ASTFE
American Society
of Thermal and Fluids Engineers

5th Thermal and Fluids Engineering Conference (TFEC)
April 5–8, 2020
New Orleans, LA, USA

TFEC-2020-32029

SHIFT IN VORTEX SHEDDING MODE FOR FLOW OVER STREAMWISE OSCILLATING CYLINDER UNDER CONSTANT CONDITIONS

Ahmad Elhares,[1] Krishna Shah,[1] Yanbao Ma[1,*]

[1]Department of Mechanical Engineering, University of California Merced, Merced, CA 95343, USA

ABSTRACT

Flow over a cylinder has attracted a lot of interest in the past few decades due to resulting complex flow phenomenon as well as its implications on a wide variety of natural and engineering systems. The present work examines experimental laminar flow over a streamwise oscillating cylinder. Vertical soap film flow has been used as the experimental apparatus to obtain laminar flow over the oscillating cylinder. Experimental flow visualization of resulting vortex street has been used to study the vortex shedding mode. Two vortex shedding modes are observed at the same frequency and amplitude of the cylinder oscillation. The first vortex shedding mode is symmetric and consists of a pair of vortices with different rotation directions being shed per oscillation cycle in simultaneous fashion. The second mode is asymmetric and consists of three vortices with the same rotation direction being shed from one side of the cylinder which alternates every oscillation cycle. Snapshots of the flow are taken to visualize the vortex shedding modes and the cylinder position at the moment of vortex detachment.

KEY WORDS: Vortex Shedding, Flow Over a Cylinder, Streamwise Oscillation, Lock-In Behavior, Soap Film Tunnel, Schlieren Optics

1. INTRODUCTION

Periodic flow phenomena and vortex shedding for fixed bodies have been studied for their importance as natural phenomena [3] and oscillatory flow [2]. Flow over different bluff bodies, and resuling flow phenomana have attracted researchers due their large application range. Vortex induced vibrations (VIV), and forced oscillation of the bluff body such as a cylinder have been attractive for researchers due to its importance in many fields such as heat transfer and building structures [12]. The most studied body is the circular cylinder due its frequent uses in numerous applications. This study investigates flow over a cylinder with forced oscillations in streamwise direction.

Lock-in phenomenon has been observed for forced streamwise oscillation frequency in the range of $1 < f_d/f_n \leq 2$ (the ratio of the cylinder oscillation frequency to the natural shedding frequency) . The oscillation amplitude required for lock-in behavior has been found to be lower for streamwise oscillation than for transverse oscillation[13, 14]. Initially, two asymmetric modes of vortex shedding under lock-in condition had been observed and reported [7]. In the first mode, a complex vortex shedding pattern has been observed where two vortices are generated for each cycle of cylinder oscillation [7]. This leads to shedding at a frequency equal to the oscillation frequency of the cylinder. In the second mode, one vortex is generated for each cycle of oscillation resulting in the shedding frequency half of the oscillation frequency [7].

It has been found that as the oscillation frequency approaches $f_d/f_n = 2$, amplitude of oscillation required

*Corresponding Yanbao Ma: yma5@ucmerced.edu

for lock-in reduces. Numerical simulations have also been done showing that higher amplitude of oscillation is required for expanding the lock-in region away from $f_d/f_n = 2$ [1]. Additional vortex shedding modes are reported by other experimental studies [9, 15]. These include both asymmetric and symmetric vortex shedding patterns. Symmetric vortex shedding pattern has also been shown at much higher frequencies near $f_d/f_n = 3$ [9]. In the latest work [8], vortex shedding modes in lock-in and non-lock-in regions, including symmetric and asymmetric modes, are reported.

Past works have reported a single vortex shedding mode at certain oscillation parameter of the cylinder while the present work shows a change in lock-in mode for vortex shedding under the same frequency and amplitude of experimental streamwise oscillation of the cylinder. Using vertical soap film flow and schlieren optical technique, wake flow and vortex shedding are visualized for quantitative and qualitative analysis.

