Journal of Fluids and Structures (2001) **15**, 533–541
doi:10.1006/jfls.2000.0365, available online at http://www.idealibrary.com on IDEAL®

ON CIRCULAR CYLINDERS UNDERGOING TWO-DEGREE-OF-FREEDOM FORCED MOTIONS

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(Received 15 August 2000, and in final form 15 November 2000)

Cylinders undergoing one- and two-degree-of-freedom (DoF) motions were studied. Since the forces on the cylinder fluctuate in both the streamwise and transverse direction, it is believed that such motions are more natural than transverse-only vibrations. A set of experiments was conducted in a water tunnel using both digital particle image velocimetry (DPIV) and force measurements. Several qualitative differences were noted, including a dramatic increase in phase coherence and the disappearance of the "2P" mode. It appears that the transverse motion sets the frequency of shedding, and the streamwise motion the relative phase therein.

1. INTRODUCTION

Although the phenomenon of vortex-induced vibration of bluff bodies has been studied extensively, the vast majority of these studies have concentrated solely on transverse vibrations. Works by Feng (1968), Sarpkaya (1979), Khalak & Williamson (1999), and Gharib (1999), among many others, have highlighted the behavior of an elastically mounted cylinder free to vibrate in the transverse direction. Various response curves have been measured showing the amplitude, frequency, and phase of cylinders undergoing vortex-induced vibration. The effects of damping and mass ratio and Reynolds number have also been scrutinized. However, since the fluctuating forces responsible for these oscillations have unsteadiness in both lift and drag, the role of streamwise vibrations cannot be ignored. Although the lift fluctuation is generally quite a bit larger than the drag fluctuation, the resultant streamwise vibration must have some effect upon the wake. Previous studies that have looked at two-degree-of-freedom (2-DoF) mechanical systems have indicated that while the behavior is qualitatively similar, some interesting differences exist. For example, Gharib (1999) found that his 2-DoF free vibration cases were much less likely to exhibit lock-in behavior (where the wake locks to the natural frequency of the structure for some range of parameters).

Forced vibration studies have been even more focused on 1-DoF vibrations. Two particular useful papers on 1-DoF forced motion are Bishop & Hassan (1964) and Williamson & Roshko (1988). Bishop & Hassan demonstrated that a phase shift in the lift force occurs near when the vibrations are on either side of the Strouhal frequency of the stationary cylinder. The wake seems to aid the motion of the cylinder at some frequencies and oppose it at others. Williamson & Roshko demonstrated a connection between the motions in this region of parameter space with a change in wake shedding patterns. The wake was shown to change from the so-called "2S" (two single vortices per cycle) to the "2P" (two opposite-signed pairs of vortices per cycle) mode near the Strouhal frequency. This change in mode was associated with the change in lift phase.

0889–9746/01/040533 + 09 $35.00/0

Using the results from previous 1-DoF forced vibration studies, a series of 2-DoF forced vibration cases was analyzed to better understand what differences result from the addition of streamwise motion. Since it is believed that nature prefers a figure-eight-type motion, this study was undertaken to discern the effects of the addition of streamwise motion, and to see which effects a transverse-only experiment would miss.

2. THEORY

Since the goal of this work was to study natural vibrations, motion parameters were chosen accordingly. Most researchers report typical free-vibration amplitudes slightly above 0·5 diameters — with cases of peak values in excess of 1 diameter being reported by some researchers — so, that value was chosen for the transverse vibration amplitude. Transverse frequencies were chosen from the Williamson & Roshko (1988) mode map, such that cases in the "2S" and "2P" regions were represented. (The corresponding positions on the 1-DoF parameter map are shown in Figure 1.) Streamwise frequency was fixed to be double the transverse frequency in order to generate the figure-eight patterns commonly observed. Streamwise amplitude was held at 0·1 diameters, or one-fifth of the transverse amplitude; this produced figure-eight patterns of approximately the correct aspect ratio.

