Journal of Fluids and Structures (2001) **15**, 597–605
doi:10.1006/jfls.2000.0358, available online at http://www.idealibrary.com on IDEAL®

PASSIVE CONTROL OF VIV WITH DRAG REDUCTION

J. C. Owen, P. W. Bearman

Department of Aeronautics, Imperial College of Science, Technology and Medicine London SW7 2BY, U.K.

AND

A. A. Szewczyk

Department of Aerospace and Mechanical Engineering, University of Notre Dame Notre Dame, IN 46556, U.S.A.

(Received 13 September 2000, and in final form 9 November 2000)

An experimental investigation has been carried out to measure the drag and vortex-induced vibration amplitudes of a circular cylinder, a circular cross-sectional body with a sinuous axis and a circular cylinder with hemispherical bumps attached. A wide range of Reynolds number has been studied, up to a maximum value of 10^5. Suppression of vortex shedding and drag reductions up to 47% have been observed for the body with a sinuous axis. Drag reductions of about 25% and suppression of vortex shedding have been recorded for the cylinder with bumps. VIV experiments over a range of the mass damping parameter from 2×10^{-2} to 5 have shown that amplitudes of oscillation for the wavy body and the cylinder with bumps still develop at low values of mass damping, even though shedding cannot be detected from the bodies when they are fixed. VIV can be suppressed at significantly lower values of mass-damping than required to stabilize a circular cylinder.

1. INTRODUCTION

Vortex shedding from bluff bodies is a challenging area of fluid dynamics and it continues to present problems to designers in a number of key industrial areas. For example, the large drag loads and possible vortex-induced vibration (VIV) of pipes and long slender tubular members are important design issues in the offshore industry. The widespread use of bluff sections has stimulated an interest in finding ways to weaken or even suppress vortex shedding. One avenue of research has been to take a nominally two-dimensional bluff body and to apply some form of three-dimensional geometric disturbance to the basic form. Naumann *et al.* (1966) varied the separation position along a circular cylinder by attaching short lengths of wire fixed alternately at two angular positions across the span. It is reported that this suppressed vortex shedding. Following this idea of breaking the separation line, a number of researchers, including Tanner (1972), Rodriguez (1991) and Petrusma & Gai (1994), have studied the reduction of the drag of blunt-trailing-edge wings by introducing a segmented trailing edge. Drag reductions up to 64% were found. The work reported here continues this theme but relates to bluff bodies where the geometry has some spanwise perturbation with a sinusoidal form.

In experiments carried out over the past few years it has been found that vortex shedding from bluff bodies can be weakened, and in some cases suppressed, when the flow separation

0889–9746/01/040597 + 09 $35.00/0

lines are forced to be sinuous. Three sets of experiments have been conducted: one using a blunt-based section with a wavy trailing edge (Tombazis & Bearman 1997), a second on rectangular cross-section bodies where the front face is wavy (Bearman & Owen 1998), and a third on bodies with a circular cross-section with constant diameter along the span and an axis that is sinuous (Owen *et al.* 1999). In all cases the introduction of the waviness is observed to reduce the drag and, for the rectangular and circular cross-sectional bodies, vortex shedding is suppressed if the ratio of peak-to-peak wave height, w, to wavelength, λ, of the sinuous form is above a critical value. The effectiveness of modifying the separation line appears to be greatest when the ratio λ/D of the wavelength to the body cross-flow width, D, is close to that of the mode A wavelength. This may or may not be a coincidence but it should be noted that vortex shedding can be suppressed across a wide range of Reynolds number, and not just in the regime normally associated with mode A. In the case of the wavy blunt-trailing-edge body, vortex shedding was not totally suppressed at the maximum wave steepness examined of 0·14, whereas for the other bodies von Kármán-type shedding disappeared for values of w/λ above about 0·1. Hence it might be deduced from this that the wavy front face also plays a role in vortex shedding suppression.

