Journal of Fluids and Structures (1998) **12,** 123–130

SPECIAL BRIEF NOTE

REDUCTION OF BLUFF-BODY DRAG AND SUPPRESSION OF VORTEX SHEDDING BY THE INTRODUCTION OF WAVY SEPARATION LINES

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(Received 1 September 1997 and in revised form 17 October 1997)

The results of an experimental investigation to study the influence of spanwise waviness of the separation lines on the flow around common bluff forms are presented. Wind-tunnel measurements were made on thin plates normal to the flow and on rectangular cross-section bodies at Reynolds numbers of about 40 000. The plates have a spanwise sinusoidal form and the front faces of the rectangular bodies are also sinusoidal. Compared to the equivalent straight bodies, drag reductions of up to at least 30% are achieved. Also, for ratios of peak-to-peak wave height divided by wavelength in excess of between 0·06 and 0·09, vortex shedding is completely suppressed.

1. INTRODUCTION

IT HAS BEEN KNOWN for a long time that the drag of nominally two-dimensional bluff bodies can be reduced by introducing some three-dimensional geometric disturbance which interferes with and weakens regular vortex shedding. Naumann *et al.* (1966) showed that shedding from a circular cylinder could be suppressed by attaching broken separation wires which consist of short straight lengths of wire fixed alternately across the span at two angular positions. Although no results are presented, they also note that a separation wire attached in the form of a sawtooth wave across the span will also suppress shedding. This idea was carried further by Tanner (1972), who concluded that to reduce drag it was most important to have a break in the separation line. He investigated the effect of various forms of segmented trailing edge on the drag of blunt-trailing-edge wings and measured drag reductions of up to 64%. The study of segmented trailing edges was continued by Rodriguez (1991) and Petrusma & Gai (1994).

Bearman & Tombazis (1993) and Tombazis & Bearman (1997) also studied the effect of three-dimensional geometric disturbances on bluff-body wakes but from a different perspective. They were interested in the large-scale three-dimensional features found in the wakes of nominally two-dimensional bluff bodies. These are generally known as vortex dislocations and are associated with local changes in vortex-shedding frequency. They found that, for a two-dimensional body, dislocations appear apparently randomly in time and in spanwise position. The body shape they used was also a blunt-trailing-edge section,

0889-9746/98/010123 + 08 $25.00/fl970128

and in order to try to fix dislocation positions they then introduced a spanwise wavy trailing edge. The base height remained fixed, and so initially it was not expected that the average shedding frequency across the span would change. The introduction of the waves fixed the dislocation positions, but two significant modifications to the flow were observed. The first was that the vortex shedding formed a regular pattern of cells along the span with a predominant frequency associated with each cell. Two distinct shedding frequencies were measured and, as a result of this frequency difference, vortex dislocations formed between the cells. The second observation was that the base pressure increased with increasing steepness of the waves introduced across the base. Increasing base pressure is associated with drag reduction and wave steepness is defined as the peak-to-peak wave height divided by the wavelength. It was deduced from these observations that dislocations are a natural feature of high Reynolds number bluff-body wakes and that encouraging dislocations to form reduces drag.

The purpose of the present paper is to show how this technique for reducing bluff-body drag can be applied to more common structural sections. It is clear that the key feature is the introduction of a wavy separation line and so two basic sinusoidal forms were studied: a wavy thin plate normal to the flow and a rectangular cross-section cylinder with a wavy front face and a flat rear face. Rectangular cylinders are particularly interesting because, as shown first by Nakaguchi *et al.* (1968), drag coefficients can rise to as high as 3 for depth-to-height ratios around 0·6.

2. EXPERIMENTAL ARRANGEMENT

Two low-speed wind tunnels were used during the course of this study: one with a test section 0·91 m × 0·91 m for measuring base pressure and vortex-shedding frequency; and a second, with a test section 1·37 m × 1·2 m and equipped with a three-component balance, for measuring drag.

