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Vortex shedding from square prisms in smooth and turbulent flows

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Visualization and measurements of velocity and pressure were made for the flow past prisms of variable length with square cross-section, placed normal to smooth and turbulent approaching flows. Square prisms shed vortices in one of the two fixed wake planes. The plane of shedding is switched irregularly from one to the other. Flow visualization confirms the two main effects of small- and large-scale turbulence on the flow past square prisms that had previously been suggested. In particular, large-scale turbulence intensifies vortex shedding from square prisms through resonant interaction, thereby reducing the base pressure considerably.

1. Introduction

Recently, many engineering problems such as the aerodynamic design of various forms of road vehicles and the wind-resistant design of buildings and structures exposed to the natural wind have stimulated renewed interest in the flow past three-dimensional bluff bodies. A number of experiments have been conducted on this subject. Many of them detected weak vortex shedding from three-dimensional bluff bodies. These include Fail, Lawford & Eyre (1959), Calvert (1967*a*, *b*), Achenbach (1974), Taneda (1978), Perry & Lim (1978), Fuchs, Mercker & Michel (1979) and Xia & Bearman (1983). Flow visualization by Taneda (1978) among others gave the important information on the flow past a sphere that vortex shedding is in a plane of the wake which slowly rotates.

The generally accepted model for the time-mean wake of symmetrical three-dimensional bluff bodies is that of a closed wake cavity (Bearman 1980; MacLennan & Vincent 1982), where the main physical process that sets up a recirculating flow field and controls base pressure is the entrainment of the separated shear layers. Accordingly, it has been widely accepted that vortex shedding from three-dimensional bluff bodies is relatively weak and its effect on the mean pressure field is less significant.

However, our recent work (Nakamura & Ohya 1983) on the effects of turbulence on the mean flow past square prisms showed that the base pressure of a square plate is much more significantly reduced by large-scale turbulence than by small-scale turbulence. It was then suggested that large-scale turbulence enhances the roll-up of the separated shear layers. It remains, therefore, to ask how the roll-up of the shear layers in large-scale turbulence is correlated to vortex shedding.

The purpose of this paper is to gain a better understanding of the near wake of three-dimensional bluff bodies. In particular, it is intended to examine the effects of

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	X_G/M	u'/U (%)	L_x (cm)
Large grid	10	10.0	19.7
	14	7.6	24.0
Small grid	7	10.8	3.2
	10	8.0	3.6

TABLE 1. X_G is the distance from the grid, u'/U and L_x are respectively the intensity and integral scale of the u-component velocity fluctuation.

free-stream turbulence on vortex shedding of three-dimensional bluff bodies. In the experiments, flow visualization and measurements of velocity and pressure were made for square prisms of various lengths in smooth and grid-generated turbulent flows.

2. Experimental arrangements

The experiments were conducted in a wind tunnel with a 4 m high by 2 m wide by 6 m long rectangular working section. The tunnel can provide a very uniform smooth flow with turbulence intensity of about 0.12 %. To create a nearly homogeneous isotropic turbulence field, two square-mesh biplanar grids of rectangular-section bars were used. The large grid had $M = 60$ cm and $b = 15$ cm and the small one had $M = 13$ cm and $b = 2.5$ cm, where M and b are the mesh and the bar size of a grid. The 6 m long working section was too short for the experiment using the large grid, so the diffuser was modified to extend the length of the working section by 6 m. The characteristics of the grid turbulence relevant to the present experiments are given in table 1. A more detailed description of the grids and the turbulence characteristics is found in Nakamura & Ohya (1983).

The models used in this investigation were square prisms, namely prisms with square cross-section made of plywood or acrylic resin. They had four different values of the length-to-size ratio, i.e. $d/h = 0.1$ (square plate), 0.5, 1.0 (cube) and 2.0, where h is the size of the square cross-section and d is the prism length. The prism size was varied from $h = 5$ to 22 cm. The model was mounted in the working section with its square cross-section normal to the approaching flow. As shown in figure 1, it was connected at the centre of the rear face to a supporting metal tube of 40–90 cm in length with a diameter smaller than approximately $0.1h$. The whole assembly of the model and its support was suspended by piano wires.

The measurements of the u-component velocity fluctuations were made with constant-temperature hot-wire anemometers. The speed of the approaching flow was $U = 10$ m s^{-1} with Reynolds numbers of $Re = (3.4\text{–}14.7) \times 10^4$ in terms of h. The smoke-wire method was used for flow visualization with fine nichrome wire 0.2 mm in diameter to generate the smoke. Visualization was carried out at a flow speed of about 1.2–1.4 m s^{-1} with $Re = (0.5\text{–}1.8) \times 10^4$. Figure 1 also shows the apparatus used in the flow-visualization experiment. The exposure time for photography was $\frac{1}{125}$ s.

