Experimental Investigation of Flow Past Bluff Body of Square Section Placed on Ground Plane*

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This paper presents an experimental investigation of a flow past a bluff body of square section placed on ground plane. The experiment was carried out in an N. P. L. type wind tunnel having a working section of 500 x 500 x 2000 mm at the Reynolds number 4.79×10^4 . The distributions of velocities, static pressures and turbulent intensities of the flow past a bluff body were measured, and the drag and lift coefficients were determined from the pressure distribution on the surface of the bluff body. The vortices generated behind the bluff body were visualized by ink in a water tank at a Reynolds number 1.06×10^3 . It is found that the drag coefficient decreases with an increasing length/width ratio and the wake is almost the same as that for square plate and bodies of length/width ratio 0.5 and 1.0, except for length/width ratio 1.5.

Key Words : Turbulence, Bluff Body, Surface Pressure, Drag, Lift, Vortex, Wake

1. Introduction

A number of investigations of a flow past a three-dimensional bluff body on a ground plane have recently been performed in connection with the air flow past a structure, such as building, gas tank, and cooling tower, for the purpose of getting information for the design of structures and the prevention of air pollution.

The flow past a three-dimensional obstacle placed on a plane boundary was initially studied by Schlichting⁽¹⁾ in relation to the effect of surface roughness. Klemin et al.⁽²⁾ studied the drag of a sphere placed on a ground plate, and Hunt⁽³⁾ investigated the flow past a building in a uniform stream. Peterka and Cermak⁽⁴⁾ measured a mean velocity defect and turbulence in the wake behind a rectangular cylinder, and Sforza and Mons⁽⁵⁾ studied the wall wake behind a flat plate of finite length placed at the leading edge of a flat plate immersed in a turbulent boundary layer. Sakamoto et al.⁽⁶⁾ (7) (8) studied the surface pressure, the drag and the flow pattern of a normal flat plate of finite length and a rectangular cylinder.

However, a few systematic studies have been hitherto performed on the flow, especially the formation of vortices, past a three-dimensional obstacle and the wake flow behind an obstacle. In relation to this problem, Okamoto et al. studied the flow past a circular cylinder of finite length⁽⁹⁾ and a cone⁽¹⁰⁾ placed on a ground plane, and the author investigated the flow past a sphere⁽¹¹⁾ and a hemisphere-cylinder⁽¹²⁾ placed on a ground plane.

This paper presents an experimental investigation of the flow field past a square plate and a cylinder of square section placed on a ground plane in a uniform flow and the wake behind them.

Nomenclature

- b : Position of peak velocity defect
- C_D : Drag coefficient
- C_L : Lift coefficient
- C_p : Pressure coefficient $= (P - P_\infty) / (1/2) \rho U_\infty^2$
- D : Side length of frontal section of model
- l : Length of recirculation region
- n : Frequency of arch-vortices shedding
- P : Static pressure
- P_0 : Stagnation pressure
- P_∞ : Pressure of free stream
- Re : Reynolds number $= U_\infty D / \nu$
- St : Strouhal number $= nD / U_\infty$
- U : Time-mean velocity in X-direction
- U_∞ : Velocity of free-stream
- u', v', w' : X, Y and Z-components of velocity fluctuation
- X, Y, Z : Coordinate axes with origin at center of bottom of model, X is taken in direction of free-stream, Y horizontally and Z vertically
- X' : Distance in X-direction from center of frontal face of model
- δ : Thickness of shear layer
- ν : Kinematic viscosity of air
- ρ : Density of air

2. Experimental Apparatus and Procedure of Measurement

The experiment was carried out in an N. P. L. type wind tunnel having a 500mm x 500 mm test section of 2000 mm length. The ground plate, an aluminium plate of 4 mm thickness, was set with a spacing of 25 mm from the bottom wall of the tunnel exit in order to avoid the boundary layer developed on the tunnel wall, (see Fig. 1). The model was placed down-

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stream at a distance 500 mm from the leading edge of the ground plate. The thickness of the boundary layer and the displacement thickness at the model position were about 6 mm and 2 mm, respectively.

