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Side Force on an Ogive Cylinder: Effects of Control Devices

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This study is an extension of our earlier work (Luo, S. C., Lim, T. T., Lua, K. B., Chia, H. T., Goh, E. K. R., and Ho, Q. W., "Flowfield Around an Ogive/Elliptic-Tip at High Angle of Attack," *AIAA Journal*, Vol. 36, No. 10, 1998, pp. 1778–1787), which examined the effectiveness of using an elliptic tip to control the side force acting on an ogive cylinder. In that study, only one tip was considered, and thus the effect of tip eccentricity on the side force was not known. In the present study, we examine another elliptic tip of a smaller eccentricity to get an insight into how tip eccentricity affects the local and overall side force distribution. Our measurements show that, although the smaller eccentricity tip has a side force distribution similar to that of the larger eccentricity tip, there are some major differences in their flow characteristics. For example, the larger eccentricity tip is found to reduce the onset angle of attack and delay the disappearance of the side force to a higher angle of attack. Furthermore, when $\alpha \approx 60$ deg, only the lower eccentricity tip displays a hysteresis effect in its side force distribution. To the best of our knowledge, this phenomenon has not been observed on an elliptic tip before, even though a similar phenomenon has been observed on a conical body with a rounded tip when the cone was subjected to unsteady bleeding.

Nomenclature

Cy	= side force coefficient, $Fy/(0.5\rho U_\infty^2 S)$
$Cy(x/D)$	= local side force coefficient, local side force/$(0.5\rho U_\infty^2 D \sin^2\alpha)$
D	= cylinder diameter
Fy	= side force
L	= length of body
Re_D	= Reynolds number, $U_\infty D/\nu$
S	= model base area, $\pi D^2/4$
U_∞	= freestream velocity
x	= axial distance from nose tip
α	= angle of attack
ν	= kinematics viscosity of fluid
ϕ	= roll angle
ρ	= density of fluid

I. Introduction

WHEN an ogive cylinder is pitched at a high angle of attack to an oncoming flow, in spite of its symmetric geometry, a large side force can be generated on the forebody. Previous studies have attributed this to the generation of asymmetric vortices on the forebody. To date, the origin of the vortex asymmetry remains unclear, but it is generally accepted that the asymmetry is caused by nonuniform surface roughness and/or microgeometrical imperfections.[1–3]

In the past few decades, extensive studies[4–12] have been carried out to obtain either a more predictable side force or a reduction in its magnitude. Recently, Moskovitz et al.[10] and Bridges and Hornung[11] attempted to do this by incorporating an elliptic cross-section tip on an ogive nose cylinder and a right-angle cone, respectively. Based on the results obtained, they concluded that the elliptic cross-section tip shows good potential for providing directional control for flight vehicles. Along the same line of investigation, Luo et al.[13] studied the effects of elliptic tip on the side force acting on an ogive cylinder, and their results, in general, agree with those of Moskovitz et al.[10] and Bridges and Hornung.[11] In addition, they found that the elliptic tip reduces the onset angle of attack and delays the disappearance

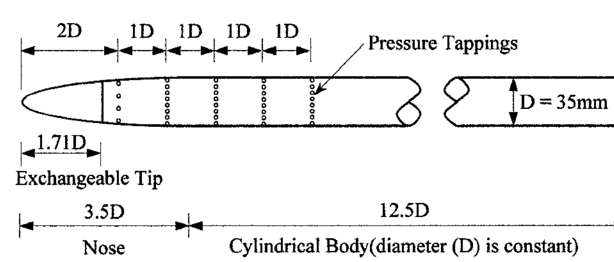

Fig. 1 Sketch of the experimental model.

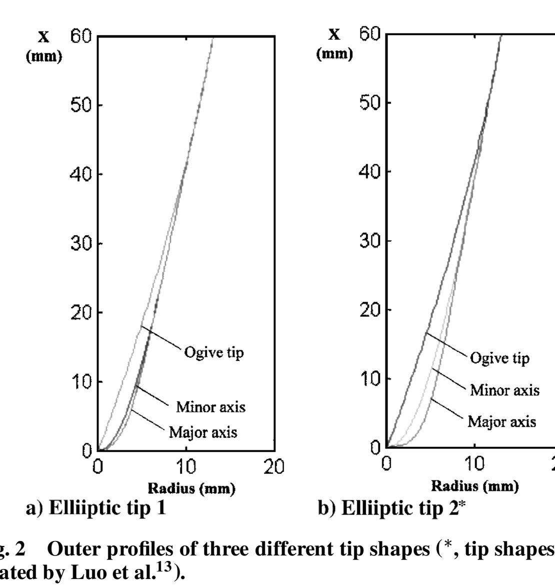

Fig. 2 Outer profiles of three different tip shapes (*, tip shapes investigated by Luo et al.[13]).