In order to gain a better understanding of the interaction between turbulence and vortex shedding, an experiment was added where mean base pressure was measured for a square plate oscillating transversely in smooth flow. The experiment was conducted in a 3 m high by 0.7 m wide wind tunnel using a square plate with $h = 20$ cm.

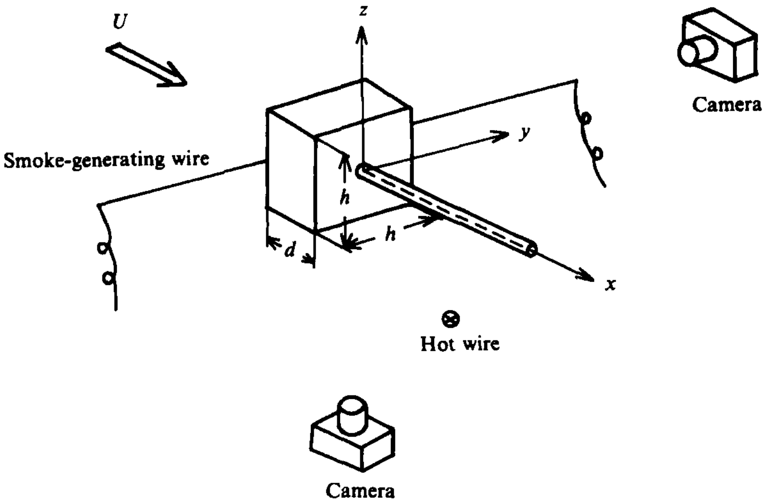


FIGURE 1. Experimental arrangement for hot-wire measurement and flow visualization.

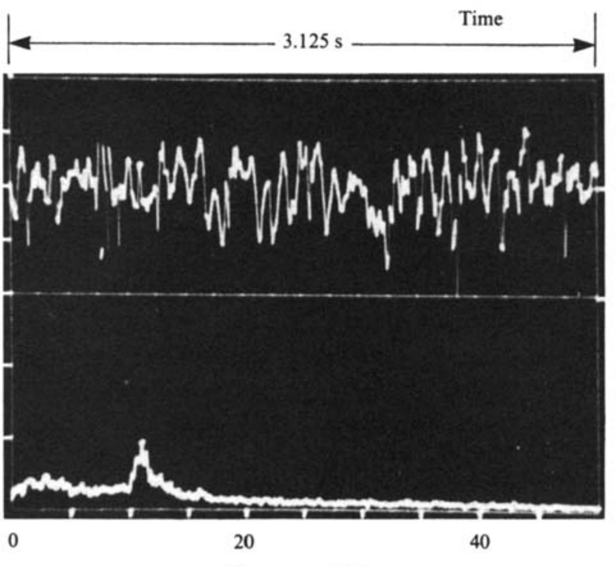


FIGURE 2. Hot-wire signal and power spectrum of the u-component velocity for a square plate in smooth flow.

3. Vortex shedding in smooth flow

3.1. *Hot-wire measurements*

The frequency of vortex shedding from a square prism was estimated from the output signal of a hot wire positioned in the vertical plane containing the wake centreline (i.e. the (x, z)-plane in figure 1), h downstream of the rear face and h or $1.5h$ below the lower face (i.e. $x = h$, $y = 0$ and $z = -1.5h$ or $-2h$).

Figure 2 shows the u-component velocity fluctuation and its power spectrum for a square plate ($d/h = 0.1$). The amplitude of the velocity fluctuation was very small and of the order of about 1 % of the free-stream speed. The power spectrum in figure 2

