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NOTE

AERODYNAMIC CHARACTERISTICS AND FLOW PATTERNS OF A RECTANGULAR BLOCK

By Yasuharu NAKAMURA* and Taketo MIZOTA**

This note is concerned with one of a series of wind tunnel experiments on the static and aeroelastic characteristics of a rectangular block of a side ratio 2 : 1, and includes the results of the static force measurements and the measurements of the Strouhal number together with those of the flow visualization by a smoke filament technique.

1. Introduction

In order to throw light on the complicated flow around high-rise buildings and their flow-induced instabilities, a series of wind tunnel experiments on a rectangular block of a side ratio 2 : 1 has been programmed. In a previous paper[1] the galloping and the vortex excitation were investigated. The purpose of the present note is to supply the knowledge of the static aerodynamic characteristics of this particular model in order to understand its aeroelastic characteristics more precisely. The note includes the results of the static force measurements and the measurements of the Strouhal number together with those of the flow visualization by a smoke filament technique.

In his study on galloping of cylinders of various bluff sections, Parkinson[2] pointed out that rectangular sections including one having a side ratio 2 : 1 were characterized by negative lift curve slope, and he presented the detailed aerodynamic arguments on its origin. Although the model used in the present experiment was a three-dimensional one, much of the results obtained so far was found to be consistent with those presented by Parkinson on a two-dimensional model.

2. Wind Tunnel and Model

The 4 m × 2 m low-speed wind tunnel at the Research Institute for Applied Mechanics, Kyushu University was used for the present experiment. The model was a wooden rectangular block of a side ratio 2 : 1 which was geometrically similar to one used in the dynamic experiments. Fig 1 shows

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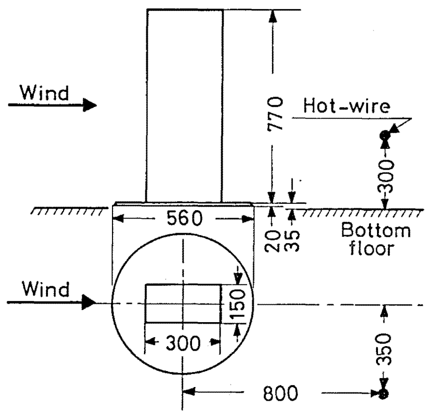


Fig 1 Diagram showing the rectangular block used in the present experiment with the position of the hot-wire probe for $\alpha=0$ deg

the dimensions of the model. The model was placed on the bottom floor of a 2 m high by 4 m wide test section with a gap of 1.5 cm, and was supported by the sting of a six-component balance. The circular disk of 56 cm in diameter was attached to the bottom of the model to minimize the effects of the air flow through the wall clearance on the model aerodynamic characteristics, particularly in dynamic experiments.

The incidence of the model α was varied from -5 deg to 90 deg, i.e., with the longer side normal to the flow. The intensity of turbulence of the main flow was 0.1 %, approximately, and the thickness of the wall boundary layer at the model position was of the order of 10 cm.

3. Experimental Results

3.1. Static force measurements

The results of measurement of the static aerodynamic forces and moment are summarized in Fig 2. Here, the aerodynamic lift, drag and moment coefficients are respectively defined by

$$C_L=\frac{L}{1/2\rho V^2(2h)l},$$

$$C_D=\frac{D}{1/2\rho V^2(2h)l},$$

$$C_M=\frac{M}{1/2\rho V^2(2h)^2l},$$

where L and D are respectively lift and drag forces, M, moment about the vertical centre axis of the model (positive clockwise), $2h$, the longer side length of the model section (=30 cm), l, the height of the model (=77 cm), ρ, the air density, and V, the flow velocity. The Reynolds number is denoted

