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Brief communication

Flow field of self-excited rotationally oscillating equilateral triangular cylinder

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Abstract

This paper studies the flow field of a particular fluid-structure interaction phenomenon—the continuous angular oscillation of a centrally pivoted equilateral triangular cylinder (prism), under uniform two-dimensional incompressible flow. Dye flow visualization of a 30 cm long and 10 cm wide cylinder in a two-dimensional water tunnel was conducted. Under a uniform incoming flow of 7.5 cm/s, the cylinder oscillated continuously after an initial perturbation. On the windward side of the cylinder, a vortex was formed at the sharp edges of the cylinder during the initial phase, whereas on the leeward side, the flow stayed attached. The phase-averaged particle image velocimetry (PIV) measurements are also presented. PIV results show the interchange of flow patterns from that over a flat plate to flow past a sharp edge and vice versa.

Keywords: Self-excited rotational oscillation; Equilateral triangular cylinder (prism)

1. Introduction

Oscillating flaps or duck-fins are commonly used to suppress the ocean surface waves approaching the shore. The flaps or duck-fins have the drawback that they work only on the water surface. Recent studies (Nagashima and Hirose, 1982) revealed that if an isosceles triangular wedge is placed in an otherwise uniform flow, it can be induced to oscillate incessantly. The equilateral triangular wedge is more effective than the flap or duck-fin, since it can also function when submerged in the water. One can also extract energy from the oscillating and/or spinning motion of the wedge when it is under the influence of incoming flow or wave. The detailed motion of the wedge is, however, not fully understood. This is due to the unsteady surrounding flow, as well as continuously moving boundary (the wedge either oscillates or rotates). This coupled fluid-structure interaction was first noticed by Nagashima and Hirose (1982) and it has not yet been well studied. Previous research only dealt with the stationary wedge at a different position or oscillation in translational mode (Luo et al., 1993), or with other geometries (Naudascher and Wang, 1993; Nakamura and Nakashima, 1986; Sakamoto et al., 2001; Hu et al., 2002).

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Previous experiments (Srigrarom, 2003) investigated such behaviour by means of dye and Laser Induced Fluorescence flow visualization. For a Strouhal number in the range $0.13 < St < 0.18$, the cylinder oscillates continuously. Beyond this range, the cylinder either remains stationary or rotates only in one direction.

In this paper, we present our observations. The continuous oscillation of the wedge is sustained by the symmetrical flow structure. On one side, the flow will be flow-past-flat-plate like, whereas the other side will be flow-past-sharp-edge like. When the wedge rotates, these mechanisms switch side interchangeably, causing the wedge to oscillate continuously. The observation is supported by dye flow visualization images and particle image velocimetry (PIV) measurements.

2. Proposed oscillation model

The explanation of the self-excited oscillation behaviour was elaborately discussed in Srigrarom (2003). The key features are excerpted here. Consider the flow pattern around a symmetrical triangular cylinder rotating in the clockwise direction (Fig. 1(a)). The upstream flow is uniform at zero angle of attack, and is brought to stagnation at the front of the cylinder. The flow is divided into two identical zones: upper and lower. The divided stream varies smoothly from a 90-degree turn at S to a stream merging with the free stream at edge A or B. At A or B, the flow separates from the cylinder at both tips or shape edges of the cylinder, creating back flow or eddies on both lateral sides. At the trailing edge C, the flow pattern changes according to the free-stream Reynolds number. At low Reynolds number ($10^4 < Re < 10^5$), the two divided streams create alternating vortices, shed downstream. At higher Reynolds number