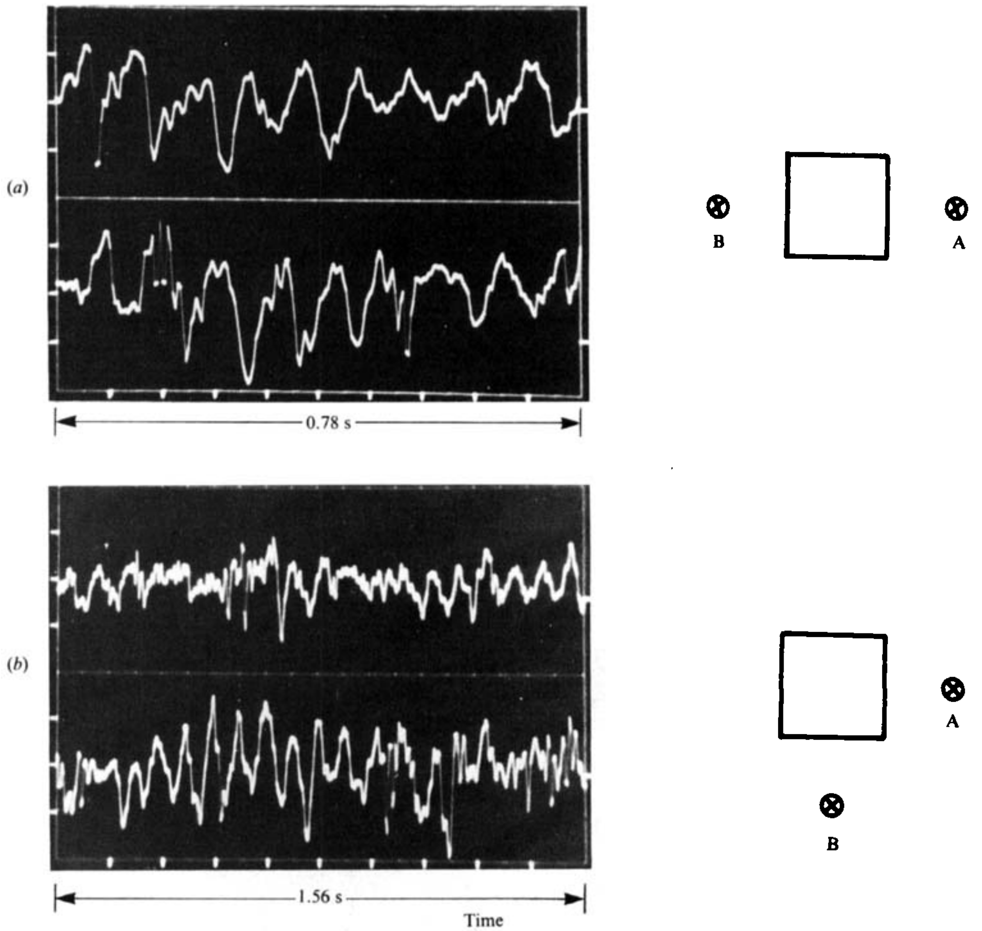
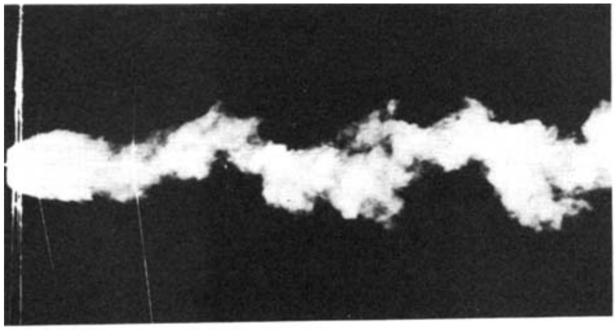


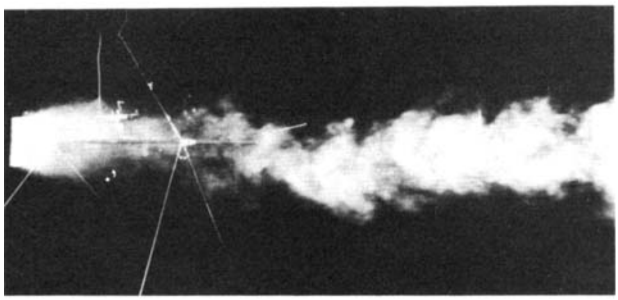
FIGURE 3. Two hot-wire signals recorded simultaneously. (*a*) 180° arrangement. (*b*) 90° arrangement.

has a detectable peak and the Strouhal number, defined by $St = fh/U$, where f is the vortex-shedding frequency, is found to be 0.115. The value is in good agreement with the result of Fail *et al.* (1959). As is seen in the hot-wire signal in figure 2, the velocity fluctuations were not always regular, and regular and irregular phases were repeated at irregular intervals. The Strouhal numbers for a square prism with $d/h = 0.5$ and a cube were 0.120 and 0.118 respectively. The degrees of regularity of the u-component velocity fluctuations were comparable to that for a square plate. For a square prism with $d/h = 2.0$, there was no detectable peak in the power spectrum.

Figures 3 (a, b) show the results of measurements for a square plate using two hot wires. Figure 3 (a) corresponds to the case where two hot wires were positioned at 180° to each other, i.e. at $x = h$, $y = 1.5h$, $z = 0$ (hot wire A) and $x = h$, $y = -1.5h$, $z = 0$ (hot wire B). The coherency of the two signals at the vortex-shedding frequency was 0.94 with a phase angle of about 180°. In contrast, figure 3 (b) corresponds to the case where two hot wires were at 90° to each other. The velocity fluctuations show that when one signal is regular, the other is irregular. Correspondingly, the coherency



(a)



(b)

FIGURE 4. Two smoke patterns of the wake of a square plate taken simultaneously (*a*) from below and (*b*) from the side.

of the two signals is found to be nearly zero. Similar results were obtained for a square prism with $d/h = 0.5$ and a cube using two hot wires.

