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NUMERICAL INVESTIGATION OF TURBULENT FLOW PAST 3D TWO CYLINDERS IN TANDEM ARRANGEMENT

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ABSTRACT

Unsteady turbulent flow past 3D two circular cylinders in tandem arrangement is investigated numerically by using OpenFOAM LES model. Reynolds number is 3900 and center to center spacing between two cylinders varies from 2D to 3.5D and then to 5D. The flow characteristics have been investigated from upstream, downstream and gap between two cylinders. Pressure and velocity distribution, drag coefficient and lift coefficient at different spacing from both cylinders are compared with each other and experimental data. Results are in agreement with previous work. The concept of "Critical Spacing" is validated by this study at 3.5D spacing setup, which shows a sudden change flow pattern in the gap between two cylinders and eventually causes a drop on pressure profile. Subject study also confirms that 5D distance is sufficient for vortex formation from upstream cylinder and the interaction between two cylinders (impingement from upstream to downstream cylinder) is less obvious at such distance.

Keywords: Circular cylinder, Tandem arrangement, Turbulent flow, Vortex shedding.

I. INTRODUCTION

Flow past a single cylinder is a basic and classic phenomenon in fluid mechanics. Extensive research have been conducted on this topic. However, when two or more cylinders are placed in the same flow field and within proximate distance, the mechanism becomes complicated due to the interference of one cylinder to another. The results from single cylinder case cannot accurately explain these complications. Among the various configurations, two cylinders in tandem is the most typical one and it can be found in many engineering design and applications, such as subsea risers, offshore structures, bridge foundations, etc. Numerous studies have been done to investigate the complex mechanism behind this, from both experimental and numerical aspects. Igarashi (1981) [1] carried out experiment on flow around two cylinders under Reynolds number $8.7 \times 10^3 \leq Re \leq 5.2 \times 10^4$ with cylinders spacing $1.03 \leq d \leq 5.0$. In his study, the results on pressure distribution, drag coefficient, location of reattachment points have been reported at different spacing. Later, similar experiment was conducted by Ljungkrona (1991) [2] with $Re = 2 \times 10^4$and spacing between $1.25 \leq d \leq 5.0$. Ljungkrona concluded that effect of increased free-stream turbulence intensity largely relies on the cylinder spacing d. The critical spacing between cylinders was found to decrease when the turbulence intensity was increased. With the increasing computation power of computer and development of commercial CFD packages, many numerical investigations have been done in the past decade. Kitagawa and Ohta (2008) [3] performed numerical analysis on tandem arranged cylinders at $Re = 2.2 \times 10^4$ at various spacing (up to 5d). The influence of vortex shedding from upstream cylinder onto downstream cylinder and how the upstream vortex interacted with downstream vortex were discussed. Abrahamsen-Prsic (2015) [4], recently conducted numerical simulation on free stream flow around two cylinders under $Re = 1.31 \times 10^4$ with distance between the cylinder centers d from 2 to 5. The values of drag and lift coefficients were compared against one single cylinder case and near wake flow characteristics were discussed in their study. One thing worth mentioning is, in 2010, Sumner [5] published paper to give an overview of the subject topic by considering the major reviews more than 20 years ago, from both experiential and numerical perspective.

This study focuses on numerical investigation of unsteady flow past 3D cylinders in tandem arrangement at Reynolds number $Re = 3900$ and spacing varies from 2D to 3.5D then to 5D by using OpenFOAM LES turbulent model. Few previous research have been found for subject topic at such low Reynolds number. The time-averaged pressure distribution, mean stream-wise velocity, drag and lift coefficient are compared against

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experimental and numerical results. The results of the present study mostly agree with the experimental and numerical results in the literature. The flow characteristics between the gap of two cylinders are also discussed.

II. GOVERNING EQUATION

LES provides higher accuracy degree than other turbulent simulation approach as the large eddies contain most of the turbulent energy and are responsible for most of the momentum transfer and turbulent mixing; and therefore were chosen for this study. In LES, only the influence of the small eddies has to be modeled by sub-grid scale model, whereas the large energy-carrying eddies are computed directly. Small eddies are more universal, random, homogeneous and isotropic, which simplifies the development of appropriate models.

