Special Brief Communication

Controlled oscillations of a cylinder: a new wake state

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Abstract

The wake states resulting from the controlled oscillation of a cylinder transverse to the free stream are presented. A new wake state is revealed by instantaneous measurements of the total and vortex lift phases, and the phase-referenced, quantitative wake structure. This "intermediate wake state" occurs at oscillation frequencies between the previously observed low- and high-frequency states. It cannot be deduced from classical, time-averaged representations of the loading on the cylinder.

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1. Introduction

The flow-induced motion of a body in a free stream is important in the design and maintenance of engineering structures. Periodic forcing caused by the regular shedding of vortex structures can excite the natural structural frequency of the body, resulting in vortex- or flow-induced motion. A common approach to studying fluid-structure interactions is to force the body to oscillate with a predefined motion that approximates the flow-induced motion. This is done with the intent of simulating the loading and wake structures of the freely oscillating case. One of the most robust and widely studied cases is that of a circular cylinder constrained to oscillate transverse to the free stream. A number of investigations have considered either the elastically mounted freely oscillating case, or the controlled motion case, where the cylinder's motion is a pure sinusoid:

$$y(t) = A \sin(2\pi f_e t). \tag{1}$$

As the frequency at which the cylinder is forced to oscillate, f_e, passes through the natural Kármán frequency of the stationary cylinder wake, f_o, a number of changes occur. At $f_e/f_o \approx 1$ Bishop and Hassan (1963), and a number of subsequent investigations, observed abrupt changes in the averaged values of both the phase and amplitude of the lift force on the cylinder. Additionally, at $f_e/f_o \approx 1$, a change in either the mode of vortex shedding, or in the sign of the phase-referenced vortex structures, have been observed by a number of investigations, including Williamson and Roshko (1988) and Ongoren and Rockwell (1988). The work of Carberry et al. (2001a, 2002) showed that these changes are intrinsically linked and correspond to a transition between two distinctly different wake states: the low- and high-frequency states. For the case of a freely oscillating cylinder, Khalak and Williamson (1999) found a transition between two different response branches, the initial and lower branches, at $f_e/f_o \approx 1$. Additionally, at low mass-damping values, they observed a third upper response branch between the initial and lower branches. The wake states and response branches are characterised by the structure of the near wake as well as the total and vortex forces on the cylinder. Essentially, the total force is made up of two components: the vortex force, due to changes in the position and strength of vortex structures in the wake, and the apparent mass force generated by the acceleration of fluid as the body

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accelerates, as discussed by Leonard and Roshko (2001). Thus,

$$F_{\text{total}} = F_{\text{vortex}} + F_{am}, \tag{2}$$

or in terms of the lift force coefficients

$$C_L(t) = C_{L\,\text{vortex}}(t) + C_{L\,am}(t). \tag{3}$$

When the wake is "locked-on" to the motion of the cylinder, the total and vortex lift forces can be approximated by sinusoidal functions:

$$C_L(t) \approx C_L \sin(2\pi f_e t + \phi_{\text{lift}}), \tag{4}$$

$$C_{L\,\text{vortex}}(t) \approx C_{L\,\text{vortex}} \sin(2\pi f_e t + \phi_{L\,\text{vortex}}). \tag{5}$$

Thus C_L and $C_{L\,\text{vortex}}$ are the amplitude of the total and vortex lift forces respectively, and ϕ_{lift} and $\phi_{L\,\text{vortex}}$ are the phases with respect to the displacement of the cylinder. The extraction of the vortex lift force from the total lift force on an oscillating cylinder, and in particular the phase of the vortex lift force, was first used by Govardhan and Williamson (2000) in their study of an elastically mounted cylinder. Subsequently, Carberry et al. (2001b, 2002) considered both the total and vortex forces on a cylinder undergoing controlled oscillations.

Carberry et al. (2002) showed that for the low- and high-frequency states, the general frequency dependence of the total and vortex lift phases is similar, in particular the transition between the two states corresponds to a jump in both ϕ_{lift} and $\phi_{L\,\text{vortex}}$. The transition also corresponds to a change in both the mode and phase of vortex shedding.

To date the wake states of a cylinder undergoing controlled oscillations have been characterised in terms of either the total or vortex forces on the cylinder, rather than considering the simultaneous behaviour of both parameters. In particular, the temporal variation of both the total and vortex forces on the cylinder and the corresponding near wake flow field has not been examined. In this work, a third, previously unknown, state has been found using simultaneous force measurement and quantitative imaging. The properties of the new wake state are discussed and compared with those of the low- and high-frequency states.