2. EXPERIMENTAL SETUP

The experimental setup consists of a vertical soap film tunnel, a Z-type schlieren based optical setup for flow visualization, and an oscillating circular cylinder set-up in the streamwise direction. These three key elements of the setup are described below.

2.1 Vertical soap film tunnel

Soap film is a good experimental approximation for a two-dimensional flow [4, 6, 10]. In this study, it is used for its simplicity and to be able to generate two-dimensional laminar flow. As shown in figure 1 (a), a vertical metal frame is used to support the nylon wire for a vertical soap film flow. The nylon wire geometry has three main sections: diverging, parallel and converging. The point at the top for introducing fluid injection is created by tying the two wires together.Dimensions of the setup are shown in 1. Soap-water solution with 2% Dawn commercial dish washing detergent by volume gets injected using 15-gauge nozzle from the inflow reservoir into the diverging section of the nylon wire. The flow goes into a parallel section followed by a converging section to the outflow reservoir. The streamwise oscillating cylinder is placed in the center parallel section to insure uniform flow. Flow regulator valve is used to maintain constant flow rate throughout the experiment.

2.2 Schlieren setup

Schlieren optics is a powerful technique to visualize the change in refraction index of transparent media [11]. The Z-type schlieren optical setup is used for flow visualization and measurement. The schematic of the optical setup with all optical components and the beam path is presented in figure 1 (c). A 12 cm diameter Telescopic parabolic mirror is used to reflect a parallel beam of light through the soap film to visualize the flow. The light starts from a LED point source through 2 double convex lenses that concentrate it to the pinhole which is located at the focal point of the mirror. After penetrating the soap film, the light beam gets reflected again by another identical mirror which concentrate it into its focal point where a sharp edge is placed to control the image contrast. After that it gets received by a Photron FastCam SA3 high speed camera through focusing lens. Both the telescopic mirrors are tilted by a small angle of $3°$ with respect to the principal axis of the mirror.

2.3 Cylinder oscillation setup

The schematic for the oscillating cylinder setup has been shown in figure 1 (b). A small L-shape PVC bar is attached to a 50 W speaker. A very light plastic cylinder is attached to the tip of the bar using a needle linkage. All the parts used in this setup to transfer the vibrations from the speaker to the cylinder are chosen to be light in weight to minimize damping. The speaker is connected to a 350 W amplifier which is powered by a DC power source. A mobile application is used to generate sine wave signal that is fed to the speaker using 3.5 mm audio jack. Frequency and signal intensity (in dB) are specified from the mobile application. The signal intensity is calibrated to the peak-to-peak amplitude of the displacement of the cylinder.

