Note the slight deviation in all of the curves in Fig. 2 between the 50 and 60% marks. In this region of the system, the speckle mask enters the beam path twice, once while in the beam traveling to the second focusing mirror and again in the beam reflecting back to the cutoff grid. Through this region and beyond, previous analytical predictions[1] fail and measurements such as those presented here are required.

To quantify shock wave visibility, the rms values for the deviation of the intensity peaks of the shock waves are computed. This rms measure correlated well with observations of images; the shocks are visible in all cases. Hence, the data are not presented, though they are available in Ref. 10.

Conclusions

A single numerical measure of noise reduction, computed from the gray-scale histogram, appears to correlate well with visual observation of the images. It is shown that simple multiple-source modifications to an existing conventional schlieren system are a practical means of reducing the sensitivity of the system to spurious density gradients, typically, thermal currents outside the test section. Currents closest to the test section may fail to be attenuated significantly, depending on the integration length of the system. Thus, image noise generated by turbulent boundary layers or scratches on the test section windows are more difficult to alleviate than that from a drafty room.

Trends predicted by previous analysis are supported by the present experiments. Knowledge of noise reduction as measured for uniform flow regions and for shock visibility allows the effective design of multiple-source schlieren systems with desired amounts of noise reduction.

Experimental results for a system with *f*/10 spherical mirrors used 5 deg off axis demonstrate that the practical maximum grid size is approximately 15% of the mirror diameter. Regardless, the results show that simple modifications (only three to five slits) to existing mirrored schlieren systems can improve the quality of images originally obscured by the effects of spurious density gradients outside of the wind tunnel.

Acknowledgments

This research was supported through the 1992 U.S. Air Force Office of Scientific Research (AFOSR) Summer Faculty Program, and the 1993 AFOSR Summer Research Extension Program, Subcontract 93-144. Technical supervision was provide by George Seibert of Wright Laboratories.

References

[1]Collicott, S. H., and Salyer, T. R., "Noise Reduction Properties of a Multiple-Source Schlieren System," *AIAA Journal*, Vol. 32, No. 8, 1994, pp. 1683–1688.

[2]Settles, G. S., Hacket, E. B., Miller, J. D., and Weinstein, L. M., "Full-Scale Schlieren Flow Visualization," *Flow Visualization VII*, Proceedings of the 7th International Symposium on Flow Visualization (Seattle, WA), 1995, pp. 2–13.

[3]Burton, R. A., "A Modified Schlieren Apparatus for Large Areas of Field," *Journal of the Optical Society of America*, Vol. 39, Nov. 1949, pp. 907, 908.

[4]Kantrowitz, A., and Trimpi, R. L., "A Sharp-Focusing Schlieren System," *Journal of the Aeronautical Sciences*, Vol. 17, No. 5, 1950, pp. 311–314.

[5]Fish, R. W., and Parnham, K., "Focusing Schlieren Systems," Aeronautical Research Council, TR IAP 999, Nov. 1950.

[6]Boedeker, L. R., "Analysis and Construction of a Sharp Focusing Schlieren System." M.S. Thesis, Dept. of Aeronautics and Astronautics, Massachusetts Inst. of Technology, Cambridge, MA, May 1959.

[7]Weinstein, L. M., "Large-Field High-Brightness Focusing Schlieren System," *AIAA Journal*, Vol. 31, No. 7, 1993, pp. 1250–1255.

[8]Price Cook, S., and Chokani, N., "Quantitative Results from the Focusing Schlieren Technique," AIAA Paper 93-0630, Jan. 1993.

[9]Gartenberg, E., Weinstein, L. M., and Lee, E. E., Jr., "Aerodynamic Investigation wigh Focusing Schlieren in a Cryogenic Wind Tunnel," AIAA Paper 93-3485, Aug. 1993.

[10]Salyer, T. R., "Quantitative Noise Reduction Measurements of a Multiple-Source Schlieren System," M.S. Thesis, School of Aeronautics and Astronautics, Purdue Univ., West Lafayette, IN, May 1994.

