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Experimental studies of passive control of vortex-induced vibration

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Abstract

Measurements of vortex-induced vibration of a plain circular cylinder and cylinders fitted with strakes and bumps are presented. Experiments were carried out in water with mass ratios in a range from about 1.5 to 5.5 and combined mass and damping values between about 2×10^{-3} and 7×10^{-3}. Reynolds numbers were within the range 10^3 to 10^4. Although the wakes of fixed cylinders with strakes or bumps show little or no evidence of regular vortex shedding it was found to establish itself across a range of reduced velocity when the mass and damping parameters are sufficiently small. However, the amplitudes of vibration were less than those for a plain cylinder. It is observed that the modes of shedding found for an oscillating plain cylinder are also present for a responding cylinder fitted with vortex suppression devices.

1. Introduction

The possibility of vortex-induced vibrations (VIV) of cylindrical, or near cylindrical, bluff bodies presents a serious design constraint for many types of structure. The likelihood of VIV is greatly increased if the structure has low density, compared to the surrounding fluid medium, and low structural damping and hence the problem can become particularly acute for cylindrical structures in flowing water. The damaging oscillations possible with VIV has led to the development of a number of passive methods to reduce the magnitude of the periodic fluctuating side force resulting from regular vortex shedding with the aim of lessening or even completely suppressing VIV. These techniques, which in many applications need to be equally effective in all flow directions, entail modification of the body geometry and most often involve the introduction of some three-dimensional disturbance into the flow. A wide range of passive VIV suppression methods has been reviewed by Zdravkovich [1]. The literature on VIV reveals that research is also being carried out into active control techniques but only passive methods will be discussed here. In most practical applications the need for simplicity and reliability has led designers to favour passive control measures.

The most successful application of a passive technique is found in wind engineering where helical strakes are used to suppress VIV of steel chimneys and other types of slender, circular cross-section towers. Strakes, which were first studied by Scruton and Walshe [2], are fitted to the top third of a structure and are normally three start with a pitch of 5 tower diameters and a height equal to 10% of the tower diameter. While strakes are effective in suppressing VIV of lightly damped steel chimneys they introduce a substantial increase in drag and hence increase base bending moments. Flow separation position is most likely fixed at the sharp edges of the strakes and the well known Reynolds number dependence of the drag coefficient, C_D, of a circular cylinder disappears with a straked cylinder. For a circular cylinder fitted with strakes with a height equal to 10% of the cylinder diameter C_D is equal to about 1.4, using the cylinder diameter as the reference length, over a wide range of practical Reynolds numbers. There has been no convincing explanation as to why strakes are so effective at suppressing VIV of chimneys. A popular theory is that the strakes do not necessarily suppress shedding but they prevent the shedding from

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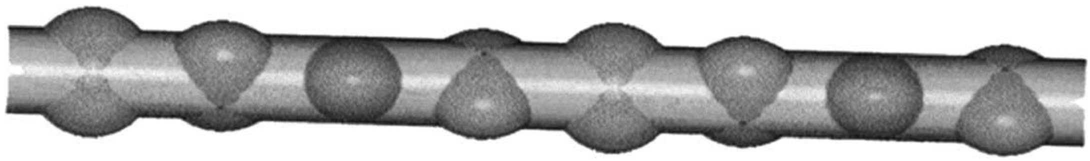

Fig. 1. Circular cylinder fitted with bumps.

becoming correlated along the span. However, it seems equally possible that the three-dimensionality of the separating flow introduced by the strakes could destroy regular vortex shedding. For example, experiments reported by Bearman and Owen [3] on fixed bluff bodies with wavy flow separation lines have indicated complete suppression of vortex shedding.

