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The Effect of Turbulent Uniform Flow around A Square Cylinder

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Abstract **–**Turbulent uniform flows past a two-dimensional square cylinder are investigated numerically. By varying the turbulence intensity and turbulence length scale of the approaching flow, the flow behaviour and the flow effect of the cylinder are compared to that in a laminar approaching-flow case. In addition, the variations of drag and lift with respect to the changes of turbulence intensity and turbulence length scale are analyzed on a systematic basis. In the study, the method of large eddy simulation is adopted. The approaching-flow turbulence is considered homogeneous and isotropic and is generated by a spectral method according to *Karman* spectrum. Two levels of turbulence intensities (5% and 10%) and three turbulence length scales (0.25, 0.50 and 1.0 times of the cylinder width) are selected in the program to examine the effect on the cylinder due to existing turbulence in the approaching-flow. Results show that the Strouhal number associated with the turbulent approaching flows remains unchanged compared to that in the laminar approaching-flow case. On the other hand, approaching-flow turbulence has noticeable effect on the resulting drag and lift. When the approaching flow becomes turbulent, generally, the resulting mean and root-mean-square values of drag as well as the magnitude of lift fluctuations are promoted. An increase of the turbulence length scale leads to a mild increase of the mean drag and the fluctuating lift, while the effect due to a change of the turbulence intensity appears insignificant. Moreover, a larger value of turbulence intensity results in a greater value of drag fluctuation.

Keywords**:** Square Cylinder; Turbulent Approaching Flow; Turbulence Intensity; Turbulence Length Scale; Large Eddy Simulation

1. Introduction

A uniform flow past a two-dimensional square cylinder is a typical bluff-body-flow problem, which involves fundamental researches of the surrounding flow behaviour and the effect of the body. Physically, as the flow passes the body, separation is initiated at the leading edges of the cylinder due to a sudden pressure drop. The separation lines from both sides of the body roll and form pairs of alternative vortices downstream. As a result, the so-called vortex shedding phenomenon can be found in the wake region of the flow. Due to the unsteady behaviour of the wake flow, therefore, the resulting drag and lift associated with the body become time-dependent.

In the past, a majority of the related studies concentrated on such a flow problem under the condition that the uniform approaching flow is laminar. The investigations of the flow behaviour and flow effect on the cylinder can be performed by conducting laboratory experiments. However, as the approaching flow is considered turbulent, technical difficulties may be encountered. To obtain a turbulent uniform approaching flow in a wind or water tunnel, for instance, a grid panel was commonly set at the upstream of the test section to produce initial flow turbulence. Since the generated turbulence was highly non-equilibrium, it often decayed rapidly along the streamwise direction. Consequently, the approaching-flow turbulence characteristics were not easy to control precisely. For the same reason, the achievement of a relatively larger turbulence intensity level was generally considered difficult. In contrast, the use of numerical simulation to deal with the analysis can be another choice. In large eddy simulations, the velocity components at the inlet boundary of the computational domain have to be correctly specified to ensure that the turbulence characteristics remain unchanged along the streamwise direction.

2. Problem Description

The goal of the study is to investigate numerically the flow and its effect on a two-dimensional square cylinder with uniform approaching flows containing isotropic and homogeneous turbulence. By varying the turbulence intensity and the length scale, the resulting shedding frequency (f_S), drag (F_D) and lift (F_L) are analyzed to assess the approaching-flow turbulence effect on the wake flow and the force on the body systematically.

Fig. 1 illustrates the schematic of the problem. The attack angle of the approaching flow is zero. The turbulence intensity (I_u) and length scale (L_u) in the approaching flow are referred to the component in the streamwise (x) direction. Two turbulence levels (I_u= 5% and 10%) and three turbulence length scales (L_u = 0.25D, 0.50D and 1.0D) are selected in the study. The Reynolds number (U_0D/ν; ν is kinematic viscosity) is taken as 10^5.