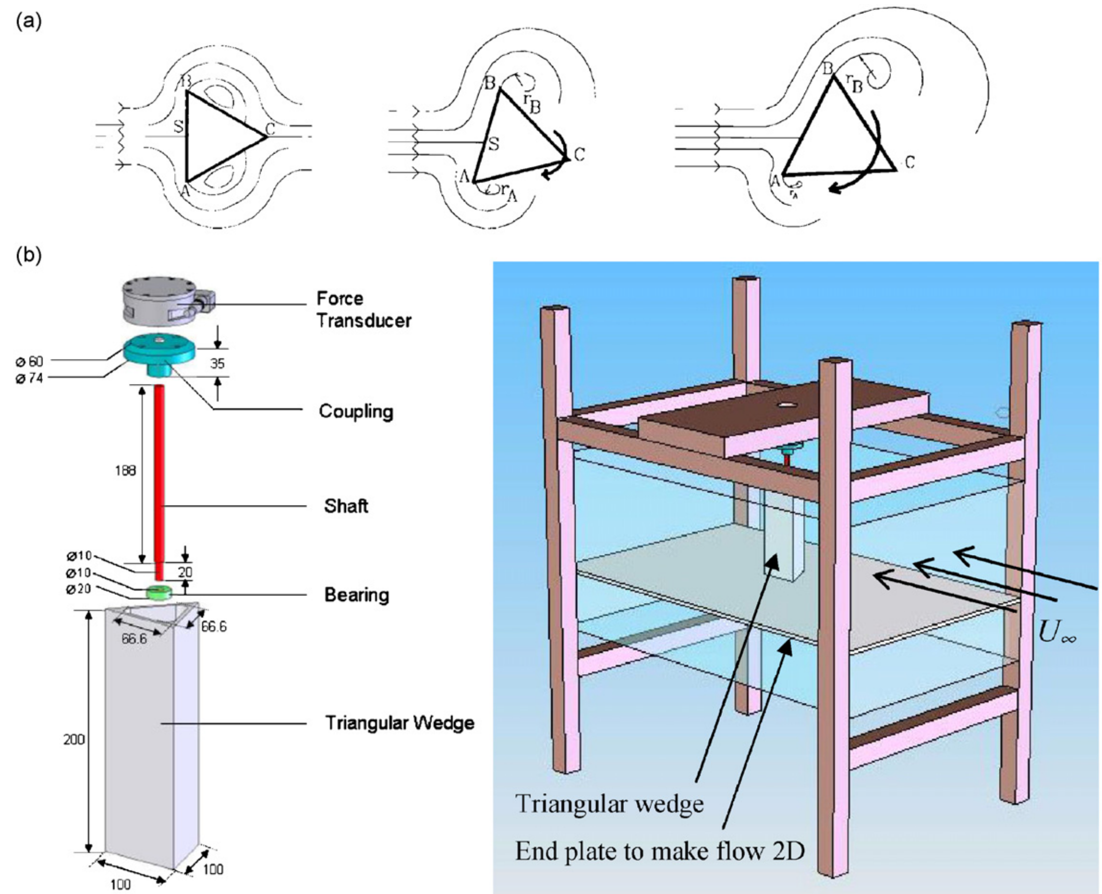


Fig. 1. (a) Sequence of flow past the equilateral triangular cylinder, rotating in clockwise direction. (b) The geometry of the cylinder (wedge), with the built-in bearings and the mounted force transducer (left). All dimensions are in millimeters (mm). Experimental set-up (only the test-section in the water tunnel shown) (right).

