Effects of Probe Interference on Side Force of an Inclined Ogive Cylinder

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I. Introduction

FLOW over an ogive cylindrical body at high incidence is known to produce a large side force, which can be attributed to the asymmetric shedding of tip vortices.[1–6] Quite often, the variation in the mean side force with the roll angle exhibits a square-wavelike behavior, which can be traced to the switching over of the vortex configuration.

Apart from the force measurements, various attempts have also been made to relate vortex circulation[7,8] and intervortex spatial distance[9] to the surface pressure distribution, as well as the side force acting on the body. Quite often, these studies require measurements of the wake velocity distribution with either laser Doppler anemometry (LDA), hot-wire, or pressure probes. Whereas a nonintrusive technique such as LDA is ideal for vortical flow, the latter two techniques are not as suitable because concentrated vortices are known to meander in the presence of the probe[10,11] and result in changes to the original flowfield. The effects of probe interference are usually manifested as 1) vortex breakdown that propagates upstream, 2) instability waves or other disturbances traveling upstream, 3) changes in vortex core trajectory, and 4) changes in the local flowfield around the probe due to probe generated pressure field. In this Note, we examine the severity of probe interference on the side-force measurements of an ogive cylinder at high incidence because the side force is sensitive to changes in the vortex configuration caused by the probe.

This work started off as part of a larger research program on high-angle-of-attack (AOA) aerodynamics.[3,12–14] The original objective was to relate the side force acting on an ogive cylinder with the strength (or circulation) and the configuration of the trailing vortices by mapping the velocity field in cross-stream planes behind the cylinder. However, because of unavailability of nonintrusive systems like LDA and particle laser velocimetry (PIV), hot wires were chosen for the tasks. As far as we know, no quantitative data on the severity of probe interference are available in the literature from which we could make our judgement on whether to proceed with the measurements. It is this lack of quantitative data that prompted us to conduct the present investigation. Results obtained show a significant error in the side-force coefficients, reaching as high as 20%, when the probe is in the vicinity of the vortices. This leads us to abort our initial plan of using hot-wire probes in the ogive cylinder wake measurement. Nevertheless, we feel that the present results serve as a useful guide to those who are planning to conduct hot-wire or pressure measurements in symmetry sensitive vortex-dominated flows, and they also give indications on the sensitivity of vortex-dominated flows to disturbances.

II. Experimental Setup

The experiment was carried out in an open-loop suction wind tunnel with a rectangular test section measuring 0.6 m (height) × 1.0 m (width). The turbulence intensity of the empty wind tunnel was about 0.23%. The ogive cylinder used in the present study is identical to that used by Luo et al.,[3] and interested readers can refer to Ref. 3 for more details. All of the measurements were conducted at a freestream velocity U of 15 m/s, giving the Reynolds number Re, based on the diameter ($D = 35$ mm) of the cylindrical section of the model, of about 3.5×10^4. A load cell was used to measure the side force F_y to obtain the corresponding side-force coefficient C_{Fy} acting on the model. [$C_{Fy} = F_y/(0.5\rho U^2 S)$, where ρ is the air density and S is the model base area.] The accuracy of the load cell is ±1.16 g, which corresponds to an error of ±0.089 in the side-force coefficient. The experiment was conducted at the AOA α of 45 deg and the roll angles ϕ of 0, 72, 158.4, and 244.8 deg because these conditions were found to exhibit a maximum side force.

The experimental setup is shown in Fig. 1a. The Cartesian coordinate system adopted here is such that the origin is at the tip of the model, with x directed in the freestream direction, y toward the starboard side of the model, and z vertically upward. The ogive model was mounted on an inclined mechanism, which was placed on the floor under the wind tunnel, and the model protrudes through the floor of the wind tunnel into the test-section area. The probe (of adjustable length) was held by a T-shaped holder, which was, in turn, secured onto a two-dimensional traversing mechanism placed on top of the wind tunnel. The adjustable probe's length ranges from 0.86 to 1.0 m and has a diameter of 5 mm. The experimental procedure involved the acquisition of the side force while the probe was positioned at different spanwise locations across the tunnel, that is, along y direction for given x–z coordinates. The idea was to map out a region in the wake of the ogive cylinder where the hot-wire probe has significant influence on the side force. The measurement stations in the x–z plane are shown in Fig. 1b, with the spanwise station ranges from $y/D = -5$ to 5. The positional error is estimated to be about $\pm 0.0857D$.

