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Computational Study of Vortex Generated Oscillations Caused by a Pair of Cylinders in Abreast Position

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ABSTRACT

The present research is focused on vortex generated oscillations and vortex shedding due to elastically fixed pair of cylinders. Several non-dimensional key process parameters such as mass ratio, Reynolds number, transverse gap ratio, frequency ratio and reduced velocity, relating to the present problem are identified and their relative importance are also observed. The investigations are carried out at several frequency ratios and reduced velocities by considering the flow to be laminar and incompressible. The numerical model involves governing transport equations of continuity and momentum in two dimensions. The model uses finite volume method (FVM) with pressure based SIMPLE algorithm to carry out numerical simulation for getting the flow fields involved. The oscillations originated from the interacting vortices through a pair of cylinders are completely examined in terms of cylinder trajectory and vibration frequency/amplitude.

Keywords: Reduced velocity, Frequency ratio, Trajectory, Amplitude, Shedding

I. INTRODUCTION

Flow over cylinder is a common research problem owing to not just minimalism but for voluminous engineering applications. The aerodynamic effects thus created, reasons for vibration in the cylinder (along both in-line and transverse directions), caused by vortex shedding and elastic excitation. The vortex shedding is related to the boundary separation phenomenon. When both vortex shedding frequency and the natural frequency of the vibrating cylinder are equal, resonance takes place.

Researchers are in search of novel materials and products having numerous, incomparable and unmatched properties such as light weighting, high strength-to-weight ratio, resistance to corrosion along with wear and tear, superb manufacturability and trouble-free recyclability, presently which can be used almost everywhere starting from industrial to household purposes. Definitely, the talked about materials/products will be highly susceptible to vibrations because of the light weighting. The flow induced vibration is one such frontier field upon which at present more and more attention is focused by the researchers.

The details about the flow over bluff bodies have been illustrated by Schlichting [1]. Tests on flow over cylinder at elevated Reynolds number is also demonstrated in literature by Roshko [2]. Numerical analysis of fluid flow problems is described in texts by Ralston and Rabinowitz [3]. Additionally, the numerical fluid flow is also exhibited by Patankar [4]. The particulars about the hydrodynamic stability is analyzed by Chandrasekhar [5]. The influences of surface roughness on flow past cylinder is also studied by Nakamura and Tomonari [6]. Fundamentals about boundary layer in fluid flow is presented by Schetz [7]. Physical and computational traits of fluid flow is exemplified by Cebeci and Bradshaw [8]. Basics of fluid mechanics is reported by Landau and Lifshitz [9]. In addition, the effect of boundary layer in fluid flow is specified by Young [10]. The intricacies about viscous flow is portrayed by White [11]. Simulation scheme for flow around circular cylinder is also stated by Kondo [12]. Iterative methods to solve linear systems of equations are depicted by Saad [13].

Stability analysis due to wake around cylinder is investigated by Barkley and Henderson [14]. Numerical solutions of linear systems of equations are also given away by Trefethen and Bau [15]. The rudiments of CFD has also been explained by Versteeg and Malalasekera [16]. The basics of fluid mechanics is also elucidated by Kundu and Cohen [17]. Fluid flow over porous cylinder with incessant suction/blowing is expounded by Fransson *et al.* [18]. Effects of traveling wave on von Karman vortex street about a cylinder is explicated by Wu *et al.* [19]. Influence of synthetic jet on wake around cylinder is detailed by Feng and Wang [20]. The interference of synthetic jet with wake vortex shedding nearby a cylinder besides its decomposition analysis is further expanded by Feng *et al.* [21, 22]. In addition, synthetic jet usage on separation control near cylinder is also extended by Feng and Wang [23]. The suction flow practice for diminishing vortex induced vibration of cylinder is also added by Chen *et al.* [24]. Also, the suction flow technique on unsteadiness reduction around the cylinder is further experimented by Chen *et al.* [25].