[11]Collicott, S. H., "Evaluation of Options for Improved Large Grid Multiple-Source Schlieren Systems," AIAA Paper 94-2301, June 1994.

Drag of Freely Rotatable Cylinder/Splitter-Plate Body at Subcritical Reynolds Number

John M. Cimbala and Jonathan Leon
Pennsylvania State University,
University Park, Pennsylvania 16802-1412

Introduction

ROSHKO[1] was the first to show that attachment of a splitter plate to the back of a circular cylinder reduces the strength of shed vortices. Later, Bearman[2] showed that the addition of a splitter plate to the back of various kinds of bluff bodies could lead to significant reduction in body drag. Apelt and co-workers[3,4] conducted drag measurements on circular cylinders with splitter plates of various lengths; they showed that drag coefficient C_D decreased in general as splitter-plate length increased, except near $L/D = 2$, where the drag increased slightly. In all of these experiments, the splitter plates were rigidly mounted to the body at 0-deg angle of attack with respect to the freestream. The shortcoming of using rigidly mounted splitter plates is that flow in natural environments is rarely unidirectional. In engineering applications involving flow over a circular cylinder, such as offshore oil rigs, smokestacks, ocean thermal energy conversion systems, and five-hole probe measurements in three-dimensional flowfields, the direction of the freestream flow is not known a priori. Such applications would benefit greatly if the splitter plate could rotate freely, aligning itself with the flow direction. Cimbala and co-workers[5,6] studied the flow over a freely rotatable cylinder/splitter-plate body, hoping to attain similar benefits (i.e., reduction in the drag and the strength of shed vortices) as are attained with fixed splitter plates, but with the additional benefit of being omnidirectional. What they found was somewhat surprising: The freely rotatable splitter plate does not align itself with the freestream flow direction, but rather rotates to some nonsymmetric equilibrium position at an angle θ with respect to the freestream direction. (The equilibrium angle could, of course, be positive or negative with equal probability.) They measured this equilibrium angle as a function of L/D, the ratio of splitter-plate length to cylinder diameter, and found that θ decreased from nearly 90 deg for very small splitter-plate lengths to 0 deg for large splitter plates ($L/D > 5$), as shown in Fig. 1 of Ref. 6.

Cimbala and Garg[6] measured wake profiles downstream of cylinders both with and without splitter plates, and for cases with the splitter plate either rigidly attached at 0 deg or free to rotate. They also obtained smoke-wire photographs of these wakes. When L/D was less than about 2, the wake of the freely rotatable cylinder/splitter-plate body was not significantly altered by the presence of the plate, but the fixed splitter plate altered the wake significantly. However, splitter plates larger than about two cylinder diameters had nearly the same effect on the wake of the cylinder regardless of whether rigidly attached or free to rotate. Drag was not measured in these earlier experiments.

Since the discovery of this nonsymmetric behavior of freely rotatable cylinder/splitter-plate bodies, Xu et al.[7,8] have done extensive numerical analyses to help explain the phenomenon. Most importantly, they predicted a critical Reynolds number below which the cylinder/splitter-plate body remains at 0-deg angle of attack and above which it becomes unstable and rotates to its nonsymmetric orientation. The Reynolds number at which this bifurcation occurs

Received March 25, 1996; revision received May 20, 1996; accepted for publication May 31, 1996; also published in *AIAA Journal on Disc*, Volume 1, Number 4.

*Associate Professor, Department of Mechanical Engineering. Member AIAA.

†Undergraduate Assistant, Department of Mechanical Engineering; currently Engineer, Engineering Department, Voith Hydro, Inc., York, PA 17405.

depends on L/D but is typically very small (between 20 and 50 for the plates they tested).

