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LETTERS

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A novel method to promote parallel vortex shedding in the wake of circular cylinders

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Slanted vortex shedding dominates the wake of circular cylinders of finite aspect ratio in the Reynolds number range of 72–158. Parallel vortex shedding can be induced in the wake of a circular cylinder by imposing a symmetric pressure boundary condition at the two ends of the cylinder. This condition can be achieved by positioning two upstream circular cylinders of larger diameter normal to it. The resulting Strouhal–Reynolds number curve shows no discontinuity. Also, the turbulent transition in the wake of a circular cylinder could be delayed by using this technique.

The process of vortex shedding from finite aspect ratio cylinders is greatly influenced by the flow and geometrical conditions at the cylinder ends (Slaouti and Gerrard[1] and Gerich and Eckelmann[2]). It is known that the state of the boundary layers on the walls of wind or water tunnels can promote slanted vortex shedding, spanwise discontinuity in the frequency of vortex shedding, and large changes of the base pressure coefficient (Stansby[3]) over the entire span of circular cylinders. Discontinuities in the Strouhal–Reynolds number curve, as observed by Tritton[4] and others, have been attributed to the condition of the approaching flow (Gaster[5] and Maull and Young[6]), cylinder vibration (Van Atta and Gharib[7]), or nonparallel vortex shedding (Williamson[8]). For aspect ratios over 2500 and highly uniform upstream flow conditions, Van Atta and Gharib have demonstrated that in their experiment all discontinuities in the vortex shedding frequency-Reynolds number curve can be attributed to the cylinder vibration. For experiments where the aspect ratios are not large enough, even with good flow conditions, minimizing the wall boundary layer effect is difficult, if not impossible. In this regard, Williamson has shown that discontinuities in the Strouhal–Reynolds number curve (with aspect ratios less than 300) can be caused by the phenomenon of nonparallel vortex shedding.

A natural approach to miminize the wall boundary layer effect or suppress three-dimensional effects, and consequently induce parallel vortex shedding, has been to employ endplates. There are various means to improve the effectiveness of endplates through changes in their geometry (Stansby[3]), their angle with respect to the free stream (Ramberg[9] and Williamson[8]), or by combining them with other geometries (Eisenlohr and Eckelmann[10]). Our own experiences with various endplate geometries have convinced us that extensive iteration is required to reach the optimum configuration for achieving parallel vortex shedding in the wake of circular cylinders. This major drawback is due to the fact that the optimum configuration strongly depends on Reynolds number and the cylinder aspect ratio.

The purpose of this Letter is to introduce an alternative to endplates: a novel technique that eliminates most of the empiricism and sensitivity that endplate techniques show to the aspect ratio, Reynolds number, and upstream flow conditions. It simply involves positioning of two circular cylinders of diameter D (hereafter referred to as "the control cylinders") upstream and normal to the cylinder for which parallel vortex shedding is sought. The geometrical arrangement of the control cylinders with respect to the main cylinder is depicted in Fig. 1. Experiments were conducted in the 24 in. × 24 in. test section of a low-turbulence wind tunnel. Here L_1 and L_2 represent the respective distances measured from the rear stagnation points of the corresponding control cylinders to the rear stagnation point of the main cylinder. The distance H between the two control cylinders was used to define an effective aspect ratio H/d for the main cylinder. Flow visualization was obtained with a smoke wire positioned at $x/d = 30$ downstream of the main cylinder and parallel to it.

In the absence of the control cylinders, the vortex filaments shed by the main cylinder are parallel to its axis and continue to be so up to $\mathrm{Re} \simeq 72$, where they become slanted. This Reynolds number constitutes a threshold value for the onset of slanted vortex shedding. Slanted vortex shedding

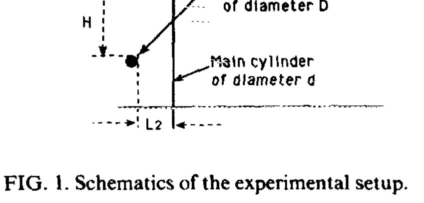

FIG. 1. Schematics of the experimental setup.

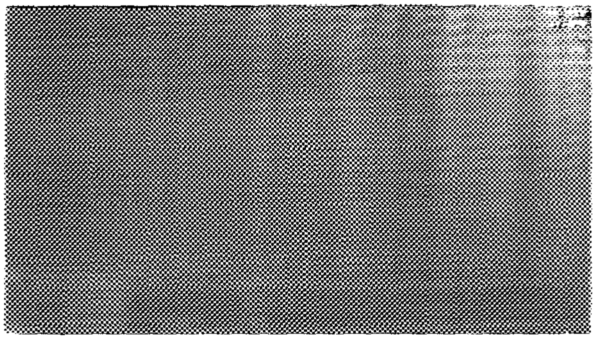

FIG. 2. Spanwise flow visualization of the laminar vortex shedding $\mathrm{Re} = 135$, $d = 0.032$ in. Aspect ratio 750 based on the test section width.