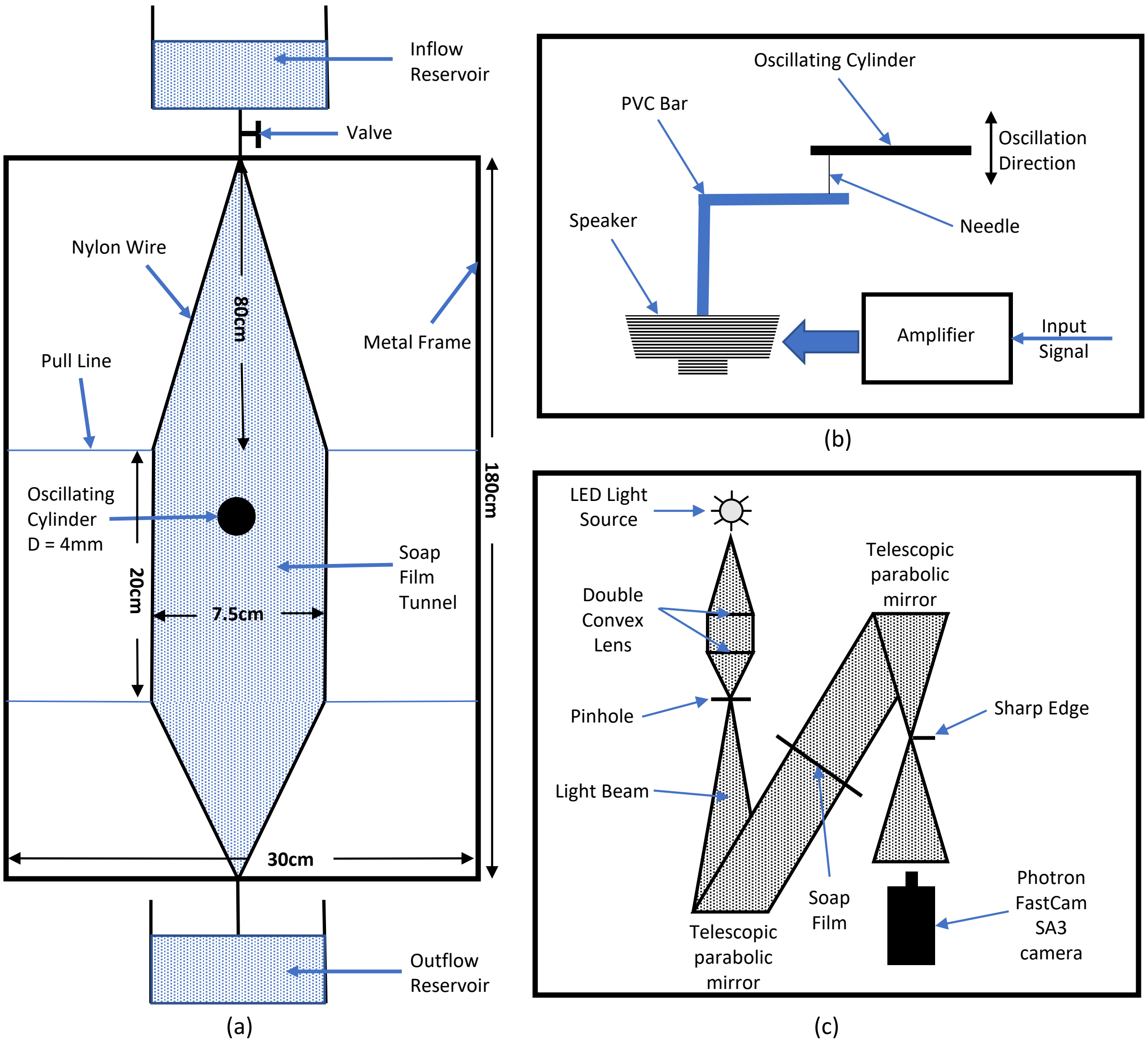

Fig. 1 Experimental Setup: (1) Schematic of soap film flow setup (2) Schematic of oscillating cylinder setup (3) Schematic of Z-type schilern setup

3. RESULTS AND DISCUSSION

In this experiment, soap film is formed using an object with flat edge such as a metal ruler scale or squeegee. After a stable soap film is established, cylinder is positioned in the film. Oscillations are induced in the cylinder and flow is visualized by capturing schlieren image using the high-speed camera. A high-speed video is captured as soon as the symmetric shedding mode is first observed.The flow rate is kept constant in the soap-film tunnel. The velocity is 1.8 ± 0.07 m/s and is measured 10 mm above the cylinder using particle tracking velocimetry. The Reynolds number (Re) based on the cylinder diameter (D= 4 mm) is around 1800 based on the kinematic viscosity of 0.04 $cm^2 s^{-1}$ from similar films [5, 16]. At this flow Re, the natural shedding frequency (f_n) is measured around 100 Hz. The cylinder oscillation frequency is fixed at $f_d = 140$ Hz ($f_d/f_n \approx 1.4$). The amplitude of the oscillations (A) has been measured to be 1.25 ± 0.05 mm which results in $A/D \approx 0.3125$. A high-speed video of the flow using schlieren imaging is recorded at a frame rate of 3000 frames per second to obtain snapshots for flow visualization.

Although the cylinder is oscillated at a constant frequency and amplitude, a change in shedding mode is observed. Two main vortex shedding modes are captured, the first one is symmetric vortex shedding and the second one consists of complex asymmetric vortex shedding. Figures 2, 3 and 4 show the first mode, transition state, and second mode of shedding, respectively.