To obtain reference values for the side-force coefficient C_{Fy0}, the experiment was first run in the absence of the probe, after which the

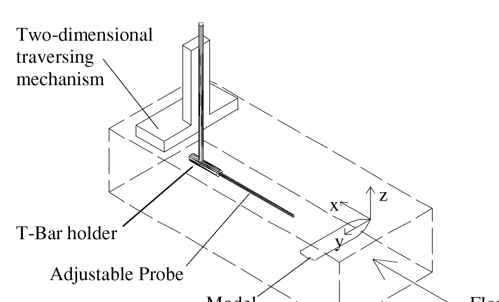

Fig. 1a Experimental setup: – – –, boundary of the test section; probe is referenced relative to the Cartesian coordinates fixed to the model nose tip.

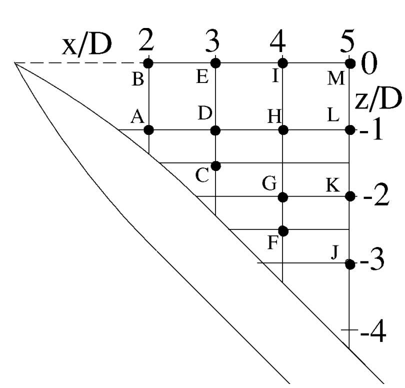

Fig. 1b Various probe positions at the near wake of the ogive cylinder; at each probe position, the probe also traverses (out of page) from *y/D* = 5 to −5 and then back to *y/D* = 5.

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model was rolled to the angular position of maximum side force, for example, at $\phi = 0$ deg, based on the measurements without the probe. A probe was then placed at predetermined x–z coordinates, for example, at position A as shown in Fig. 1b, and the side force was measured by the probe's traversing to different spanwise locations, first from $y/D = +5$ to -5, and then retracing the path from $y/D = -5$ to $+5$. The procedure was repeated for the other roll angles that gave the maximum side force, that is, at $\phi = 72$, 158.4, and 244.8 deg. Based on the results obtained, the probe was then moved to the y/D position that gave the maximum influence, and the variation of the side force with the roll angle was then measured. The same sequence of measurements is repeated for other x–z coordinates shown in Fig. 1b (B, C, D, etc.) until the entire acquisition volume is covered.

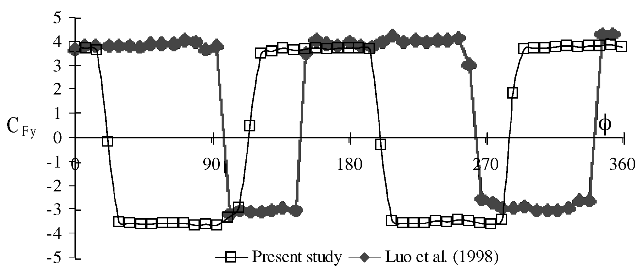

Fig. 2 Square wave variation of C_{Fy} with ϕ at $\alpha = 45$ deg when probe is absent; square wave distribution is seen in both the present data and those of Luo et al.[3]

III. Results and Discussion

A. Variation of C_{Fy} with Probe Position

Without the probe, the variation of C_{Fy} with the roll angle at $\alpha = 45$ deg displays the characteristic square wave pattern, as shown in Fig. 2, which is in good agreement with that obtained by Lamont,[1] Luo et al.,[3] and Zilliac.[15] The magnitude of the C_{Fy} obtained in this experiment is comparable to those reported by Luo et al.[3] except for the location at which C_{Fy} crosses over, that is, the roll angle ϕ at which C_{Fy} changes sign, which is sensitive to the model's tip and wind-tunnel conditions. Because the surface conditions for the two models are different, it is no surprise that the crossover position differs.

Four distinct roll angles ($\phi = 0$, 72, 158.4, and 244.8 deg) were chosen for study. They are the angular positions where the maximum magnitude in the side force occur, and the corresponding C_{Fy0} at these positions are 3.766, -3.593, 3.702, and -3.570, respectively. For the sake of brevity, only the representative results at $\phi = 0$ deg (positive C_{Fy}) and 72 deg (negative C_{Fy}) will be discussed here. To show the severity of the probe's influence on C_{Fy}, all of the C_{Fy} data will be normalized with C_{Fy0} at the respective roll angle.