A series of thin plates with height, h, 30 mm and thickness 4 mm were constructed with various degrees of spanwise waviness. A diagram of a typical plate is given in Figure 1. Peak-to-peak wave heights, w, varied between 0 and 0·5 h and wavelengths, L, between 3·5 h and 5·6 h. This provided a range of wave steepnesses, w/L, up to 0·143.

It was not clear what wavelengths should be selected and in these experiments they were made comparable to typical spanwise correlation lengths of vortex shedding from cylinders. The sinusoidal plates were constructed using both carbon and glass fibre composites and a length of pressure tubing was moulded into the rear face for measuring the distribution of base pressure. The basic rectangular cross-section body used was based on a square with side h of 30 mm and only the front face had the sinusoidal form, as shown in the sketch in Figure 2. With a wavy front face the maximum depth along the span remains h but the minimum depth becomes h–w, and the average depth-to-height ratio across the span is $1-\frac{1}{2}w/h$. As for the thin plates, w/h was varied between 0 and 0·5 and, hence, the average depth-to-height ratio across the span for the different models varied between 0·75 and 1. For the largest wave height used the depth-to-height ratios across the span varied between 0·5 and 1, i.e., across the range where Nakaguchi *et al.* (1968) had recorded very high values of drag coefficient. A range of wavelengths similar to those for the thin plates, and hence wave steepness, was used for the rectangular bodies. Again, pressure tubing was inserted in the rear face for measuring base pressure. Velocity fluctuations were sensed using hot-wire equipment and signals were analysed by suitably interfacing to a PC. As mentioned earlier, drag was measured directly by mounting the bodies from a balance in the 1·37 m × 1·2 m

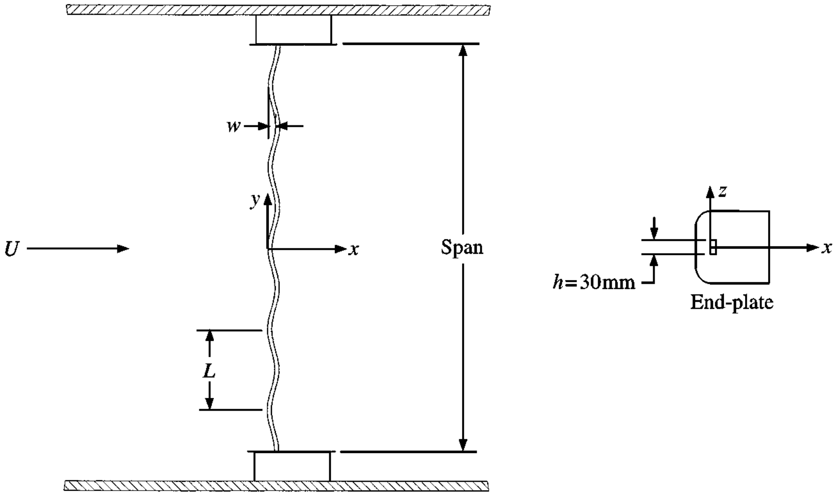

Figure 1. Diagram of a wavy plate model.