2. Experimental method

A brief description of the experimental method is outlined below. For further details, the reader is referred to Carberry et al. (2002) and Carberry (2002), where the same experimental method was used. The experiments were performed in a free surface water channel with a working section width 914 mm, depth 609 mm and length 4928 mm and a turbulence level of less then 0.1%. A 25.4 mm diameter cylinder, with an aspect ratio of 12.5, was oscillated transverse to the free stream such that its displacement is given by Eq. (1). The results discussed in this paper are for two oscillation amplitudes, $A/D = 0.5$ and 0.6, where for both cases $\mathcal{R}e = 2300$. Over the range of oscillation frequencies considered, $0.5 \leqslant f_e/f_o \leqslant 1.4$, the wake was "locked-on" to the motion of the cylinder and the total and vortex lift forces could be represented by Eqs. (4) and (5), respectively. For each value of f_e/f_o the cylinder started oscillating from rest at $t = 0$ corresponding to the beginning of the force measurements.

The span-averaged lift force on the cylinder and the near wake flow field were measured simultaneously, allowing direct comparison of the lift force with the wake structure. The force on the cylinder was measured using strain gauges configured in a full Wheatstone bridge, and the lift force calculated by subtracting the time varying mass inertia force from the measured force trace. The instantaneous near wake velocity fields were measured using a laser scanning PIV technique, described in detail by Rockwell et al. (1993). The images were recorded onto a 35 mm high-resolution film and interpolated using a single-frame cross-correlation technique. A 90×90 pixel interrogation window with a 0.50 overlap ratio resulted in 3700 vectors per field.

3. Intermediate wake state

The low- and high-frequency wake states have characteristic wake structures and force properties, as described by Carberry et al. (2001, 2002). However, at certain amplitudes of oscillation, there is a third wake state, located between the low- and high-frequency states, which we will call the intermediate state. The intermediate state is an independent state whose phase-referenced wake structure and characteristic lift forces are distinctly different from either the low- or high-frequency wake states. In the following section, we describe the properties of the intermediate state in terms of the lift forces on the cylinder and the phase-referenced structure of the near wake.
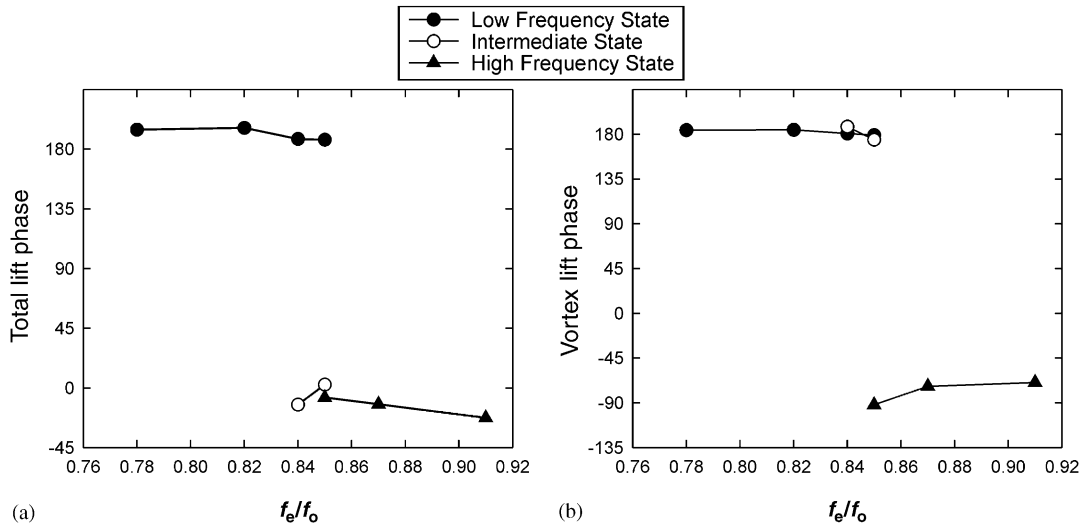
Fig. 1. Variation of ϕ_{lift} and $\phi_{L\text{ vortex}}$ with f_e/f_o showing the three wake states, $A/D = 0.6$, $\mathscr{R}e = 2300$.

The frequency dependence of the wake was considered over a range of oscillation and flow parameters: $(A/D, \text{Re}) = \{(0.25,4410),(0.25,9100),(0.4,2300),(0.5,2300),(0.5,4410),(0.5,9100),(0.6,2300)\}$. The intermediate state was only observed at the two highest oscillation amplitudes, $A/D = 0.5$ and 0.6, at Re = 2300. The properties of the intermediate wake state will be discussed using the results from these two sets of experiments.