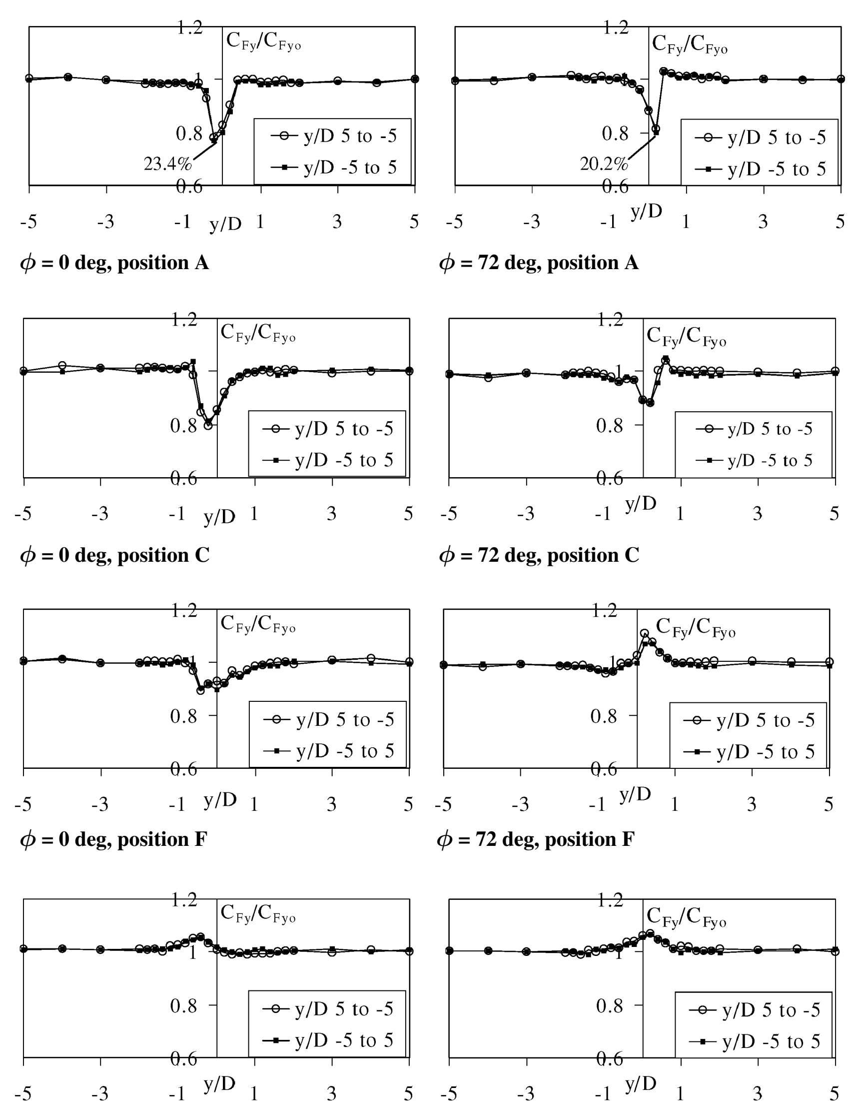

Fig. 3a Variation of C_{Fy}/C_{Fy0} with y/D at different probe positions close to the model at A, C, F, and G for $\phi = 0$ and 72 deg.