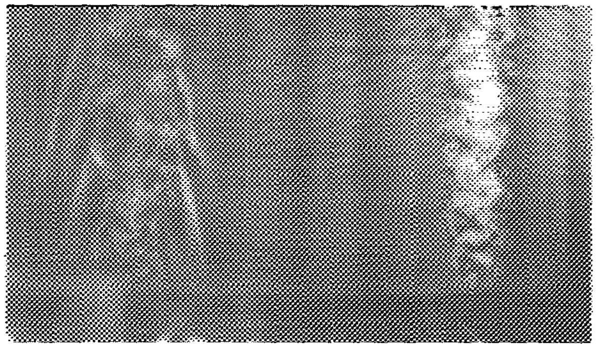

FIG. 4. The effect of staggering of control cylinders. $\mathrm{Re} = 135$, $d = 0.032$ in., $D = 0.25$ in., $H/d = 265$, and $L_1 \neq L_2$.

continues to dominate the wake of the main cylinder up to $\mathrm{Re} \approx 156$, where a three-dimensional transition occurs. Figure 2 shows a typical slanted vortex shedding pattern at $\mathrm{Re} = 135$ for a cylinder of diameter $d = 0.032$ in. and an aspect ratio 750, based on the width of the test section.

In Fig. 3 we present the similar case of $\mathrm{Re} = 135$ when the technique is implemented with control cylinders of identical diameters ($D = 0.25$ in., $D/d = 7.8$, $H/d = 265$), positioned at an equal distance of $L_1 = L_2 \approx 0.625$ in. ($\approx 2.5D$) upstream of the main cylinder. It is interesting to note that the region between the control cylinders exhibits parallel vortex shedding while the outside regions show slanted vortex shedding. For the same configuration (i.e., $L \approx 0.625$ in. and $D/d = 7.8$), the condition of parallel vortex shedding could be achieved over the entire Reynolds number range of 40–156. Using only one control cylinder failed to promote parallel vortex shedding, regardless of its position. We also found that the technique was effective as long as the two control cylinders have a larger diameter than the main cylinder ($D/d > 3$). Their positioning with respect to the main cylinder has a critical effect on the shape of the vortex shedding from the main cylinder. True parallel vortex shedding is obtained only for a specific optimum value of L (noted L_0). For $L_1 = L_2 \neq L_0$, the vortex filaments are not straight lines but rather arcs, somewhat like left parentheses for $L < L_0$ or right parentheses for $L > L_0$ if the flow is from left to right. If the two control cylinders are positioned at different distances from the main cylinder, i.e., $L_1 \neq L_2$, again the vortex shedding becomes slanted (Fig. 4).

We believe that the main function of the control cylinders is to provide symmetric pressure boundary conditions at the main cylinder and therefore to prohibit the evolution of three-dimensional instabilities. Also, the observation that the control cylinders should be positioned at a specific distance in order to be effective can be understood if one studies the distribution of the pressure coefficient along the centerline of the wake of a circular cylinder. This pressure coefficient distribution is characterized by a sharp decrease from its value at the base followed by a sharp rise back to the freestream value (Roshko[11]). In this respect, we postulate that if the main cylinder is positioned at a specific distance from the rear stagnation point of the control cylinders, where the wake pressure value is close enough to the base pressure of the main cylinder, a uniform pressure distribution will be induced along the base of the main cylinder, which consequently promotes parallel vortex shedding. In his studies of the optimum angle of endplates to generate parallel vortex shedding, Ramberg[9] reaches a similar conclusion regarding matching of the base pressure with end pressure imposed by the endplates. At this stage, we have not measured the pressure distribution along the wake centerline of the control cylinders to substantiate our intuitive explanation, but we have conducted two experiments that support the above arguments. Based on our intuitive model, one should be able to obtain the symmetric pressure boundary condition by using two control cylinders of different diameters and positioning them at their respective optimum distances upstream of the main cylinder. Figure 5 presents one such case in which parallel vortex shedding could be obtained by replacing one of the control cylinders of diameter $D_1 = 0.25$ in. in Fig. 3 by a control cylinder of smaller diameter $D_2 = 0.148$ in. The smaller control cylinder was positioned at a distance $L_2 < L_1$