The square-plate and the cylinders of square section used in this experiment are shown in Fig. 2. Two models of 70 mm and 40 mm in side length were provided, the former being used for measurement of the surface pressure and the latter for measurement of velocity, static pressure, and turbulence intensity. The ratio of width to length (W/D) of body was varied as 0.06, 0.1, 0.5, 1.0 and 1.5. It was confirmed that there was no blockage effect even for a large model of 70 mm length, because the blockage ratio for this case was 0.021 which was less than the limiting value 0.05 obtained by Farell et al. (13). Pressure holes of 0.5 mm diameter were bored over the whole surface of the square plate and the cylinders of square section. The surface pressure was transmitted to a manometer, passing through the root of the model. The free-stream velocity was $U_\infty = 10.2 \text{ m/s}$ and $U_\infty = 17.9 \text{ m/s}$ for the models of $D = 70 \text{ mm}$ and $D = 40 \text{ mm}$ respectively. The experiment was carried out at a Reynolds number, $Re = U_\infty D / \nu = 4.74 \times 10^4$. The time-mean velocity and the static pressure were measured by the Pitot and static-pressure tubes of 1 mm diameter and turbulence was measured by a constant-temperature hot-wire anemometer. The velocity vector was obtained by use of a cylindrical yawmeter of 6 mm diameter.

3. Results and Discussions

3.1 Surface-pressure

The surface-pressure distributions on the frontal and rear faces of the square plate are shown in Figs. 3 and 4 respectively. The pressure at the frontal face attains a maximum at $Y/D = 0$ because the

Fig.1 Schema of apparatus and nomenclature

Fig.2 Models

Fig.3 Surface-pressure distribution on frontal face of square plate ($W/D = 0.06$)

Fig.4 Surface pressure distribution on rear face of square plate ($W/D = 0.06$)

Fig.5 Iso-pressure lines ($W/D = 0.06$)

Fig.6 Iso-pressure lines on side face of cylinder of square section

effect of the free ends of both sides reaches near the center portion for the square plate, while it has a constant value in the neighbourhood of the center portion for the flat plate of a large aspect ratio. Then the surface-pressure distribution on the frontal face is almost unaltered except at $Z/D=0.79$ and 0.93 . On the other hand, the pressure of the rear face has a constant value of $C_p = -0.5$. Figure 5 shows the iso-pressure lines in the frontal and rear faces of the square plate. It is seen from this figure that a high pressure occurs at the center of the frontal face, and the pressure is almost constant on the rear face.

Figure 6 shows the iso-pressure lines on the side faces of the cylinders of square section. A low pressure appears in the vicinity of $X/D=-3$ for $W/D=1.5$, but different patterns are seen for $W/D=0.5$ and 1.0 . The flow separated from the frontal edges approaches the side faces of the cylinder. The surface-pressure distributions on the frontal and rear faces in the center section ($Y/D=0$) are shown in Figs.

7 and 8 respectively, where the broken line represents the result of the two-dimensional flat plate(14)(15). It is found from Fig. 7 that the point of maximum pressure which is assumed to be the stagnation point, on the frontal face for the square plate and cylinders of square section is located at $Z/D=0.45$ as in the case of the sphere(11) and hemisphere-cylinder(12). This location is considered to be the point of reattachment of a flow separated from the ground plate in front of an obstacle. The location of the point of reattachment is $Z/D=0.6$ for the two-dimensional flat plate, which is slightly high as compared with those for a square plate and cylinders of square section. The difference between them is considered to be due to the flow separation from the upper edge and the side edges in the cases of the square plate and cylinders of square section.

Figure 8 shows the base-pressure distribution in the center section ($Y/D=0$) of the rear face. The base pressure is nearly the same for $W/D=0.06$ and 0.5 , and

Fig.7 Surface-pressure at center section ($Y=0$) of frontal face

Fig.8 Base pressure at center section ($Y=0$) of rear face

Fig.9 Drag coefficient

Fig.10 Lift coefficient

Fig.11 Separation line on ground plate (case of square plate)

Fig.12 Comparison of separation lines on ground plate

recirculation region inside the area enclosed by the streamline. The length of the recirculation region, which is the distance from the origin to the point of reattachment, is shown in Fig. 16. The position of the highest pressure on the ground plane may be recognized as the point of reattachment of the outer streamline enclosing the recirculation region.

Fig.17 Arch vortices for square plate

Fig.18 Strouhal number of arch-vortices shedding

It is found that the recirculation region is reduced as the value of W/D increases, as expected from the previously mentioned distribution of pressure on the rear face.