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of side force to a higher angle of attack when compared to a smooth ogive nose tip.

From the finding of Luo et al.,[13] which is based on only one elliptic tip, an inevitable question arises as to how the tip eccentricity affects the overall side force distribution. The desire to obtain an answer to this question has motivated us to carry out the present investigation. Our attention is focused primarily on how the tip eccentricity affects both the maximum magnitude and the side force distribution.

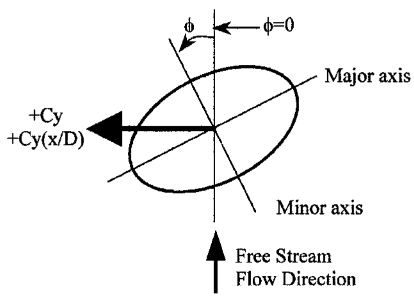


Fig. 3 Reference for azimuth angle and side force.

II. Experimental Apparatus and Techniques

The experimental apparatus and procedure used in the present investigation are the same as those described by Luo et al.,[13] except for the smaller tip eccentricity used in the present study. The elliptic tip was designed based on the method adopted by Bridges and Hornung.[11] However, unlike Bridges and Hornung,[11] who mounted their elliptic tips on a cone, here the tips were mounted on an ogive cylinder. The location where the nose tip merges with the rest of the ogive body is shown in Fig. 1. Figure 2a shows the outer profiles of the elliptic tip used in the present study. For the purpose of comparison, the profile of the nose tip investigated by Luo et al.[13] is shown in Fig. 2b. For easy reference, we shall refer to the present tip (smaller eccentricity) as elliptic tip 1 and that used by Luo et al.[13] (larger eccentricity) as elliptic tip 2.

III. Results and Discussion

The sign convection for roll angle ϕ is shown in Fig. 3, with the side force pointing in the starboard direction defined as a positive one. This applies to both the local [i.e., at a particular axial (x/D) location] and the overall side force coefficients [$Cy(x/D)$ and Cy, respectively].

In Fig. 4, the side force coefficient distribution for a cylinder with elliptic tip 1 is presented for different angles of attack α. For the