Most recently, Cimbala and Chen[9] examined the behavior of cylinders with freely rotatable splitter-plate bodies at much higher Reynolds numbers. They found that for any given L/D, the equilibrium angle decreased suddenly in the transitional Reynolds number regime (where the boundary-layer separation on the cylinder changes from laminar to turbulent), much like the well-known drag crisis on cylinders and spheres. Furthermore, at supercritical Reynolds numbers, where the boundary-layer separation is turbulent, angle θ rises slowly and then levels off at very high Reynolds numbers to a value significantly smaller than that at subcritical Reynolds numbers. Cimbala and Chen[9] attributed this behavior to the downstream shift of boundary-layer separation point as the Reynolds number passes from subcritical to supercritical. Unfortunately, drag was not measured in these experiments either.

Although it is well known that addition of a fixed splitter plate (at 0-deg angle of attack) reduces cylinder drag, drag measurements on a cylinder with a freely rotatable splitter plate have not been reported to date. This lack of data was the motivation for the present experiments. Before freely rotatable splitter plates are seriously considered for application in actual engineering devices, it is necessary to determine the effect of such a splitter plate on the cylinder's drag.

Objective

The objective of the present study is to investigate how the drag coefficient of a circular cylinder is affected by a freely rotatable splitter plate, and how the drag compares to the case where the splitter plate is fixed at 0-deg angle of attack. The Reynolds number range of these experiments is roughly $2 \times 10^4 < Re < 8 \times 10^4$, which is confined to the subcritical Reynolds number range.

Experimental Setup

Drag measurements were conducted in the Penn State Mechanical Engineering Undergraduate Wind Tunnel, which attains a maximum freestream speed of about 45 m/s and has a test section of cross section 41 × 41 cm. The cylinder was manufactured from a hollow, 25.4-mm-diam Plexiglas® tube of 3.2-mm wall thickness. A shaft running through the axis of the cylinder was press-fit into ball bearings at each end of the cylinder, which enabled the cylinder to rotate freely about the shaft. The shaft passed vertically through holes at both the top and the bottom walls of the wind tunnel and was mounted to a drag balance located under the test section. Air leakage through these holes was not of concern because drag was only measured actively on the central portion of the cylinder, far away from end effects, as discussed below. The drag balance was of the full strain-gauge type, where deflection of a cantilever beam was measured; its accuracy was better than ±1%, based on calibration with known weights. A large U-shaped support outside of the wind tunnel connected the top of the shaft to the drag balance as well, so that the entire cylinder model floated with respect to the wind tunnel walls, being attached only to the drag balance.

The cylinder itself was 30 cm high, shorter than that of the test section (41 cm). Hollow shrouds of the same diameter as the cylinder were mounted at both the top and the bottom of the cylinder so that the shaft would not be exposed to the flow, and would not affect the drag measurements. Whenever splitter plates were mounted to the cylinder, similar splitter plates were attached to these shrouds as well (and were rotated to the same angle), ensuring that the flow over the central part of the cylinder/splitter-plate body was nearly two dimensional and that wall effects were negligible. For the drag measurements, the aspect ratio of the cylinder was about 12, but the overall aspect ratio was 16. The gap between the central active portion of the cylinder and the shrouds was about 1 mm, eliminating concern about flow in the gaps.

A groove, 1.6 × 1.6 mm, was cut radially along the outside wall of the cylinder, into which were placed 1.6-mm-thick splitter plates of various lengths. Small brass collars at either end of the cylinder were used as well to help hold the splitter plates in place. A small clamp was constructed to secure the cylinder rigidly to the shaft for cases in which drag was measured with the splitter plate fixed at 0-deg angle of attack. These rigidly mounted cases were tested for direct comparison with the freely rotatable cases.