In order to separate the large and small scale motions, the three-dimensional, time dependent Navier–Stokes equations are filtered. In the present study a box filter is applied as a filter kernel and an incompressible fluid is assumed. The governing equations are given by:

$$\frac{\partial \overline{u_i}}{\partial x_i} = 0 \qquad (1)$$

$$\frac{\partial \overline{u_i}}{\partial t} + \frac{\partial}{\partial x_j}(\overline{u_i}\,\overline{u_j}) = -\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_i}[\frac{1}{\mathrm{Re}}(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i})] - \frac{\partial \tau_{ij}}{\partial x_j} \qquad (2)$$

$$\tau_{ij} = \overline{u_i u_j} - \overline{u_i u_j} \qquad (3)$$

Where $\overline{u}_i$ is the velocity component of the resolved scales, $\overline{p}$ is the corresponding pressure. The filtering procedure provides the governing equations for the resolvable scales of the flow field. Although the continuity equation (1) of the resolved quantities is equal to the original unfiltered one, the filtered momentum equation (2) includes an additional term for the non-resolvable sub-grid scale stressesτ_{ij}, which results from filtering the non-linear convective fluxes. τ_{ij} describes the influence of the small-scale structures on the larger eddies. Only this effect has to be modeled by a sub-grid scale model [6].
For one-equation SGS Model, the eddy viscosity is calculated from:

$$\mu_{T,a} = \rho_a C_k \Delta k_{sgs}^{1/2} \qquad (4)$$

Where k_{sgs}represents the SGS kinetic energy, which is obtained by solving for transport equation for k_{sgs},

$$\frac{\partial}{\partial t}(\rho_r \alpha_r k_{sgs}) + \nabla(\rho_r \alpha_r u_r k_{sgs}) = -\nabla(\alpha_r \frac{\mu_{eff,r}}{\sigma_k} \nabla k_{sgs}) + \alpha_r (G_r - C_\varepsilon \frac{k_{sgs}^{3/2}}{\overline{\Delta}}) \qquad (5)$$

Where, G_r is the production term, defined as:

$$G_r = \mu_{T,a} \left| S_{ij} \right| \qquad (6)$$

The value of model constants (C_ε=1.05 and C_k=0.07) in equation are considered on the basis of recommendation by Davidson [7].

III. NUMERICAL DETAILS

Computational Domain

Figure 1 below shows the computational geometry created for subject case. A 10D and 16D distance from cylinder to inlet and outlet, respectively, in order to let the flow fully developed. Span wise distance is 3.5D so that a 3D effect can be captured. X varies from 2D to 3.5D then to 5D in the study to investigate the effect of spacing on flow characteristics.

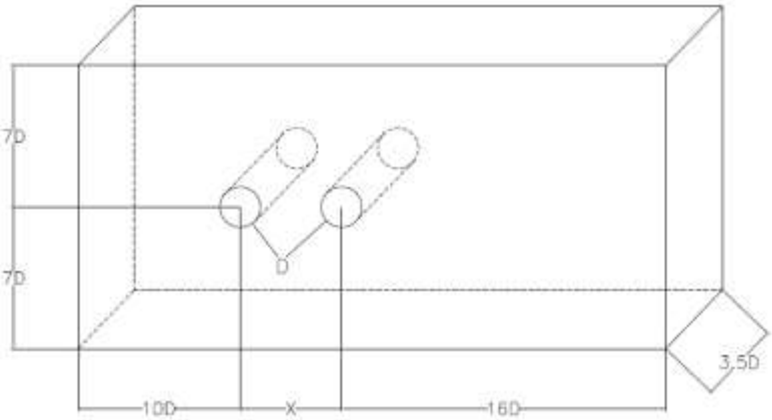

Figure 1. Computational Geometry

Numerical scheme

The simulation is performed by OpenFOAM. PisoFOAM solver is selected due to the transient turbulent nature of the case. Cylinder boundaries are set as wall (wall function used) and velocity and pressure are given to inlet and outlet, respectively. The rest of the plane are assigned as symmetric plane. The grid size varies from 220,744 to 249,640 due to the spacing difference.

IV. RESULTS AND DISCUSSION

Time-averaged pressure distribution

By looking at Figure 2, the pressure distribution of 5D spacing setup agrees well with that of the single cylinder, which means five times the diameter spacing is large enough to eliminate the interaction of downstream cylinders. For 2D and 3.5D setup, the presence of downstream cylinder prevents the vortex formation and therefore causes an overall lower pressure when comparing to 5D setup. Further, the 3.5D spacing gives even lower pressure distribution after separation point, which proves the “critical spacing” from previous works.