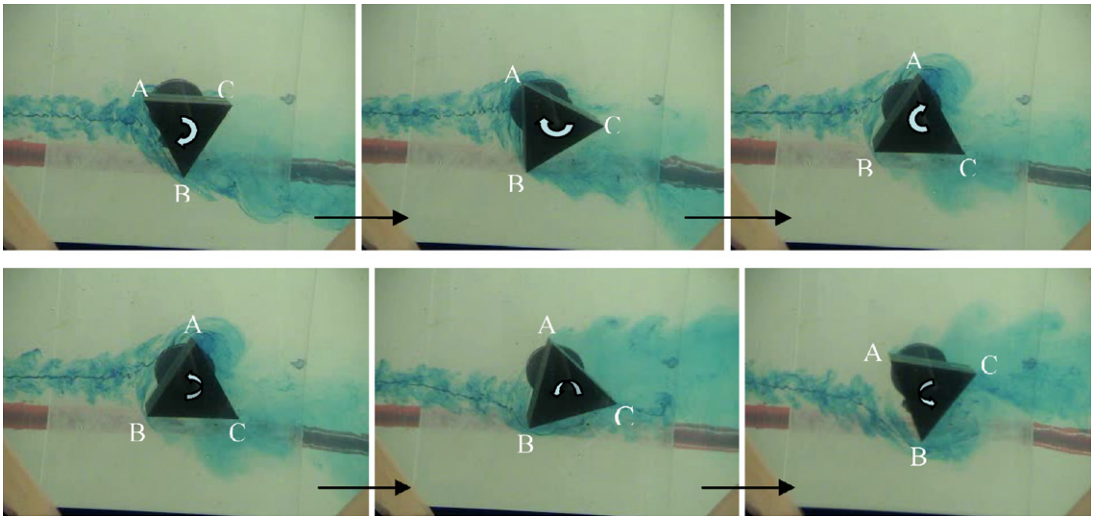


Fig. 2. Cylinder oscillation in clockwise (upper row) and counterclockwise (lower row) motion.

(Re$>10^5$), the two streams join together at alternating streamwise locations creating a turbulent wake downstream of the cylinder (Luo et al., 1993).

When the front face of the cylinder AB is inclined with the free stream, the flow separates at both A and B (the pattern is asymmetrical). The radius of curvature of the separated streamline at A, r_A, is smaller than the radius of curvature at B, r_B. As a result of conservation of angular momentum, the velocity at A is higher than at B; therefore, the pressure at A is lower than at B ($P_{AC}<P_{BC}$). Hence, the cylinder rotates clockwise about the pivot, and the frontal surface AB becomes more aligned with the free stream.

With the continuous motion, the triangle will arrive at a position where AC is parallel to the free stream. The flow separates at the upper tip of the cylinder (B), but the flow in the lower part separates only at the lower tip of the cylinder (A), before reattaching to the lower lateral face (AC). The flow is then similar to that over a flat plate.

Because of the difference between the two flow patterns, the local pressures differ at the upper and lower parts of the cylinder. The upper part, with the existence of a large eddy, has lower pressure, compared with the free stream; whereas at the lower part the pressure is equal to the free-stream pressure. The pressure in the lower part is now greater than the upper part, ($P_{AC}>P_{BC}$) and the cylinder tends to rotate back to its original position.