This left one main parameter — the relative phase between the streamwise and transverse motion. The phase is defined relative to the transverse motion in the following manner: for a given transverse motion $\sin(\omega t)$, phase ϕ is such that the streamwise motion is $\sin(2\omega t + \phi)$. The phase value tends to drift in free-vibration cases (along with frequency and amplitude), but is usually in the range of 0 to $-45°$. Consequently, phases of 0 and $-45°$ were chosen for examination. (Negative 45 degrees of phase results in a figure-eight pattern with the lobes bent slightly downstream.)

It is worth noting that this represents a very small perturbation on the overall motion. As shown in Figure 2, if one were to plot the x–y position of the cylinder through time, motions with and without the streamwise vibration are virtually identical. Since the cylinder moves about 5 diameters downstream per cycle, it is not surprising that a 0·1 diameter perturbation is nearly invisible on this plot. However, the effect on the wake is not so minuscule.

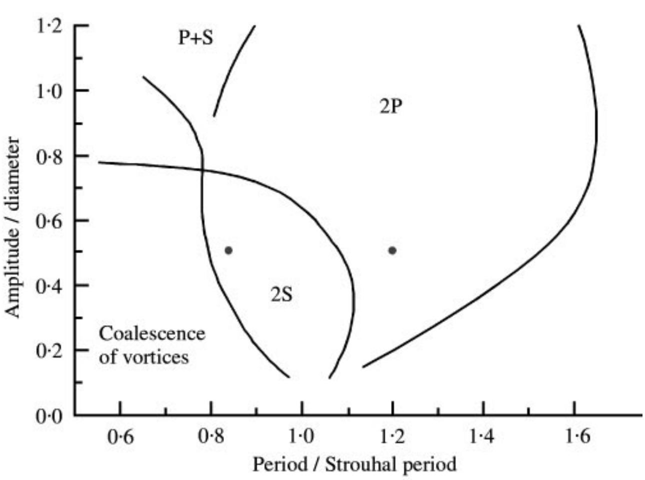

Figure 1. Transverse motion parameters plotted on the Williamson & Roshko (1988) mode map.

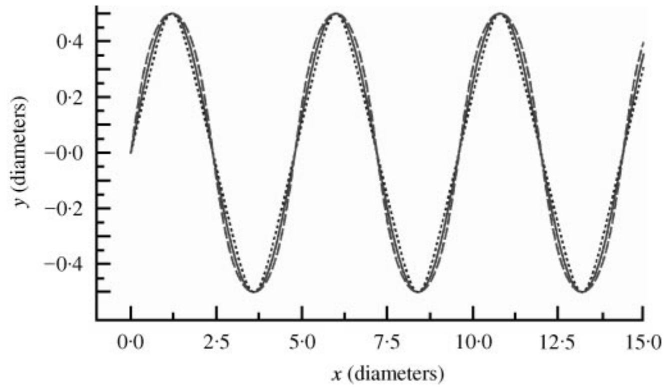

Figure 2. Trajectory of the cylinder in an X–Y plane. Although the transverse scale is greatly exaggerated, the effect of the streamwise perturbation is barely visible.

3. EXPERIMENTAL SETUP

The experiments were conducted in a low-speed water tunnel located at Caltech. Above the test-section, a two-independent-axes traversing system was mounted, which permitted arbitrary motions in the streamwise and transverse directions. Glass cylinders between 2 and 2·5 cm were used; with a test-section approximately 45 cm wide and 58 cm deep, this gives about 5% blockage and an aspect ratio around 25 : 1. A schematic of this setup is shown in Figure 3.

Data were taken with a digital particle image velocimetry (DPIV) system and a strain gage force balance. The DPIV system used a pulsed laser to illuminate the region around the cylinder and a video camera looking from underneath. To minimize parallax effects (i.e., the bottom of the cylinder obstructing the view near the plane of interest), the camera was placed approximately 6 m from the imaging plane. The strain gage balance was located between the cylinder and traverse and was used to verify lift and drag forces computed from the flow data. In order to keep the flow velocities low enough for the traverse and the DPIV system, freestream velocities of the order of 4–6 cm/s were used. This results in very low force values; consequently, an alternative force deduction method was also employed (Noca *et al.* 1997, 1999).