3.2. *Flow visualization*

Figures 4 (*a*, *b*) present two smoke patterns showing the wake of a square plate which were obtained simultaneously using two cameras, one at the bottom and one at the sidewall of the working section. The smoke was generated by wires located just behind the square plate.

One photograph shows a wavy motion of the wake while the other does not. That is, a square plate sheds vortices from two opposite sides, and the shedding is switched irregularly from one pair of opposite sides to the other. This observation is compatible with the hot-wire measurements in the foregoing section. A similar observation on vortex shedding in a plane was reported by Taneda (1978) for the flow past a sphere. However, the plane of vortex shedding from a sphere rotates slowly and irregularly about the wake axis, while the plane of vortex shedding from a square plate is switched irregularly from one to the other pair of parallel sides. Vortex-loop structures have been suggested by Perry & Lim (1978) for circular jets and wakes and by Calvert (1967 *b*) for an inclined circular plate. It appears that the wavy motion of the wake for a square plate is somewhat inconsistent with the vortex-loop structures, but no attempt has been made here to clarify this point.

A square prism with $d/h = 0.5$ and a cube showed similar vortex shedding, while for a square prism with $d/h = 2.0$ no such vortex shedding was detected.

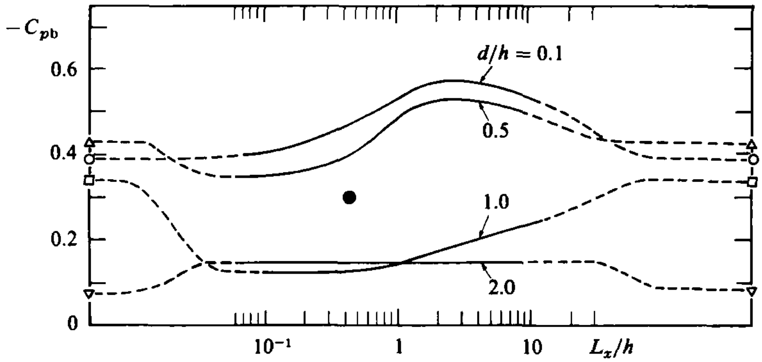


FIGURE 5. Base-pressure coefficients *vs* turbulence scale relative to prism size (Nakamura & Ohya 1983). Turbulence intensity 10.0% for $d/h = 0.1$, 0.5 and 1.0; 8.0% for $d/h = 2.0$. ——, experimental trend; ----, extrapolation.

4. Vortex shedding in turbulent flow

4.1. *The effects of turbulence on the mean-flow characteristics of square prisms*

Figure 5 summarizes the variations of the base-pressure coefficients of four different square prisms with the ratio of turbulence scale to prism size. The solid lines represent the experimental trends obtained in the previous study (Nakamura & Ohya **1983**) while the dotted lines show the hypothetical variations outside the experimental range. On this basis the previous paper suggested the presence of two main effects of small- and large-scale turbulence on the mean-flow characteristics of square prisms; namely small-scale turbulence increases the growth rate of the separated shear layers while large-scale turbulence enhances the roll-up of the shear layers, both resulting in an increased entrainment of fluid from the base region to sustain low base pressure. Small-scale turbulence specifically refers to the case where the size of the energy-containing eddies is comparable to the thickness of the shear layers, while large-scale turbulence refers to the case where the size of the energy-containing eddies is comparable to that of the whole near wake. Accordingly, the previous paper suggested that small-scale turbulence increases the base pressures of the three square prisms other than a square plate through the promotion of the shear-layer–edge direct interaction, while large-scale turbulence reduces the base pressures of short square prisms such as those with $d/h = 0.1$ and 0.5 through the enhanced roll-up of the shear layers. The visualization of the turbulent flow in the present paper is specifically intended to shed further light on the two main effects of turbulence just mentioned.

4.2. *Flow visualization*

Figures 6(*a–c*) show the flow patterns of a square plate for three representative flow conditions, namely smooth flow and small- and large-scale turbulence. Figure 6(*c*), in particular, presents four successive frames of photographs which were taken by a motor-driven camera at a time interval of 0.27 s.