Arch vortices are generated in the recirculation region. Figure 17 shows the generation of arch vortices visualized by the ink shedding in the water channel for the square plate. The arch vortices are periodically generated behind the separation line on the surface of the obstacle and shed downstream. The Strouhal number of the arch-vortices shedding is shown in Fig. 18. It is found from this figure that the Strouhal number is about 0.112 for the square plate ($W/D=0.06$) and cylinders of $W/D=0.5$ and 1.0 and it decreases slightly to 0.09 for a cylinder of $W/D=1.5$. The arch vortices are shed downstream, inclined and fall down on the ground plane by a strong downwash behind the obstacle. This movement of the arch vortices can be seen from the pressure distribution on the ground plate shown in Fig. 19. There are a pair of portions of the lowest pressure behind the square plate and cylinders of square section except in the case of $W/D = 1.5$, at which the roots of the arch vortices are likely to attach to the ground plane. It is supposed that the arch vortices rotate about those attachment points and fall down. However, there is no portion of the lowest pressure behind the cylinder of $W/D=1.5$, because of the reduction of recirculation region.

Fig.19 Static pressure distribution on ground plate

Table 1 Values of A and m

Bluff bodies	W/D	A	m
Square plate	0.1	4.8	-0.55
Cylinder	0.5	4.6	-0.55
Cylinder	1.0	4.2	-0.55
Cylinder	1.5	2.2	-0.14
2D flat plate ⁽¹⁶⁾		1.4	0.40

Fig.20 Lines of $(U_{\infty} - U)/U_{\infty} = 0.10$ in wall wake behind square plate

3.5 Velocity profile and turbulence intensity in far wake

The recirculation region generated in the near wake behind a square plate, ends at $X/D=4.3$, as surmised from the pressure distribution on the ground plane, and a turbulent shear layer is formed along the ground at $X/D \geq 5$. In order to investigate the downstream change in the far-wake, Figure 20 shows the lines of $(U_\infty - U)/U_\infty = 0.10$ in the wake for the square plate. It is found from this figure that the wall wake behind a three-dimensional obstacle becomes thin and spreads transversely with an increase in the downstream distance. Figure 21 shows the time-mean velocity profiles in the center section ($Y=0$) for the square plate. The thickness of a turbulent shear layer is defined by the value of Y when U is equal to $0.99U_\infty$. The thickness of the shear layer decreases with an increasing downstream distance, as shown in Fig. 22. The thickness may be expressed by the following equation,

$$\delta/D = A(X/D)^m$$

with the values of A and m shown in Table 1. The thickness of turbulent shear layer for the cylinder of $W/D = 1.5$ decreases slowly as the downstream distance increases, which is different from the cases of other obstacles because of a weak downwash behind the obstacle. It should be noticed that the thickness of the turbulent shear layer increases with an increasing downstream distance in the case of a two-dimensional flat plate⁽¹⁶⁾, contrary to the case of the three-dimensional flat plate and rectangular cylinder.

Figure 23 shows the profiles of the velocity defect in the wake at $X/D = 10$. At $Z/D=0.2$, the velocity defect becomes large and two peaks appear in the profiles. The velocity defect decreases with an increasing vertical distance from the ground

Fig.21 Profiles of mean velocity in center section of square plate

plane, but two peaks still remain in the case of the cylinders of $W/D=0.06$, 0.5 and 1.0 , while the distributions of velocity defects have a peak at $Z/D = 0.8$ for the case of the cylinder of $W/D=1.5$ unlike the cases of other cylinders. The transverse spread of the velocity profile is large at lower value of Z/D , and it decreases with an increasing upward distance from the ground plate. It becomes small for the case of $W/D=1.5$, as compared with other cylinders.

Figures 24~26 show the distributions of the turbulence intensities in the X-, Y- and Z-directions at $X/D=10$, respectively. Since the wall wake spreads transversely with an increasing downstream distance, the Y-component of turbulent intensity is larger than the X-component of turbulence intensity in the horizontal section at $Z/D=0.2$ and 0.4 . The Y-component of turbulence intensity is larger than the

Fig.22 Thickness of shear layer in center section ($Y=0$)

Fig.23 Profiles of velocity defect at $X/D=10$

X-component of turbulence intensity in the center section at $Z/D=0.6$ and 0.8 , but is smaller in other sections. The Z-component of turbulence intensity becomes small compared with the X- and Y-components of turbulence intensity, because the wall wake becomes thin and approaches the ground plane.