The variation of the total and vortex lift phases with f_e/f_o for the low-frequency, intermediate and high-frequency states are shown in Figs. 1a and b, respectively. The low-frequency state is characterised by high values of both ϕ_{lift} and $\phi_{L\text{ vortex}}$, whilst for the high-frequency state ϕ_{lift} and $\phi_{L\text{ vortex}}$ are both low. Thus when the intermediate state is not present, or is not resolved, the transition between the low- and high-frequency states is interpreted as a jump in both ϕ_{lift} and $\phi_{L\text{ vortex}}$. However, when the wake transitions to the intermediate state from either the low- or high-frequency states, the changes in ϕ_{lift} and $\phi_{L\text{ vortex}}$ are markedly different. For the intermediate state the value of the total lift phase is small and similar to that of the high-frequency state, whilst the vortex lift phase is similar to that observed for the low-frequency state. Thus the transition from the low-frequency to the intermediate state is characterised by a jump in ϕ_{lift} while $\phi_{L\text{ vortex}}$ remains essentially unchanged, but at the intermediate to high-frequency transition, ϕ_{lift} changes very little, and there is a jump in $\phi_{L\text{ vortex}}$.

3.1. Transition between states

At both $A/D = 0.5$ and 0.6, the intermediate state occurred over a relatively narrow range of oscillation frequencies. At these oscillation amplitudes, the wake did not move to the intermediate state immediately after the cylinder, initially at rest, started oscillating at a constant amplitude and frequency. Rather, the intermediate state was observed after a self-excited transition from either the low- or high-frequency states. In Fig. 2a, the self-excited transition from the low-frequency state to a stable intermediate state is shown for $A/D = 0.6$ and $f_e/f_o = 0.84$. Immediately after the oscillations begin, the values of both ϕ_{lift} and $\phi_{L\text{ vortex}}$ are high and the wake is in the low-frequency state. Before $t \approx 223$ s, there appear to be a number of short duration transitions to the intermediate state: ϕ_{lift} drops abruptly towards $0°$ while $\phi_{L\text{ vortex}}$ remains high and close to $180°$. However, the transitions to the intermediate state within the first 200 s appear to be unstable as the wake returns to the low-frequency state after only a small number of oscillations. At $t \approx 223$ s there is a final self-excited transition to a stable intermediate state, and the wake remains in this state until the end of the experiments at $t \approx 320$ s.

3.2. Relationship between the total and vortex lift forces

The characteristic values of the lift phase are commonly used to identify the different wake states and, as shown in Fig. 1, clear identification of the intermediate state requires the evaluation of both the total and vortex lift forces.
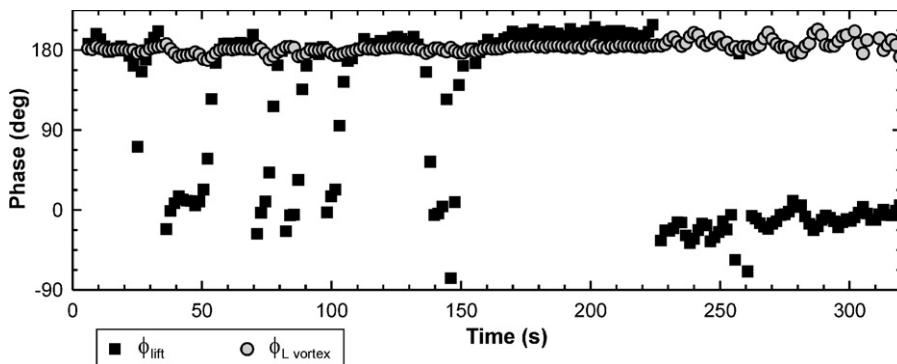
Fig. 2. Time variation of ϕ_{lift} and $\phi_{L\,\text{vortex}}$ showing transitions from the low-frequency state to the intermediate state, with a stable transition occurring at $t = 223$, $A/D = 0.6$, $f_e/f_o = 0.84$.
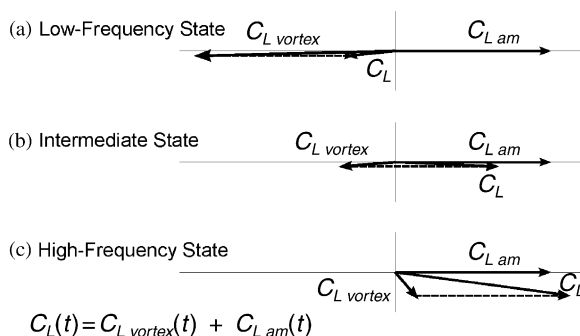

Fig. 3. Vector diagram showing the relationship between the phases and amplitudes of $C_L(t)$, $C_{L\,\text{vortex}}(t)$ and $C_{L\,\text{am}}(t)$ for the low-frequency, intermediate and high-frequency states.