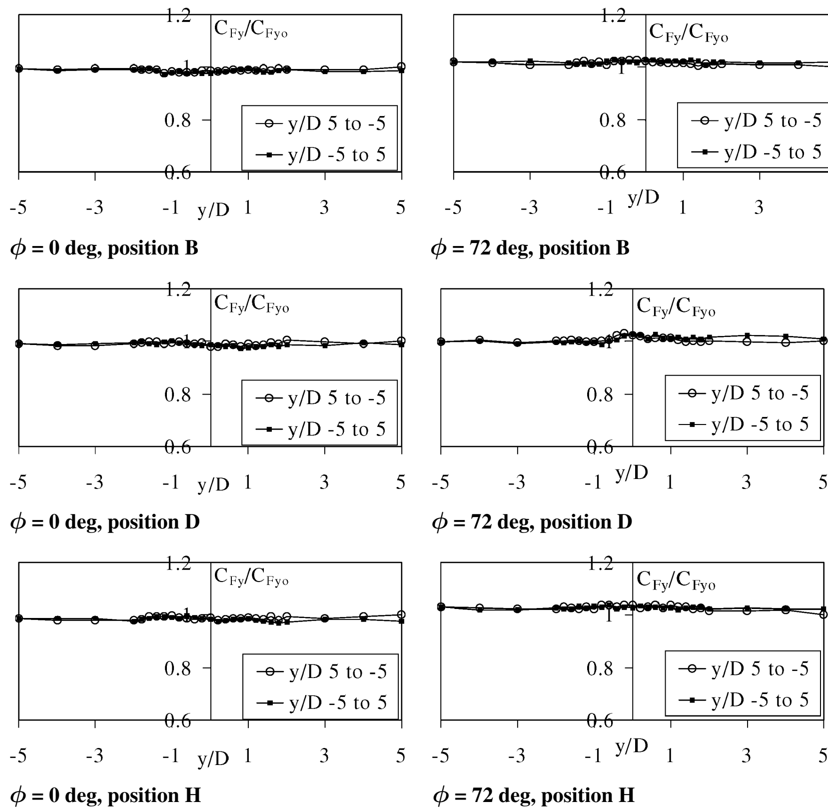

Fig. 3b Variation of C_{Fy}/C_{Fy0} with *y/D* at different probe positions, farther away from the model at B, D, and H for ϕ = 0 and 72 deg; little probe interference observed at these positions.

In Fig. 3a, the variations in C_{Fy}/C_{Fy0} with y/D are displayed for the measurement locations A, C, F, and G, indicated in Fig. 1b. These positions are relatively close to the model. As Fig. 3a shows, the presence of the probe causes a drastic attenuation in the side force magnitude at A and C for both $\phi = 0$ and 72 deg, for example, 23.4% of C_{Fy0} at position A and 20.2% at position C, respectively. Note that, at positions A and C, the minimum point in the C_{Fy}/C_{Fy0} curve for $\phi = 0$ deg (positive side force) occurs at $y/D = -0.2$ and that for $\phi = 72$ deg (negative side force) occurs at $y/D = 0.2$. This difference can be explained in terms of the configuration of the two trailing vortices. It is well known[3,9] that when the C_{Fy} is positive, the starboard trailing vortex is located closer to the ogive model than the port side vortex. Hence, when the probe scans across the near wake of the ogive cylinder, it is likely that the probe interferes more with the portside vortex because it is located farther away from the cylinder, that is, closer to the probe, than the starboard trailing vortex. Conversely, when the C_{Fy} is negative, the probe interferes more with the starboard trailing vortex. This vortex–probe interaction results in the reduction in magnitude of C_{Fy} when the trailing vortices are being pushed away from the cylinder by the probe. Note that the minimum point locations in the C_{Fy}/C_{Fy0} curves are independent of the direction of the probe movement.

When the probe is moved farther downstream to locations F and G, the results (as shown in Fig. 3a) show that the probe at location F leads to an attenuation in the C_{Fy}/C_{Fy0} for $\phi = 0$ deg, but causes an amplification at $\phi = 72$ deg. At location G, the C_{Fy}/C_{Fy0} increases for the both roll angles. The difference in the trend of C_{Fy}/C_{Fy0} for these two roll angles suggest that the probe could have displaced the vortices away from their normal position, thereby giving rise to the changes in magnitude of C_{Fy}. Furthermore, the C_{Fy}/C_{Fy0} variation with y/D at positions F and G appears to have a broader base compared with those at positions A and C. This could be due to the greater extent of the probe influence as the vortex core size increased from $x/D = 2$ (at position A) to $x/D = 4$ (at positions F and G).[9]

When the probe is moved farther away from the model, the influence on the C_{Fy} becomes negligible. Some representative results are shown in Fig. 3b for positions B, D, and H, which essentially show that the magnitude of the C_{Fy} is not influenced significantly by the probe.