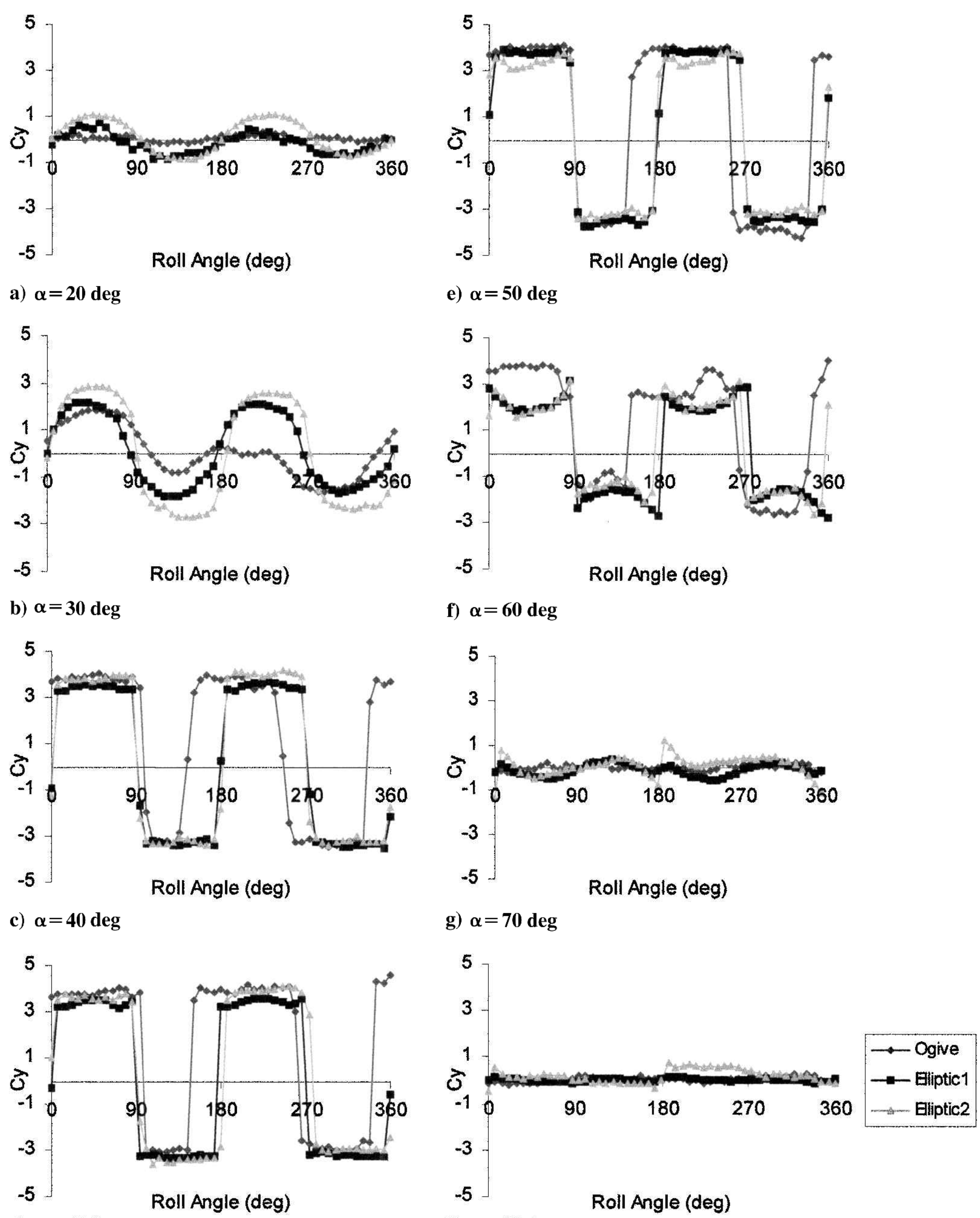


Fig. 4 Side force coefficient *Cy* vs roll angle ϕ for ogive tip, elliptic tip 1, and elliptic tip 2 at different angles of attack.

purpose of comparison, the results of Luo et al.[13] for the ogive tip and elliptic tip 2 are also shown.

From Fig. 4, it can be seen that, at low angles of attack of 20 and 30 deg, the side force distribution of elliptic tip 1 undergoes sinusoidlike variation with the zero crossover positions (positions where side force changes sign) at $\phi = 0$, 90, 180, and 270 deg. This behavior is similar to that of elliptic tip 2 but is in contrast to that of the ogive cylinder, where the force distribution is more random, particularly at $\alpha = 30$ deg. In addition, Figs. 4a and 4b show that the maximum side force acting on the tip increases with the eccentricity. This suggests that tip eccentricity can have a significant influence on the onset angle of attack, which is defined as the angle of attack at which side force becomes appreciable in magnitude.

At an intermediate angle of attack ($\alpha = 40$, 45, and 50 deg), the side force distribution of elliptic tip 1 undergoes a square-wave-like variation (sometimes referred to as a "bistable" state) with the roll angles. At these angles of attack, the zero crossover positions are located at approximately $\phi = 0$, 90, 180, and 270 deg, which agrees well with the results of elliptic tip 2 at $\alpha = 40$, 45, and 50 deg. However, for an ogive cylinder, although the side force distribution is also square wave like, its zero crossover positions are more random. Figure 5 shows the local side force distribution $[Cy(x/D)]$ along the axial direction for a few selected roll angles at which overall side force undergoes bistable states. Here the angle of attack was 40 deg. Although the overall side force at these roll angles are nearly constant (Fig. 4c), close examination shows that the peaks of the local side force along the axial location depend very much on the roll angle (Fig. 5). The same behavior also occurs at $\alpha = 45$ and 50 deg, which agrees well with the results of Luo et al.[13] for elliptic tip 2 at the same angle of attack. Interestingly, Figs. 4c–4e also show that the three nose tips, in spite of having a different geometry, possess the same the maximum side force.

In Fig. 4f, it can been seen that, when elliptic tip 1 at $\alpha = 60$ deg, the side force distributions are distinctly different from those at the

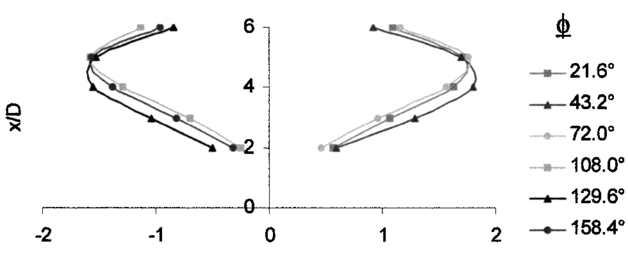
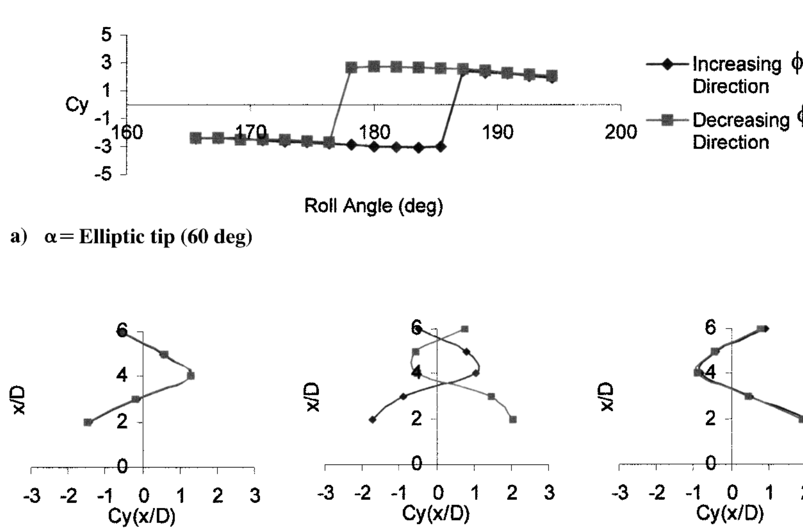