Introducing strakes is not an efficient design solution because of the need for the structure to be strengthened to resist the increased base bending moment caused by the higher drag. Nowadays it is more common for chimneys to be built without strakes but with significantly enhanced structural damping. A popular method of enhancing stability of chimneys is to attach a tuned damper at the free end. However, adding significant damping is normally not a practical option for cylindrical structures in flowing water. The experience in the offshore industry is that when strakes of a similar design to those used on chimneys are applied to riser pipes exposed to a current VIV is still observed to occur although the transverse amplitudes attained are less than those for a bare pipe. While some modification to vortex shedding does take place it is clear that for a flexible cylinder these strakes neither suppress vortex shedding nor prevent it becoming correlated in the spanwise direction. Unacceptable levels of transverse oscillation are prevented from developing in riser pipe applications by increasing the height of the strakes above the values typically used in wind engineering. This causes even further increases in drag above that for a plain cylinder.

It is not difficult to understand why VIV is more challenging to suppress in water than in air, particularly if we use the simplistic fluid/structure interaction model described by Bearman [4]. The structure is represented by a linear mass-spring-dashpot system with mass M, fraction of critical damping δ_S and natural frequency in the absence of fluid effects N_0. It is assumed that for large amplitude VIV the structure has a constant amplitude, harmonic response y, where $y = y_m \sin 2\pi N t$ and y_m is the maximum value of the transverse displacement and N is the observed frequency of oscillation. The transverse force due to vortex shedding drives the oscillator system and is assumed to lead the transverse displacement by a phase angle ϕ, where the maximum force is given by $F_m = C_{ym} 1/2 \rho U^2 D$. Here ρ is fluid density, U is flow velocity, D is cylinder diameter and C_{ym} is the maximum value of the transverse force coefficient. It is assumed that the instantaneous transverse force coefficient, C_y, is given by $C_y = C_{ym} \sin(2\pi N t + \phi)$. If the assumed solutions for C_y and y are substituted into the oscillator equation then the ratio of the oscillation frequency to the natural frequency is given by Eq. (1) and the amplitude y_m/D is represented by Eq. (2).

$$N/N_0 = \left[1 - C_{ym} \cos\phi \left(1/4\pi^2\right)\left(\rho D^2/2M\right)(U/N_0 D)^2 (y_m/D)^{-1}\right]^{1/2}, \tag{1}$$

$$y_m/D = C_{ym} \sin\phi \left(1/8\pi^2\right)\left(\rho D^2/2M\delta_s\right)(U/N_0 D)^2 (N_0/N). \tag{2}$$

A key parameter in Eq. (1) is the mass parameter $2M/\rho D^2$. For a similar structure exposed to first air and then water this parameter reduces by a factor of about 800. Hence in air it is likely that N/N_0 will be very close to 1 whereas in water it can be substantially different, and vary with reduced velocity, $U/N_0 D$. Eq. (2) shows that the amplitude of oscillation depends on the inverse of the combined mass-damping parameter $2M\delta_s/\rho D^2$. In the context of wind engineering this parameter is referred to as the Scruton number. So even if strakes are successful in reducing C_{ym}, Eq. (2) indicates that it is more difficult to suppress any resulting VIV in water compared to air because of the much smaller mass-damping parameter.

It should be noted that there are different definitions of mass ratio in use. An alternative form, m^*, is given by $4M/\rho\pi D^2$, which can be seen to be equal to the system mass divided by the mass of fluid displaced by the cylinder. m^* is used in the rest of the paper. The coefficient C_y includes the total contribution from the fluid and for an oscillating cylinder combines an inertia component related to the potential flow field and a vortex component derived from the vorticity field. For VIV to occur Eq. (2) shows that ϕ must be greater than 0° but less than 180 degrees. If ϕ is between 0° and 90° then from Eq. (1) the frequency of oscillation will be less than the natural frequency whereas for ϕ between 90° and 180° the structure will oscillate at a frequency above its natural frequency.

Owen et al. [5] studied an alternative means of reducing C_{ym} through the use of 'bumps' attached to the cylinder surface, as illustrated in Fig. 1. For a fixed circular cylinder fitted with bumps they found no predominant vortex shedding frequency and a reduction in drag below that for a plain cylinder. However, just as for strakes, they found that a flexible cylinder with bumps and a low mass-damping parameter, $m^*\delta_S$, of 0.036 experienced VIV but with a lower amplitude than that for a circular cylinder without bumps.