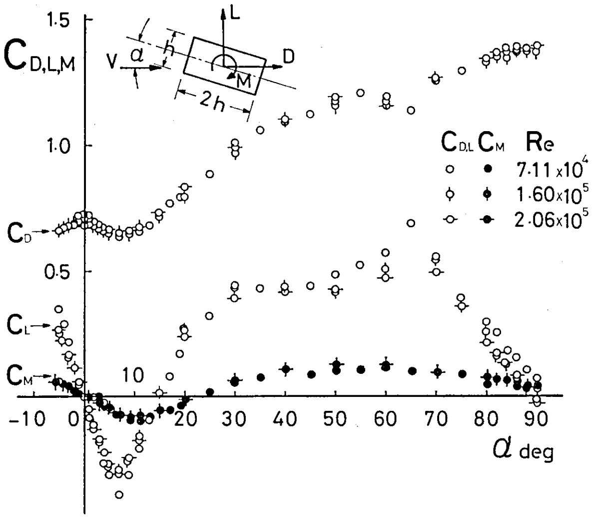


Fig 2 Variation of aerodynamic lift, drag and moment coefficients with incidence

by $Re=\frac{2hV}{\nu}$ where ν is the kinematic viscosity for air.

The measurements were made at the flow velocities of 6.9, 15.5 and 20.0 m/s, respectively, the corresponding Reynolds numbers being 7.11×10^4, 1.60×10^5 and 2.06×10^5, respectively. Since the size of the model was small enough compared with that of the test section, no wall correction was applied to any of the data obtained.

For each of the three aerodynamic coefficients in Fig 2, the points corresponding to different values of Reynolds number seem to collapse well into a single curve probably because of the fixed separation points. The value of C_D which is approximately 0.7 at $\alpha=0$ deg decreases with an increase in α, and takes a minimum at $\alpha=7.5$ deg, approximately. With further increase in α, C_D increases again up to $C_D=1.38$ at $\alpha=90$ deg except around $\alpha=60$ deg, where it decreases slightly. On the other hand, the C_L curve at $\alpha=0$ deg shows a negative slope, namely, the value of C_L which is zero at $\alpha=0$ deg for symmetry, decreases linearly until $\alpha=7.5$ deg is reached, and then the slope of the curve changes sign from negative to positive. Between $\alpha=30$ deg and 50 deg, approximately, there is no increase in the value of C_L, and for $\alpha>65$ deg, approximately, the curve has again a negative slope. The variation of C_M with α is similar to that of C_L.

The value of C_D for $\alpha=0$ deg in the present experiment shows close agreement with the two-dimensional value. At $\alpha=90$ deg, however, there is an indication of the three-dimensional effects, namely, the present value of C_D which is 1.38 is much lower than the two-dimensional one which is 2.21.

3.2. Measurement of Strouhal number

A hot-wire probe was placed somewhere downstream of the model to measure the vortex shedding frequency f. The position for $\alpha=0$ deg is indicated in Fig 1. With increasing α the position was gradually shifted so as to obtain a more periodical signal. The measurements were made at several flow velocities between 1.5 and 7 m/s, approximately. Fig 3 shows the variation of the Strouhal number $S(=\frac{fh}{V})$ with the incidence. For $\alpha=0$ and 90 deg, the values of S are in good agreement with the two-dimensional values. Corresponding to the force measurements, a rather abrupt increase in S is seen for α between 5 and 7.5 deg.