4. RESULTS

To facilitate the comparative effects of streamwise motion, the phase-averaged nondimensional vorticity fields are plotted in Figures 4 and 5. (Vorticity is scaled by the freestream velocity and the cylinder diameter.) In each figure, the data is taken at the same relative transverse phase, so that the only differences should arise from differences in the cylinder motion. Each column represents data taken at the same transverse frequency and each row, data at the same class of streamwise motion. In particular, Figure 4 is taken when the cylinder is near the upper extrema of motion, and Figure 5, when the cylinder is near the middle, during a falling stroke. It is worth pointing out here that the familiar “2S” and “2P” modes are recovered when only transverse motions are used.

By plotting the various cases at constant phase, the apparent phase flipping of the wake is also quite evident. For example, in Figure 4, the vortex that is about to be shed is consistently negative (leeward) on the higher-frequency motions and consistently positive on the lower-frequency motions.

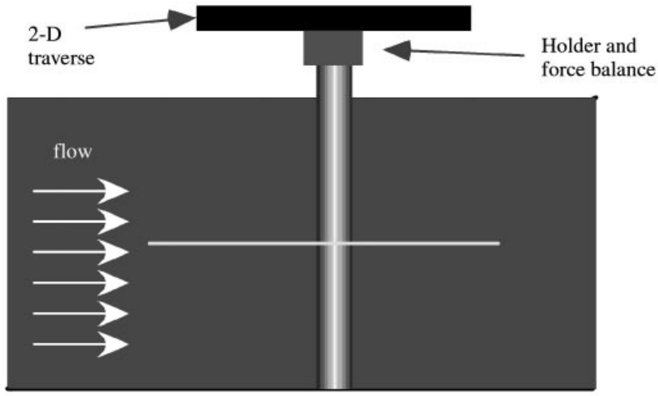

Figure 3. Schematic of the 2-DoF forced oscillation setup.

The computed lift forces are plotted in Figure 6. For comparison, lift is plotted both with and without the added mass term. In a sense, the "wake" component of the force (total lift – added mass) represents the work that the wake is doing on the cylinder. As expected from work like Bishop & Hassan's (1964), the total lift forces are nearly 180° out-of-phase in the transverse-only case. However, the phase relationship is not so simple once the streamwise motions are added.

5. DISCUSSION

The effect of streamwise motion on the wake is quite noticeable. In the higher-frequency case (2S), there is a dramatic increase in phase coherence. The vorticity plots change from blobs of vorticity into compact circular vortices. This is most likely due to a regularization of the phase of the vortex shedding. In other words, the streamwise motion helps to control when, within the period, a vortex is shed. In the lower-frequency case (2P), an equally dramatic change occurs — the disappearance of the 2P mode. The pairing mode is quite evident in the 1-DoF case and the motion of the pair is easily tracked through time. However, with the addition of streamwise motion, the second vortex in the pair does not seem to form. It is believed that the primary vortex of the pair is produced in either case, but that the streamwise motion suppresses the formation of the secondary vortex.

On the other hand, the effect of relative phase is more subtle. Figure 5 shows how the phase of the wake can be directly altered by the phase of the streamwise motion. For example in the higher-frequency case, at the same point in phase, the shed vortex is displaced by nearly a diameter in the streamwise direction. This again suggests that streamwise vibration affects the phase of shedding. The phase change is also reflected in the lift curves. Compare either the two dotted or solid lines in the lower two panels of Figure 6. The advance of the lift force relative to the cylinder motion is quite evident, caused solely by the change in the relative phase of the streamwise motion. This can have a large effect on the energy balance of the system. For example, similarly to Blackburn & Henderson (1999), the lower-frequency case showed a net power transfer from the wake, while the higher-frequency case was the opposite. When the streamwise motion is added, the lower-frequency case actually changes sign (transfers to the wake) at 0° phase and has more than 50% higher power gain at $-45°$ phase. It would seem, then, that the large transverse motion sets the frequency of shedding, but the streamwise motion affects the relative phase therein, and that the effects of relative phase are significant.