The aim of this paper is to describe the results of a study into VIV of a circular cylinder with low mass and damping and fitted with two forms of vortex shedding suppression device: strakes and bumps. Flow visualisation is used to investigate the

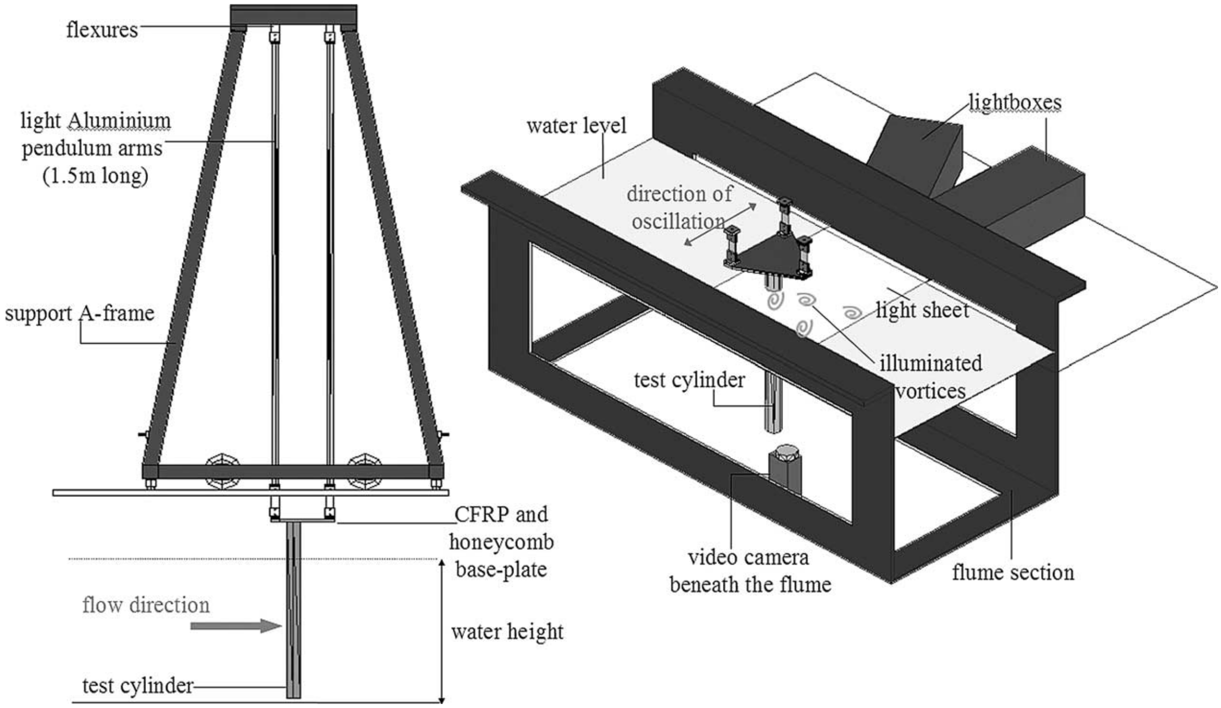

Fig. 2. The pendulum rig and flow visualisation set-up used to investigate VIV in a water flume.

modes of vortex shedding and to determine if the 2S, 2P and possibly P + S modes, as observed by Williamson and Roshko [6] for a plain circular cylinder, are found on cylinders undergoing VIV but fitted with suppression devices.

2. Experimental arrangement

Experiments were conducted in a water channel in which the flow speed can be varied up to 0.3 $m \cdot s^{-1}$. The test section is 0.61 m wide by 0.69 m deep by 1.8 m long and is fitted with large glass windows that allow the flow to be observed from all sides. To maintain good flow quality in the test section, the settling chamber is fitted with a honeycomb grid and several fine screens, followed by a 4 : 1 contraction. The cylinder suspension system used for most of the experiments is shown in Fig. 2 and it consists of a light-weight platform supported by three pendulum arms from a heavy A frame. This ensured both low mass and low damping and constrains cylinders to move in the transverse direction. In order to achieve even lower values of the mass-damping parameter an air bearing suspension was constructed following closely the earlier design of Anagnostopoulos and Bearman [7].