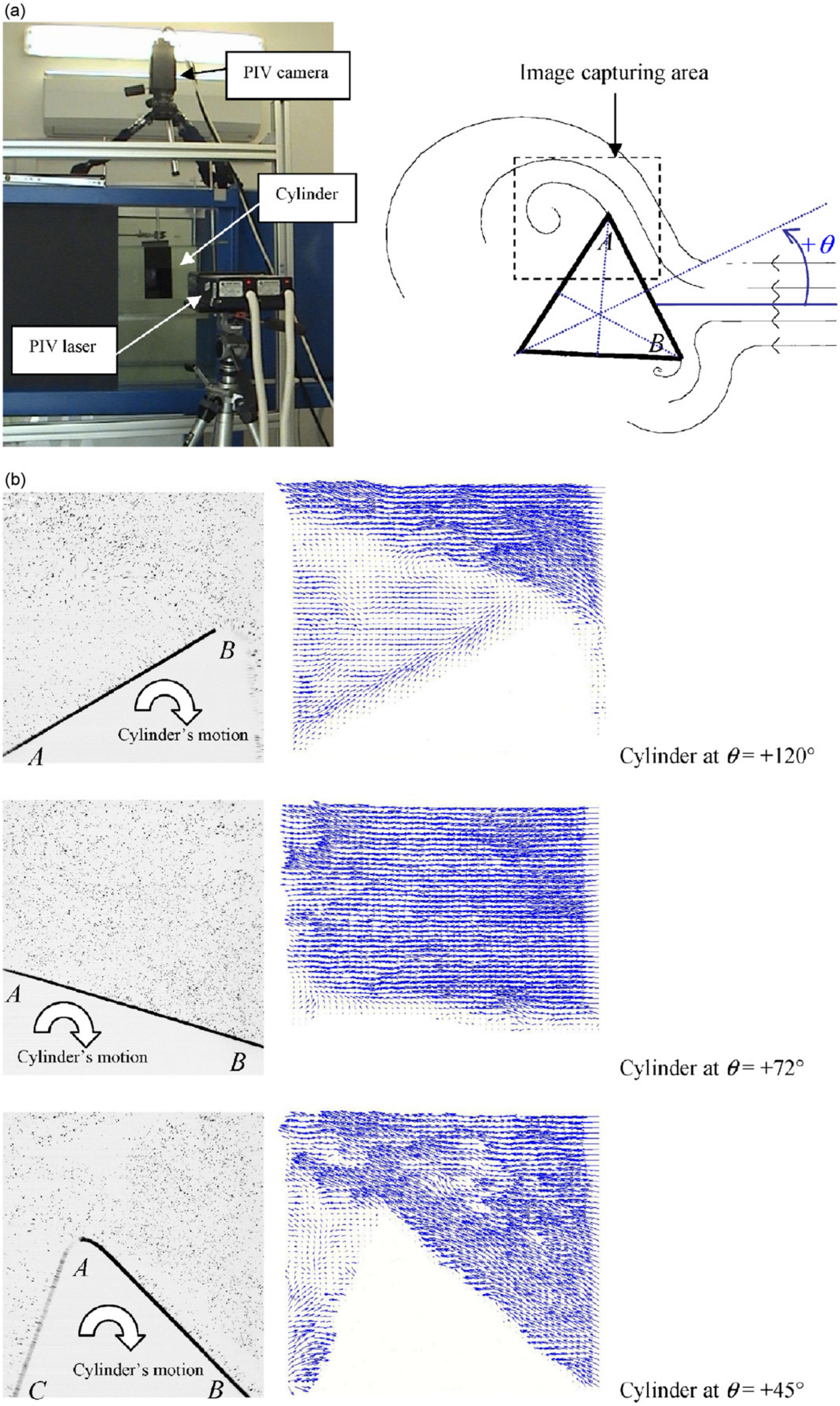
As a consequence of the above, the resultant pressure forces the cylinder to rotate counterclockwise back to its original position (under the assumption that the cylinder starts rotating in a clockwise direction, as described in the previous step). Due to the inertia of the cylinder, the motion does not stop when it returns to the original symmetric position as shown in the left sequence of Fig. 1(a). Instead, the cylinder continues to swing in the counterclockwise rotation. The flow patterns are just flipped from those in Fig. 1(a). The overall phenomenon can be viewed as the interchange of the flow patterns, from the flow past the sharp edge to flow over the flat plate, and *vice versa*.

3. Direct dye injection flow visualization

The flow was visualized using direct dye flow injection and PIV. The experiment was conducted in the $45\,\text{cm} \times 45\,\text{cm} \times 100\,\text{cm}$ water tunnel facility at Nanyang Technological University, Singapore. The free-stream velocity, U_∞ was 7.5 cm/s. The cylinder was made from Delrin® plastic with density, $\rho = 1400\,\text{kg/m}^3$. The cylinder width, W, was 10 cm. This corresponds to Reynolds number, Re_W, of 7500 based on the cylinder width. We put the plate at the end of the cylinder, such that the flow surrounding this cylinder was essentially two-dimensional. The cylinder geometry and the experimental setup are shown in Fig. 1(b).

Firstly, the direct dye injection technique was used to observe the flow pattern. The food colouring dye was released upstream of the cylinder. The images were captured by digital video camera as are shown in Fig. 2. The oscillation

Fig. 3. (a) Experimental set-up for particle image velocimetry (left) and image capturing area (right). (b) Sequence of captured camera images (left) and the corresponding velocity fields (right), when the cylinder was swinging against the flow (clockwise motion).