The relationship between the total and vortex lift forces, described by Eq. (3), is an apparently simple vectorial addition. However, the behaviour of these forces as the wake moves between the different states is not always intuitive.

The vectorial relationships between the total, vortex and apparent mass lift forces are shown in the phase plots of Fig. 3 using typical values for all the three wake states. The direction and magnitude of each vector represents the phase and magnitude of the lift forces, respectively, where the displacement of the cylinder (not shown) lies along the $0°$ axis. The apparent mass force is always in-phase with the displacement of the cylinder and its magnitude varies with $(f_e/f_o)^2 A/D$. For the cases in Fig. 3, A/D is constant and f_e/f_o changes very little; thus the magnitude of $C_{L\,\text{am}}(t)$ is essentially constant. The total lift force depends on both the vortex and apparent mass forces, but as the apparent mass force in Fig. 3 is essentially constant, the changes in the total lift force are instigated by changes in the vortex lift force. In the following discussion, it is shown that the nature of the changes in the total lift force are directly linked to the way in which the vortex lift force changes relative to the apparent mass force.

For the low-frequency state, the vortex and the apparent mass forces are approximately out of phase with each other and $C_{L\,\text{vortex}}$ is greater than $C_{L\,\text{am}}$, the magnitude of the apparent mass force. The resulting value of ϕ_{lift} is similar to that of $\phi_{L\,\text{vortex}}$, as indicated by the direction of the vectors in Fig. 3(a). When the wake moves from the low-frequency to the intermediate state, the change in $\phi_{L\,\text{vortex}}$ is relatively small; however, the magnitude of $C_{L\,\text{vortex}}$ decreases to become smaller than $C_{L\,\text{am}}$. The change in the relative magnitudes of the vortex and apparent mass forces causes a large change in the phase of the resultant total lift force. Thus the change ϕ_{lift} is linked to the change in the relative magnitudes of $C_{L\,\text{vortex}}$ and $C_{L\,\text{am}}$. The transition from the intermediate to the high-frequency state corresponds to a change in $\phi_{L\,\text{vortex}}$, but $C_{L\,\text{vortex}}$ remains much smaller than $C_{L\,\text{am}}$ and the change in ϕ_{lift} is relatively small.

The phase and magnitude of the vortex lift force relate directly to changes in the vorticity field. Therefore, the changes in the total lift force are linked to the vorticity field via the relationship between the vortex and apparent mass forces. As demonstrated by Fig. 3, this relationship can produce some unexpected results.

3.3. Wake structures

The phase-averaged vorticity fields in Fig. 4 show the structure of the near wake at the top and mid-point of the cylinders' downwards stroke for each of the three wake states. Each image has been calculated by phase averaging nine consecutive images representing four and one-half oscillation cycles of the cylinder. The wake patterns shown in Fig. 4 at $A/D = 0.5$ for the three different states are similar to those observed at $A/D = 0.6$.

The low-frequency wake in Fig. 4(a) is characterised by the formation of long extended shear layers with a relatively wide wake. The mode of vortex shedding is described as 2P, with two counter-rotating vortex pairs shed per oscillation cycle. As the cylinder moves through the downward stroke, two separate negative vortex structures are shed into the near wake. The first and weaker of these structures separates from the end of the shear layer not long after the top of the oscillation. However, the major large-scale shedding of negative vorticity occurs close to the mid-point of the downward stroke, as captured in the right-hand image of Fig. 4(a). The mode of vortex shedding for the high-frequency wake, shown in Fig. 4(c), is the Kármán mode, which is also known as the 2S mode, and the wake is significantly narrower than the low-frequency wake. Moreover, the phase of vortex shedding clearly differs from the low-frequency wake, with positive vorticity shed into the lower half of the wake soon after the top of the cylinder's oscillation cycle.

