3D-FLOW STRUCTURE ANALYSIS AROUND A CIRCULAR CYLINDER USING IB-METHOD

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ABSTRACT

2D and 3D fluid simulations for flow around an in-line forced oscillating circular cylinder have been conducted in order to clarify the mechanism of flow induced vibration. Immerged boundary method is used to solve the moving boundary. Additionally, OpenFOAM which is open source CFD-tool is used. The vibration modes of a cylinder are categorized into two excitation region in terms of the reduced velocity. In the first excitation region, it is shown that a low drag force forms by contacting between high pressure region and a circular cylinder. It is considered that an in-line oscillation of a cylinder comes from the contact phenomena. In the second excitation region, it is shown that the time averaged lift drag doesn’t reach zero on some oscillating conditions. It is considered that a cross-flow oscillation of a cylinder comes from the phenomena.

1. INTRODUCTION

The flow-induced vibration of a cylinder is one of the important phenomena in various engineering fields, because the vibration causes a lot of noise or fatigue breakdown. In nuclear power plants, cylindrical structures subjected to cross-flow conditions are widely used. Therefore a lot of researches have been reported so far [1,2]. Through previous researches, it is known that shear layer separates from a cylinder and generates various vortex structures in the wake region. It has been made clear that these vortex structures produce a vibration in a cylinder.

In the flow-induced vibration of a cylinder, essential information is the drag coefficient, the lift coefficient and the vortex shedding frequency. The drag and lift coefficients are related to the force acting on the cylinder. The vortex shedding frequency is related to resonance with vibration of a cylinder. These values must be correctly evaluated in engineering applications.

The 2D and 3D-vortex structures in the wake region have an important role on these values. In the vortex structures around a cylinder, 2D vortices are basically dominant, although 3D vortices also have an effect on 2D vortices. However, there are many points that are unclear about effects which 3D vortices have on 2D vortices. The quantitative and qualitative evaluation of the effects is very important to engineering applications.

In the present study, 2D and 3D fluid simulations for flow around an in-line forced oscillating circular cylinder have been conducted in order to clarify the mechanism of flow induced vibration. The vibration of a cylinder is categorized into 2 types based on the reduced velocity $U_r = U/f_c D$. Here, $U$, $f_c$, and $D$ are the main velocity, the cylinder vibration frequency and the diameter of the cylinder respectively. The vibration of a cylinder in the in-line direction is shown when the reduced velocity is smaller than about 4.0. The region is called as the first excitation region. When the reduced velocity is larger than about 4.0, the cross-flow vibration is dominant. The region is called as the second excitation region.

In the present study, the vortex structures in the two excitation regions are quantitatively and qualitatively evaluated and discussed about the effects on 2D vortex structures. Immersed boundary method [3] is used to solve the moving boundary. Additionally, OpenFOAM which is open source CFD-tool is used.

2. NUMERICAL SIMULATION

The discretization schemes implemented in OpenFOAM is finite volume method. The three dimensional incompressible Navier-Stokes equation using finite volume method and immersed boundary method is formulated as follows,

\[
\int_{V'} \frac{\partial u}{\partial t}dV' = - \int_{V'} div(u\nabla u)dV' - \int_{V'} div(p\nabla)dV' + \frac{1}{Re} \int_{V'} div[\nabla u]dV' = \int_{S_{int}} (u\nabla dS) - \int_{S_{int}} (p\nabla) dS + \frac{1}{Re} \int_{S_{int}} \nabla dS
\]

Figure 1 shows conceptual diagram of the present method. In the case that a structure exists in a fluid cell, a virtual boundary is set in the cell. The area and centre of boundary faces which overlap with a structure are recomputed. The areas of faces which are completely buried
in a structure are set to zero. The volume and centre of the cells also are recomputed. The non-slip condition for the velocity and the zero-gradient condition for the pressure are imposed to the virtual boundaries. In the present study, the class library to treat immersed boundary method in OpenFOAM has been newly developed.

The simulation domain is $12.5D \times 10D$ for 2D-simulations and $12.5D \times 10D \times 6.4D$ for 3D-simulations. The cylinder is placed at the location of $(x, y) = (5.0D, 5.0D)$. The slip conditions are applied at boundaries in $y$-direction and the cyclic condition are used at boundaries in $z$-direction. The Reynolds number, $Re = UD/\nu$, is set to 1000. Here, $\nu$ is the kinematic viscosity. The Strouhal number of a cylinder vibration, $St_c = f_cD/U$, is set from 0 to 0.67. Here, $f_c$ is the cylinder vibration frequency.