The experiments of Tombazis & Bearman (1997) were carried out to study three-dimensional features found in the wakes of nominally two-dimensional bluff bodies known as vortex dislocations. These are associated with spanwise changes in vortex shedding frequency and they provide a means by which vortices from adjacent cells, shedding at different frequencies, can join together. The occurrence of vortex dislocations was first investigated at low Reynolds numbers where the wake is unsteady but laminar [see for example, Williamson (1989)]. Bearman & Tombazis found that for a two-dimensional body at higher Reynolds numbers, dislocations appear apparently randomly in time and in spanwise position. In order to try to fix dislocation positions in the wake of a blunt-trailing-edge section they introduced a spanwise wavy trailing edge. It was found that the introduction of the waves fixed the dislocation positions but they also caused a further significant effect. It was observed that the base pressure increased as the wave steepness, w/λ, increased. Increasing base pressure is associated with drag reduction and hence it was deduced from these observations that encouraging the formation of dislocations reduces drag.

Bearman & Owen (1998) extended this work to rectangular cross-sectional cylinders with the front face normal to the flow. In order to generate a wavy separation line, the front face was machined into a sinusoidal form. For small values of w/λ similar vortex dislocation patterns and drag reduction to those for the wavy trailing edge body were observed. However, when w/λ was increased to 0·09, vortex shedding could not be detected. Drag reductions of over 30% were measured. Owen *et al.* (1999) took the research a stage further by studying how the flow around a circular cylinder changes if the axis is made sinusoidal. With the wavy axis in the plane of the flow they found similar features to those of the wavy rectangular sections, with vortex shedding suppression occurring for values of w/λ above 0·167. Distorting the axis of a circular cylinder may not necessarily generate wavy flow separation lines, but observations showed that the separation position did vary across the span. A common feature of the bodies where vortex-shedding suppression occurred is a wavy face onto which the free-stream flow impinges.

One of the aims of this paper is to attempt to explain why the introduction of relatively small degrees of spanwise waviness should have such a large effect on von Kármán vortex shedding. Also, it is of importance to know that waviness not only reduces drag but can also be used to reduce or even suppress VIV. One of the most widely used devices to suppress VIV, the helical strake, has the disadvantage that it increases drag. One obvious drawback of employing waviness is that it will be directionally sensitive, with perhaps little or no effect when the body is orientated with the plane of the waves normal to the flow. It is proposed to show how some simple modifications to the geometry of a circular cylinder, based on ideas developed from studying wavy bluff bodies, may be used to reduce drag and to weaken and even suppress shedding.

2. EXPERIMENTAL ARRANGEMENT

Experiments have been carried out on slender bluff sections over a large range of Reynolds numbers from 10 to 340 000, using both air and water facilities. Insight into the structure of flows has been obtained from flow visualization studies at low Reynolds numbers in a towing tank 3 m long by 0·8 m wide and 0·6 m deep. Experiments at substantially higher Reynolds numbers in two low-speed wind tunnels with working sections 0·92 m by 0·92 m and 1·22 m by 1·37 m have shown that similar effects due to small spanwise waviness are present. Surface-pressure measurements and hot-wire anemometry studies were carried out in the smaller wind tunnel. The larger wind tunnel is equipped with a three-component balance and this was used for direct measurements of drag. PIV measurements of the wake structure of bluff bodies were also conducted in this tunnel.

Experiments to measure response amplitudes of bluff bodies due to VIV were conducted in a water channel with a test section 0·61 m wide and 0·69 m deep. The maximum flow speed in the channel is about 0·3 m/s. Two important structural parameters to consider are damping ratio, ζ, and mass ratio, m^*, where $m^* = m_{sys}/m_d$ and m_{sys} is the effective mass of the oscillating body and m_d is the mass of fluid it displaces. One of the advantages of working with water is that mass ratios can be kept low and in a similar range to that experienced by offshore structures. Low damping was achieved by mounting bodies from a double-pendulum suspension system situated above the test-section of the water channel. The pendulum, which is shown in Figure 1, was constructed using four arms with low-stiffness flexures at each end. The motion of an attached cylinder is predominantly in the horizontal plane and the vertical movement during a typical VIV experiment is extremely small. When discussing the parameters that control VIV, it is common to use the product of m^* and ζ to form the single combined mass-damping parameter. However, care must be taken when m^* is small, because the magnitude of the fluid added mass becomes significant compared to m_{sys} and it can have a marked influence on the frequency at which the body oscillates. In the experiments, $m^*\zeta$ was varied over the range 2×10^{-2} to 5 and the Reynolds number was varied between 10^3 and 10^4. Full details of all the facilities and the experimental techniques used are described by Owen (2000).