The models used were constructed from thin-wall aluminium tube 0.6 m long with an outer diameter of 44 mm. For the cylinder fitted with strakes, the height of the strakes was equal to 12% of the cylinder diameter and they were three start with a pitch of 5 diameters. The arrangement of bumps shown in Fig. 1 was similar to that described by Owen et al. [5] with an angular separation of 45°, a pitch of 7 diameters and a height equal to 0.25 of a diameter. Typically Reynolds numbers were in the range 10^3 to 10^4. A non-contacting fibre optic sensor was used to measure transverse cylinder displacement. In order to visualise the flow a fluorescent dye was used and vortex shedding sequences were recorded on video. The arrangement for the visualisation can be seen in Fig. 2.

3. Results and discussion

Fig. 3 shows the maximum transverse amplitude non-dimensionalised by diameter, y_{max}/D, for a plain cylinder plotted against reduced velocity. It should be noted that here reduced velocity is formed by using the frequency obtained by displacing the cylinder in still water and measuring the frequency of the decaying oscillations. The mass ratio for this experiment was 2.58 and the combined mass and damping parameter was 6×10^{-3}. For the plain cylinder the 2S mode of shedding was observed in the initial and upper branches, 2P in the lower branch up to V_r of about 12 and the P + S mode beyond that up to V_r of about 15. Also shown in Fig. 3 are measurements of the cylinder oscillation frequency divided by the oscillation frequency in still water. In the initial and upper branches the cylinder frequency is seen to follow the expected vortex shedding frequency for a fixed cylinder whereas in the lower branch the oscillation frequency is constant and about 50% higher than the still water frequency.

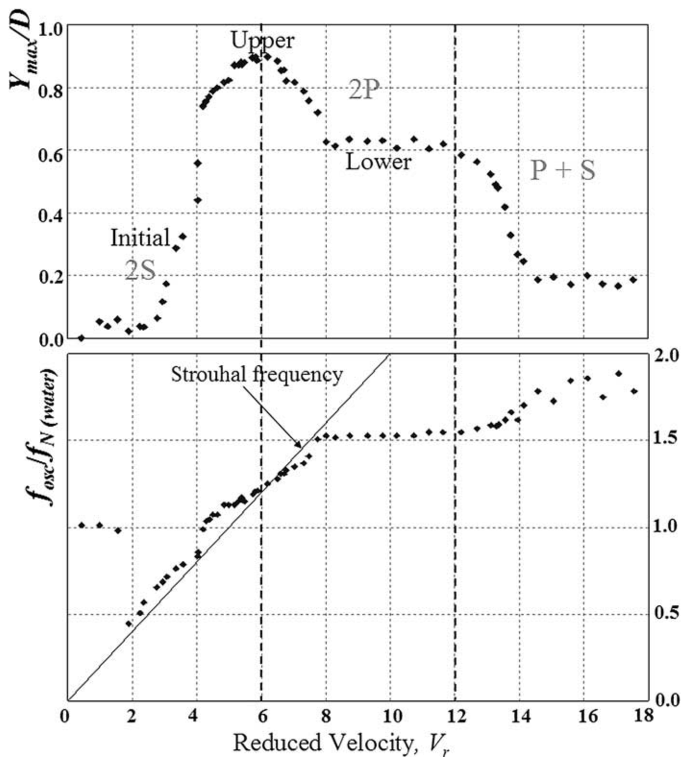

Fig. 3. Response characteristics for a plain cylinder with low damping and a mass ratio of 2.58.