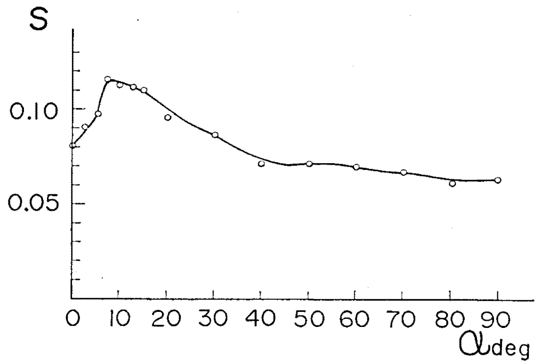


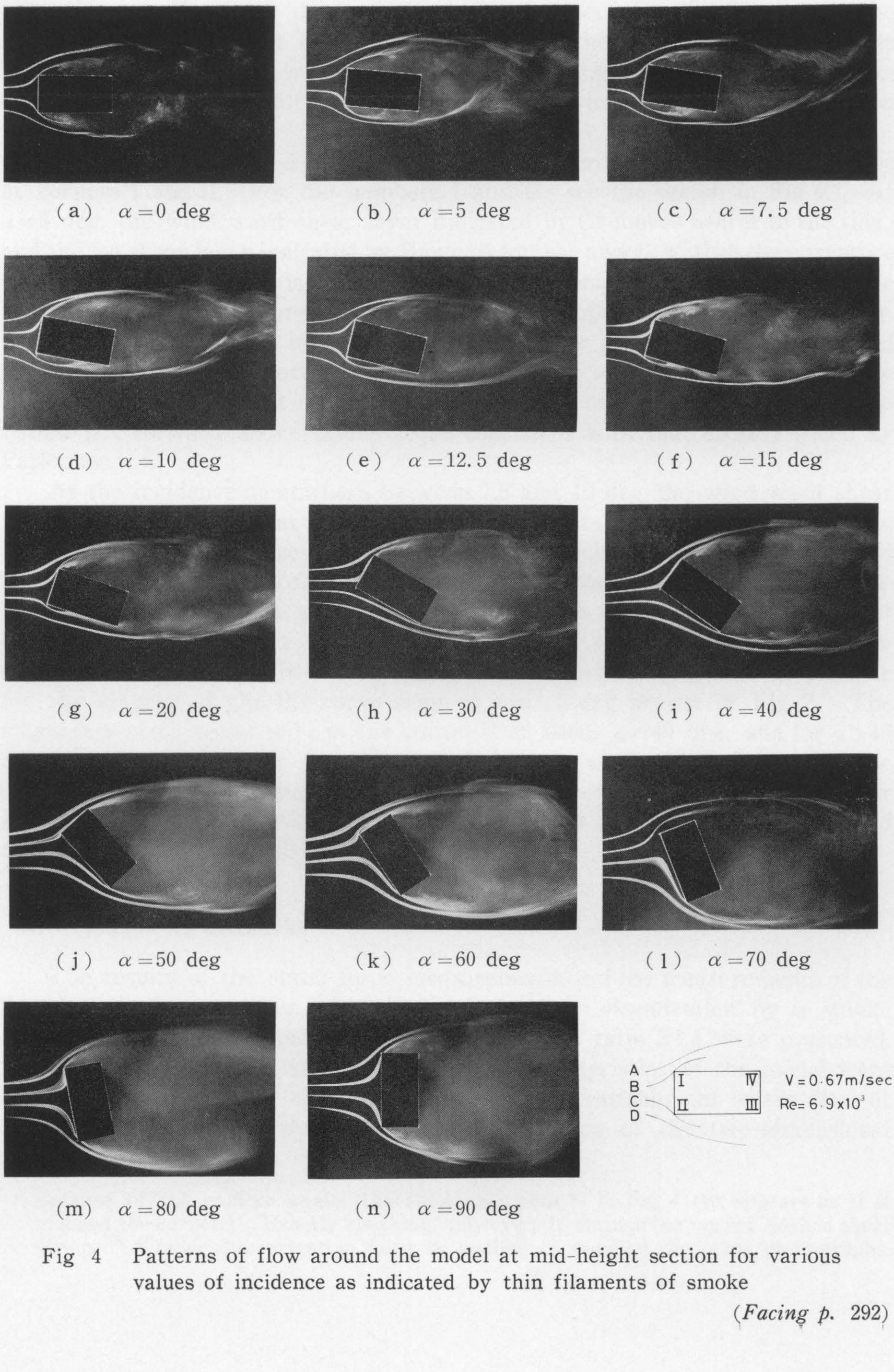
Fig 3 Variation of Strouhal number with incidence

3.3. Flow visualization

Fig 4 presents the patterns of flow around the model at the midheight section for various values of α which are indicated by thin filaments of liquid parafin smoke. A smoke generator of Preston-Sweeting type[3] was used, and a row of four smoke nozzles of 3 mm in inner diameter and 3 cm in length, with a pitch of 5 cm, was fitted with the trailing edge of a NACA 0021 aerofoil of 15 cm in chord and 30 cm in span which was set parallel to the flow at the position 30 cm upstream of the model.