3. EXPERIMENTAL RESULTS AND DISCUSSION

Low Reynolds number flow visualization results for a wavy circular cylinder, presented by Owen *et al.* (2000), show no evidence of regular Kármán vortex shedding above a value of w/λ of 0·167. Also, there is seen to be a periodic variation of the wake width across the span, with a wide wake behind the body where the axis is furthest downstream and a narrow wake where it is furthest upstream. In addition, there is evidence of longitudinal vortices in the wake which vary in sign in an alternate way across the span. Their senses of rotation are such as to induce the variation in wake width mentioned above. The origin of these vortices is thought to be in the skewed shear layers shed from the wavy body and the maximum strength of the longitudinal vorticity along the span is expected to be where the axis of the body is at the steepest angle to the free stream flow. This would provide a dependence of the flow on wave steepness, w/λ, which is what is observed. Cross-flows generated on the attached flow part of the bodies with a wavy front face must also play a role in weakening

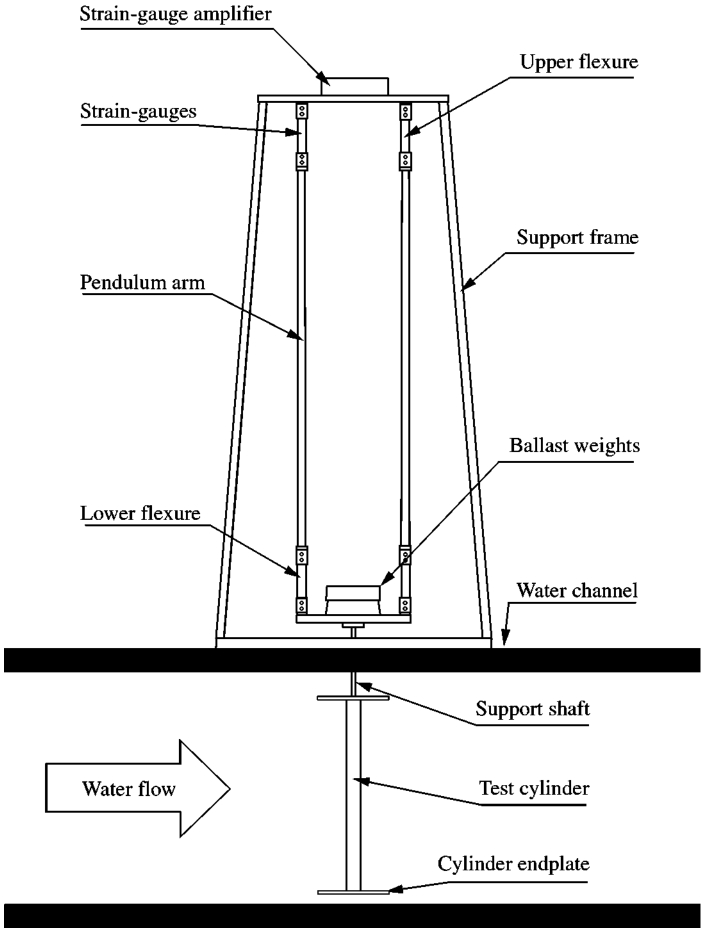

Figure 1. Schematic diagram of the double-pendulum system used for VIV experiments mounted above the water channel.

vortex shedding. The magnitude of these cross-flows would again be expected to depend on wave steepness. While the precise mechanism of how this flow stabilizes the near-wake and suppresses vortex shedding will probably only be revealed by hydrodynamic stability analysis, it seems clear that the longitudinal vortices play a dominant role.

Figure 2 shows the effect of wave steepness on the drag coefficient of a sinuous circular cylinder with a wavelength, λ, of $7{\cdot}5D$ and at a Reynolds number of $3{\cdot}3 \times 10^4$. A large drag reduction of 47% is recorded when the wave steepness is just over 0·3, but even for w/λ of 0·1 the drag reduction is more than 30%. At the higher wave steepnesses hot-wire measurements revealed no discrete frequency at the expected vortex shedding periodicity. From results reported by Roshko (1954) on the effect of long splitter plates on circular cylinder flow, it is to be expected that drag reduction should accompany vortex shedding suppression. Changing the incidence of the flow approaching a wavy cylinder, the drag coefficient increases back to almost the same value as that for a straight cylinder when the incidence reaches 90°.