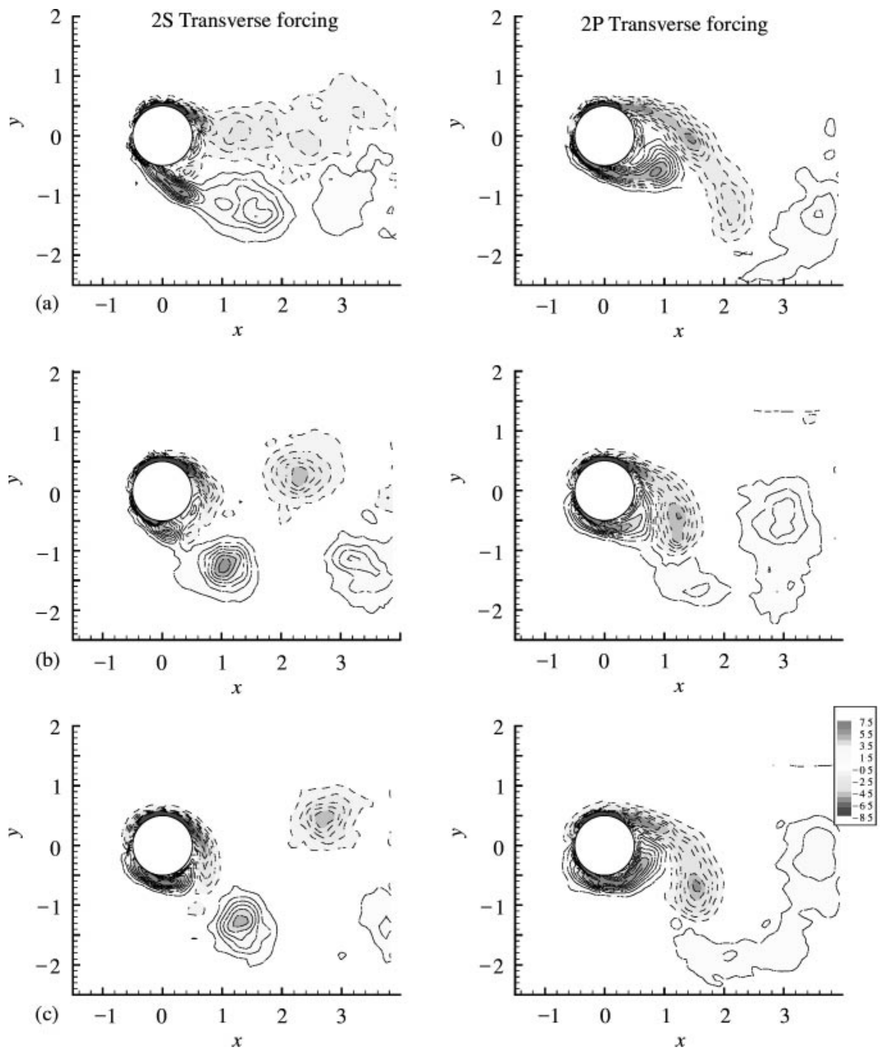

Figure 4. Comparison of the phase-averaged nondimensional vorticity in the wake of the oscillating cylinder. Cylinder approaching the upper extrema of motion (one-quarter period). Left column at higher frequency, right column at lower frequency (corresponding to the 2S/2P modes in the 1-DoF case). (a) No streamwise motion of the cylinder; (b) streamwise motion; $\phi = 0$; (c) streamwise motion, $\phi = -45°$.

Yet, it should not be surprising that streamwise motion of this magnitude should have a profound effect on the wake. If one looks at circulation production [see Morton (1984)], one sees that there are two primary sources of production for this class of problem: pressure gradients on the body and surface acceleration. Presuming the pressure gradients to change little between the various cases, one looks instead at the surface acceleration. Since the streamwise motion is at twice the frequency of the transverse motion, even though the motion amplitude is much smaller, the contribution to acceleration is quite comparable. Hence the contribution to circulation production from streamwise motion can be of the same order as that from transverse motion. This effect can be seen in the circulation of the shed vortices. For example, the 1-DoF cases resulted in vortices around 1·6 units of nondimensional circulation while their 2-DoF brethren were clustered around 2·1 units.