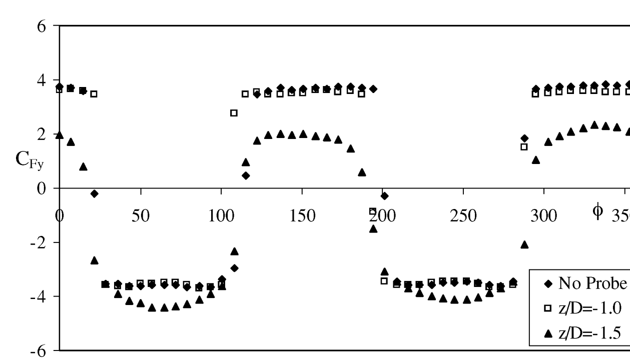

Fig. 4 Variation of C_{Fy} with ϕ for different probe positions; *x/D* = 3 and *y/D* = −0.2 are kept fixed, and the probe position was altered in the *z/D* direction only.

B. Influence of a Stationary Probe on the C_{Fy} vs ϕ Relation

The preceding results showed that it is possible for the probe to either attenuate or amplify the magnitude of C_{Fy}. This prompted us to examine how a stationary probe affects the C_{Fy} vs ϕ relation. Several different probe positions were investigated, but for conciseness, only the results for two probe positions at C and D, and with $y/D = -0.2$ for both cases, are shown in Fig. 4 and compared to the C_{Fy} data without the probe. The first position, at C, corresponds to the minimum C_{Fy}/C_{Fy0} for $\phi = 0$ deg in Fig. 3a, whereas the second position, at D, is located above the first one. Not surprisingly, Fig. 4 shows that the probe at position D has a minimum effect on the side-force distribution. However, with the probe at location C, the normally square-wavelike distribution gives way to a distribution

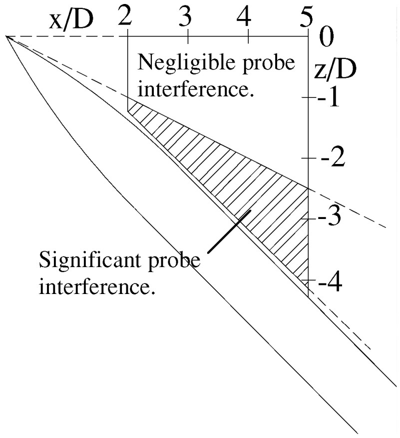

Fig. 5a Schematic of regions of significant and negligible probe interference.

Fig. 5b Dye flow visualization of flow over an ogive cylinder at α = 45 deg.

that is more rounded at the edges and that shows a slight change in the transition position. All of these suggest that the probe has disturbed the original configuration of the trailing vortices.

C. Region of Probe Interference in the Wake of Inclined Ogive Cylinder Flows

The present study has systematically investigated the regions in the wake where there is significant probe interference, and the results can be better presented pictorially by categorizing the regions into different zones of influence, namely, regions of strong probe influence and regions of negligible probe influence. This is shown in Fig. 5a. Here, negligible probe interference is defined as one with less than $\pm 5\%$ variation in the results. As expected, when the probe is in close proximity to the ogive cylinder, its influence on the side force is most significant. A comparison of Fig. 5a with the dye flow visualization conducted at $\alpha = 45$ deg, as shown in Fig. 5b, indicates that the regions of strong probe influence coincide with the vortical region in the wake of the inclined cylinder.

IV. Conclusions

The effects of probe interference on the side force have been investigated and quantified for an ogive cylinder at $\alpha = 45$ deg. Results show that when the probe is in close proximity to the vortices, there is either an attenuation or amplification of the side forces, which causes an error in the side-force coefficient that can reach as high as 20% of the corresponding value without the probe. The inaccuracy could be due to the displacement of the vortices from their normal positions and/or changes in the local flowfield around the probe. The region of significant probe influence has been also mapped out relative to the ogive cylinder and, when compared to dye visualization, corresponds to the region of the vortical flow.

The authors would like to stress that the present results are obtained specifically for an ogive cylinder only and they will no doubt differ from other vortical flows, such as that past a delta wing. Nonetheless, the quantitative results obtained here reinforce the earlier finding that the presence of a probe in symmetry sensitive vortex dominated flow can cause considerable changes to the flowfield. Furthermore, the probe can be regarded as a perturbation to the flowfield, and the present results demonstrate the sensitivity of the flowfield to disturbances. All of these effects lead to significant errors in the flowfield measurement.

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