While there may be important applications for wavy cylinders when the flow is unidirectional, such as for cylinders in tidal flows or for heat exchanger tubes, there is also

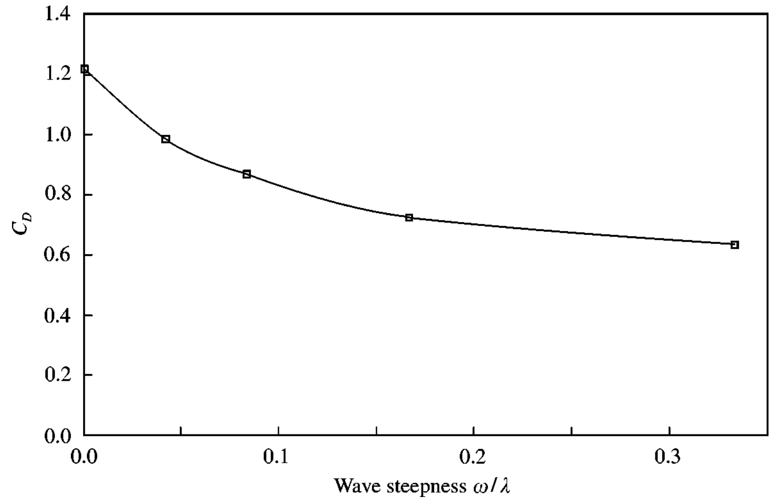

Figure 2. Measurements of drag coefficient versus wave steepness for a sinuous circular cylinder, $\lambda/D = 7{\cdot}5$, Re $= 3{\cdot}3 \times 10^4$.

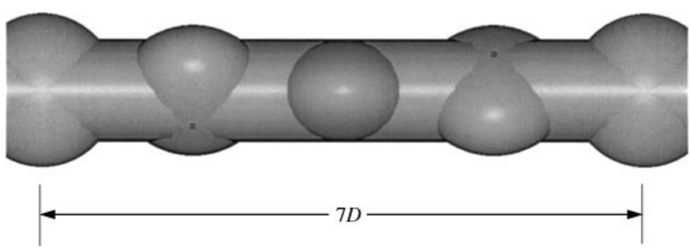

Figure 3. A view of a circular cylinder fitted with a spiralling arrangement of surface control bumps. Angular separation = 45°, longitudinal pitch of spiral = 7D.

a requirement for VIV suppression and drag reduction of cylinders in multi-directional flows. Hence, how can the ideas discussed above be used to suppress VIV when the direction of the approach flow is unknown? In order to reproduce some of the effects of a wavy cylinder, hemispherical bumps or caps were attached to the forward-facing side of a straight cylinder at a similar spacing to the wave crests on the wavy cylinders. These were found to reduce the drag and to suppress vortex shedding but they are only effective for a relatively small range of flow incidence. The next step was to apply the bumps in a spiral pattern around the cylinder with a constant longitudinal spacing and an angular separation of 45°. A view of a typical arrangement of bumps is shown in Figure 3. Measurements of C_D for a body with a spacing between bumps of 7D, versus incidence are shown in Figure 4 for a series of Reynolds numbers between 2×10^4 and 10^5. At 0° incidence a row of bumps is normal to the oncoming flow and since the bumps are distributed in a regular pattern it was only necessary to make measurements up to an incidence of up to 22·5°. It can be seen from Figure 4 that the addition of bumps reduced C_D by 25%, where C_D is based on the diameter of the plain cylinder.

Figure 5 shows three vorticity fields obtained from velocity measurements acquired using PIV at a Reynolds number of $2{\cdot}7 \times 10^4$. One is for a spanwise position where the bumps are