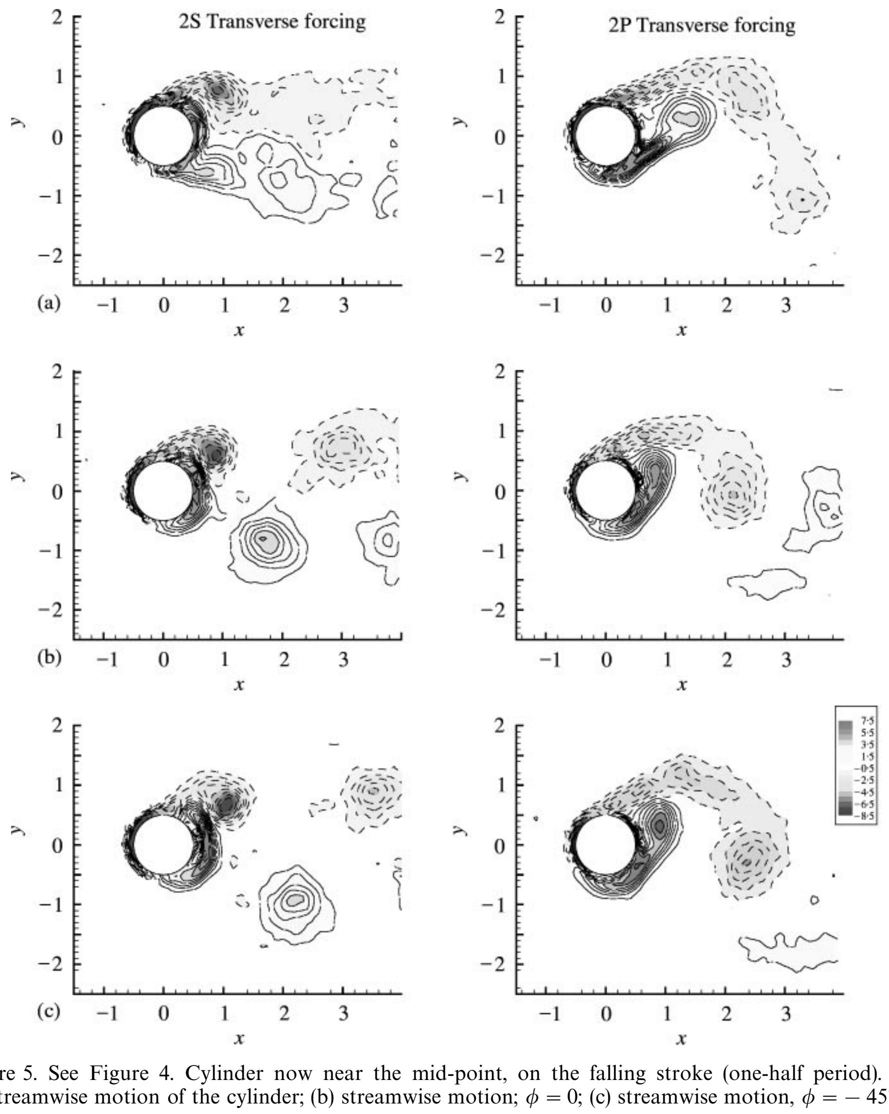

Figure 5. See Figure 4. Cylinder now near the mid-point, on the falling stroke (one-half period). (a) No streamwise motion of the cylinder; (b) streamwise motion; $\phi = 0$; (c) streamwise motion, $\phi = -45°$.

From a circulation production point of view, one cannot ignore the contribution from the streamwise motion.

At this point, it is worth considering Figure 7. Plotted here are the positions of the attached vortices as a function of phase. The origin is always centered on the cylinder, so the indicated positions are not in laboratory coordinates. Starting with the simplest case, consider first Figure 7(a), which corresponds to the high-frequency, no-streamwise-motion case. This results in the 2S wake mode, which can be easily seen in the vortex tracks. (One vortex trajectory from each side per cycle.) When the streamwise motion is added to this transverse motion [Figure 7(b, c)], the picture is qualitatively similar, although the vortices form and shed faster (formation/shedding time is indicated by the length of the track). Looking at motions at lower frequency [Figure 7(e, f)], one is first struck by the longer residence time of the vortices. Recall that in either case, only one vortex is formed and shed from each side in each cycle. Nevertheless, the residence time is nearly twice as long at lower