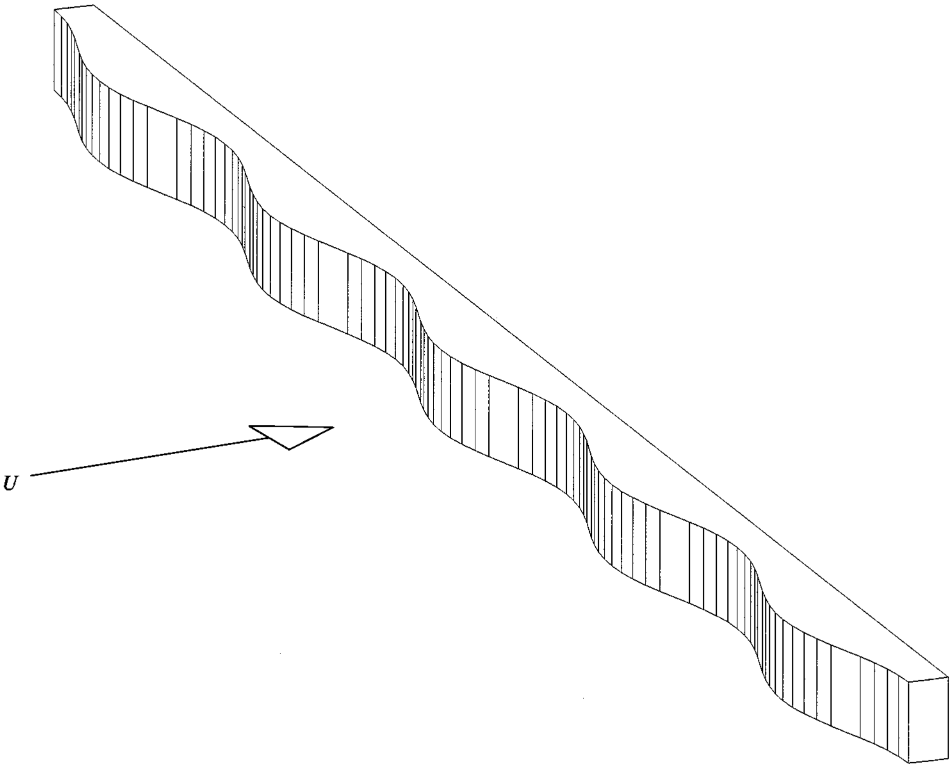

Figure 2. Sketch of a wavy model with a rectangular cross-section.

wind tunnel. Further details of the experimental arrangement and all the measurements are reported by Owen (1997).

The maximum Reynolds number for the experiments, based on h, was about 4×10^4. End-plates were fitted, giving an active span of 0·84 m and an aspect ratio of 28, with the longest wavelength used there were five waves across the span. Although the geometric blockage was small ($\leq 3{\cdot}3\%$) the correction method due to Maskell (1963) was applied to *all* the pressure and drag data.

3. RESULTS

Measurements of base-pressure coefficient, C_{pb}, across half a wavelength, for the series of wavy plates are plotted in Figure 3 against y/L, where y is the distance from a peak. Peaks are defined as locations where the face of the body extends furthest in the stream direction; valleys are where it extends furthest upstream. The base-pressure coefficient is also shown for a two-dimensional flat plate. The results show a similar trend to those presented by Bearman & Tombazis (1993), with small degrees of waviness producing large increases in base pressure. With a value of wave steepness of only 0·09, C_{pb} is found to be about $-0{\cdot}65$ and this should be compared with $-1{\cdot}28$ for a flat plate. The contribution to the drag coefficient from the front face of a two-dimensional plate is about 0·8 and changes little with changing base pressure. Hence, the above results suggest a drag reduction of about 30%.

Power spectra of velocity fluctuations measured just outside one of the shear layers from a wavy plate with $w/L = 0{\cdot}06$ are plotted in Figure 4. The hot-wire probe was positioned approximately $2h$ downstream of the body and $2h$ above the centreline of the wake and spectra are presented for a number of spanwise positions between a peak and a valley. Again, there is similarity with the results of Bearman & Tombazis (1993) for a wavy blunt-based section with two main shedding frequencies observed. However, with w/L increased to 0·09, no vortex shedding could be detected and the spectra were flat up to the maximum reduced frequency studied of 0·4.

Very similar results were obtained from the series of rectangular models with a wavy front face and the physical processes involved seem identical to those for the thin plates. Measurements of drag coefficient (C_D), based on an area equal to the product of body height and span, for both the rectangular cross-section bodies and the thin plates are plotted in Figure 5 against wave steepness. It can be seen that C_D reaches its lower level for values of w/L in excess of between 0·06 and 0·09.