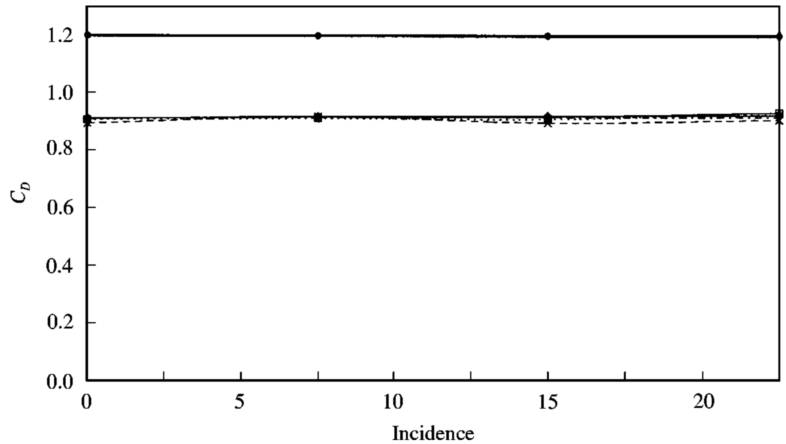

Figure 4. The effect of incidence on the drag of a circular cylinder fitted with a spiral arrangement of surface bumps: •, circular cylinder; ×, Re $= 2 \times 10^4$; □, Re $= 4 \times 10^4$; △, Re $= 6 \times 10^4$; ◇, Re $= 2 \times 10^4$; +, Re $= 10^5$. Angular separation $= 45°$, longitudinal pitch of spiral $= 7D$.

situated at $\pm 90°$, another is for a position where bumps are at 0° and 180° and the third is for a plain cylinder. In both cases with bumps there is no evidence of Kármán-type vortex shedding and the flow has many similar features to that found around a wavy cylinder. Having demonstrated some drag reduction and suppression of vortex shedding the next stage in the investigation was to study how susceptible these cylinders are to VIV.

Maximum transverse response amplitude $Y_{\max}$, divided by D, is shown plotted in Figure 6 as a function of reduced velocity V_r, where $V_r = nD/U$ and n is the oscillation frequency of the body in still water and U is the flow velocity. Two sets of results are plotted: one for a plain circular cylinder and the other for a cylinder with an array of bumps along the leading edge at a spacing of 1·5D. The height of the bumps was equal to 25% of the diameter of the cylinder. The Reynolds number range was from 1650 to 7500 and $m^*\zeta = 3{\cdot}6 \times 10^{-2}$. The plain cylinder results are similar to those found by other researchers and at first glance the results for the cylinder with bumps are disappointing. They indicate that when the body is flexibly mounted it is able to detect a very weak force fluctuation at a shedding frequency and that as it responds the excitation increases. The transverse oscillations of the cylinder with bumps developed extremely slowly compared to the plain cylinder and achieved a maximum amplitude about 25% lower. Hence it appears that with a relatively small amount of additional damping it may be possible to significantly reduce the response. This behaviour is similar to that found for cylinders with helical strakes which are effective at suppressing VIV for cylinders in air but still show a response at the lower mass damping parameters typical for water.

Figure 7 shows $2Y_{\max}/D$ plotted against $m^*\zeta$ for a series of body geometries. $Y_{\max}$ is the maximum amplitude recorded over a range of reduced velocity that more than spans the expected lock-in regime. The Reynolds number for maximum response in all cases is about 4000 and m^* is held constant at 14·3. Results are shown for a plain cylinder, a wavy cylinder ($w/\lambda = 0{\cdot}167$) and cylinders with small, medium and large bumps. The heights of the three sets of bumps are, respectively, 25%, 33% and 50% of the diameter of the cylinder. The largest suppression of VIV is observed for the wavy cylinder, but the results for the cylinders with bumps are very close, with the cylinder having small bumps being almost as effective as