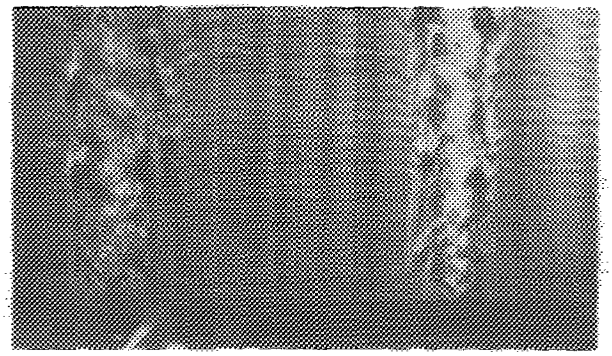

FIG. 3. Flow visualization of the wake when control cylinders are implemented. $\mathrm{Re} = 135$, $d = 0.032$ in., $D = 0.25$ in., $H/d = 265$, and $L \approx 0.625$ in.

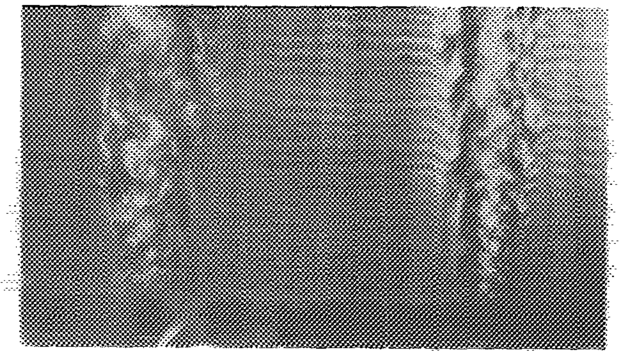

FIG. 5. Flow with control cylinders of different diameters but positioned at their corresponding optimum distances. $\mathrm{Re} = 135$, $d = 0.032$ in., $D_1 = 0.25$ in., $D_2 = 0.148$ in., and $H/d = 265$.

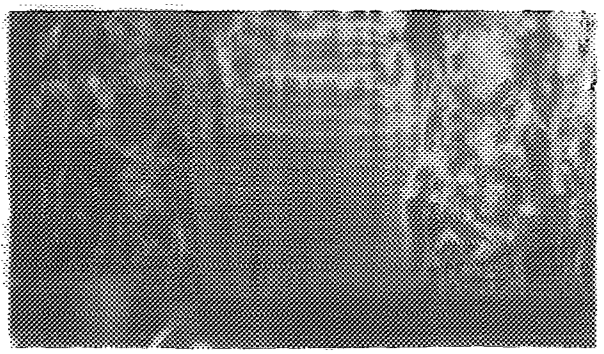

FIG. 6. Island of laminar parallel vortex shedding for $\mathrm{Re} = 157$, $d = 0.032$ in., $D = 0.25$ in, $H/d = 265$, and $L \approx 0.625$ in.

upstream of the main cylinder to achieve the optimum configuration that produces parallel vortex shedding. Again, any nonoptimum positioning of either control cylinders resulted in slanted vortex shedding. The second experiment involves placement of control cylinders downstream of the main cylinder. Parallel vortex shedding could not be achieved for this case.

Another important feature of the control cylinder technique is its capability to delay transition to turbulence. In the absence of control cylinders, and as the Reynolds number of the main cylinder is increased, a transition occurs in the nature and uniformity of vortex filaments at the cylinder at $\mathrm{Re} \approx 157$, which leads to turbulent flow farther downstream. This transition can be characterized by temporal and spanwise variations of the angle of vortex shedding. Flow visualization of the wake of the main cylinder in the absence of control cylinders showed turbulent behavior as early as $\mathrm{Re} \approx 157$. However, when control cylinders are in place, an island of laminar and parallel vortex shedding could be seen. This is illustrated in Fig. 6 for $\mathrm{Re} = 157$. Note that the wake of the main cylinder is turbulent, except in the region between the two control cylinders. The technique failed to perform for $\mathrm{Re} > 157$ while the control cylinders were kept at $L = 0.625$ in. for $D = 0.25$ in., i.e., the inside region became turbulent as well. However, we discovered that the inside region could be made laminar and parallel vortex shedding restored up to $\mathrm{Re} \approx 163$ if the distance L_0 was reduced to a new value $L_0' \approx 0.25$ in. for the particular case of $D = 0.25$ in. (Fig. 7). This new optimum value for L might be due to a change in the base pressure value of the main cylinder in the vicinity of the transition region. We noted that reducing the aspect ratio may increase the Reynolds number range in which laminar parallel vortex shedding is restored even further. Figures 8(a) and 8(b) show hot wire spectra of the velocity fluctuations obtained at $\mathrm{Re} = 163$ in the inside and outside regions. The spectrum shows a sharp single frequency for the vortex shedding in the inside region, while in the outside turbulent region it is characterized by multiple peaks and a higher noise level. The spectrum shown in Fig. 8(a) is typical of the flow obtained with the control cylinder technique over the Reynolds number range of 50–163. One last important observation is the fact that as long as parallel vortex shedding is achieved, the Strouhal–Reynolds number curve does not show any discontinuities (Fig. 9). A