The series of snapshots presented in figure 2 show the sequential change in schlieren images captured at the interval of 0.00119 s for one vibration periods after the flow becomes periodic. Snapshot 2a is taken at $t = t_0$, when the cylinder is located at the top position (T) of the oscillation cycle. A vortex with clockwise (CW) rotation and a vortex with counter clockwise (CCW) rotation start detaching from the cylinder at the same time. Here, the rotational direction is identified, and solid arrows with affixed labels are placed in the snapshots to show the position and direction of each vortex that detached along with time stamps, starting from snapshot 2a. After approximately one sixth of the oscillation period (0.00119 s), as the cylinder moves downward away from the top position, the CW rotation and the CCW rotation vortices start moving away from the cylinder. At $t = t_0 + 0.00238$ s and $t = t_0 + 0.00357$ s , both vortices continue to move away from the cylinder while the cylinder moves downward to the bottom position (B). At $t = t_0 + 0.00476$ s and $t = t_0 + 0.00595$ s, the cylinder moves upward (see snapshot 2e and 2f) and the formation of two new vortices with CW rotation and CCW rotation begin before being shed as shown in the beginning of the next oscillation period in snapshot 2a.

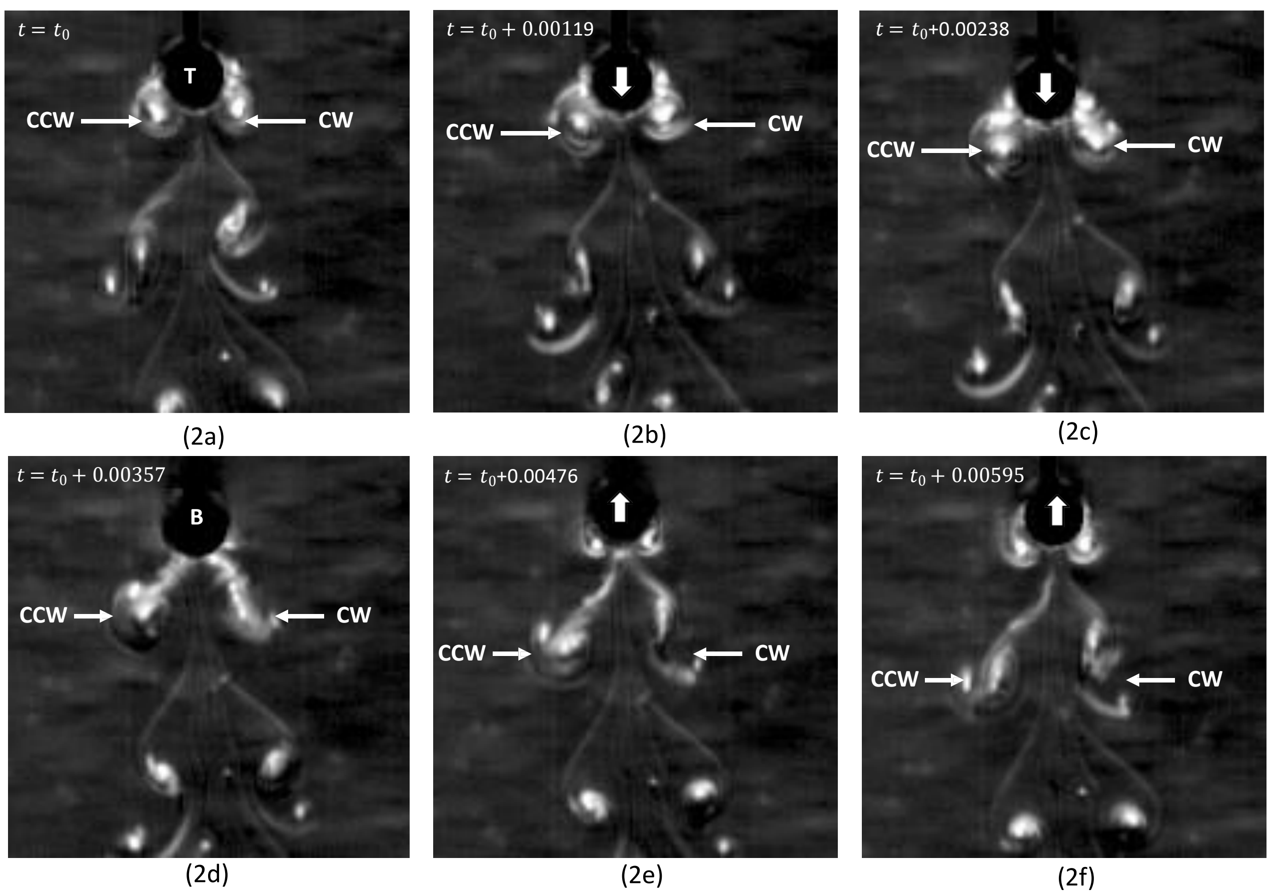

Fig. 2 Snapshots obtained using schlieren imaging showing first mode of vortex detachment over one oscillation cycle

Fourier analysis is conducted on the experimental data. It is found that there is a fixed shedding frequency ($f = 140$ Hz) for first mode of shedding which is consistent with the observation on vortex shedding shown in figure 2. Therefore, the vortex shedding is observed in the locked-in mode with forced oscillation of the cylinder.

In figure 3, snapshots present the sequential change in schliren image every 0.00167 s, and show the mode transitioning from mode 1, as shown in figure 2, to mode 2 in figure 4 under the same cylinder vibration frequency and amplitude. In snapshot 3a, the vortex shedding is still symmetrical as in mode 1 but, becoming visually unstable as it starts shifting gradually into asymmetric vortex shedding as shown in snapshots 3c–3f. In snapshots 3g–3i, the shedding is in mode 2 and becoming more stable.