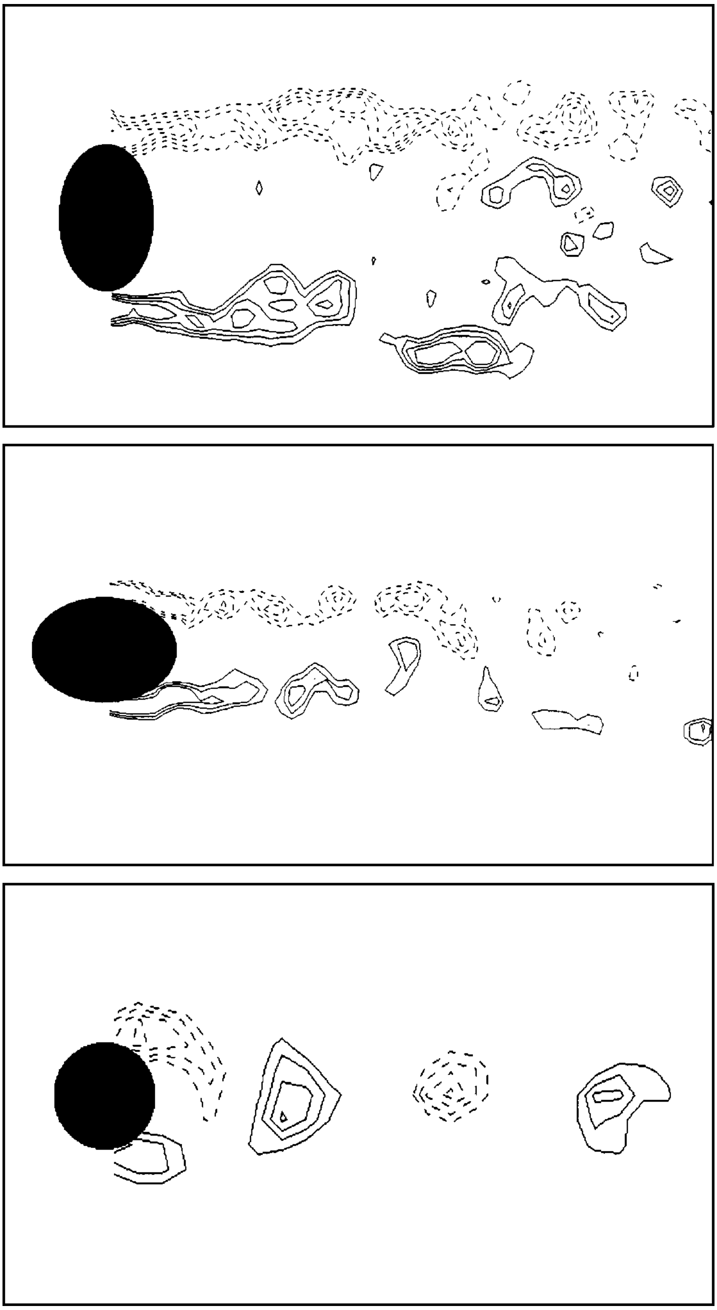

Figure 5. Nondimensional vorticity fields obtained using PIV in the wake of a circular cylinder fitted with surface bumps. The upper plot is from a spanwise position where the bumps are 90° to the flow, the middle plot is where the bumps are in-line with the flow and the lower plot is a plain circular cylinder. For bumps: angular separation = 45°, longitudinal pitch of spiral is equal to $7D$, $\mathrm{Re} = 2{\cdot}7 \times 10^4$.

the cylinders with the two other sizes of bumps. It should be noted that no detailed attempt has been made to optimize the shape of the bumps, or their distribution, but the results demonstrate the potential for using this idea for suppressing VIV and reducing drag.

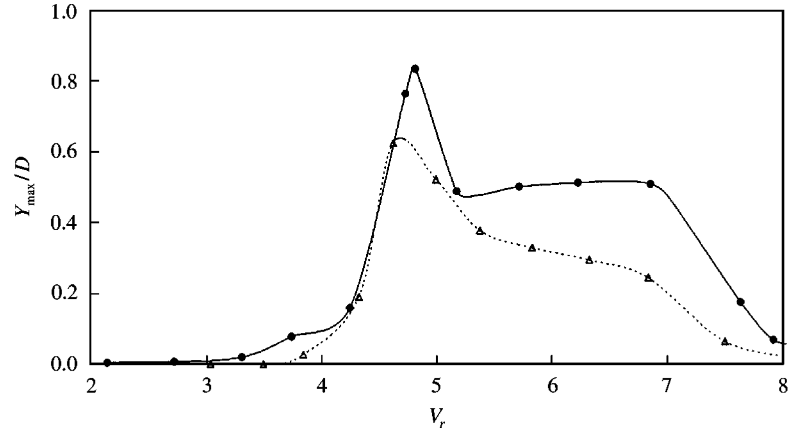

Figure 6. Maximum transverse response amplitude of an oscillating cylinder: ●, circular cylinder; △, cylinder with control bumps fitted to leading edge at a spacing of 1·5*D*. $m^*\zeta = 3{\cdot}6 \times 10^{-2}$, Re = 1650–7500.