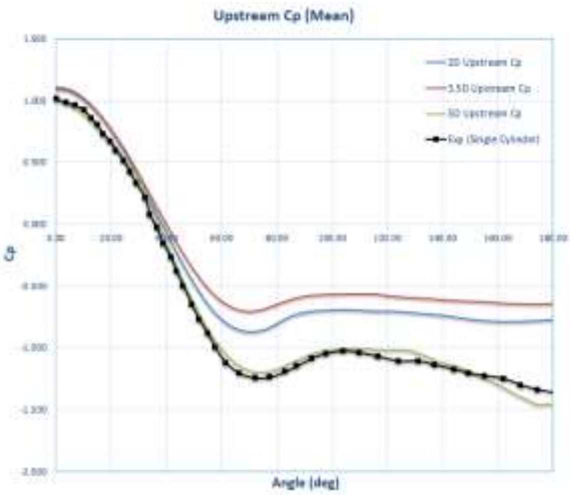

Figure 2. Upstream Cp at different spacing

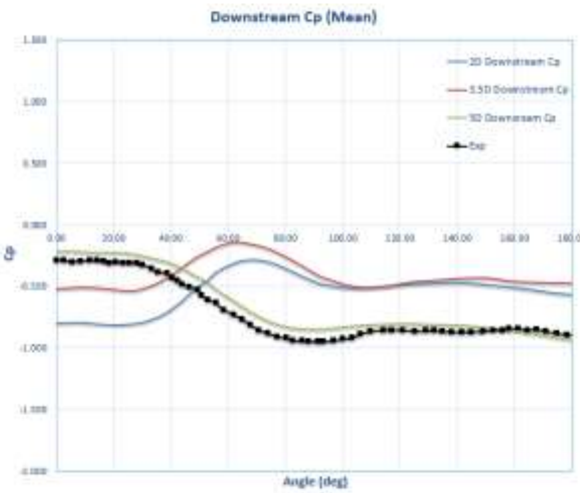

Figure 3. Downstream Cp at different spacing

In Figure 3, the pressure distribution from all three setup present a more “flatten” and irregular shape. This is mainly due to the vortex from upstream cylinder acting on the downstream cylinder. 5D setup still agrees well with experimental results except the overall pressure magnitude slightly less. The difference on Reynolds number can be a contributing factor. The minimum Cp shown in this graph could be resulted from the reattachment of upstream cylinder shear layer. When the spacing decreases, the shear layer from upstream generates unstable fluid which makes the pressure fluctuated on the downstream cylinder under 2D and 3.5D setup.

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Mean stream-wise velocity

Figure 4 plots the mean stream-wise velocity from downstream cylinder and same from experimental data of single cylinder. It is clearly that the single cylinder velocity tends to stabilize after approximated a distance of 2D while it takes longer (at least 6D distance) for downstream cylinder to reach the same level of velocity. This is mainly due to the impingement of the vortex shed from upstream cylinder.