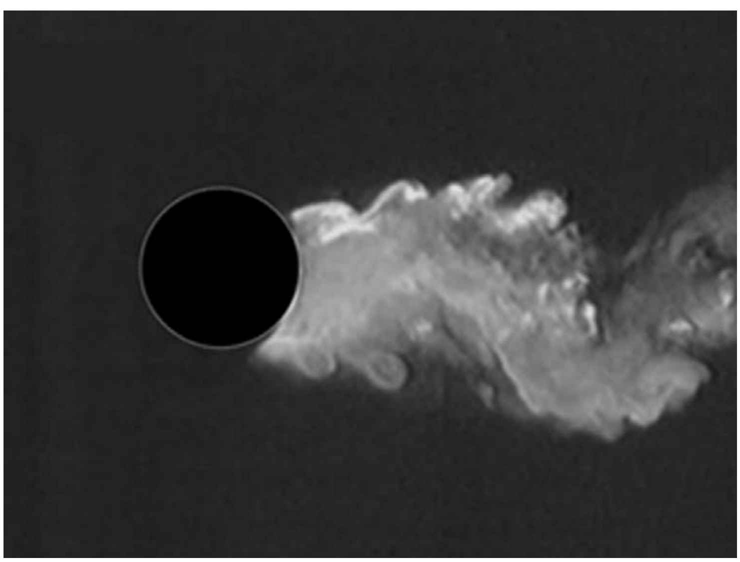

Fig. 4. Visualisation of the flow in the wake of a cylinder fitted with strakes.

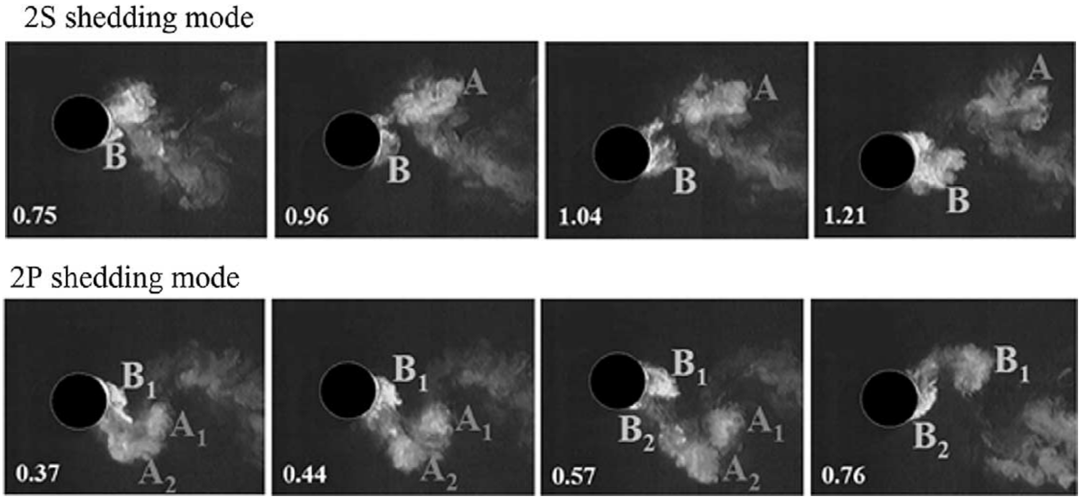

Fig. 5. Visualisation of vortex shedding from a responding straked cylinder showing the 2S and 2P mode.