Suction was applied over the rear part of the aerofoil surface to suppress the wake through small holes which were drilled at the 75 % chord from the leading edge. This method of boundary layer control was necessary to obtain thin filaments of smoke. However, due to the limitation of the power of the suction blower, the maximum flow velocity for the flow visualization was about 1 m/s, and at the flow velocities larger than this, the smoke filament became turbulent and diffused shortly after it left the nozzle exit.

The test was made at flow velocity of 0.67 m/s, i.e., at $Re=6.9\times10^3$. The photographs were taken with an exposure time of 1/8 second. A preliminary test showed that the flow pattern observed at the mid-height section



(a) $\alpha = 0$ deg (b) $\alpha = 5$ deg (c) $\alpha = 7.5$ deg
(d) $\alpha = 10$ deg (e) $\alpha = 12.5$ deg (f) $\alpha = 15$ deg
(g) $\alpha = 20$ deg (h) $\alpha = 30$ deg (i) $\alpha = 40$ deg
(j) $\alpha = 50$ deg (k) $\alpha = 60$ deg (l) $\alpha = 70$ deg
(m) $\alpha = 80$ deg (n) $\alpha = 90$ deg

Fig 4 Patterns of flow around the model at mid-height section for various values of incidence as indicated by thin filaments of smoke

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was representative over most of the sections except top and bottom of the order of 10 % in model height. The value of the flow velocity where the visualization was made is low compared to the range for the force measurement, but not too low for useful comparison, in view of the fixed separation points.

The photograph for $\alpha=0$ deg indicates that the flow completely separates at corners I and II. (For the numbers I and II, see the sketch in Fig 4.) At $\alpha=5$ deg, the wind ward shear layer indicated by C* moves nearer to the side, and the lee shear layer indicated by B moves further away, so that the curvature of the wind ward shear layer at the corner II becomes larger than that of the lee shear layer at the corner I. Under the assumption of small shift of stagnation point this change in the curvatures of shear layer at the corners I and II induces a static pressure at the wind ward side lower than that at the lee side, and as a result, a net negative lift can act on the model. The explanation put forward above seems to be consistent with that already given by Parkinson.

At the incidence somewhere between 7.5 and 10 deg the wind ward shear layer seems to reattach at the surface at the corner III and form a separation bubble. With an increase in α the point of reattachment moves on the wind ward side toward the corner II, and the bubble becomes shortened. It is reasonable to guess that the pressure rise downstream of the reattachment point of the shear layer at the wind ward side together with the reduction in suction peak at the corner II due to the shift of stagnation point are responsible for the reverse of the lift curve slope at $\alpha=7.5$ deg shown in Fig 2. The stagnation point seems to be at the corner II at about $\alpha=40$ deg, and for $\alpha>40$ deg, the flow separation and reattachment occur at the surface between the corners I and II on one hand with the separation point being fixed at the corner III on the other. The process again corresponds to the changes in forces and moment coefficients at about $\alpha=65$ deg.

4. Concluding Remarks

The results of the static force measurements and the measurements of the Strouhal number together with those of the flow visualization by a smoke filament technique of a rectangular block of a side ratio 2 : 1 were presented. It was shown that the basic aerodynamic characteristics of the model were to be closely associated with the separation and reattachment of the flow at the surfaces, and they were quite similar to those of the two-dimensional section.

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* Because of the camera angle, the smoke filament C in Fig 4 (b) appears as if it touched the corner II. Exactly speaking, however, it turned the corner with a short distance. Similar interpretation must be applied to some of the other photographs.

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