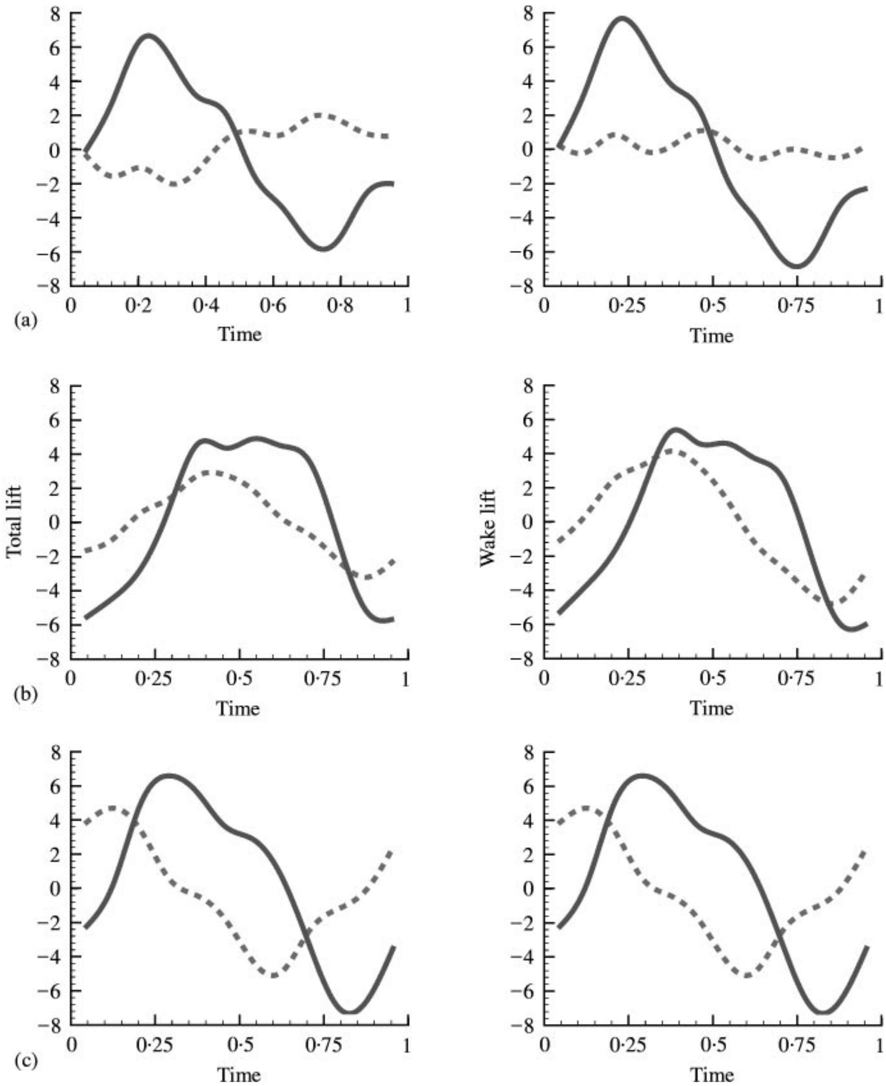

Figure 6. Deduced lift forces for the cases shown in Figures 4 and 5. Total lift on the left column and the wake component of lift on the right. - - -, 2transverse forcing, higher frequency; —, 2P transverse forcing, lower frequency. (a) No streamwise motion; (b) streamwise motion; $\phi = 0$; (c) streamwise motion, $\phi = -45°$.

frequency. Another interesting point is that formation happens on the opposite side of the cylinder. (A negative vortex resides on the upper side in the higher-frequency case and on the lower in the lower-frequency case.) This effect can be seen in either Figure 5 or 6 and is a result of the elongation of the vortical structure at lower frequency. The trajectory of the vortex pair in the 2P case is presented in Figure 7(d). The double tracks indicate the double vortices shed per cycle. It is worth pointing out that the first vortex formed on a given side appears to cross the axis and shed on the opposite side, pulling along the second vortex formed on the opposite side. This leads us to believe that the 2P mode is not so much a vortex pair (in the sense of a 2-D vortex ring) but more of a dominant primary vortex that pulls along the secondary vortex from the opposite side as it passes by.