Results

Drag measurements were obtained for the cylinder/splitter-plate body under both freely rotatable and nonrotatable (splitter plate rigidly fixed at 0 deg) conditions. The splitter-plate length was varied from 0 (bare cylinder) to 5 diameters for both cases. The drag coefficient was defined in the usual fashion, i.e., $C_D = \text{Drag}/(\frac{1}{2}\rho V^2 A)$, where V is the wind-tunnel freestream speed, as measured via an upstream pitot static tube and differential pressure transducer, ρ is the air density, and A is the frontal area of the cylinder. Data were acquired at 40–50 different wind-tunnel speeds for each case, resulting in a Reynolds number range of about 2×10^4–8×10^4, where Re is defined as $Re \equiv (\rho V D)/\mu$, with μ being the viscosity of the air.

Figure 1 shows C_D as a function of Re for several representative values of L/D for both the freely rotatable case and the case of the rigidly mounted cylinder/splitter-plate body (splitter plate fixed at 0-deg angle of attack). It is clear that in either case, increasing splitter-plate length reduced the drag. The size of the data symbols corresponds approximately to the overall accuracy of the experiments. The freely rotatable cases with $L/D = 3$ and $L/D = 5$ were repeated on different days, and multiple data sets are shown on the figure, giving a good indication of the repeatability of the experiments. The differences between C_D of the fixed cases and C_D of the free-to-rotate cases are small, within the range of repeatability of the experiments. Also, for a given plate length, especially in the range $4 \times 10^4 < Re < 8 \times 10^4$, drag coefficient was found to be largely independent of Reynolds number. In some of the cases, however, the drag coefficient was noticeably larger over some range of Reynolds number. (See, for example, the free-to-rotate $L/D = 1.0$ case at $3.6 \times 10^4 < Re < 4.2 \times 10^4$.) These anomalies were traced to excessive lateral vibration of the model, which occurred at certain natural modes, presumably associated with Kármán vortex shedding lock-in, and which could not be avoided. Vibration was not as severe for the rigidly mounted case (because these had one less degree of freedom).

Drag coefficient was averaged for each case for the range of Reynolds numbers over which C_D remained fairly flat, i.e., $4 \times 10^4 < Re < 8 \times 10^4$, but ignoring the regions of anomalous behavior attributable to excessive lateral vibration, as discussed above. These average values are plotted in Fig. 2 as a function of splitter plate length. As in Fig. 1, the size of the data symbols represents the overall accuracy of the experiments, and the degree of repeatability is indicated by multiple symbols at the same L/D, indicating results that were repeated on different days. The data of Apelt and co-workers[3,4] (for splitter plate fixed at 0 deg) also are shown in Fig. 2 for comparison. The most striking result of the plot is that, at a given splitter-plate length, within the degree of repeatability of the present experiments, the drag coefficient was nearly the same

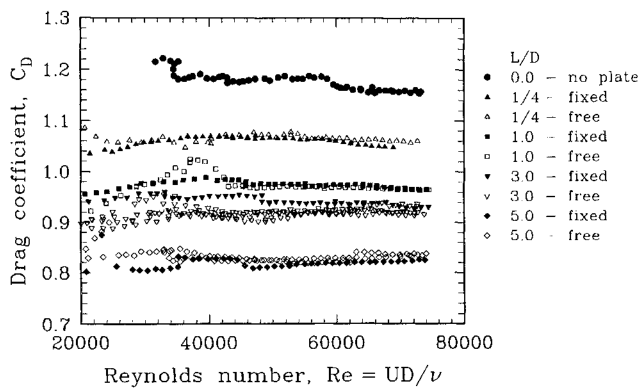

Fig. 1 Drag coefficient of circular cylinder with splitter plates of various lengths: filled symbols, splitter plate fixed at 0 deg and open symbols, splitter plate free to rotate (size of symbol represents approximate accuracy of measurement; multiple data points at same *L/D* are for runs on different days).