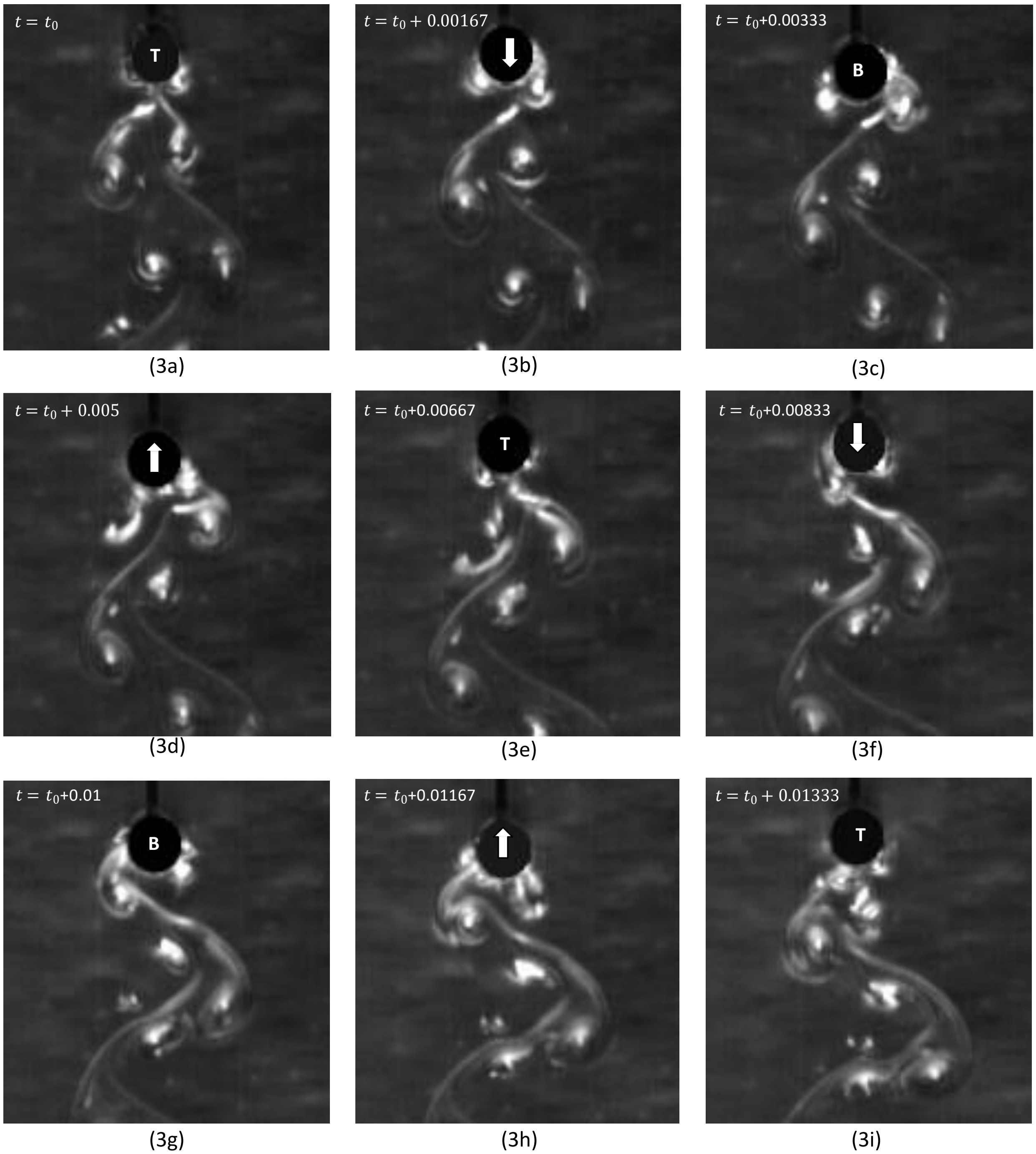

Fig. 3 Snapshots obtained using schlieren imaging showing transition from first mode to second mode of vortex detachment over two oscillation cycle

Figure 4 shows the second mode of shedding for one cylinder oscillation cycle. Snapshots are taken after the mode has shifted and the flow is in periodic state. The time difference between the snapshots is not kept fixed to ensure that each vortex shedding is captured as it is shed. In snapshot 4a, as the cylinder is in between the bottom and central position moving upward, a CCW rotation vortex begins detachment. After 0.001 s, the cylinder has moved upward above the central position; here, the CCW rotation vortex is seen to be moving away from the cylinder. In snapshot 4c, at $t = t_0{+}0.00267$ s, a second CCW rotation vortex begins detachment from the left side of the cylinder which is in its top position. After 0.002 s, while the cylinder has moved back to the bottom, a third CCW rotation vortex is shed from the same side as shown in snapshot 4d. At time $t = t_0 + 0.00633$ s, the cylinder reached the bottom before proceeding upward at $t = t_0 + 0.00733$ s; here, a CW rotation vortex begins detachment from the right side (see snapshots 4e and 4f). The above process occurs on the right side of the cylinder leading to three vortices with CW rotation in the next oscillation cycle. These vortices shed in the same order as described earlier for the vortices shed from the left side.