![Figure 1 Conceptual diagram of immersed boundary for finite volume method.](image)

**3. CHARACTERISTICS OF 3D STRUCTURE**

To investigate characteristics of 3D-vortex structures, a comparison between 2D-simulation results and 3D-simulation results has been carried out. A summary of the results is listed in Table 1 and Table 2. The Strouhal number of the vortex shedding, $St_c = f_cD/U$, characterizing the vortex shedding frequency $f_c$ is based on the pressure frequency at the point $(x,y)=(8D,5D)$. The drag coefficient $C_D$ and the lift coefficient $C_L$ are the temporal average value.

The Strouhal number of the vortex shedding, $St_h$ obtained from the 2D-simulation tends to be higher than the 3D-simulation results as shown in Table 1. The drag coefficient of the 2D-simulation also tends to be higher than the 3D-simulation results. The high drag coefficient means that the force acting on a cylinder is high. The present results indicate that 3D-vortex structures enhance the safety of the cylindrical structure.

Table 2 shows the squared-vorticity and the pressure $p_h$ evaluated in the wake region at the back of a cylinder ($x=5.7D-7.0D$, $y=4.0D-6.0D$). These values are spatiotemporal average. The squared-vorticity which is shown in Table 2 is dimensionless value by using vorticity in $z$-direction obtained from 2D-simulations in the case of $St_c=0.0$ (case-1). In the case of 3D-simulations, the 2D-vortex ($\alpha_2$) in the wake region becomes relatively larger than 2D-simulation results. However, the pressure in the wake region becomes smaller as shown in Table 2.

![Figure 2 Time variations of squared-vortex in the wake region.](image)

**Table 1. Comparison of Strouhal number, drag coefficient and lift coefficient between 2D-simulation results and 3D-simulation results.**

<table>
<thead>
<tr>
<th>Cases</th>
<th>$St_c$</th>
<th>$U_c$</th>
<th>$St_h$</th>
<th>$C_D$</th>
<th>$C_L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2-D</td>
<td>0.0</td>
<td>0.25</td>
<td>1.48</td>
<td>-0.05</td>
</tr>
<tr>
<td>2</td>
<td>2-D</td>
<td>0.20</td>
<td>5.0</td>
<td>1.42</td>
<td>-0.36</td>
</tr>
<tr>
<td>3</td>
<td>2-D</td>
<td>0.67</td>
<td>1.5</td>
<td>0.25</td>
<td>1.15</td>
</tr>
<tr>
<td>4</td>
<td>3-D</td>
<td>0.0</td>
<td>0.21</td>
<td>1.04</td>
<td>-0.02</td>
</tr>
<tr>
<td>5</td>
<td>3-D</td>
<td>0.20</td>
<td>5.0</td>
<td>0.21</td>
<td>1.20</td>
</tr>
<tr>
<td>6</td>
<td>3-D</td>
<td>0.67</td>
<td>1.5</td>
<td>0.21</td>
<td>0.87</td>
</tr>
</tbody>
</table>

**Table 2. Comparison of vorticity and pressure between 2D-simulation results and 3D-simulation results.**

<table>
<thead>
<tr>
<th>Cases</th>
<th>$St_c$</th>
<th>$\alpha_2^+%$</th>
<th>$\alpha_2^-%$</th>
<th>$\alpha_2^0%$</th>
<th>$p_h$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2-D</td>
<td>0.0</td>
<td>-</td>
<td>-</td>
<td>1.00</td>
</tr>
<tr>
<td>2</td>
<td>2-D</td>
<td>0.20</td>
<td>-</td>
<td>-</td>
<td>1.12</td>
</tr>
<tr>
<td>3</td>
<td>2-D</td>
<td>0.67</td>
<td>-</td>
<td>-</td>
<td>0.78</td>
</tr>
<tr>
<td>4</td>
<td>3-D</td>
<td>0.0</td>
<td>0.43</td>
<td>0.28</td>
<td>1.07</td>
</tr>
<tr>
<td>5</td>
<td>3-D</td>
<td>0.20</td>
<td>0.74</td>
<td>0.56</td>
<td>1.14</td>
</tr>
<tr>
<td>6</td>
<td>3-D</td>
<td>0.67</td>
<td>0.35</td>
<td>0.22</td>
<td>0.94</td>
</tr>
</tbody>
</table>
4. MECHANISM OF FIRST EXCITATION REGION

The vibration equation in 1-D system (here, x-axial direction) are given by

\[
mx + (c + c_0)x + kx = 0
\]  

(2),

where \( m, c, \) and \( k \) are mass, damping constant, and spring constant. \( c_0 \) is the coefficient obtained from the assumption that the force acting on a cylinder is proportional to the cylinder velocity. The following equation (3) and (4) for energy balance are computed by performing energy integration of equation (2),

\[
\int_0^T \left\{ \frac{d}{dt} \left( \frac{1}{2} \dot{x}^2 + \frac{1}{2} kx^2 \right) \right\} dt = E
\]  

(3),

and

\[
E = -\int_0^T (c + c_0) \dot{x}^2 dt
\]  

(4).

