reduce the side force. In the present analysis, measurement of the rolling moment for different ring heights indicated that the rolling moments for almost all the cases were similar having a slight variation in the magnitude (Fig. 8). However, for the case of ring having 2.5 per cent ring height of the local diameter, a decrease in the rolling moment was observed at higher angles of attack. Such ring geometry will reduce the side force and could eliminate the possibility of rotating the slender body at higher angles of attack. However, more detailed investigations are required to ascertain the effectiveness of the ring. Further Kumar & Prasad[8] also reported that the use of two rings of height 3 per cent of the local diameter placed at X/D = 2.5 and 4.5 drastically reduces the side force at all the angles of attack. But the measurement of the rolling moment with two rings on the slender body showed a random variation (Fig. 9) at different angles of attack. This indicates the use of two rings could prove to be unsatisfactory in terms of the rolling moment.

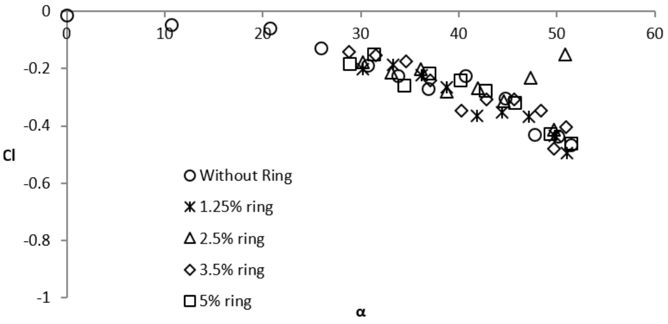


Figure 8. Measured rolling moment for different ring heights.

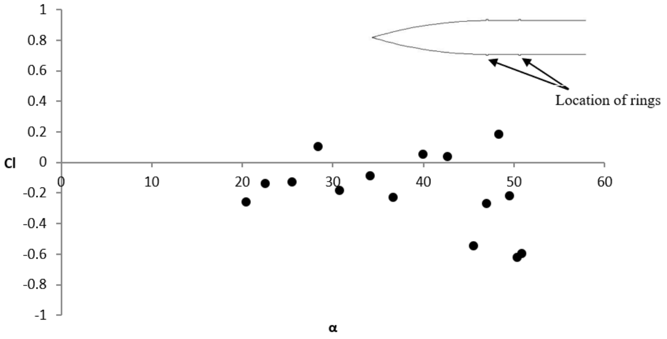


Figure 9. Measured rolling moment for two rings combination placed at X/D = 3.5 and 4.5.

4. CONCLUSIONS

Experiments were made over a long slender body having a length to diameter ratio of 16. The investigations were made at a freestream velocity of 17 m/s which corresponds to a diameter Reynolds number of 29000. The angle of attack was varied from 0° to 50°. It was established that the use of rings placed suitably reduces the side force on the body at large angles of attack. The present investigation aimed to obtain the moments for the case of with and without a ring. Experiments indicated an increase in the pitching, yawing and rolling moments with increasing angle of attack. However, a reduction in the pitching and yawing moment was observed with the use of the ring. Another important aspect of the present investigation was the effect of angle of attack and rings on the rolling moment of the body. It was observed that the rolling moment of the body also increases with the increase in the angle of attack. Use of the rings did not reduce the rolling moment of the body significantly. Further, it was also observed that the use of two rings which significantly reduces the side force, indicated random variation in the rolling moment at different angles of attack. Henceforth, it is necessary to reduce the moments on the slender body at higher angles of attack as well in addition to the side force.

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CONTRIBUTOR

Dr Priyank Kumar obtained his PhD in Engineering from Birla Institute of Technology, Mesra Ranchi. He is presently working as Assistant Professor at Department of Space Engineering and Rocketry, BIT Mesra. His research area includes : Low speed aerodynamics, high angles of attack, experimental aerodynamics.