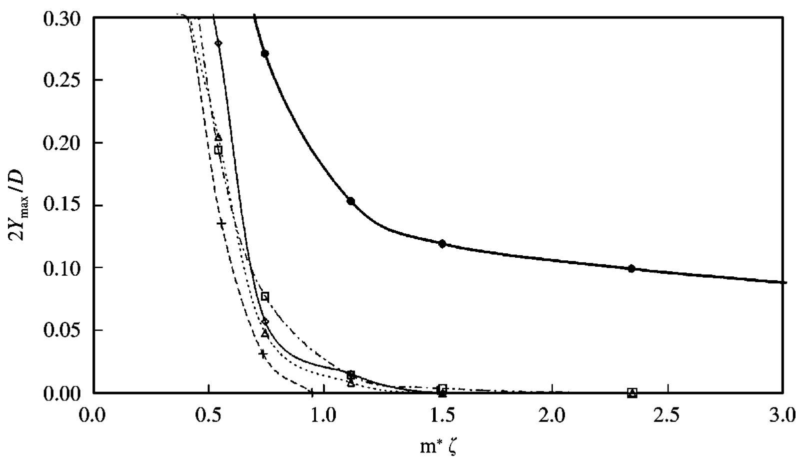

Figure 7. The effect of mass damping parameter ($m^*\zeta$) on the maximum transverse response amplitude of various bodies: ●, circular cylinder; +, sinuous cylinder ($w/\lambda = 0{\cdot}167$); and cylinders fitted with increasingly large bumps to the leading edge: ◇, 1·25*D*; △, 1·50*D*; □, 2·00*D*. $m^* = 14{\cdot}3$.

4. CONCLUSIONS

It is shown that sizeable reductions in drag can be achieved when the separation lines on a bluff body are forced to be sinuous. Drag reductions up to 47% are recorded for a circular cross-sectional body with a wavy axis. Above a certain value of wave steepness, regular vortex shedding can no longer be detected. The near-wake width is found to vary across the span in a sinusoidal way and longitudinal vorticity is introduced into the wake. Similar effects can be induced on a circular cylinder by attaching hemispherical bumps at regular intervals along the attachment line. Dependence on the angle of incidence can be removed by attaching the bumps in a spiral pattern. Measurements of VIV amplitudes show that a transverse response is recorded for the cylinder with bumps at low values of $m^*\zeta$, even though vortex shedding could not be detected for the same body when it was fixed.

However, the excitation is weakened and VIV can be totally suppressed for a cylinder with bumps at substantially lower values of $m^*\zeta$ than for a circular cylinder.

ACKNOWLEDGEMENTS

J. C. Owen was in receipt of a student bursary from EPSRC and A. A. Szewczyk acknowledges the support provided by ONR via Grant No. 0014-96-1-0756.

REFERENCES

BEARMAN, P. W. & OWEN, J. C. 1998 Reduction of bluff-body drag and suppression of vortex shedding by the introduction of wavy separation lines. *Journal of Fluids and Structures* **12,** 123–130.

NAUMANN, A., MORSBACH, M. & KRAMER, C. 1966 The conditions of separation and vortex formation past cylinders. In *Separated Flow*, pp. 539–574; *NATO AGARD Conference Proceedings No*. 4.

OWEN, J. C., SZEWCZYK, A. A. & BEARMAN, P. W. 1999 Suppressing Kármán vortex shedding by use of sinuous circular cylinders. *Bulletin of the American Physical Society* **44,** 124.

OWEN, J. C., SZEWCZYK, A. A. & BEARMAN, P. W. 2000 Suppression of Kármán vortex shedding. Gallery of Fluid Motion. *Physics of Fluids* **12,** 1–13.

OWEN, J. C. 2000 Passive control of vortex shedding in the wakes of bluff bodies. Ph.D. Dissertation, University of London, London, U.K.

PETRUSMA, M. S. & GAI, S. L. 1994 The effect of geometry on the base pressure recovery of segmented blunt trailing edges. *Aeronautical Journal* **98,** 267–274.

RODRIGUEZ, O. 1991 Base drag reduction by the control of three-dimensional unsteady vortical structures. *Experiments in Fluids* **11,** 218–226.

ROSHKO, A. 1954 On the drag and shedding frequency of two-dimensional bluff bodies. NACA Technical Note 3169.

TANNER, M. 1972 A method of reducing the base drag of wings with blunt trailing edges. *Aeronautical Quarterly* **23,** 15–23.

TOMBAZIS, N. & BEARMAN, P. W. 1997 A study of three-dimensional aspects of vortex shedding from a bluff body with a mild geometric disturbance. *Journal of Fluid Mechanics* **330,** 85–112.

WILLIAMSON, C. H. K. 1989 Oblique and parallel modes of vortex shedding in the wake of a circular cylinder at low Reynolds numbers. *Journal of Fluid Mechanics* **206,** 579–627.