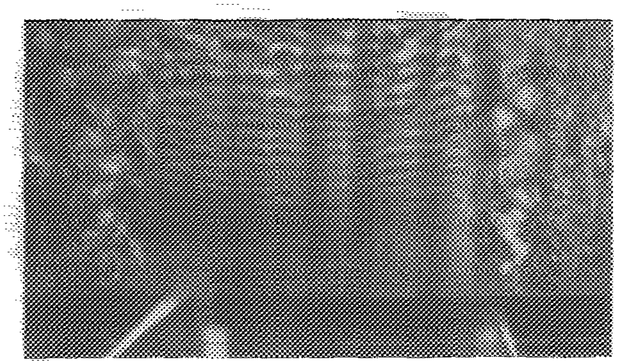

FIG. 7. Restored laminar wake for $\mathrm{Re} = 163$, $d = 0.032$ in., $D = 0.25$ in., $H/d = 265$, and $L \approx 0.25$ in.

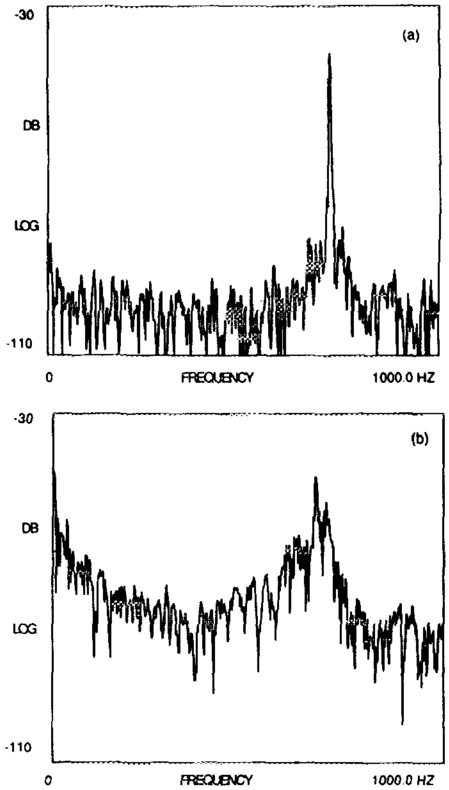

FIG. 8. Velocity fluctuation spectra for the flow shown in Fig. 7. (a) Hot wire positioned in the laminar parallel shedding region. (b) Hot wire positioned in the outside turbulent region.

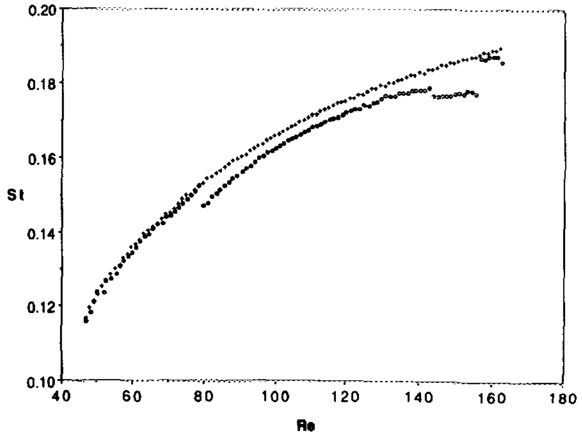

FIG. 9. Strouhal–Reynolds number data for circular cylinder, $d = 0.032$ in. O, without control cylinders, aspect ratio 750; +, parallel shedding obtained with control cylinders, $D = 0.25$ in., and $H/d = 265$.

similar conclusion has been reached by Williamson[8] and Eisenlohr and Eckelmann.[10] Furthermore, the curve is independent of the choice of the diameter D, therefore suggesting a behavior that can be represented by the relationship

$$\mathrm{St} = 0.212 - 5.35/\mathrm{Re}.$$

This relationship is very close to the one suggested by Williamson.

We have presented a novel approach to promote parallel vortex shedding in the wake of circular cylinders. Furthermore, this technique shows great potential for delaying the three-dimensional transition to turbulence. Also, we have shown some convincing evidence that imposing a symmetric pressure boundary condition is essential for the operation of our technique. Further experiments are planned to address the importance of symmetric pressure boundary conditions by detailed pressure measurements.

ACKNOWLEDGMENTS

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