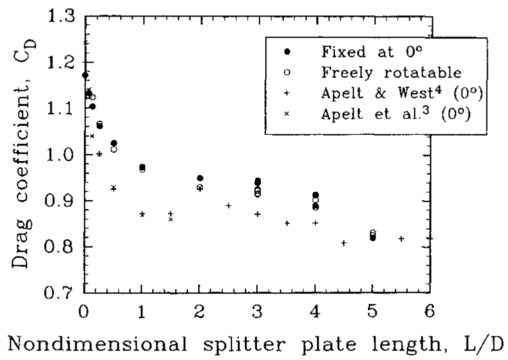

Fig. 2 Averaged drag coefficient of circular cylinder with splitter plates of various lengths: filled symbols, splitter plate fixed at 0 deg and open symbols, splitter plate free to rotate (size of symbol represents approximate accuracy of measurement; multiple data points at same *L/D* are for runs on different days).

whether the splitter plate was fixed at 0-deg angle of attack or free to rotate. In both cases, C_D decreased rapidly up to $L/D = 1$, leveled off around $2 < L/D < 3$, and then decreased slowly at higher L/D.

Discussion

For the first time, drag measurements have been obtained on a freely rotatable cylinder/splitter-plate body. It has been shown that the splitter plate reduced the drag significantly, with drag reduction increasing with splitter-plate length, just as in the case of a nonrotatable cylinder with splitter plate attached at 0 deg. In fact, there was very little difference between the drag on the cylinder with splitter plate attached at 0-deg angle of attack, and that on the cylinder/splitter-plate body free to rotate. This is consistent with the wake measurements and flow visualizations of Cimbala and Garg,[6] who reported that splitter plates larger than about 2 cylinder diameters had nearly the same effect on the wake of the cylinder regardless of whether rigidly attached or free to rotate.

For the bare-cylinder case (no splitter plate), our measured C_D is about 1.17, lower than the 1.24 reported by Apelt et al.[3] Both of these are somewhat high compared to that reported by Schlichting[10] in this Reynolds number range, i.e., around 1.12 for a smooth bare cylinder. With the addition of splitter plates, however, the present data are consistently higher than those of Apelt and co-workers.[3,4] There is also a dip in their drag coefficient between $0.5 < L/D < 2$, which did not appear in the present data, although C_D did tend to level off somewhat in this L/D range. The reasons for these discrepancies are discussed now. Model blockage in the wind tunnel was about 6% for the present experiments, the same as that of the water-tunnel experiments of Apelt and co-workers,[3,4] and neither set of data was corrected for blockage. The aspect ratio of the model used by Apelt et al.[3] was 20.6, whereas the total aspect ratio of the present model was 16. Thus, neither tunnel blockage nor aspect ratio should have played a significant role in the differences between the two experiments. The discrepancies in the two sets of data may be because Apelt et al.[3] calculated drag solely from pressure measurements on the body, whereas total drag (both pressure drag and skin friction drag) were measured in the present experiments. White[11] shows that for a bare circular cylinder, skin friction drag accounts for only about 3% of the total drag. This is not enough to bring the data of Apelt et al.[3] up to the level of the present experiments. However, additional skin friction drag would be caused by the splitter plate itself, and this was not accounted for by either Apelt et al.[3] or Apelt and West.[4]

Conclusion

In summary, for engineering applications where it is desirable to reduce the drag on a cylinder, but where the freestream flow direction is not fixed, or not known a priori, a freely rotatable splitter plate can provide nearly the same drag reduction as can a fixed splitter plate, even though it migrates to an angle not in line with the flow. A freely rotatable splitter plate, mounted to a cylinder, therefore has potential as an omnidirectional drag-reducing device.

References

[1]Roshko, A., "On the Development of Turbulent Wakes from Vortex Streets," NACA TN 2913, March 1953.

[2]Bearman, P. W., "Investigation of the Flow Behind a Two-Dimensional Model with a Blunt Trailing Edge and Fitted with Splitter Plates," *Journal of Fluid Mechanics*, Vol. 21, Pt. 2, 1965, pp. 241–255.