The flow pattern for large-scale turbulence in figure 6(*c*) is of particular interest and it shows much stronger roll-up of the shear layers than for smooth flow. It is also seen that roll-up is repeated for several cycles as for smooth flow. In other words, large-scale turbulence intensifies vortex shedding from a square plate. The Strouhal number, estimated by a sequence of photographs, was about 0.12 and roughly equal

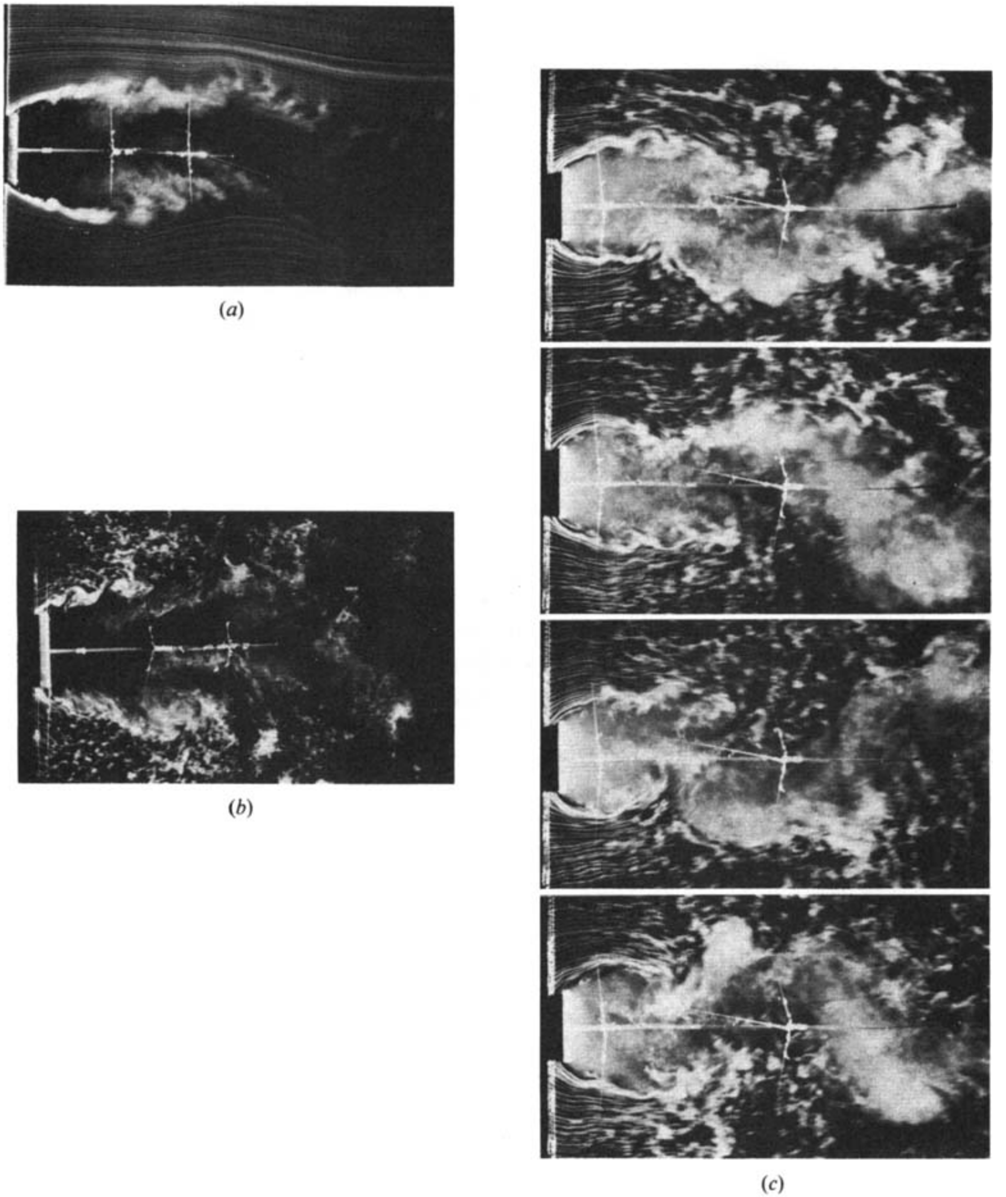


FIGURE 6. Near wake of a square plate for different flow conditions. (*a*) Smooth flow. (*b*) Small-scale turbulence, $L_x/h = 0.21$, $u'/U = 10.8\%$. (*c*) Large-scale turbulence, $L/h = 1.97$, $u'/U = 10.0\%$.

to that for smooth flow. Strong roll-up of the separated shear layers in large-scale turbulence was also observed by Makita & Morikawa (1983) in the flow past a rectangular block mounted on a ground plate.