If energy balance per cycle \( E \) is positive, a cylinder is excited in the in-line direction because the damping effect is lower than the force acting on a cylinder.

Table 3 shows \( E \) obtained from 3D-simulations. In the case of \( St_c = 0.67 \) (\( Ur = 1.5 \)) which is in the first excitation region, \( E \) is positive as shown in Table 3. Conversely, In the case of \( St_c = 0.20 \) (\( Ur = 5.0 \)) which is in the second excitation region, \( E \) is equal to almost zero.

<table>
<thead>
<tr>
<th>( St_c )</th>
<th>( E ) (energy balance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.2</td>
<td>-8.0x10^-8</td>
</tr>
<tr>
<td>0.67</td>
<td>1.44x10^-5</td>
</tr>
</tbody>
</table>

Figure 4-a shows time variations of the drag coefficient in the case of \( St_c = 0.67 \) (\( Ur = 1.5 \)). In the case that a cylinder moved with the flow, drag coefficient exhibits a declining trend because the flow resistance to a cylinder decreases. Conversely, in the case that a cylinder moved against a cylinder, drag coefficient exhibits a increasing trend. Figure 4-b shows the extended figure in the range that the dimensionless time, \( \tau = \tau U/D \), is from 7.5 to 10.0 in Figure 4-a. As shown in Figure 4-b, the peaks of drag coefficient are not corresponding to the peaks of the cylinder velocity \( U_c \). Although the cylinder velocity against the flow shifts to the decreasing tendency, the drag coefficient continues to decline. Consequently, the drag coefficient is limited to the low level.

Figure 5 shows pressure contour at the time when the drag coefficient is the lowest level. It can be seen that the high pressure region contacts with the back of cylinder at the time. The high pressure region depresses the drag force acting on a cylinder. As the result, the energy balance shown in equation (4) is positive and a cylinder is excited in the in-line direction.
5. MECHANISM OF SECOND EXCITATION REGION

As shown in Table 3, a cylinder in the second excitation region is not excited in the in-line direction because energy balance per cycle is not positive. However, as shown Table 1, it can be seen that the time averaged lift coefficient is larger than one of the first excitation region. As the lift coefficient is the value defined by the force in the cross-flow direction, a cylinder is expected to be excited in the direction.

Table 4 shows positive and negative vorticity obtained from 2D-simulations. The vorticity is temporally averaged. As shown in Table 4, there is no difference between positive and negative vorticity of the first excitation region, although there is a significant difference between positive and negative vorticity of the second excitation region.

Table 4. Temporal average positive and negative vorticity obtained from 2D-simulations.

| Cases | $St_c$ | $\omega_z$ | $\omega_x$ | $|\omega_z/\omega_x|$ |
|-------|--------|-----------|-----------|-----------------|
| 2     | 2-D    | 0.20      | 0.18      | 0.17            | 1.06            |
| 3     | 2-D    | 0.67      | 0.12      | 0.12            | 1.00            |

When the cylinder vibration frequency corresponds with the vortex shedding frequency, i.e. lock-in condition, the alternative of positive or negative vortex is enhanced. Due to the one-sided enhancement of the vortex, the lift force is enhanced in a particular direction. As the temporal averaged lift coefficient doesn't reach zero, it is considered that a cylinder is excited in the cross-flow direction.

7. CONCLUSION

2D and 3D fluid simulations for flow around an in-line forced oscillating circular cylinder have been conducted in order to clarify the mechanism of flow induced vibration. 3D-simulation results indicate that the the pressure at the back of a cylinder become relatively smaller by the evolution of the 3D-vortices ($\omega_y$ and $\omega_z$). As the result, the drag coefficient obtained from 3D-simulations becomes smaller than one of 2D-simulations.

Additionally, in the first excitation region, it is shown that a low drag force forms by contacting between high pressure region and a circular cylinder. It is considered that a in-line oscillation of a cylinder comes from the contact phenomena. In the second excitation region, it is shown that time averaged lift drag doesn't become zero on some oscillating conditions. It is considered that a cross-flow oscillation of a cylinder comes from the phenomena.

ACKNOWLEDGEMENT

This work was supported by JSPS KAKENHI Grant Number 40465977.
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