From the aforementioned texts, to the best of authors' understanding, it is quite obvious that there is no such exhaustive computational analysis relating to the influences of reduced velocity and frequency ratio on cylinder vibration in terms trajectory of cylinder centre together with the amplitude, frequency and deflection of cylinder. With this standpoint, the present research aims primarily at the computational investigations of the above stated intents (apart from the fluid flow behavior) around a pair of cylinders in abreast position. The current numerical model practices finite volume method (FVM) with pressure based SIMPLE algorithm to carry out simulation for getting the desired flow fields. Lastly, the computational results are analyzed and compared for realizing the expected physical feel and sagacity. The predictions of the model concerning various non-dimensional key process parameters are along expected lines. In addition, for comparison of results, an in-house experimental setup is also planned for the future.

II. DESCRIPTION OF PHYSICAL PROBLEM

The physical problem involves the fluid flow with velocity U over a pair of elastically fixed cylinders of diameter D each. The fluid flow is assumed to be incompressible and the problem concerns with two degrees of freedom (relating to oscillations along both x and y directions). A two dimensional rectangular computational domain is chosen in order to save simulation time. Transverse gap ratio (T/D) chosen to be 3. In addition, the details about the physical problem with computational domain are illustrated in Fig. 1.

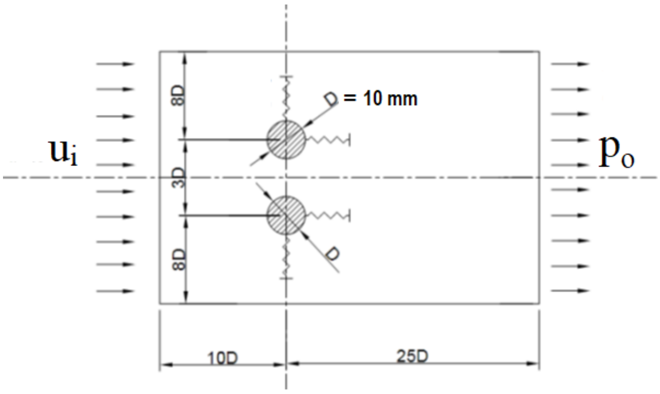


Figure 1. Physical problem with computational domain

III. MATHEMATICAL FORMULATION

A. Governing equations

The dimensionless form of the governing transport equations of continuity and momentum pertaining to the present physical problem are as mentioned below.

$$\nabla' . \mathbf{u}' = 0 \tag{1}$$

$$\frac{\partial \mathbf{u}'}{\partial t'} + \nabla' . (\mathbf{u}'\mathbf{u}') = -\nabla' p' + \frac{1}{\mathrm{Re}} \nabla'^2 \mathbf{u}' \tag{2}$$

Where, *Re (i.e. ρUD/μ)* is the Reynolds number, *μ* is the dynamic viscosity, *D* is the reference length, *U* is the reference speed, *u* this is the velocity field, *t* is the time, *p* is the modified static pressure and *ρ* is the density.

The present investigations ruminate elastically fixed rigid cylinders which oscillate along both x and y directions. The oscillation is represented by an equivalent spring mass with damper system under fluid force. Non-dimensional form of equation relating to the stated equivalent system is as mentioned underneath.

$$M^*\ddot{x}_c^* + C^*\dot{x}_c^* + K_x^* x_c^* = F_x^*(\ddot{x}_c^*, \dot{x}_c^*, x_c^*) \tag{3}$$

$$M^*\ddot{y}_c^* + C^*\dot{y}_c^* + K_x^* y_c^* = F_x^*(\ddot{y}_c^*, \dot{y}_c^*, y_c^*) \tag{4}$$

Where, M^* = dimensionless mass, C^*= dimensionless damping coefficient (zero for the present instance), K^*= dimensionless stiffness coefficient, F^*= dimensionless fluid force.