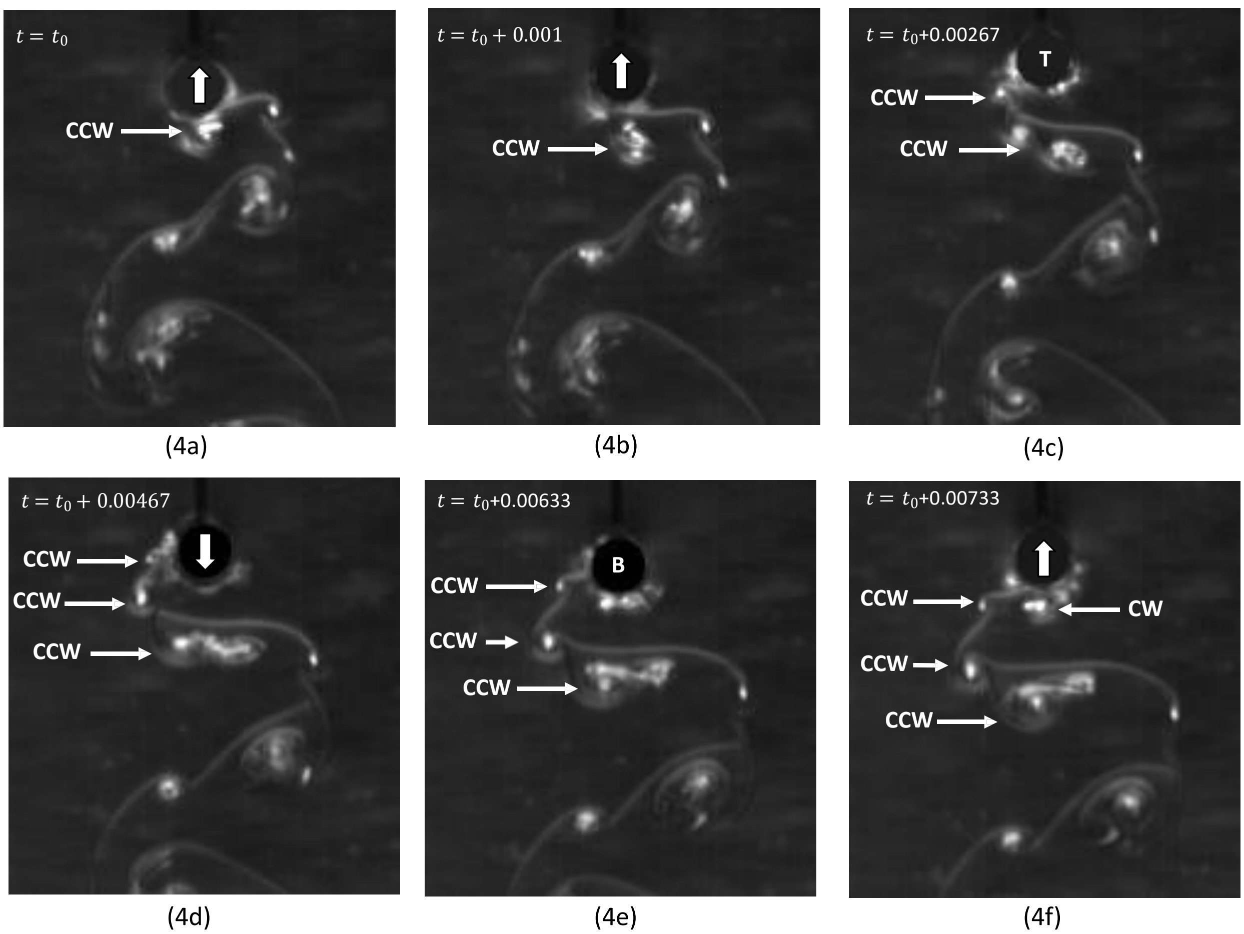

Fig. 4 Snapshots obtained using schlieren imaging showing second mode of vortex detachment over one oscillation cycle

4. CONCLUSIONS

Experimental study of flow over streamwise oscillating cylinder has been conducted. Vertical soap film flow has been used to obtain two-dimensional laminar flow experimentally. Forced oscillation with a frequency of 140 Hz ($f_d/f_n \approx 1.75$) has been implemented. It has been observed that a change in vortex shedding mode happens for constant cylinder oscillation and flow parameters. The first vortex shedding mode is symmetric, consisting of two vortices with different rotation directions shed from both sides of the cylinder at the same time during each cylinder oscillation cycle. A transition period is observed after the first mode due to instability. After the transition period, the second vortex shedding mode is observed. This mode is asymmetric with three vortices of the same rotation direction being shed from one side of the cylinder per oscillation cycle. The side of the cylinder from which shedding occurs alternates every oscillation cycle. Numerical simulations and more quantitative analysis would be the next step.

ACKNOWLEDGMENTS

The authors would like to acknowledge Mr. Jonathan Lievano Aguilar and Mr. Merari Cisneros for their valuable contribution during the initial stages of the soap film flow research at University of California, Merced.

NOMENCLATURE

f_n	natural shedding frequency	(Hz)
f_d	cylinder oscillation frequency	(Hz)
f	shedding frequency	(Hz)
D	Cylinder diameter	(mm)
A	Oscillation amplitude	(mm)
CCW	Counter clock-wise	(-)
CW	Clock-wise	(-)

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