Fig. 5 ***x/D* vs local side force *Cy*(*x/D*) for elliptic tip 1 at $\alpha = 40$ deg.**

lower angles of attack. Here the zero crossover positions are not well defined and seem to be dependent on the roll direction. Although Fig. 4f shows that both the elliptic tips have a similar side force distribution, the zero crossover positions for elliptic tip 2 seem to be more predictable. The delay in the zero crossover positions in elliptic 1 leads the authors to suspect that a hystersis effect could be present. To verify this, the model was rolled at an incremental step of 1.8 deg in the direction of increasing ϕ and then in the opposite direction in the range of $\phi = 165.6$–194.4. Figure 6a clearly shows that, when the cylinder is rolled in the direction of increasing ϕ, the zero crossover position of the side force (Cy from negative to positive) occurs at ϕ of about 186.5 deg. In contrast, when it is rolled in the opposite direction, the zero crossover (Cy from positive to negative) occurs at a different roll angle (i.e., $\phi \approx 177.5$ deg). So far, the hysteresis effect can be detected only for elliptic tip 1 at $\alpha \approx 60$ deg. It is not clear at this stage why this is so. For a closer look at the hysteresis effect, the local side force coefficients along the axial direction were plotted at a few selected roll angles: $\phi = 176.4$, 180, and 185.4 deg (Figs. 6b–6d). At $\phi = 176.4$ and 187.2 deg, it can be seen that the local side force coefficients are independent of the cylinder's roll direction. This behavior is consistent with the results shown in Fig. 6a. However, in the proximity of $\phi = 180$ deg (Fig. 6c), the local side force distributions in the direction of increasing ϕ is opposite in sign (direction) to that of decreasing ϕ, thus confirming the presence of hysteresis. Interestingly, the hysteresis effect had also been observed by Bernhardt and Williams[12] when they attempted to control the side force on a conical nose by using the unsteady bleed technique. They postulated that, when the asymmetric vortices are in the bistable mode, pressure feedback from the vortices to the model tip induces an initial flow disturbance and locks in the vortex in one of the two asymmetric vortex configurations. The vortices switch to the opposite configuration only when the forcing is able to overcome the feedback disturbance. It is not clear whether the same explanation can be applied to our model. This issue requires further investigation.

At $\alpha = 70$ and 80 deg, the side force acting on elliptic tip 1 is almost zero, and there are no well-defined zero crossover positions. This finding is consistent the results of Luo et al.[13] for the ogive tip and elliptic tip 2. Returning to Figs. 4g and 4h, it is clear that a larger tip eccentricity has a slightly higher maximum side force than a lower tip eccentricity. This implies that the larger tip eccentricity delays the disappearance of the side force to a higher angle of attack.

At this point, the authors would like to point out that Bridges[14] has also examined the effect of tip eccentricity but on a circular cone. However, his results are not as extensive as those presented here, and he did not observe the hysteresis effect in his force measurements.



a) α = Elliptic tip (60 deg)

b) Roll angle = 176.4 deg c) Roll angle = 180.0 deg d) Roll angle = 187.2 deg

Fig. 6 ***Cy* and *Cy*(*x/D*).**

IV. Conclusions

The main findings of this study are summarized as follows:

1) Elliptic tip 1 is found to be as effective in controlling the side force as elliptic tip 2, although the former has a smaller eccentricity. Moreover, its total side force distribution exhibits a bistable state similar to that of elliptic tip 2.

2) When the body pitched is at either low angles of attack (i.e., $20 \leq \alpha \leq 30$ deg) or high angles of attack ($70 \leq \alpha \leq 80$ deg), the maximum Cy is found to increase with the tip eccentricity. This implies that larger tip eccentricity reduces the onset angle of attack and delays the disappearance of the side force at a high angle of attack. At the intermediate angle of attack, tip eccentricity has a negligible effect on the maximum amplitude of the side force.

3) One of the important outcomes of this investigation is the discovery of the hysteresis effect in the Cy distribution with the roll angle of an ogive cylinder with elliptic tip 1 when the angle of attack α is approximately 60 deg. To the best of our knowledge, this behavior has not been seen on an elliptic tip, even though Bernhardt and Williams made a similar observation when they used the unsteady bleeding technique to control the side force on a conical body.

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