Furthermore,

$$M^* = M/\rho D^2 L\,, K_X^* = K_X/\rho U^2 L\,, F_X^* = C_D/2 = F_D/\rho U^2 DL$$
$$K_Y^* = K_Y/\rho U^2 L\,, F_Y^* = C_L/2 = F_L/\rho U^2 DL$$

Where, L= axial dimension of cylinder, C_L= lift coefficient, the variables x^*_c and y^*_c, $\dot{x}^*_c$ and $\dot{y}^*_c$, $\ddot{x}^*_c$ and $\ddot{y}^*_c$ are dimensionless displacement, velocity and acceleration along x and y directions respectively, t^*= dimensionless time ($= tU/D$).

$$\ddot{x}_c^* = \ddot{x}_c D/U^2\,,\ \dot{x}_c^* = \dot{x}_c D/U^2\,,\ x_c^* = x_c D/U^2$$
$$\ddot{y}_c^* = \ddot{y}_c D/U^2\,, \dot{y}_c^* = \dot{y}_c D/U^2\,, y_c^* = y_c D/U^2$$

The dimensionless form is taken into account for enabling flow consistency and easy coupling. The results of the present investigation are also expressed in terms of mass ratio m^* and reduced velocity U^*.

$$m^* = 4M/\rho\pi D^2 L\,, U^* = U/f_{ny} D$$

Where, f_{ny} = natural frequency of the system in vacuum and $f_{ny} = \frac{\sqrt{K}/M}{2\pi}$.

B. Boundary conditions

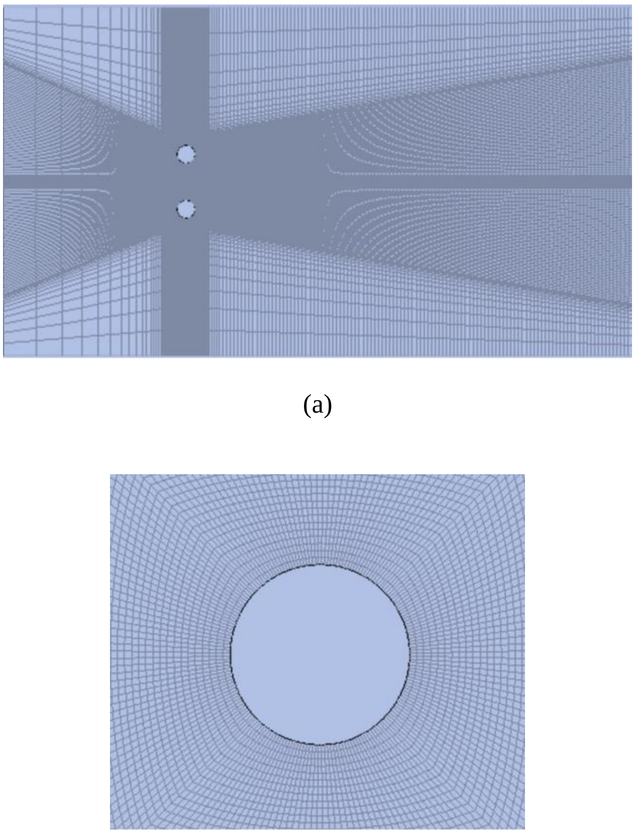
The specified velocity boundary condition is used at the inlet. However, the specified pressure boundary condition is considered at the exit. The lateral boundaries are introduced with symmetry (i.e. far field) boundary conditions (i.e. both x-velocity gradient and y-velocity are taken as zero at lateral boundaries). And also, the no-slip boundary condition is taken at the surface of the cylinders.

C. Parameters

In the present investigations, the numerical simulations are carried out for fluid flow over a pair of freely oscillating cylinder. The fluid considered is air with invariable density and viscosity of 1 kg.m^{-3} and 0.001 kg.m^{-1}.s^{-1}, respectively. The diameter of each cylinder is taken as 0.01 m. The flow over the pair of cylinders is set at inlet velocity of 1.6 m/s corresponding to Reynolds number of 160. In other words, the flow is considered to be laminar. The cylinders are unrestricted to vibrate along transverse and in-line directions. The mass ratio is taken to be three. The damping coefficient is set as zero for attaining high amplitudes due to vibrations. The reduced velocity ranges between 4 and 10. Three different frequency ratios of 1.0, 1.5 and 2.0 are taken into considerations.