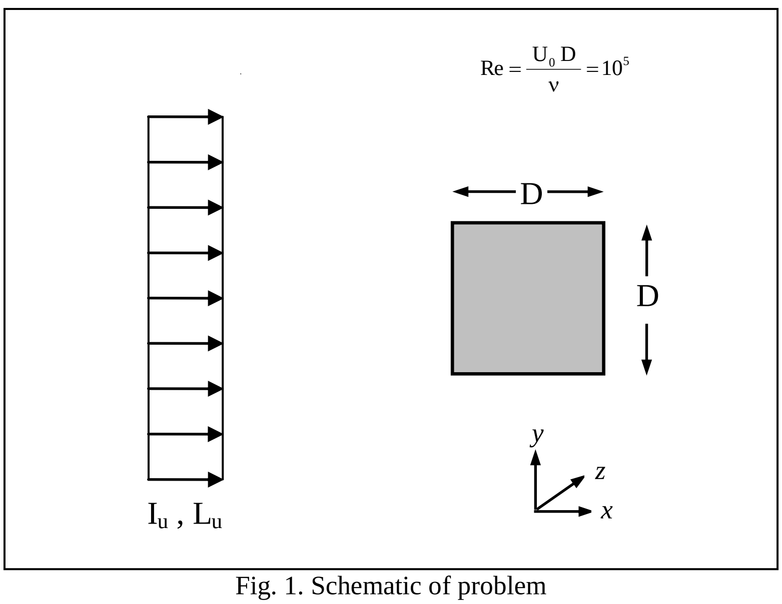

Fig. 1. Schematic of problem

3. Numerical Method

A weakly-compressible-flow method (Song and Yuan, 1988) is adopted in the flow simulation. In the method, the continuity and momentum equations are

$$\frac{\partial p}{\partial t} + k \nabla \cdot \overrightarrow{V} = 0 \tag{1}$$

$$\frac{\partial \overrightarrow{V}}{\partial t}+\overrightarrow{V}\cdot\nabla\overrightarrow{V}=-\nabla\frac{p}{\rho}+\nabla\cdot[(\nu+\nu_t)\nabla\overrightarrow{V}] \tag{2}$$

where p and $\overrightarrow{V}$ denote respectively spaced-averaged pressure and velocity; t is time; k is the bulk modulus of elasticity of air. ν and ν_t are respectively the laminar and turbulent viscosities, and the latter is determined according to a subgrid-scale turbulence model proposed by Smagorinsky (1963). Accordingly, the turbulent viscosity is obtained as

$$\nu_t=(C_S\Delta)^2\sqrt{2S_{ij}S_{ij}}\ ,\ \text{where}\ \ S_{ij}=\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right) \tag{3}$$

in which C_S is the Smagorinsky constant (0.1) and Δ is the characteristic computational grid size.

In all flow simulations, three-dimensional flow computations are carried out in a 25D×12D×8D rectangular domain and the results on the middle plane in the span-wise direction of the cylinder are taken as the basis of the analysis of the two-dimensional problem. Fig. 2 depicts a typical computational mesh system (170×100×80) on the x-y plane. The smallest grid size is 0.05D.

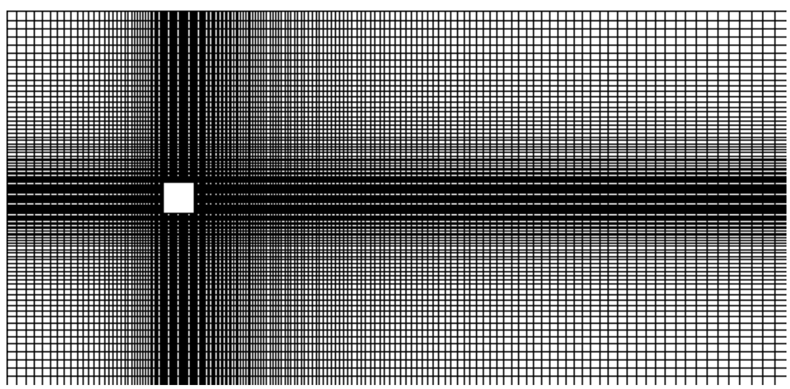

Fig. 2. Typical mesh system on the x-y plane

Appropriate values of pressures and velocities are specified at exterior cells (or phantom cells) outside of the boundaries to reflect physical nature of the boundaries. At the cylinder surface, a no-slip condition is used. At the side boundaries, the pressures and velocities at the phantom cells are specified according to a zero-gradient assumption in the direction normal to the boundaries. At the inflow section, prescribed unsteady velocities are imposed and a zero-gradient condition is applied for pressure specifications. At the outflow boundary, on the other hand, a zero-gradient condition is used for the velocities and the sectional average pressure is set as the reference pressure of the instantaneous flow field.