(a)
PIV camera
Cylinder
PIV laser
Image capturing area
A
B
+θ
(b)
B
A
Cylinder's motion
Cylinder at θ = +120°
A
B
Cylinder's motion
Cylinder at θ = +72°
A
C
B
Cylinder's motion
Cylinder at θ = +45°

frequency, f was 0.13 Hz, observed from the recorded side-force (in cross-stream direction) measurement, corresponding to a Strouhal number ($\mathrm{St} \equiv fW/U_\infty$) of 0.173.

The overall phenomenon of the triangular cylinder oscillating in a to-and-fro manner can be clearly observed. As seen from the dye, there is an interchange of flow patterns from the flow over the flat plate (AC) to flow past sharp edge (A), resulting in a clockwise rotation of the cylinder. Because of inertia, the cylinder begins to swing in the counterclockwise rotation and the reversal of flow pattern from flow past sharp edge to flow over the flat plate is observed.

4. Particle image velocimetry

PIV measurements of the velocity field was conducted, with the same flow conditions as in the previous direct dye injection experiment, i.e. $U_\infty = 7.5\,\mathrm{cm/s}$, $\mathrm{Re}_W = 7500$. The camera was mounted on the top of the water tunnel to capture the cylinder's side view flow image, whereas the laser was positioned at the side to create planar laser sheet. The set-up is shown in Fig. 3(a). The 0.1 μm nylon particles for PIV were released upstream of the triangular cylinder, at a time synchronizes to the laser firing and camera capturing time.

Since the oscillation frequency was consistently at 0.13 Hz ($\mathrm{St} = 0.173$), we could do phase-averaged PIV, i.e. capturing and processing the PIV images and data at the same angular position and rotational motion direction of the cylinder, but from different cylinder oscillation cycles. The process was done by (i) recording the cylinder motion by a high speed camera for an extended period of time to obtain sufficient oscillation history (approx. 20 cycles), (ii) synchronizing the laser firing time with the cylinder motion, and (iii) capturing PIV images at the prescribed angular position of the cylinder.

Fig. 3(b) shows the time-sequence PIV results when the cylinder moves in a clockwise direction. The camera images are shown on the left and the corresponding velocity fields are on the right. Note that, in these plots, the free-stream direction is from the right to left. In the top part of Fig. 3(b) at $\theta = +120^\circ$, the flow separates from the sharp edge at B. There is reversed flow on the observed surface AB as indicated by the velocity vectors. In the middle part of Fig. 3(b) at $\theta = +72^\circ$, the cylinder moves and the fluid adjacent to the surface AB is moved by the cylinder. The velocity vectors appear to point upwards and to the left with the clockwise motion of the cylinder. In the bottom part of Fig. 3(b) at $\theta = +45^\circ$, the velocity vectors on the right side on the observed surface AB are attached to the cylinder surface. At the lower left C, there is jet efflux, caused by the clockwise motion of the cylinder.

Overall, Fig. 3(b) shows the change of flow pattern from the flow past sharp edge like (the top part of in Fig. 3(b)) to the flow over flat plate like on the observed surface AB (the bottom part of Fig. 3(b)); which is in agreement with the dye flow visualization discussed in previous sections. When the cylinder moves in the counterclockwise direction, similar agreement was observed.

5. Conclusions

At certain uniform incoming flow velocities, the equilateral triangular cylinder can oscillate continuously, after initial perturbation. This self-excited oscillation exists when the flow is two-dimensional and the Strouhal number is in the range of $0.13 < \mathrm{St} < 0.18$. The present results from direct dye injection flow visualization as well as particle image velocimetry (PIV) support the proposed explanation of the phenomena. On one side, the flow is similar to that of flow over flat plate, whereas on the other side, it is similar to that past a sharp edge. When the cylinder rotates, these mechanisms switch interchangeably, and cause the cylinder to oscillate incessantly.

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