DNS OF TURBULENT CHANNEL FLOW WITH A FLEXIBLE SQUARE CYLINDER

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Abstract Fluid-Structure Interaction (FSI) problem is concerned with in various research fields such as mechanical, aerospace, civil and medical engineering. Their accurate prediction and control are desired. So far, in order to improve the performance of various applications, many kind of research, on the heat transfer enhancement due to vortex generator in heat exchangers, on the drag reduction through the setting of bluff body in pipe-line systems, and on the reduction of flow induced vibration, are conducted. In particular, since the wake of wall-mounted cylinder is a common flow regime in above-mentioned research, the detail of the flow has been aggressively investigated so far[1]. The present study, we pay attention to the flow control using flexible structures in the above mentioned flows. To investigate the potentiality of the control in advance, both high accurate and stable computational scheme is needed so that the actual phenomena including turbulence is well predicted. Therefore, in order to analyze the fluid-structure interaction, we propose a weak-coupling method[2] in which for flexible structures, the rigorous equations of motion are discretized with finite volume method (FVM[3]); for a flow computation, the finite difference method (FDM) is used and the flexible structures is reproduced via immersed boundary method[4]. In this present paper, we demonstrate on the result of flow structure around of rigid and elastic cylinder in turbulent channel flow.

RESULTS

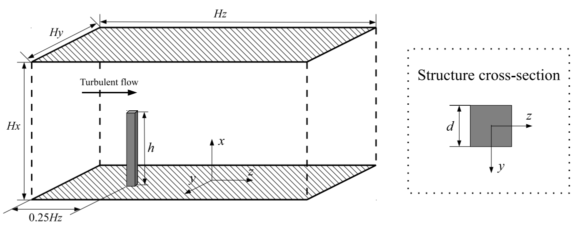

Figure 1. Computational domain of turbulent channel with a square cylinder
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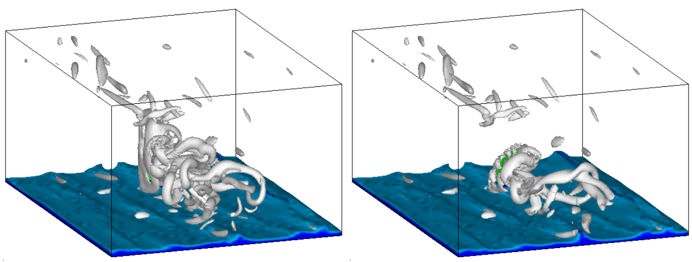
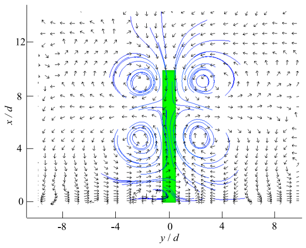


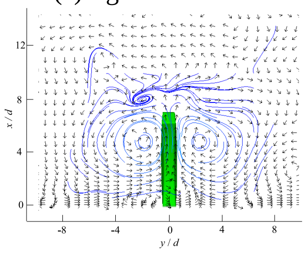
(a) rigid cylinder (b) elastic cylinder

Figure 2. Instantaneous flow structures

The computational volume is shown in Fig.1. The wall condition is enforced on the both upper and lower boundary. The cylinder is placed on the lower boundary. The inflow being generated by the upstream channel, is imposed on the left side boundary and a convective outflow boundary is used on the right side boundary. Periodicity is enforced in spanwise direction. The Reynolds number Re_τ=150. We perform the computation of both rigid and elastic square cylinder. Fig. 3 shows the instantaneous vortical structure. The coherent vortices (white color) are visualized using the isosurfaces of the second invariance of velocity gradient tensor Q. Since a high threshold value is set, strong vortex structures are captured and distribute in the wake of the cylinder. In general, it is well known that quasi-streamwise vortices govern near-wall turbulence, however not show here, we have confirmed that the quasi-streamwise vortices near the wall are observed when the threshold of Q value is set as low. Also it can be seen that the effect of cylinder on the instantaneous flow structures is limited around the wake region. In the case of both rigid and elastic square cylinder, the periodicity of vortex shedding in the wake of the cylinder are observed from the animations. In particular, in the case of the elastic square cylinder, the vortex shedding occurs according to the spanwise motion of cylinder. The result of FFT analysis about time signal of the streamwise velocity in the wake at a given position where a strong vortical structure are observed. A dominant shedding frequency f_s appears at $f_s = 14.7$ corresponding to the Strouhal number $(St = f_s d/W_m)$, 0.098. This value is good agreement with that of experimental data ($St = 0.1$ at aspect ratio $h/d = 10$,). The vortex shedding frequency f_s of elastic cylinder appears at about $f_s = 6.32$ coressponding to the spanwise vibration period of the elastic cylinder f_{st}, 6.03. And as another feature, the resonant frequency of the elastic square cylinder, 5.36 is close to the value of vibration period, f_{st}. To investigate mean flow characteristics, the mean velocity vectors and streamlines are shown in Figs. 3 . In Fig. 3(a), two vortex pairs with a focus on the saddle point $(x/d = 7.0, y/d = 0)$ are formed. The lower vortices pair entrains an ambient fluid and form an upwash flow from the lower wall, similarly the upper vortices entrains the ambient fluid and form a downwash flow. The lower vortices pair is called as "base vortex"[1]. The generation of vortices depends on a boundary layer thickness of both sides of cylinder. In particular, as a boundary layer thickness becomes thicker, the upwash flow induced by base vortex is enhanced[1]. In Fig. 3(b), a pair of vortices is formed and the upwash flow from the lower wall occurs only.