To generate homogeneous and isotropic turbulence at the inflow section, the modified discretizing and synthesizing random flow generation (MDSRFG), proposed by Castro et al. (2011), was used. By prescribing given values of turbulent intensity and length scale, the generated velocity components in all the three directions (x, y and z) were obtained based on von Karman spectrum.

4. Performance of The Generated Turbulent Approaching Flow

In each case, after the history of the generated turbulent inlet velocity at the inlet boundary corresponding to a prescribed turbulence intensity and length scale were achieved, preliminary large-eddy simulations were conducted in the computational spatial domain without the existence of the cylinder.

The longitudinal variations of the resulting turbulence characteristics (turbulence intensity, turbulence scale and energy spectrum) were analyzed to examine the validity of the generated turbulence. Fig. 3 illustrates a typical example (I_u=5% and L_u=0.25D) of the resulting power spectra at x=0 (inlet) and x=5D (the location where the cylinder would be set). It shows that the generated turbulence, initially meet von Karman spectrum, remains almost unchanged along the streamwise direction. This indicates that the longitudinal turbulence decay is insignificant.

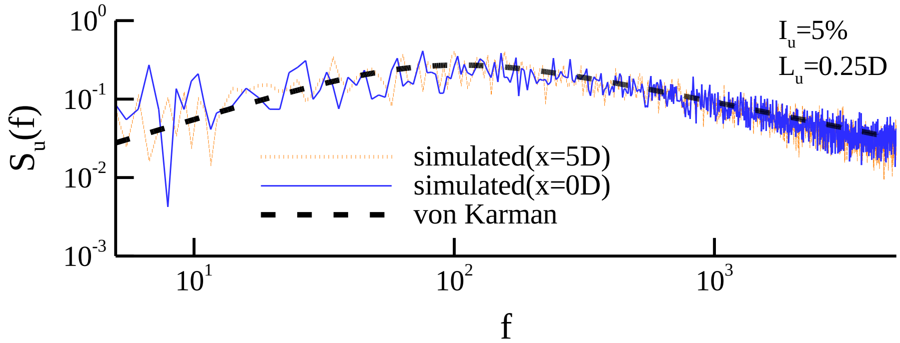

Fig. 3. Comparison of energy spectra of turbulence

5. Verification of The Numerical Method

Computation of a turbulent uniform flow past a square cylinder iss conducted in a case with I_u=5.3% and L_u=1.12D at a Reynolds number of 6.89×10^4. The results of the predicted Strouhal number (St=f_S/D) as well as the normalized coefficients of mean and root-mean-square drag and lift are listed in Table 1, together with those from the experiments by. Noda and Nakayama (2003). In the table, “bar” and “prime” denote respectively mean and root-mean-square values; $C_D = F_D / 0.5\rho U_0^2$; $C_L = F_L / 0.5\rho U_0^2$. It can be seen that good agreement between the predicted and experimental results is obtained.

Table. 1. Comparison between the predicted and experimental results

	St	$\overline{C_D}$	$C_D^{'}$	$\overline{C_L}$	$C_L^{'}$
Experimental (Noda & Nakayama, 2003)	0.133	1.989	0.203	-	0.945
Calculated	0.131	2.059	0.277	0.009	1.001

6. Results

A preliminary flow simulation is performed in a laminar approaching flow case (I_u=0%) at a Reynolds number of 10^5 and the calculated normalized quantities are shown in Table 2. Six flow computations with turbulent approaching flows at the same Reynolds number are conducted further at two turbulence intensities (I_u = 5% and 10%) and three turbulence length scale (L_u = 0.25D, 0.5D and 1.0D) and the results are compared with those in the laminar approaching-flow case.

Table. 2. Numerical result in the laminar approaching flow case

	St	$\overline{C_D}$	$C_D^{'}$	$\overline{C_L}$	$C_L^{'}$
Calculated (Re=10^5)	0.134	2.142	0.229	0.003	1.061

6. 1. Effect on the Strouhal Number

Based on the results of flow simulations, Fig. 4 depicts the power spectra associated with the lift of the square cylinder. For all the six cases of the turbulent approaching flows, it is found that the resulting Strouhal number remains unchanged (0.134), compared to that in the laminar-approaching-flow case.