3.6 Change of velocity profile and turbulence in the downstream behind obstacle

Fig.24 Profiles of X-component of turbulence intensity at $X/D=10$

The profiles of mean velocity defect and the decay of turbulence in the wake in the horizontal center section ($Z/D = 0.5$) are shown in Figs. 27, 30, 31 and 32 respectively. The profile of velocity defect has one peak at the center ($Y=0$) at $X/D=5$, and it comes to have two peaks as the downstream distance increases. The velocity defect decreases and the width of the wall wake increases with an increasing downstream distance.

Fig.26 Profiles of Z-component of turbulence intensity at $X/D=10$

Fig.25 Profiles of Y-component of turbulence intensity at $X/D=10$

Fig.27 Profiles of velocity defect in horizontal center section ($Z/D=0.5$)

Figure 28 shows the velocity defect in the center section ($Y = 0$) at $X/D > 5$, which is expressed as

$$(U_{\infty} - U)/U_{\infty} = B(X/D)^n$$

with the values of B and n shown in Table 2. The value of n for $W/D = 0.1 \sim 1.0$ is $n = -1.54$, which is close to Hunt's result (3), $n = -1.5$, for the wake behind a building. The position ($Y=b$) of peak velocity defect is shifted in the Y -direction with an increasing downstream distance, as shown in Fig. 29, and b is expressed as

$$b/D = 0.06(X/D)^{1/4} \quad (W/D = 0.1 \sim 1.0)$$

$$b/D = 0.03(X/D)^{1/6} \quad (W/D = 1.5)$$

It is found from this figure that the wall wake spreads transversely with an increasing downstream distance.

The X -component of turbulence intensity is larger than the Y -component at $X/D = 5$ to 10 except in the center portion ($Y =$

Fig.28 Velocity defect in center section ($Y=0$, $Z/D=0.5$)

Fig.29 Position of peak velocity defect ($Z/D=0.5$)

Table 2 Values of B and n

Bluff bodies	W/D	B	n
Square plate	0.1	4.5	-1.54
Cylinder	0.5	4.0	-1.54
Cylinder	1.0	3.5	-1.54
Cylinder	1.5	1.9	-1.33

Fig.30 X-component of turbulence intensity ($Z/D=0.5$)

Fig.31 Y-component of turbulence intensity ($Z/D=0.5$)

Fig.32 Z-component of turbulence intensity ($Z/D=0.5$)

0), but they are almost equal at $X/D = 14$, as seen in Figs. 30 and 31. On the other hand, the Y-component of turbulence intensity is larger than the X-component in the center portion ($Y=0$). And the Z-component of turbulence intensity is smaller than the X- and Y-components as shown in Fig. 32, but it approaches the values of X- and Y-components at $X/D=14$. It is found that the turbulence tends to be isotropic in the downstream from $X/D=14$. The Z-component of turbulence intensity is nearly equal to the X-component in the center portion ($Y=0$) except in the case of $W/D = 0.1$. Figure 33 shows the variation of the three components of turbulence intensities at $Y=0$ and $Z/D=0.5$ in the downstream distance from $X/D=5$.

4. Conclusions

This paper presents an experimental study of a flow past a square plate and cylinders of square section placed on the ground plane. The results of the present study are summarized as follows :

- (1) The drag coefficient decreases with an increasing W/D , and the lift coefficient is largest for a cylinder of $W/D=1.0$ among three bluff bodies.
- (2) The Strouhal number of arch-vortices is 0.112 for a square plate and cylinders of $W/D=0.5$ and 1.0.
- (3) The length of the recirculation region is $l/D=4.3$ for a square plate, and it is reduced with an increasing W/D for a cylinder of square section.
- (4) The wall wake behind the square plate and cylinders of square section becomes thin and spreads transversely with an increasing downstream distance. This change of the wall wake is almost the same as that of a square plate and cylinders of $W/D=0.5$ and 1.0, while that for the cylinder of $W/D=1.5$ is different from those of other obstacles.

Fig.33 Decay of turbulence intensities at $Y=0$ and $Z/D=0.5$

- (5) The turbulence in the wall wake tends to be almost isotropic at $X/D > 14$ for $W/D=0.1$ to 1.5.

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