IV. NUMERICAL METHOD

The present numerical model uses finite volume method (FVM) with pressure based SIMPLE algorithm to carry out simulation for getting the desired flow fields. Second order upwind with first order implicit scheme is applied for the present physical problem formulation. The grid independence test reveals the optimum grid size that corresponds to grids with 160 nodes on the circumference of each cylinder. Likewise, the time independence test also ensures solution stability with a sound simulation time. The meshing inside the computational domain along with the enlarged view of meshing near cylinder surface is illustrated in Fig. 2.



(a)

(b)

Figure 2. (a) Computational domain with meshing (b) Enlarged view of meshing near cylinder surface

V. RESULTS AND DISCUSSION

Numerical simulations are carried out (for flow around a pair of cylinders in abreast position), to investigate the effects of reduced velocity and frequency ratio on cylinder vibration in terms trajectory of cylinder centre along with the amplitude, frequency and deflection of cylinder.

The trajectory of (i.e. the path followed by) the cylinder centre at different reduced velocities and frequency ratios is as depicted in Figs. 3-5. It is noticed that the trajectory of the cylinder centre follows the illustrious Lissajous figure at low reduced velocity. And also, the amplitude of vibration is high at low reduced velocity. Furthermore, the amplitude of vibration decreases with the increase in reduced velocity. Additionally, with the increase in reduced velocity, the regular Lissajous figure gradually becomes irregular. Besides, as the frequency ratio decreases, the regular Lissajous figure progressively becomes stripper and distorted.

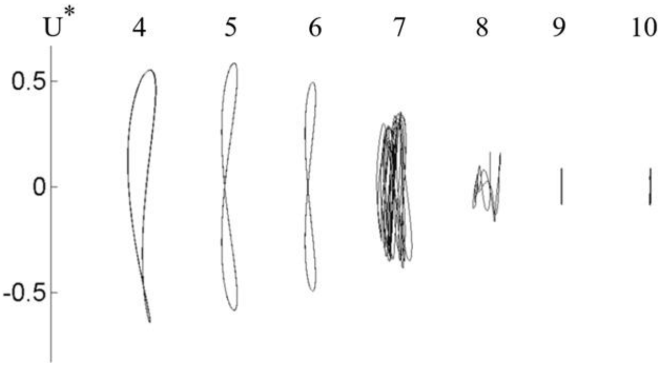


Figure 3. Trajectory of cylinder centre at different reduced velocity for frequency ratio 1

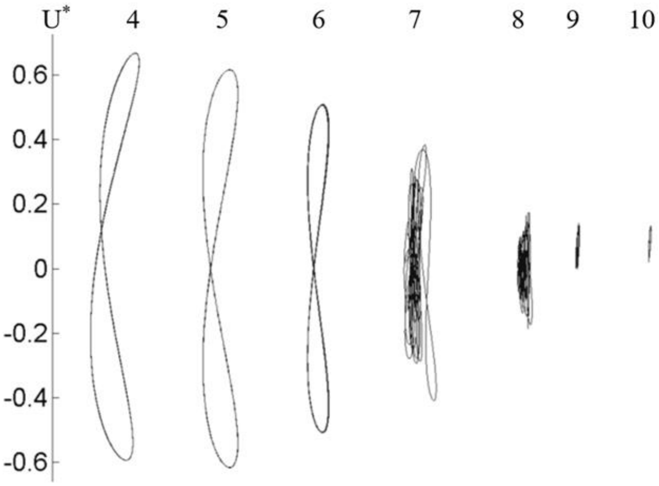


Figure 4. Trajectory of cylinder centre at different reduced velocity for frequency ratio 1.5