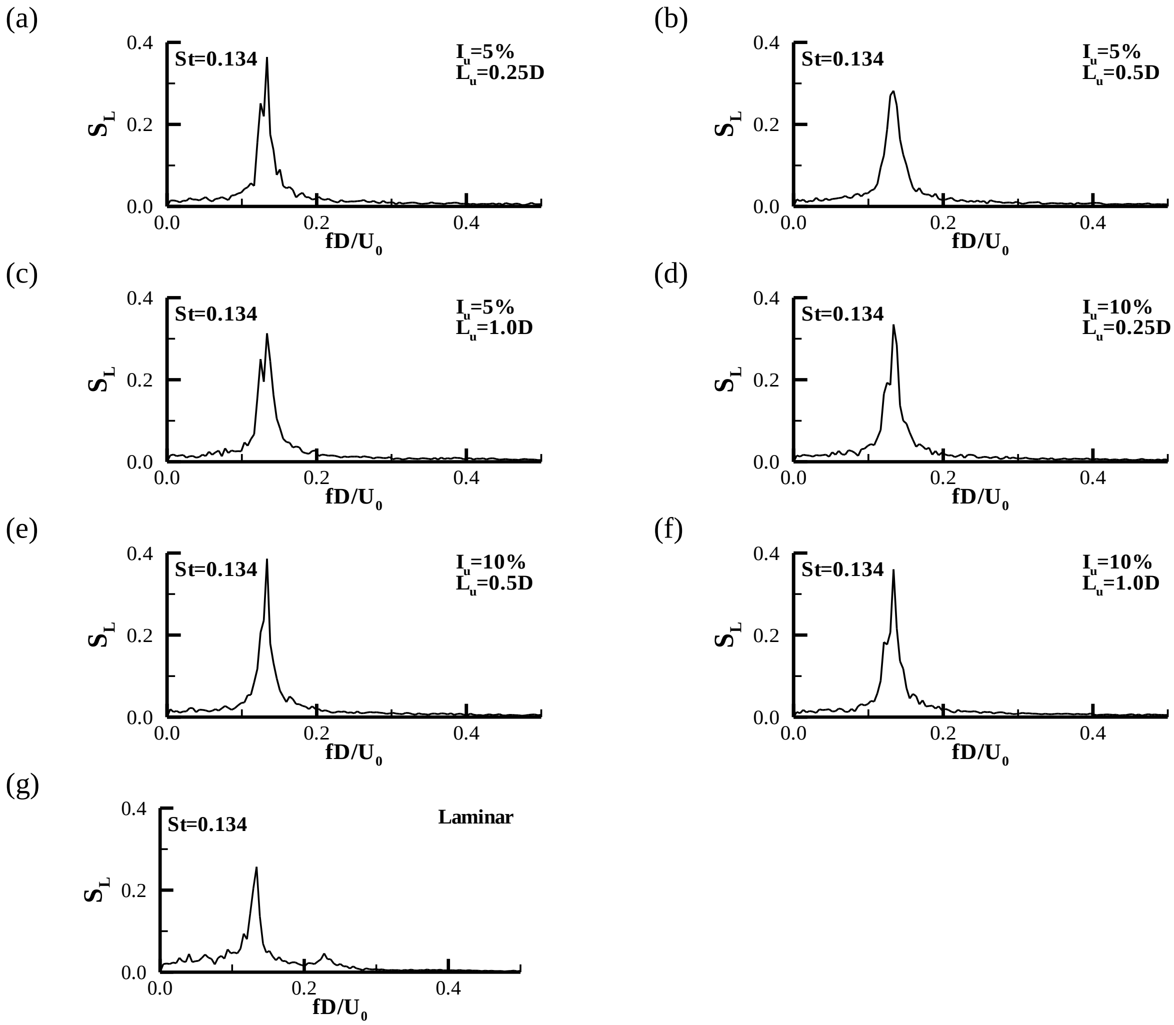

Fig. 4. Comparison of power spectra associated with resulting lift

6. 2. Effect on the Mean and Fluctuating Drag

Fig. 5 depicts the variation of the simulated mean and fluctuating drag coefficients ($\overline{C_D}$ and $C_D^{'}$). The results show that as the approaching flow are turbulent, both the mean and root-mean-square values of drag become larger compared to that in the laminar approaching-flow case. As the variation of the mean drag is concerned, generally, its variation is insensitive to the change of I_u (see Fig. 5a). At the smallest turbulence length scale (L_u=0.25D), slight increases, compared to the laminar result, are detected. As L_u is greater than 0.5D, the $\overline{C_D}$ difference becomes greater. Considering the fluctuating drag coefficient, on the other hand, it is clearly shown in Fig 5b that I_u plays an important role in affecting the extent of the drag fluctuations, primarily due to the effect of the approaching-flow turbulence. Fig. 5b indicates that a greater value of I_u leads to more significant drag fluctuations. With an increase of L_u, the resulting $C_D^{'}$ appears also increasing.

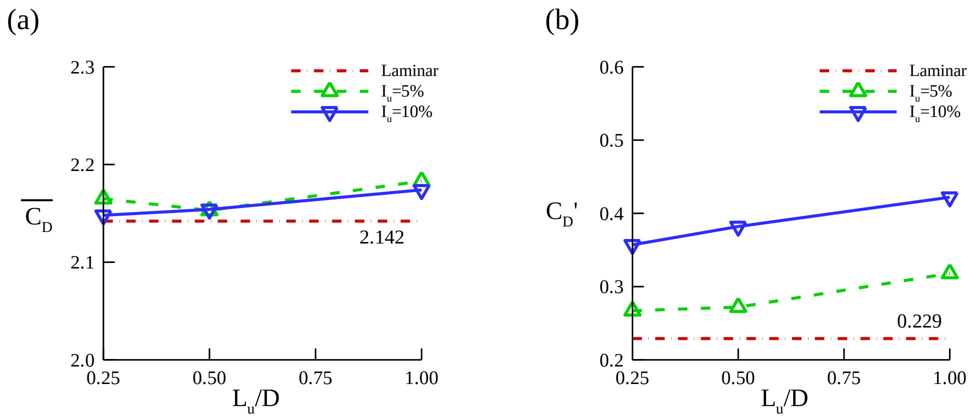

Fig. 5. Variations of normalized drag coefficients (a) mean (b) root-mean-square

6. 3. Effect on the Fluctuating Lift

