Visual Study on Wakes Behind Solid and Slotted Axisymmetric Bluff Bodies

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A flow visualization study was conducted for various configurations of solid and slotted axisymmetric bluff bodies. The geometries also included those of solid and ribbon parachute canopy models. The structures of the unsteady near wake patterns were surveyed and compared. In addition, the effect of rapid model acceleration and deceleration on the wake was visualized. This article presents, although somewhat qualitatively, analysis of results from photographs and videotapes and an overview of various pertinent phenomena observed.

Introduction

A CLEAR understanding of the wake flow behind a parachute is critical for the safe operation of parachutes. Though detailed knowledge of the wake structure is essential to predict, such phenomena as the wake recontact problem,[1] analysis of the entire wake region at once appears to be inaccessible. For example, the wakes of axisymmetric bluff bodies are found to be fully three dimensional even for the simplest form of axisymmetric geometry. The flowfield immediately downstream of a ribbon parachute is particularly complex because of irregular merging of high speed jets through multiple narrow gaps. Moreover, the detailed study of the flowfield during a full-scale drop test appears to be a nearly inaccessible task at present. Flow visualizations in carefully designed laboratory environments, on the other hand, can not only provide excellent clues to the complex flowfield but also guide quantitative measurements and computation and analysis of the flowfield. It is also to be noted that some modern flow visualization techniques have started to provide detailed quantitative information with advancement of applied optics and image processings, as seen in Ref. 2. In the past, low-speed flow visualizations have been conducted to simulate complex high Reynolds number airflows in aircraft flight conditions, and somewhat surprisingly to some, the results compared well with flight test data.[3] This means that many vortex-dominated flows are not as dependent on the differences in viscous effects. Naturally, additional compressibility effects must not be overlooked, and interpretation of flow visualizations in unsteady flowfields requires extra caution, as is often pointed out (see, for example, Gad-el-Hak[4]). In the present experimental investigation, the wake regions of the axisymmetric bluff bodies were observed using various flow visualization techniques in both air and water. Configurations studied included a circular disk, solid parachute model, slotted disk, and a ribbon parachute model. Flow visualization was also conducted to study the effect of rapid model acceleration and deceleration.

Experimental Setup

Different facilities were used for optimum visualization. The experiment in air was conducted in a closed test section of a low-speed, closed-return wind tunnel at the University of Minnesota. The test section was 1.5 m long and the cross section measured 1.37×0.97 m. Freestream velocity up to 23 m/s can be obtained, though flow visualization was conducted at a substantially lower velocity, as noted in the figures in terms of the Reynolds numbers based on the model diameter. The tunnel flow condition[5] was found adequate for the present study. The models to be described in the Results section were either sting-mounted or supported by thin wire along the centerline of the test section. The streamlined particle injector was fabricated and placed upstream of the model, and fine oil fog generated by a Rosco Model 1500 smoke/fog generator was introduced into the test section. The visualization in the empty test section as a control revealed no unsteadiness in the freestream nor any adverse effect of the injector. The diameter of particles, which are nontoxic according to the manufacturer, measured 2 μm on the average. Illumination was provided by an argon ion laser passed through a set of cylindrical lenses and front surface mirrors to produce a thin sheet of light aligned with the centerline of the model.

The experiment in water was carried out in a towing tank at the St. Anthony Falls Hydraulic Laboratory, measuring 39×61 cm in cross section and 15.2 m in length. In some tests, the tank was partitioned into a shorter segment for ease of operation. Normally, the model was towed in a stationary fluid. The towing carriage was driven by a variable speed a.c. motor. A 35-mm camera or a video camera and the lighting

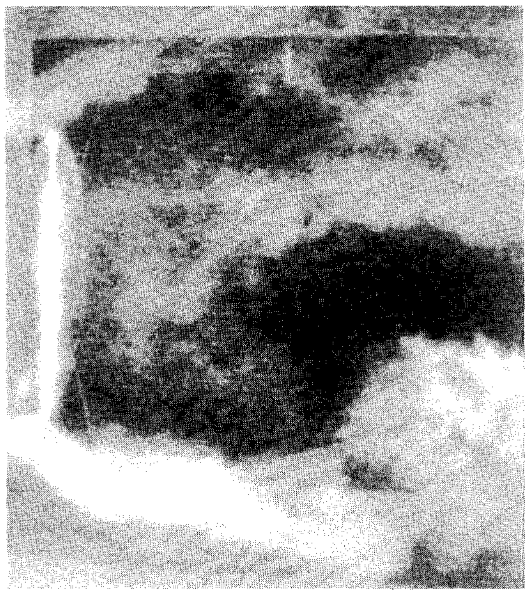

Fig. 1 Wake behind a solid disk; $Re_D = 5 \times 10^4$.