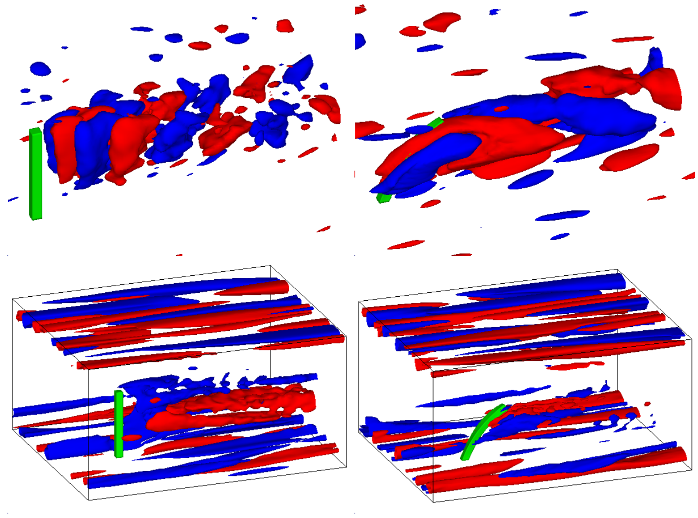


(a) rigid cantilever



(b) elastic cantilever

Figure 3. Mean streamlines and velocity vectors on $x - y$ plane (z/d =12.5)



(a) rigid cylinder (b) elastic cylinder

Figure 4. Iso surfaces of real part of first and second mode extracted with DMD. (upper: first mode; lower: second mode ; positive (red) and negative (blue))

In order to investigate the coherent motions, dynamic mode decomposition (DMD)[5] method is used. From frequency characteristics of DMD, it revealed that the first and second mode of rigid cylinder are St = $0.1011, 0.00068$, respectively. In particular, the first mode frequency is good agreement with the vortex shedding frequency extracted from FFT analysis. For the elastic case the first and second mode is St = $0.045, 0.00068$, respectively and both frequencies have the same tendency of rigid case, *i.e.*, the vortex shedding freq. and fairly lower than it occur. Figures 4 show the mode pattern defined with eigenvector extracted using DMD. In the fig., the isosurface denotes the streamwise component of eigenvector corresponding to the streamwise velocity component. The first mode of each case demonstrates that a pattern related to the vortex shedding is formed downstream of cylinder, *i.e.*, for rigid case it seems that the pair of hairpin vortex observed in Fig. 3(a) induces alternately issuing pattern from the cylinder; for the elastic case, single hairpin in Fig. 3(b) induces the spanwise oscillating pattern. It should be noted that the second mode of both cases demonstrate the streaky structures over the upper and lower wall are formed and it reveals that the streaky structures have lower frequency dynamics compared to the vortex shedding frequency.

CONCLUSIONS

1. In the calculation of the rigid square cylinder, it demonstrated that the computational result in which two pairs of the large vortices are formed in the wake of cylinder is qualitatively agreement with the experimental finding reported in the literature[1].

2. It reveals that the elastic deformation induces the different flow pattern from that of rigid case, i.e., the number of large-scale vortex structure becomes unity, and the recirculation region shrinks compared to the rigid case.

3. From the results of the DMD method, it is found that the frequency of the dominant dynamic mode quite agree well with the vortex shedding frequency and that the flow pattern is determined by the large scale-structures due to the vortex shedding according to the cylinder profile.

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