[3]Apelt, C. J., West, G. S., and Szewczyk, A. A., "Effects of Wake Splitter Plates on the Flow Past a Circular Cylinder in the Range $10^4 < R < 5\times10^4$," *Journal of Fluid Mechanics*, Vol. 61, Pt. 1, 1973, pp. 187–198.

[4]Apelt, C. J., and West, G. S., "Effects of Wake Splitter Plates on Bluff-Body Flow in the Range $10^4 < R < 5\times10^4$, Part 2," *Journal of Fluid Mechanics*, Vol. 71, Pt. 1, 1975, pp. 145–160.

[5]Cimbala, J. M., Garg, S., and Park, W.-J., "Effect of a Non-Rigidly-Mounted Splitter Plate on the Flow over a Circular Cylinder," *Bulletin of the American Physical Society*, Vol. 33, No. 10, 1988, p. 2249.

[6]Cimbala, J. M., and Garg, S., "Flow in the Wake of a Freely Rotatable Cylinder with Splitter Plate," *AIAA Journal*, Vol. 29, No. 6, 1991, pp. 1001–1003.

[7]Xu, J. C., Sen, M., and Gad-el-Hak, M., "Low-Reynolds Number Flow over a Rotatable Cylinder-Splitter Plate Body," *Physics of Fluids*, Vol. 2, No. 11, 1990, pp. 1925–1927.

[8]Xu, J. C., Sen, M., and Gad-el-Hak, M., "Dynamics of a Rotatable Cylinder with Splitter Plate in Uniform Flow," *Journal of Fluids and Structures*, Vol. 7, No. 4, 1993, pp. 401–416.

[9]Cimbala, J. M., and Chen, K. T., "Supercritical Reynolds Number Experiments on a Freely Rotatable Cylinder/Splitter Plate Body," *Physics of Fluids*, Vol. 6, No. 7, 1994, pp. 2440–2445.

[10]Schlichting, H., *Boundary-Layer Theory*, 7th ed., McGraw–Hill, New York, 1979, p. 17.

[11]White, F. M., *Fluid Mechanics*, 3rd ed., McGraw–Hill, New York, 1994, p. 413.

Interactions of a Vortex with an Oscillating Leading Edge

R. W. Jefferies* and D. Rockwell†
Lehigh University,
Bethlehem, Pennsylvania 18015-3085

Introduction

IMPINGEMENT of coherent vortical structures upon airfoils and blades occurs in a variety of flow configurations, including wings and tails of aircraft and blades of turbomachinery, helicopters, and wind turbines.

When a vortex interacts with a surface, it induces pressure fluctuations, which serve as the origin of unsteady loading and noise generation. The unsteady loads may be of the same order as, or even surpass, steady loads and can lead to early failure of an airfoil or blade. The associated noise generation often exceeds design limits and severely threatens system operation. Moreover, the overall system performance, based on steady-state criteria, is often degraded. An understanding of the flow physics of these vortex–surface interactions is therefore crucial.

The theoretical study of Rogler[1] and the experimental investigations of Gursul and Rockwell,[2] Kaykayoglu and Rockwell,[3] and Booth[4] show that the magnitude of the pressure fluctuation $\tilde{p}$ due to vortex interactions is greatest at the leading edge of the surface. Rogler,[1] Gursul and Rockwell,[2] Kaykayoglu and Rockwell,[3] and Wilder[5] indicate that the nature of the incident vortex, namely scale λ and circulation Γ, as well as its transverse offset δ from the leading edge, strongly influence $\tilde{p}$. Ziada and Rockwell,[6] Kaykayoglu

Received Nov. 20, 1995; revision received July 2, 1996; accepted for publication July 23, 1996; also published in *AIAA Journal on Disc*, Volume 2, Number 1.

*Ph.D. Candidate, Department of Mechanical Engineering and Mechanics; currently Captain, U.S. Air Force, Eglin Air Force Base, FL 32542.

†Paul B. Reinhold Professor, Department of Mechanical Engineering and Mechanics. Member AIAA.