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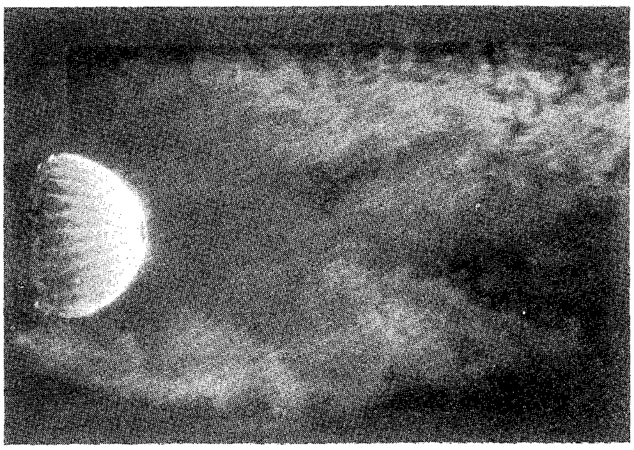


Fig. 2 Wake behind a solid parachute canopy model; $Re_D = 4 \times 10^4$.

system were attached to the carriage, which recorded the wake evolutions from a model coordinate system. The water tank could also be operated as an open-circuit water channel with variable flow velocity. Fluorescent dye (fluorescent orange or fluorescein) was injected through the model for visualization. Density of the dye fluid was matched with the test fluid adding milk and/or alcohol as needed. A flood photograph lamp or black lights provided the necessary illumination.

Results and Discussion

Wind-Tunnel Flow Visualizations in Steady Incoming Flow

Solid Disk

A wake behind a solid disk model of 25-cm diam was illuminated on its cross section, and the video showed a clear recirculation region with its front stagnation point at the center of the leeward surface of the disk and its rear stagnation point at almost 3 diam downstream. Global wake oscillations and almost antisymmetric vortex sheddings (on the cross-sectional plane) were observed. Fuchs et al.[6] measured the circumferential correlations of the velocity fluctuations at 3 and 9 diam downstream of the solid disk, where their Reynolds number was in the same range as the present wind-tunnel test. The correlations showed a dominant asymmetric mode (so-called $m = 1$ mode) at the shedding frequency. Downstream stagnation point was reported to be 2.5 diam downstream, which is consistent with the present visualization. Figure 1 shows the disk illuminated along the diameter, the recirculation zone, and the asymmetric vortical structure; here, the low image contrast of the photograph, in the earlier version of this paper,[7] has been digitally enhanced. The flow behind the solid disk was also studied in water, as will be discussed later.

Solid Parachute Canopy Model with Vent

A solid parachute model was placed in the wind-tunnel test section and its wake was studied, as shown in Fig. 2. This model is made with a fabric covering a wire frame. The base diameter is 24 cm with a vent diameter of 3.8 cm. (A 3% model blockage in the test section, although nonnegligible, was judged acceptable for the study, as was the case for a solid disk model.) A separated flow from the rim forms a recirculation zone extending as far as approximately 2.4 diam downstream. The unsteady asymmetric wake oscillations were clearly seen under a planar illumination on the video, with the intensity of the jet from the vent fluctuating synchronously with the global wake motion. Perhaps because of the slightly complex configuration with the vent, vortex shedding or periodicity of the asymmetric wake motions could not be positively identified. Achenbach[8] noted the rotation of the vortex separation point behind the sphere. Although the wake motion was asymmetric, it is expected that the axisymmetry of the vortex separation point was enforced in the present case by the rim as long as the geometry is rigid.

Slotted Disk

The slotted model of 31.8-cm diam consisted of eight equally spaced annular rings, and the geometric porosity of the model was approximately 30%. Details of model dimensions have been given in Ref. 9. The wake behind this porous disk, as illuminated by a laser sheet, is shown in Fig. 3. Unlike the wake behind the solid disk, the vortex shedding and global unsteady wake motion were suppressed downstream. Also noted in the flow visualization was the recirculation region in the wake that was detached from the model: the flow close to the model was in the downstream direction due to the porosity of the model, and the leading edge of the reverse flow region (front stagnation point) was at 1.5 diam downstream of the slotted disk. The rear stagnation point was located approximately 2.6 diam downstream. Boundaries of the reverse flow region at different porosity ratios were systematically surveyed by Feshchenko[10] using the oil film technique applied to the base model support or to the splitter plate on the symmetry plane, though there could be some questions about the accuracy of the technique. He used a disk with numerous circular perforations (e.g., 484 openings for 33.8% porosity) to control the porosity and found that the front stagnation point moves downstream monotonically with increasing porosity, whereas for another series of disks with larger but fewer perforations (e.g., 20 openings for 31% porosity), the position of the reverse flow regions did not correlate as well, perhaps due to the unstable deflection of the jets for the latter case. For the 33.8% porosity case just cited, the front and rear stagnation points were reported to be 1.3 and 3 diam downstream, and for the 31% porosity case with larger openings, 0.9 and 2.2 diam downstream, respectively.