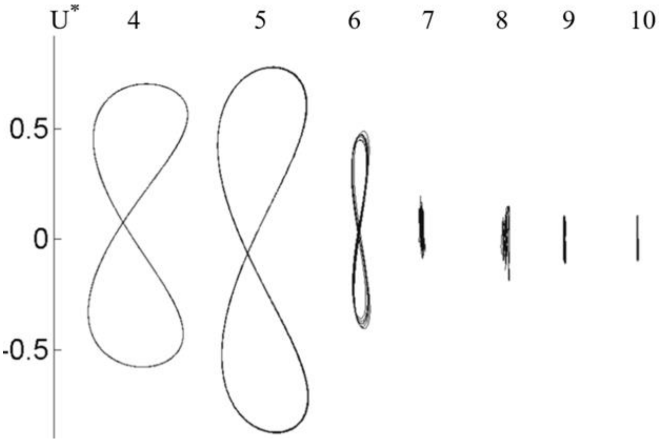


Figure 5. Trajectory of cylinder centre at different reduced velocity for frequency ratio 2

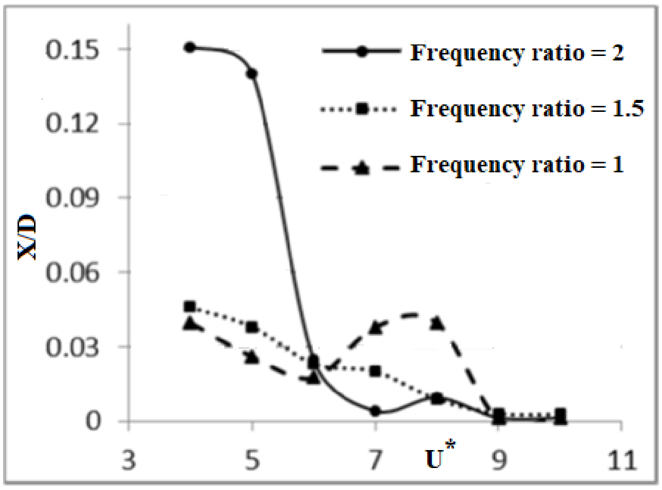


Figure 6. Ratio of rms value of amplitude in stream direction to cylinder diameter vs. reduced velocity

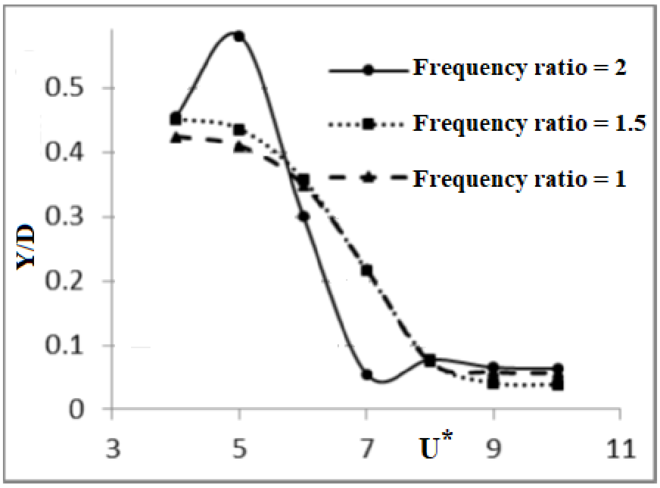


Figure 7. Ratio of rms value of amplitude in transverse direction to cylinder diameter vs. reduced velocity

Figs. 6 and 7 illustrate the dimensionless rms value of amplitude vs. reduced velocity curves at different frequency ratios. It is noticed that the maximum value of ratio of deflection in the stream direction to cylinder diameter is about 0.15. And also, the maximum value of ratio of the deflection in transverse direction to cylinder diameter is nearly 0.50. The amplitude gets decreased by an order for increase in reduced velocity from 4 to 10.

VI. CONCLUSION

Numerical simulations are carried out for flow around a pair of cylinders in abreast position, to investigate the effects of reduced velocity and frequency ratio on cylinder vibration in terms trajectory of cylinder centre along with the amplitude, frequency and deflection of cylinder. The present numerical model uses finite volume method (FVM) with pressure based SIMPLE algorithm to carry out simulation for getting the desired flow fields. Second order upwind with first order implicit scheme is applied for the present physical problem formulation. The grid independence test reveals the optimum grid size and the time independence test also ensures solution stability with a sound simulation time. The predictions of the model concerning several non-dimensional key process parameters are in line with the expectations. The comparison with a pilot-scale experimental arrangement is planned for the future.

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