The variations of fluctuating lift coefficients (C_L') with respect to L_u and I_u are depicted in Fig. 6 according the results of numerical computations. Due to the effect of approaching-flow turbulence, it is found that the extent of fluctuating lift is promoted, compared to that in the laminar approaching-flow case. Generally, a larger I_u results in a larger fluctuating lift. As L_u increases from 0.5D to 1.0D, C_L' also increases.

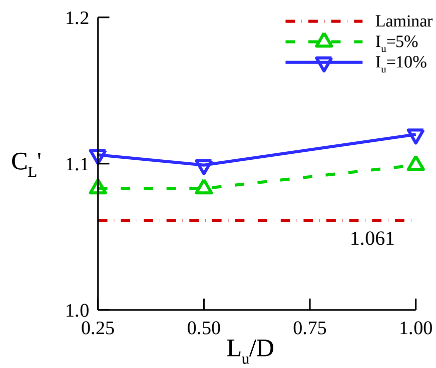

Fig. 6. Variations of normalized root-mean-square lift coefficients

7. Conclusion

The flow around a two-dimensional square cylinder with turbulent uniform approaching flows was investigated numerically at a Reynolds number of 10^5. By varying the turbulence intensity and the turbulence length scale, the flow effect on the cylinder was analyzed on a systematic basis. The results, in terms of the Strouhal number, mean and fluctuating drag coefficients and the fluctuating lift coefficient, were also compared with those in a laminar approaching-flow case. Within the test ranges of turbulence intensity and turbulence scale, several conclusions are drawn as follows:

1. As the uniform approaching flow changes from a laminar case to a turbulent one, the resulting Strouhal number remains unchanged.
2. The turbulence in the uniform approaching results in increases of the mean and fluctuating drag as well as the fluctuating lift on the square cylinder.
3. For a uniform turbulent flow past a square cylinder, the magnitude of the turbulence intensity has little effect on the mean drag. On the other hand, an increase of the approaching-flow turbulence intensity tends to promote the extent of drag and lift fluctuations.

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