Immediately downstream of the model, the irregular mergings of jets through individual annular gaps were observed (Fig. 3), which qualitatively confirm the nonuniform pressure distributions on the leeward side of slotted disks reported by Roberts.[11] Similar irregular mergings of jets were also observed in the earlier investigation on two-dimensional grid models.[5,9,12] The unstable entrainment process among multiple jets and wakes is a governing factor in both cases, but this still requires further investigations of fundamental nature, in particular, in the axisymmetric configurations.

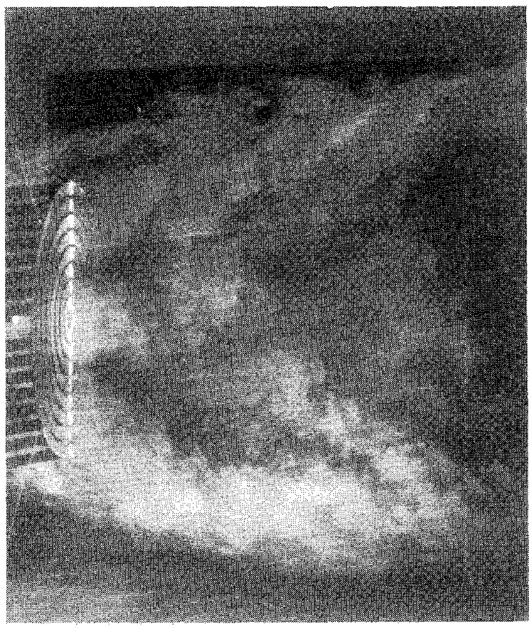
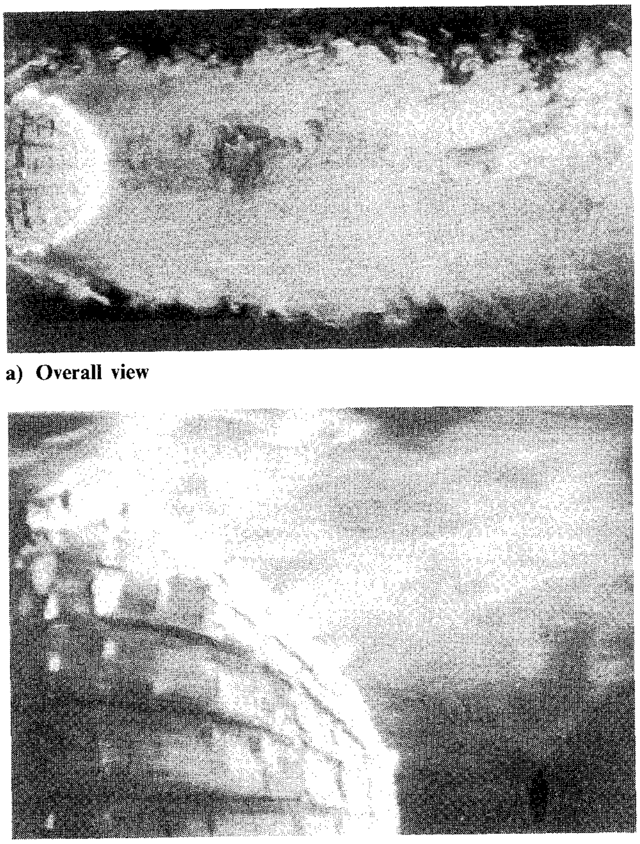


Fig. 3 Near wake region behind a slotted disk; $Re_D = 4 \times 10^4$.



a) Overall view

b) Close-up view

Fig. 4 Wake of a ribbon parachute model; $Re_D = 4 \times 10^4$.