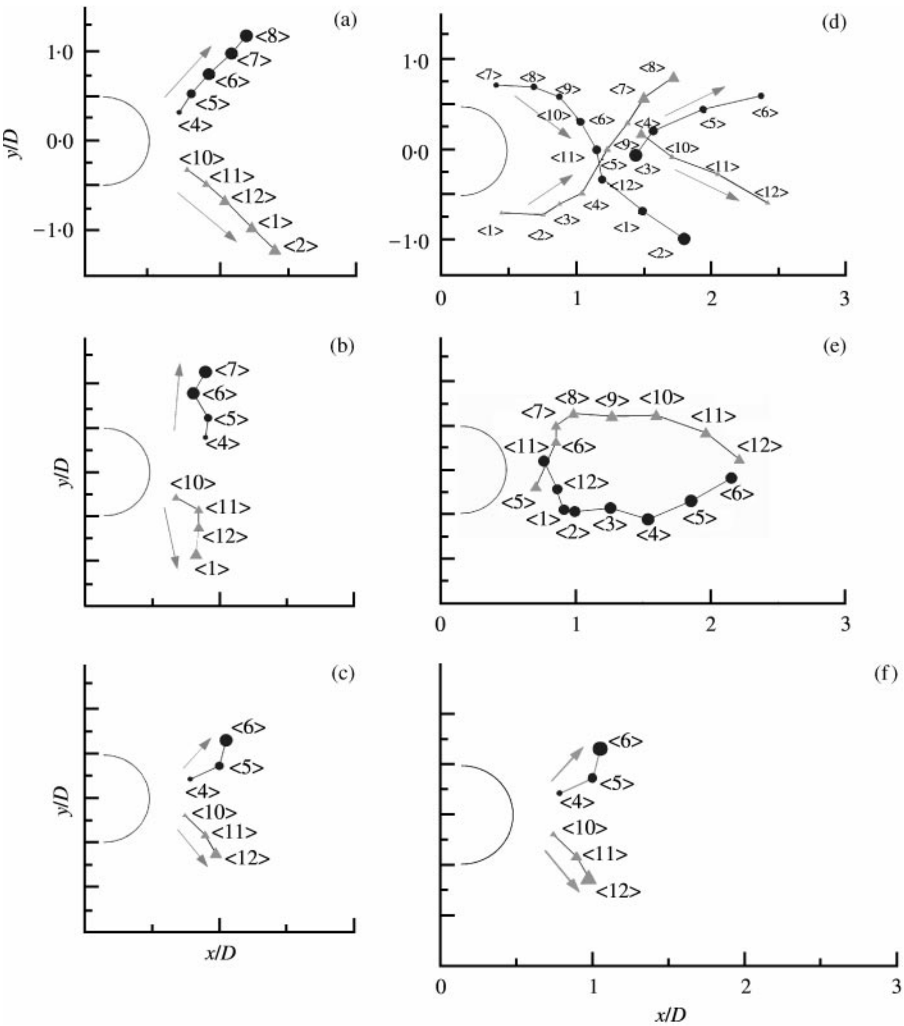

Figure 7(a–f). Trajectory of attached vortices in the wake of the cylinder: —●—, upper; —▲—, lower.

6. CONCLUSIONS

The importance of streamwise motion in forced vibration experiments has been presented here. The effect, seems primarily in the control of the phase of shedding. Changing the relative phase of shedding causes a corresponding change in the phase of the lift force. Since the energy transfer between the body and the wake is sensitive to the relative phase between the force and the body motion, the phase of the streamwise motion can control even the sign of energy transfer (wake driving the body or *vice versa*).

The addition of streamwise motion also resulted in qualitative changes in the wake. Perhaps the most dramatic is the disappearance of the pairing mode. When only a transverse vibration is used, the 2P mode is observed in our experiment; however, the wake reverts to shedding single vortices once this relatively small streamwise component is added. Since unconstrained systems will tend toward 2-DoF motions, it is hoped that this experiment has shed some light on the significance of streamwise vibration. It would seem that the effect is much more pronounced than the motion amplitude would imply.

ACKNOWLEDGEMENT

The authors would like to thank the Office of Naval Research under grant ONR-N00014-94-1-0793 for their patience and generous support of this project.

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