On the other hand, the photograph for small-scale turbulence (figure 6*b*) shows that the shear layers are more diffused and vortex shedding appears to be no stronger than that for smooth flow. The flows around a square prism with $d/h = 0.5$ for smooth flow and large-scale turbulence are found to be separated throughout and therefore similar to those for a square plate. Again, large-scale turbulence is shown to intensify

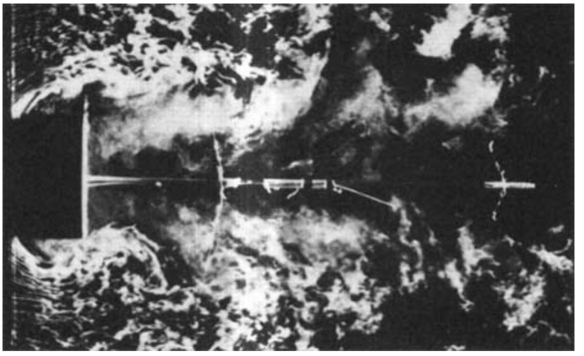


FIGURE 7. Flow patterns of a square prism with $d/h = 0.5$ in small-scale turbulence with $L_x/h = 0.21$ and $u'/U = 10.8\%$.

vortex shedding from the square prism. In contrast to these two flow conditions, for small-scale turbulence the shear layers reattach on the side faces rather frequently. This is shown in figure 7.

The flow around a cube is separated throughout for smooth flow (figure 8*a*), while the shear layers always reattach on the side faces for small-scale turbulence (figure 8*b*). As is shown in figure 8(*c*), however, the reattachment of the shear layers becomes intermittent for large-scale turbulence. It should be added that no regular vortex shedding was observed for either small- or large-scale turbulence.

Figures 9(*a–c*) show that the flow around a square prism with $d/h = 2.0$ is dominated by the shear-layer reattachment for all of the three flow conditions. The effect of turbulence is to shorten the separation bubbles. However, no scale effect is seen on the size of the separation bubbles.

5. Mean base pressure of an oscillating square plate

For a better understanding of the interaction between large-scale turbulence and vortex shedding, it may be helpful to see how mean base pressure is reduced when a bluff body is oscillated synchronously with its vortex shedding. An experiment was conducted in a 3 cm high by 0.7 m wide wind tunnel where a square plate with $h = 20$ cm was oscillated transversely in smooth flow. The model was supported by a rod of $4h$ in length with a diameter tapered from $0.1h$ at the model base to $0.2h$ at the downstream end. It oscillated vertically by a shaker at a constant frequency of 4.0 Hz with an amplitude of $0.1h$, and the wind speed was varied from 2.5 to 10 m s^{-1} approximately. Base pressure was measured at two different positions, $0.2h$ and $0.4h$ above the centre of the rear face of the model.

Figure 10 shows the variation of the mean base-pressure coefficients with the wind speed. The abscissa represents the reduced wind speed, defined by $\bar{U} = U/(f_0 h)$, where f_0 is the frequency of the body oscillation, equal to 4.0 Hz. The base-pressure coefficients were corrected for tunnel blockage by the method of Maskell (1965). The measured base-pressure coefficients for the model at rest were found to be constant and equal to -0.37 over the range of the wind speed. This value, which is in good agreement with previous measurements (Fail *et al.* 1959; Nakamura & Ohya 1983), is shown by a straight line in the figure. The hot-wire measurement indicated a Strouhal number of 0.125 for the model at rest, and the critical reduced wind speed $\bar{U}_{cr}$, which is defined by $1/St$, is also given in the figure.