Ribbon Parachute Model

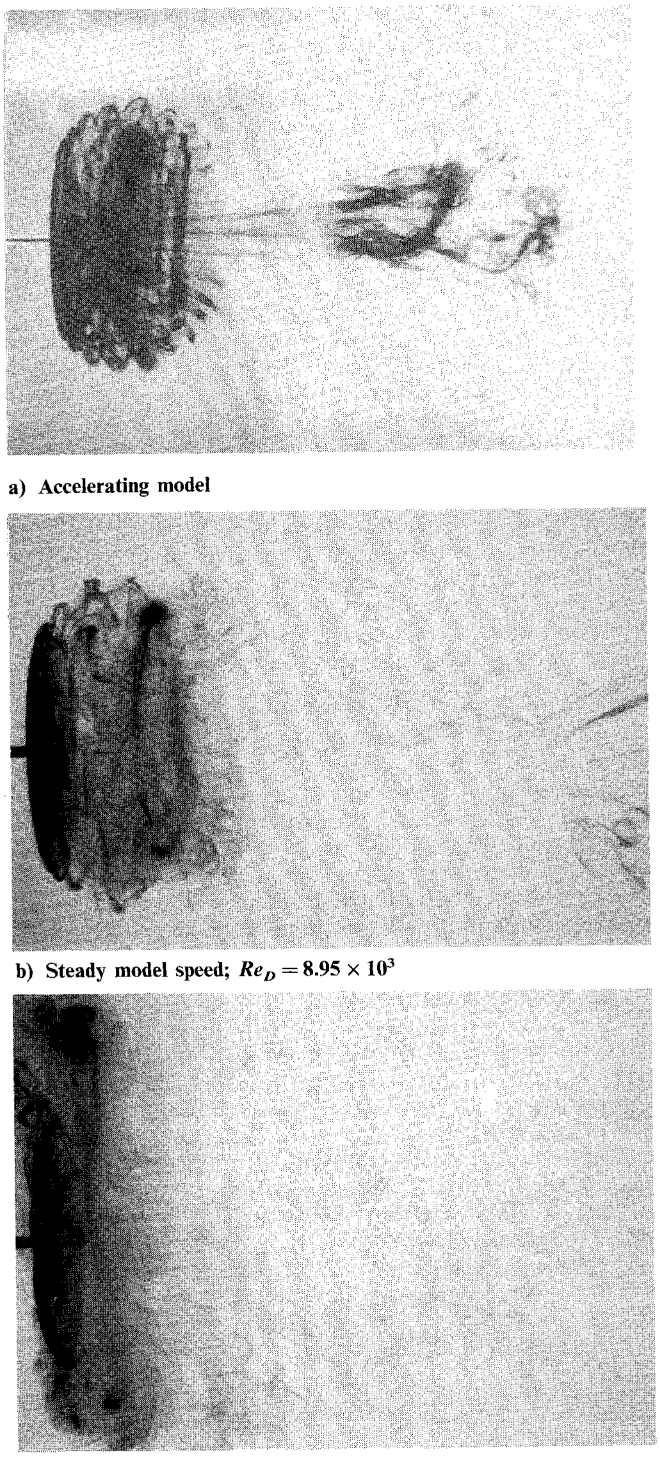
An example of a typical flowfield behind a ribbon parachute model, also taken under a laser sheet illumination, is shown in Fig. 4. This particular model measures 24 cm in diameter. It is made of nine fabric ribbons of 9.5-mm width, h, and has a spacing ratio of $s/h = 0.25$, where s is the gap size. Geometry of this canopy model is fixed by a wire frame, and the geometrical surface porosity is estimated to be approximately 18%. The overall photograph of the wake (Fig. 4a) shows a lack of global wake oscillation replaced by finer scale turbulent structures. A jet from the center vent decelerates downstream, and jets issuing from individual slots merged together downstream and the reverse flow region existed farther downstream. Analysis of the videotapes showed that, similar to the case of the slotted disk, the reverse flow region did not begin on the canopy surface but a forward flow region extended up to approximately 1.7 diam downstream due to the jets through the slots. Because of the large pressure drop across the grid, the mass flow was not sufficient through the slots and had to be supplied from downstream, causing the reverse flow zone. The reverse flow region began at that point and extended up to 2.7 diam downstream. This was also consistent with the observations on the present slotted disk and perforated disk[10] and with those on the two-dimensional flat and curved grid models.[9,12]

In light of the wake behavior behind a decelerating solid disk shown later, the detached recirculation region overtaking the parachute appears to be more detrimental due to its somewhat unexpected time delay before the wake recontact.

Figure 4b shows a close-up view of the wake interactions behind the individual ribbons, which are not unlike those observed behind two-dimensional curved models.[9] Compared to the flow behind the slotted disk, the jet deflections show further complexities due to slanted ribbon elements.