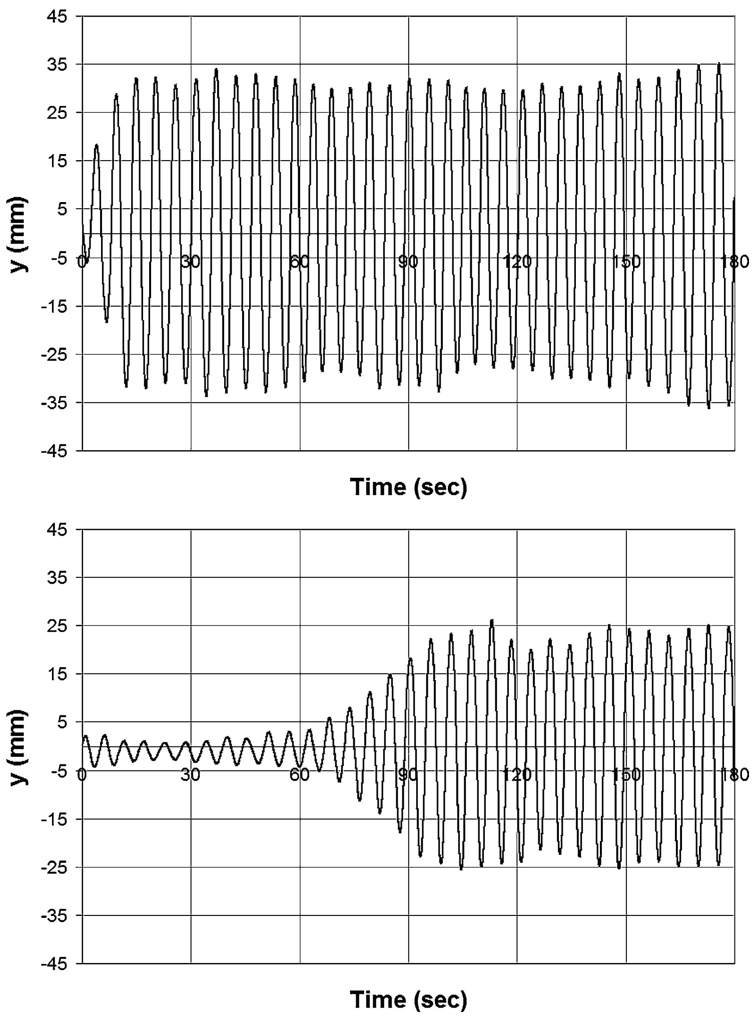

Fig. 6. Build up of response from rest for a plain cylinder (above) and a cylinder fitted with strakes (below), both with $m^*\xi \approx 0.007$.

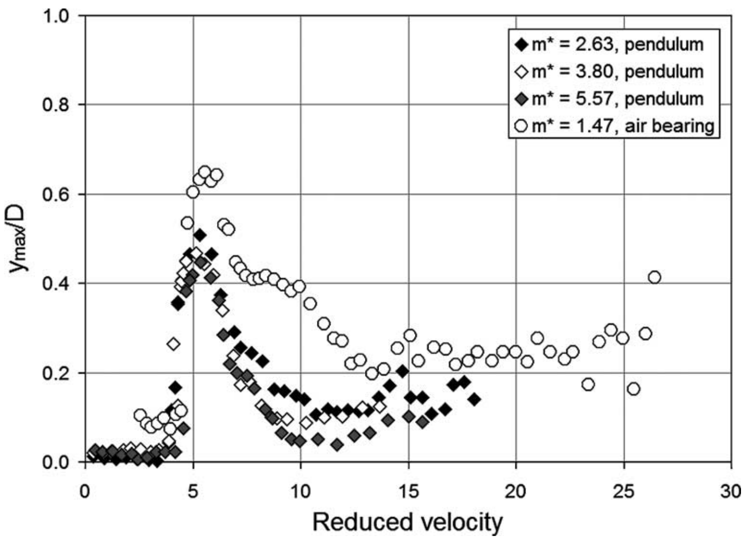

Fig. 7. Response of a straked cylinder for a range of low mass ratios.

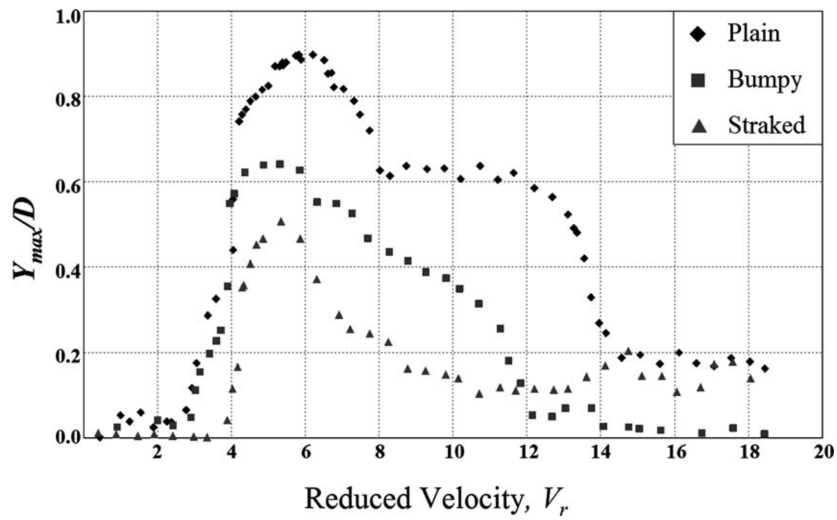

Fig. 8. Transverse response of a plain, straked and bumpy cylinder.