4. DISCUSSION

A recognized passive method for suppressing vortex shedding behind a flat plate normal to the flow is to attach a long splitter plate. Arie & Rouse (1956) showed that suppressing vortex shedding by using a splitter plate resulted in a 30% reduction in the drag coefficient. Pressure measurements by Jaroch & Fernholz (1989) on a flat plate and splitter plate combination with a similar blockage ratio to that of the present experiments record a pressure coefficient just behind the plate, similar to that measured here when shedding is suppressed. Hence, the measurements of base pressure and the drag reductions recorded in this investigation are compatible with vortex shedding being absent. Extensive investigations were carried out to substantiate that shedding had been suppressed, including performing flow visualization studies in water at Reynolds numbers an order lower than those of the wind-tunnel experiments. For bodies with steepnesses of 0·09 and higher,

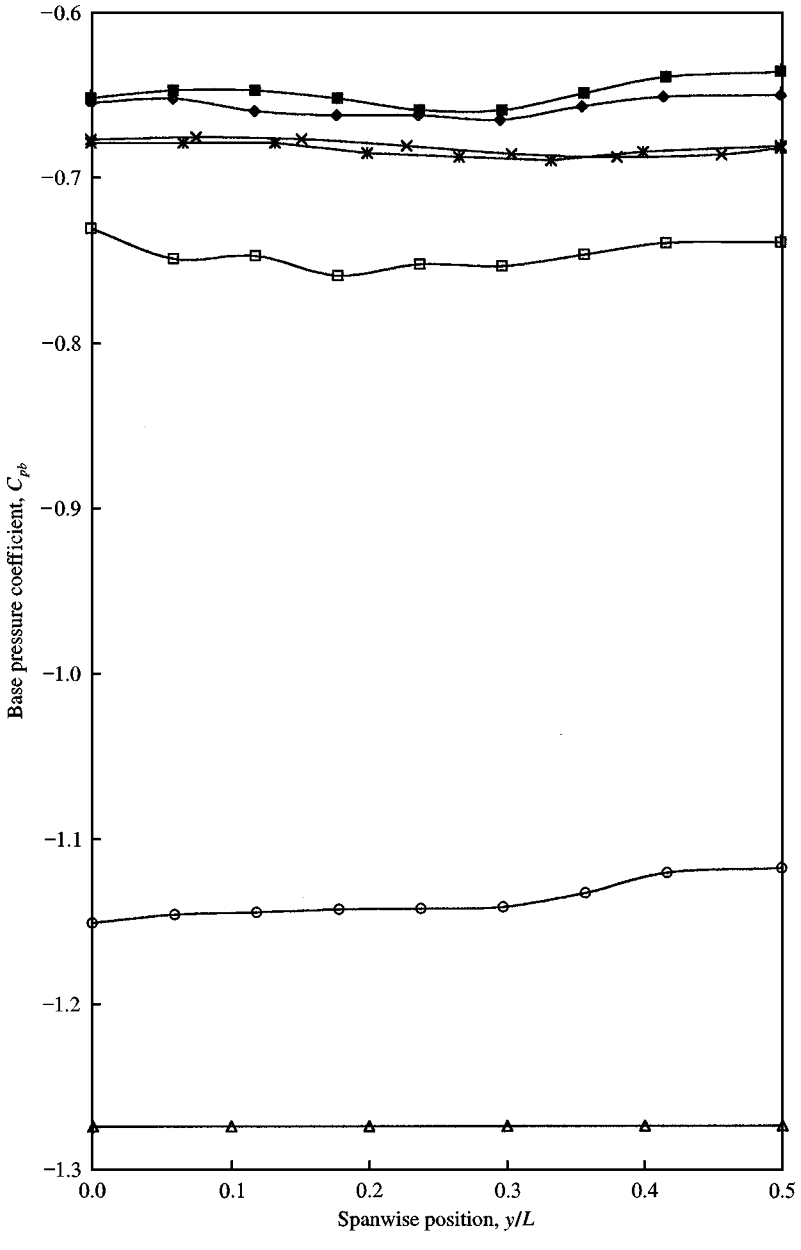

Figure 3. The variation of base-pressure coefficient along half a wavelength of the thin-plate models. △, straight model; ○, $L = 168$ mm, $w = 5$ mm; □, $L = 168$ mm, $w = 10$ mm; ■, $L = 168$ mm, $w = 15$ mm; ◆, $L = 135$ mm, $w = 15$ mm; ★, $L = 120$ mm, $w = 15$ mm; ×, $L = 105$ mm, $w = 15$ mm.

Karman vortices could not be observed. The main instability present was a convective one in the shear layers producing well-known Bloor–Gerrard vortices, which seemed to be unaffected by the waviness of the bodies.

It is very surprising that the powerful absolute instability present in bluff-body wakes can be completely suppressed by such modest levels of wave steepness. The reason for this is