Flow Visualizations Behind an Accelerating and Decelerating Solid Disk

A water towing tank was used for this experiment, as mentioned earlier. An aluminum disk model had a double-wafer structure so that the dye could be introduced in an axisymmetric manner from the edge. The disk was 10.2 cm in diameter and was sting-mounted at the centerline of the front surface with a 3.2-mm-o.d. stainless steel tubing, which also acted as a dye supply line. In the typical test procedure, the model was accelerated from rest to a specified steady state (approximately 1.3 m/s) in approximately 2 s. After the desired length of the steady-state observation, the model was decelerated to $< 10\%$ of its steady velocity within 1 s.



a) Accelerating model

b) Steady model speed; $Re_D = 8.95 \times 10^3$

c) Decelerating model

Fig. 5 Wake of a solid disk in a water towing tank.

Initial Wake Development

As the disk is accelerated, the axisymmetric shear layer rolls up into a ring vortex (Fig. 5a). The circulation contained in the ring vortex increases as well as the diameter of the vortex. The phenomenon is equivalent to the ring vortex development from the circular orifice by a piston motion (see, e.g., Ref. 13). In addition to the large scale ring vortex, Fig. 5a shows smaller scale axisymmetric structures. The axisymmetric shear layer rolls up to form sequential lobes as it becomes entrained into a recirculation region. Note the stretched tail along the centerline left by the rear stagnation region. The ring vortex starts to tilt on its side, and if the forward motion continues, the contour of the vortex becomes obscure and it forms into a three-dimensional wake downstream. Incidentally, it was noted that when the model was towed in the opposite direction with the thin sting-mount behind it, the axisymmetric vortex structure persisted longer than with the forward motion, somewhat resembling the effect of a splitter plate behind a two-dimensional wake.

Wake Development in Steady State

After the steady forward motion is established, the diameter of the ring vortex continues to increase. Due to the increase in circulation Reynolds number, the azimuthal instability waves start to form along the axisymmetric structure and, finally, the ring vortex structure becomes turbulent and undefined. Figure 5b shows a wake behind a solid disk shortly after reaching constant speed. The ring vortex is slightly deformed but is still recognizable. The Reynolds number based on the diameter was 8.95×10^3. When the ring vortex was created at the accelerated start-up, the toroidal structure later began to tilt on its axis, resulting in a three-dimensional wake. In other cases where the steady state is reached gradually, the axisymmetric mixing layer from the edge of the disk can be more clearly seen rolling up and subsequently shedding periodically. This was observed in a steady speed condition, either with the counterflow or with the towing. The wavy disturbances start to occur along the circumference of axisymmetric vortices, and neighboring vortices interact with each other within 1 diam downstream of the disk and form an irregular three-dimensional wake pattern. The tilting of the axisymmetric structures resulting in a three-dimensional "bulge" has been discussed by Oswald and Kibens[14] based on their space-time correlation measurements at $Re_D = 1.25 \times 10^4$. Further analysis is needed for a unified view of the wake structure incorporating the asymmetric vortex shedding shown in the present wind-tunnel test at a higher Reynolds number and for verification the three-dimensional structure suggested by Achenbach[8] and others. Nevertheless, these flow structures illustrate that a theoretical or numerical model assuming the axisymmetry of the flow may miss important features of the flow.

Response of the Wake to the Model Deceleration

The model was subsequently decelerated rapidly. The wake diameter increases as the model decelerates. Figure 5c shows that the wake with its ring vortex structure has overtaken the model (i.e., wake recontact) and has spread around and then ahead of the model. A similar process of the two-dimensional counterpart behind circular arc models has been studied in detail both experimentally and numerically by Sarpkaya.[15] If the model had been flexible, the model geometry could not have been maintained during this process with a back-pressure rise, as shown in the film during an actual Sandia drop test.[1] Further study of this phenomenon should help analyze the wake recontact problem of the parachute canopy. The subsequent study should also include the canopy opening sequences.

Summary and Conclusions

Exploratory flow visualization studies were conducted to investigate the behavior of the wake behind various axisymmetric bluff bodies, both in steady and unsteady freestream conditions. The geometries ranged from a simple solid circular disk to the ribbon parachute canopy models. The study showed the intricate structures behind the solid and slotted axisymmetric bodies and indicated that detailed knowledge of the flow phenomena, rather than taking a simplistic global parametric approach, was essential to the prediction of the wake behavior. The effects of the gap flows in the near wake and in the downstream region behind the slotted models were identified on the cross-sectional view. Both axisymmetric and asymmetric wake structures were observed behind the circular disk. During the rapid acceleration and deceleration process, the vortex structure essentially remained axisymmetric. The wake vortices overtaking the decelerating disk model was documented. It is hoped that, together with more quantitative flow measurements in the near future, the study will help in forming better understanding and useful analytical models of the complex wake structures in practical situations.

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