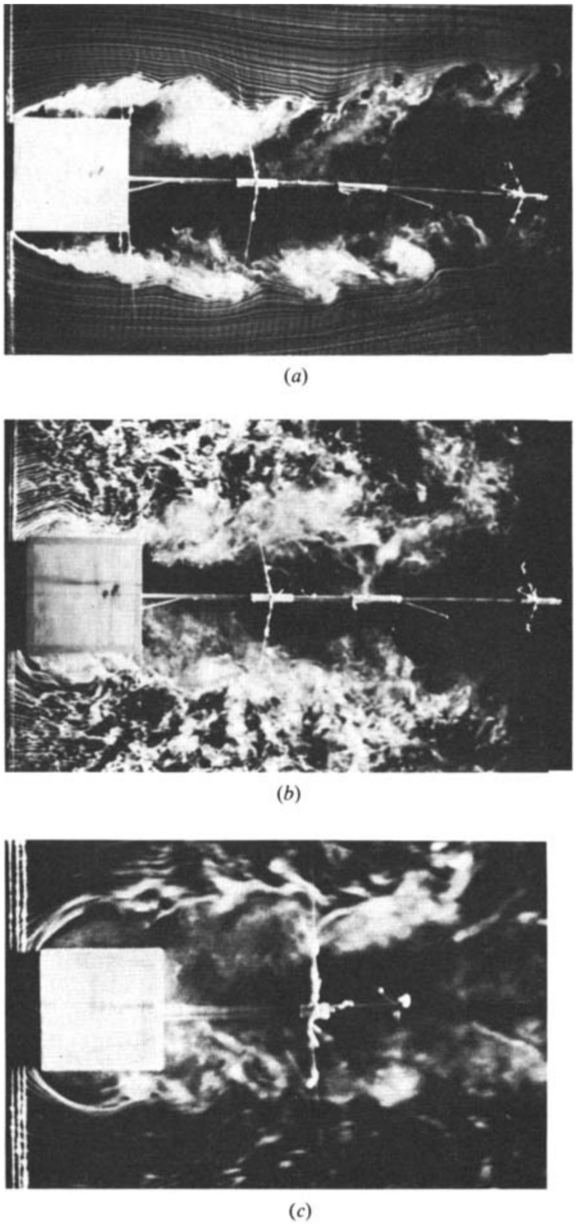


FIGURE 8. Flow patterns of a cube for different flow conditions. (*a*) Smooth flow. (*b*) Small-scale turbulence, $L_x/h = 0.21$, $u'/U = 10.8\,\%$. (*c*) Large-scale turbulence, $L_x/h = 2.81$, $u'/U = 10.0\,\%$.

It can be seen that mean base pressure is considerably reduced at resonance despite the rather weak vortex shedding of the model at rest. The pressure over the rear face at resonance is non-uniform and it is decreased toward the edge of the rear face. As the resonance wind speed is exceeded, pressure becomes uniform over the rear face and rapidly approaches the stationary value. The wind speed corresponding to the peak of $-C_{pb}$ is a little lower than $\overline{U}_{cr}$, but the difference was reduced as the amplitude of the body oscillation was lowered.

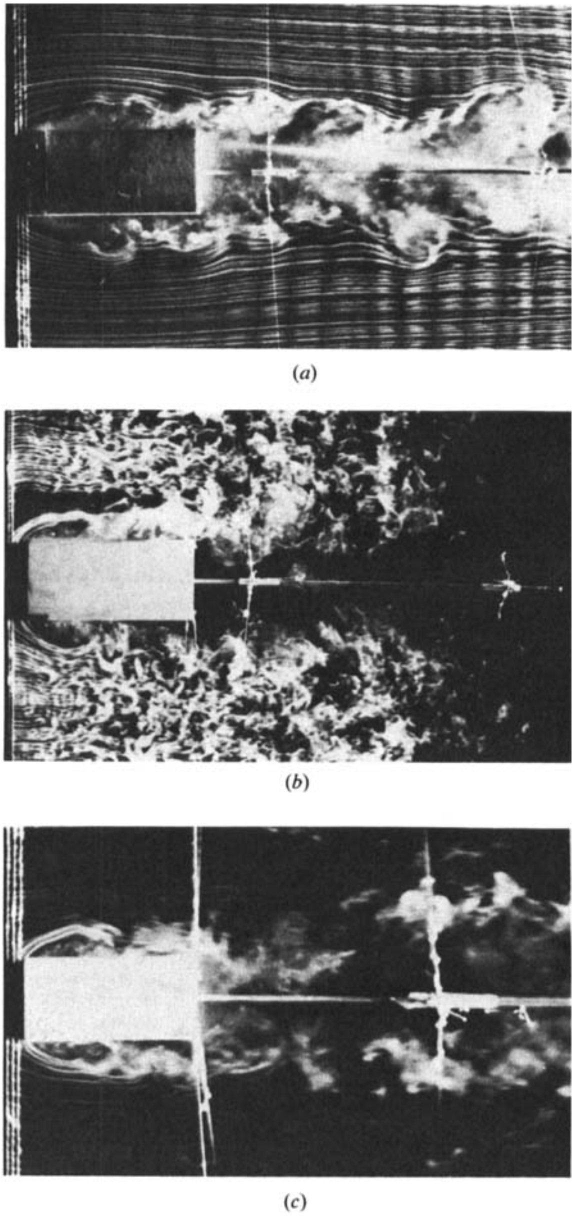


FIGURE 9. Flow patterns of a square prism with $d/h = 2.0$ for different flow conditions. (*a*) Smooth flow. (*b*) Small-scale turbulence, $L_x/h = 0.36$, $u'/U = 8.0\%$. (*c*) Large-scale turbulence, $L_x/h = 4.8$, $u'/U = 7.6\%$.