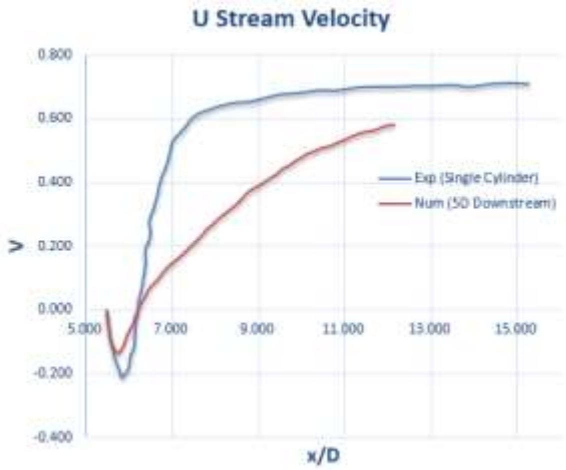

Figure 4. Mean stream-wise velocity of 5D downstream cylinder

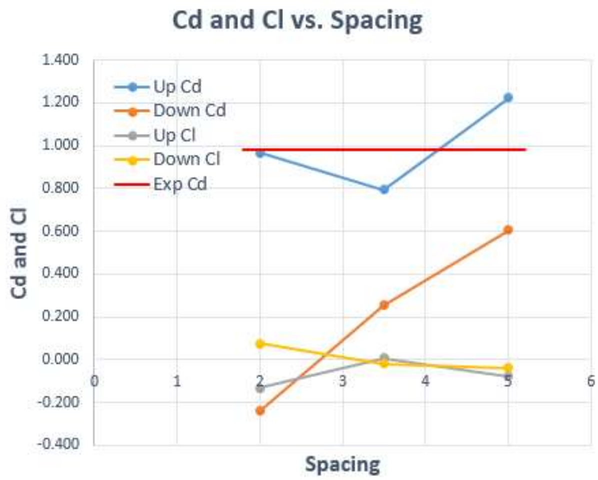

Figure 5. Mean drag and lift coefficient from different spacing

Drag and lift coefficient – Mean values and time history comparison

The drag and lift are important factor when investigating such case as the results can be widely used in engineering and industrial application. The author plotted Figure 5 above in order to conveniently visualize the drag and lift coefficient in respect to the spacing variation. The single cylinder experimental Cd is also plotted in the graph for comparison. It can be clearly seen that the 3.5D upstream Cd and Cl shows a sudden drop and yield lower value in comparison to other spacing. As mentioned in previous work, the flow pattern suddenly changes at 3.5D spacing and the upstream vortex formed between the gap of the cylinders and impinged on the downstream cylinder, which make the pressure profile drop in the gap.

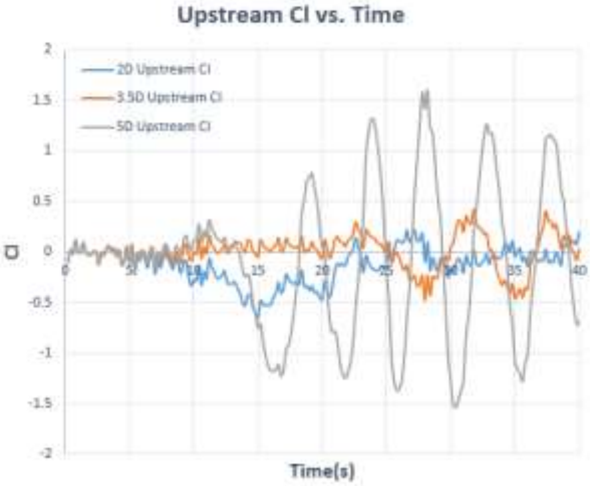

Figure 6. Lift coefficient time history of upstream cylinder

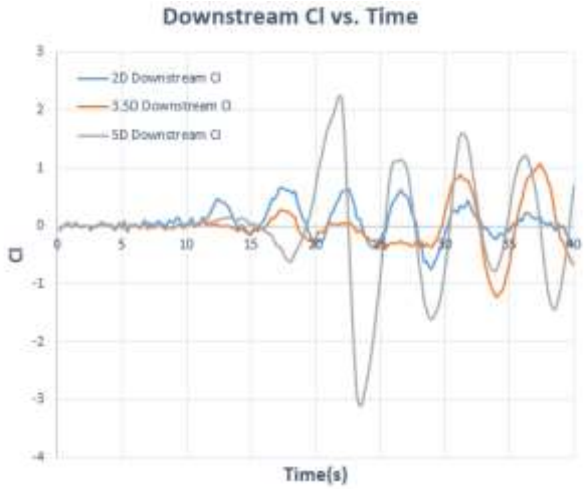

Figure 7. Lift coefficient time history of downstream cylinder

The fluctuation of lift coefficient is caused by the alternate reattachment of the shear layers and vortex shedding. By looking at Figure 6 and 7, the 2D and 3.5D spacing setup generate a more unsteady trend. This is due to the short distance between two cylinders, which makes the vortex unable to develop. When comes to 5D spacing, the shape of Cl goes back to normal trend that is similar as single cylinder. Further, at 5D setup, the scale of downstream cylinder is relatively larger than upstream. This is because the distance is large enough for the vortex to be shed from upstream cylinder and simultaneously the vortex from downstream cylinder itself can also enlarge the lift coefficient.

V. CONCLUSION AND IMPROVEMENT

As described above, the results of the present simulations mostly agree with the experimental and numerical results in the literature. The Cd and Cl plot have proved the definition of critical spacing- 3.5D, in which the flow pattern suddenly changes in the gap between two cylinders and eventually causes a sudden drop on pressure profile. Subject study also validates that 5D spacing is sufficient for the vortex to be formed and the influence of upstream cylinder to downstream cylinder is relatively smaller than the other two setup. This is also confirmed by the pressure coefficient that 5D setup can match single cylinder closely. Under 5D spacing, the drag and lift coefficient scale also resemble single cylinder case. Certain improvements can be made for future work. Subject study only focuses on same dimension (diameter) cylinders. Two different dimension cylinders can be used to explore the flow pattern. In addition, current setup is limited to two cylinders only. Future work can be achieved in different configurations, such as a series of cylinders in line or three cylinders placed in triangular arrangement. Industry would be beneficial from these research.

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