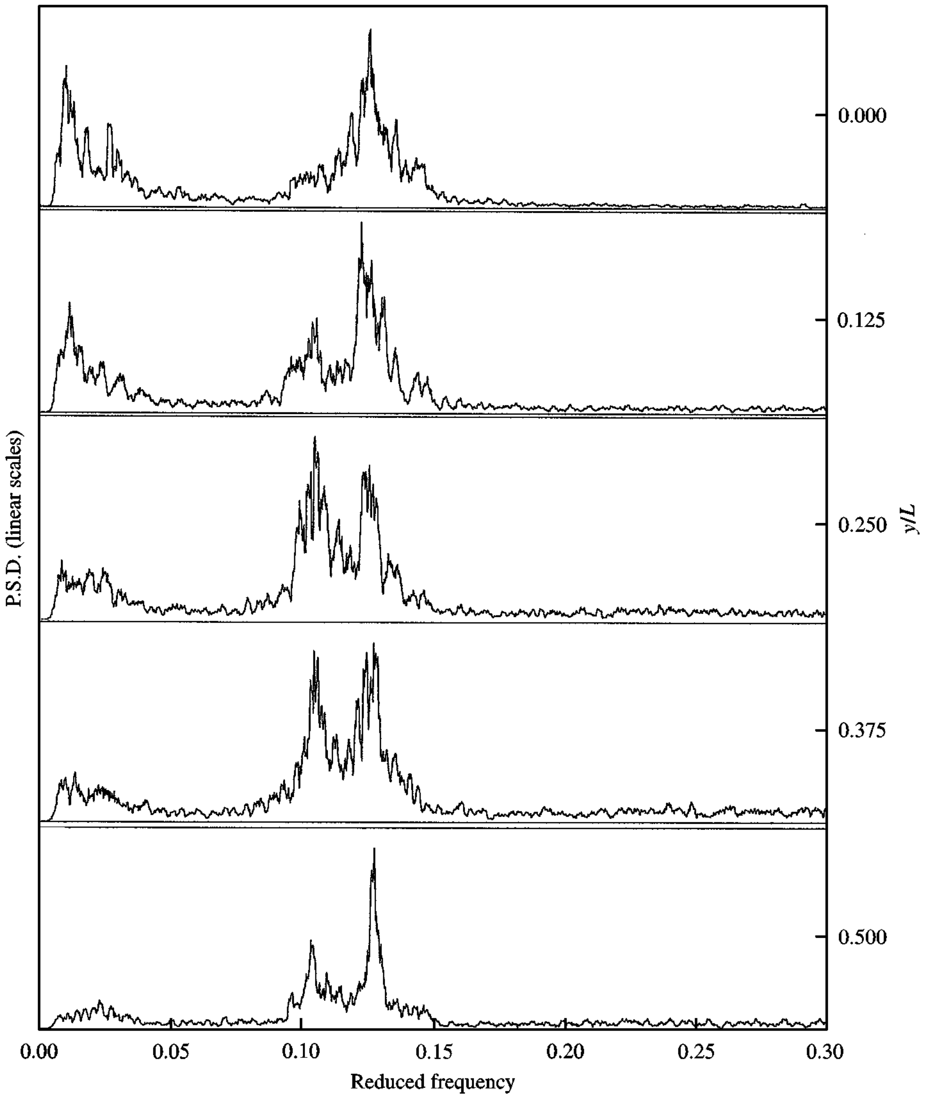

Figure 4. Velocity power spectra measured at various spanwise positions outside the wake of a wavy plate model with $L = 168$ mm and $w = 10$ mm.

unclear at present, but for w/L values less than that needed for complete suppression dislocations are introduced, with two shedding frequencies detected, and it is known that this leads to increased base pressure. With increasing wave steepness the vortices become even weaker until at some critical value they cease forming. Although wave steepness has been introduced as a controlling parameter, the phenomenon may depend separately on wave height and wavelength. This is one of a number of aspects that require further study.

An interesting question is whether this method for suppressing vortex shedding has any practical application. The fact that mean and unsteady forces are reduced on common structural forms and that body shapes can be devised which will show a beneficial effect