The development of the vorticity patterns for the intermediate state wake, as evidenced by the phase-referenced images, is shown in Fig. 4(b). These are different from those of both the low- and high-frequency wakes. However, intriguingly it shares some features with each of the other wake states. As the cylinder moves downwards, a single tightly formed positive vortex is shed from the upper surface of the cylinder, and the mode of vortex shedding for the intermediate state can be described as 2S. Thus at $A/D = 0.5$, and also at $A/D = 0.6$, the intermediate and high-frequency states have the same general mode of vortex shedding. However, the phase-referenced images in Fig. 4 show
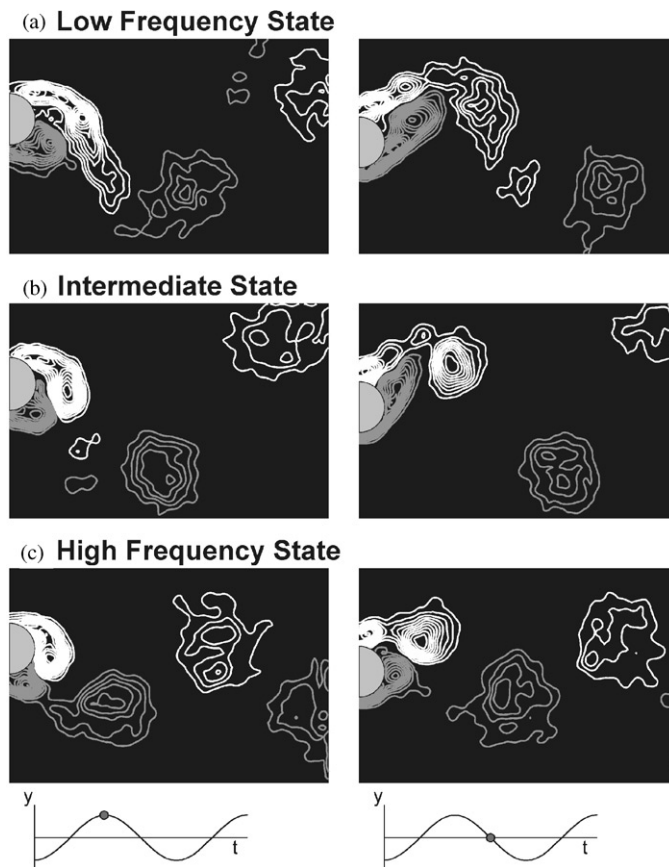

Fig. 4. Phase averaged vorticity fields at the top and mid-point of the downward motion of the cylinder for (a) low-frequency, (b) intermediate and (c) high-frequency states. $A/D = 0.5$, $\mathcal{R}e = 2300$.

that the phase of large-scale vortex shedding for the intermediate state is similar to that of the low-frequency state. In both cases the large-scale negative vortex structures are shed close to the mid-point of the downward stroke. Additionally, both wakes have a similar wide vertical distribution of vorticity. There are also clear differences in the low-frequency and intermediate wakes. In the left column of Fig. 4, at the top of the oscillation cycle of the cylinder, the negative vorticity in the upper shear layer of the low-frequency wake extends well into the lower half of the wake. The corresponding negative vorticity in the intermediate wake forms a tight structure that is adjacent to the base of the cylinder.

In conjunction with the lift phases of Fig. 1, the phase-referenced vorticity fields in Fig. 4 clearly show that the intermediate state is distinctly different from both the low- and high-frequency states. The properties of the intermediate state described above are remarkably similar to the properties of the upper response branch of an elastically mounted cylinder described by Govardhan and Williamson (2000).

An interesting aspect of the three wake states is the relationship between the mode and phase of vortex shedding and the phases of the total and vortex lift forces, where the vortex lift force relates directly to changes in the vorticity field. The vorticity fields in Fig. 4(a) and (b) show that the phase of large-scale vortex shedding for the low-frequency and intermediate states is approximately the same, but the mode of vortex shedding is different. This is consistent with the fact that the values of $\phi_{L\,\mathrm{vortex}}$, representing the phase of vorticity movement in the near wake, are similar. The values of ϕ_{lift} for the two states are very different, where, as discussed previously, this is due to a change in the magnitude of the vortex lift force. The change in the magnitude of $C_{L\,\mathrm{vortex}}$ is consistent with the observed changes in the phase-referenced distribution of vorticity and the mode of vortex shedding. As the wake moves from the intermediate to high-frequency state, there is a jump in $\phi_{L\,\mathrm{vortex}}$ that corresponds to a large change in the phase of vortex shedding.

4. Conclusions

A cylinder forced to oscillate transverse to a free stream is known to exhibit at least two different wake states: the low- and high-frequency states. Traditionally, these states have been characterised using the time-averaged properties of the total lift force and the structure of the near wake. In this work, the wake states have been described using a combination of instantaneous values of ϕ_{lift} and $\phi_{L\,\mathrm{vortex}}$ and the corresponding wake structure. This method reveals the existence of a third, new wake state, whose phase-referenced wake structure and characteristic lift forces are distinctly different from either the low- or high-frequency wake states.

Acknowledgements

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