The response characteristics for a plain cylinder with low mass and damping are well established and have been described in detail by Govardan and Williamson [8].

Visualisation of the flow in the wake of a fixed straked cylinder is shown in Fig. 4. There is no evidence of Karman-type vortex shedding close to the cylinder but there is an undulation of the wake at about two cylinder diameters downstream. The most obvious feature in the photograph is the presence of shear layer vortices. However, when the cylinder is free to respond in a range of reduced velocity around 5 and the mass and damping are low the flow pattern changes dramatically. In what appears to be a random event, a vortex of significant strength is formed and shed from one side of the straked cylinder. The resulting force on the cylinder is sufficient to give it a substantial transverse displacement. As the cylinder returns from this excursion a vortex of opposite sign is formed and shed from the other side of the cylinder and VIV develops. In order for this to happen the mass-damping parameter needs to be below some low critical value. Time histories of the build up of response of a plain and a straked cylinder, for values of $m^*\xi$ of around 7×10^{-3}, are shown in Fig. 6. It can be seen that the plain cylinder is close to its maximum response after only 2 or 3 cycles whereas the straked cylinder remains at very low amplitude for some time following its release. At around 60 seconds an event occurs that triggers a steady increase in amplitude but the amplification rate is significantly less than that for the plain cylinder. Following this change in the flow state, the straked cylinder continued to oscillate with significant amplitude.

Measurements of the response of the straked cylinder are shown in Fig. 7 plotted against reduced velocity. The mass ratio was varied between 1.47 and 5.57. It can be seen that, compared to the plain cylinder, VIV occurs over a narrower range of reduced velocity. It is interesting to note that, particularly for the lowest mass ratio, the response characteristics are surprisingly similar to those for a plain cylinder with what may be a lower branch appearing. Sequences of flow visualisation pictures of the wake of a responding straked cylinder are shown in Fig. 5. What was wholly unexpected was not only did the straked cylinder experience lock-in but it also exhibited 2S and 2P modes and generally a behaviour similar to that for the plain cylinder, although the amplitudes were smaller. The visualisation of the 2S mode was made at a reduced velocity of 4.92, which is just before the peak in what would be the upper branch for a plain cylinder. The 2P mode visualisation was recorded at a reduced velocity of 6.3 which is in what we believe to be equivalent to the lower branch although the amplitude of oscillation here is only about 0.3D.

Flow patterns and response characteristics for the cylinder with bumps were found to be very similar to that for the straked cylinder. Measurements of the responses of a plain cylinder, a cylinder fitted with strakes and a cylinder with bumps are shown together in Fig. 8. The mass ratios and the values of $m^*\delta_S$ are respectively: 2.58, 6.0×10^{-3}; 2.63, 7.1×10^{-3} and 2.71, 5.8×10^{-3}. All show a peak response at about the same value of reduced velocity but the ranges of response and the levels of response for the straked and bumped cylinders are less than those for a plain cylinder. The flow patterns exhibited by the cylinder with bumps were generally similar to those for the straked cylinder with what appeared to be 2S and 2P modes.

4. Conclusions

Experiments carried out in a water channel with cylinders having low mass and damping demonstrate the difficulty of suppressing VIV. Passive suppression devices which may work well for typical structures in air with high combined mass-damping parameters do not eliminate VIV at low values of this parameter. Visualisations for a fixed circular cylinder with strakes or bumps show no regular vortex shedding but if the cylinder is flexible a random transverse displacement can lead to the build up of VIV through strong interaction between the fluid and structure. For this to happen the reduced velocity must be in the range where VIV is expected for a plain circular cylinder. The form of the response curve as a function of reduced velocity is similar for a plain cylinder and a cylinder fitted with one of the passive suppression devices examined. Also the modes of shedding are similar with 2S and 2P modes being clearly visible.

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