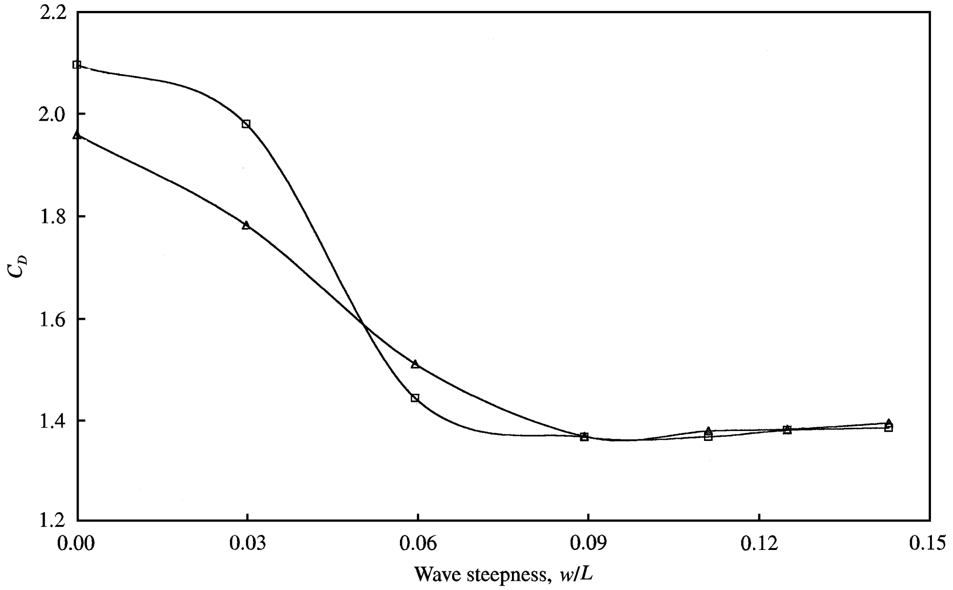

Figure 5. Measurements of drag coefficient versus wave steepness: △, thin plates; □, rectangular cross-section bodies.

regardless of flow direction indicates it does. A number of further studies are suggested by this work, including the effectiveness of waviness in reducing flow-induced vibration of bluff bodies.

5. CONCLUSIONS

The drag of thin plates and rectangular cross-section bodies can be substantially reduced by the introduction of spanwise waves into the flow separation lines. Drag reductions of up to at least 30% are achieved and for wave steepnesses in excess of between 0·06 and 0·09 vortex shedding is completely suppressed. These results may find application in a number of fields where fluids and structures interact.

ACKNOWLEDGEMENT

The concept that spanwise waves are effective in reducing the drag of bluff bodies was studied in some earlier work supported by the Office of Naval Research.

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