6. Resonant interaction of large-scale turbulence with vortex shedding

The present investigation has shown that the enhanced roll-up of the separated shear layers due to large-scale turbulence is closely related to vortex shedding from a square prism. In short, large-scale turbulence intensifies vortex shedding from a square prism through resonant interaction, thus reducing mean base pressure considerably. As noted earlier (Nakamura & Ohya 1983), the model of a closed wake

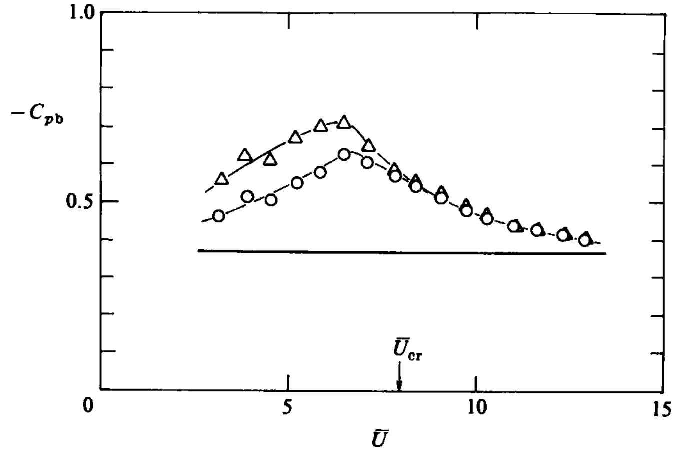


FIGURE 10. Mean base-pressure coefficients of an oscillating square plate *vs* the reduced wind speed. Position of the pressure tap measured from the centre of the rear face; ○, $0.2h$; △, $0.4h$; ——, base-pressure coefficient for the fixed model.

cavity for the flow past three-dimensional bluff bodies might be misleading unless the effects of vortex shedding are correctly taken into account. The experimental result (figure 5) that large-scale turbulence does not reduce the base pressure of long square prisms such as those with $d/h = 1.0$ and 2.0 is also compatible with the flow visualization, which showed that no regular vortex shedding is detectable in these cases.

7. Hot-wire measurements in turbulent flow

A small peak in the power spectrum of the u-component velocity fluctuations was observed in a weakly turbulent flow. For example, a Strouhal number of 0.135 was obtained for a square plate for $u'/U = 3.5\%$ and $L_x/h = 0.8$. However, the power spectra for turbulent flow with $u'/U = 8.0\%$ and above showed no detectable peaks for all the square prisms tested. Figure 11 shows the result for a square plate with $u'/U = 10.0\%$ and $L_x/h = 1.97$. The correlation of two hot-wire signals positioned in the 180° arrangement was also nearly zero. It remains unclear why hot-wire signals fail to detect the intensified vortex shedding in large-scale turbulence, and further study is needed to clarify this point.

8. Conclusions

Flow visualization and measurements of velocity and pressure were done to investigate vortex shedding from square prisms with various lengths in smooth and grid-generated turbulent flows. The main results obtained are as follows.

A square plate sheds vortices in one of the two fixed wake planes which are parallel with the plate sides. The plane of shedding is switched irregularly from one to the other. The vortex shedding from a square prism with $d/h = 0.5$ and a cube is similar, while for a square prism with $d/h = 2.0$ no such vortex shedding was observed. The effects of turbulence on the mean-flow characteristics of square prisms, which were presented in Nakamura & Ohya (1983), can be broadly explained in the light of the

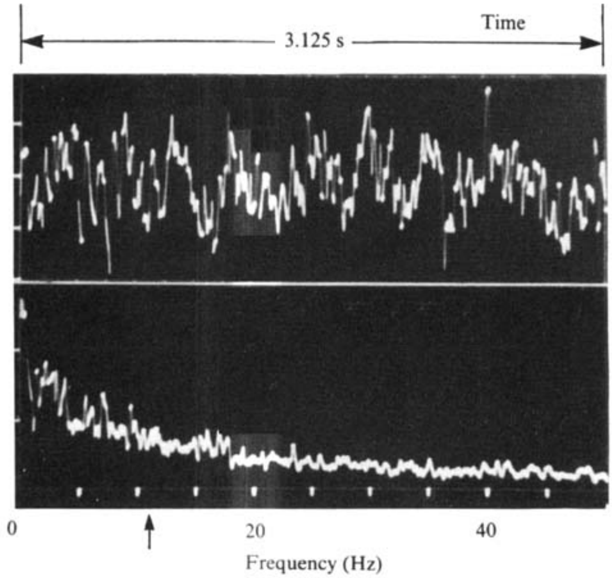


FIGURE 11. Hot-wire signal and power spectrum of the u-component velocity fluctuation for a square plate in large-scale turbulence. $L_x/h = 1.97$, $u'/U = 10.0\%$. The arrow indicates the frequency of vortex shedding in smooth flow.

findings of the present investigation. In particular, it has been shown that large-scale turbulence intensifies vortex shedding from short square prisms through resonant interaction, thereby reducing the base pressure considerably.

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