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Numerical simulation of vortex-induced vibration of elastic cylinder

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Abstract

Study of the flow around a bluff body and its effect on the flow induced vibration is relevant to design of bridges, tall buildings and similar structures. The flow around bluff bodies, arranged in tandem where one of the bodies is in the wake region of the seconds one, was studied using numerical simulation. This phenomenon is related to the response of bluff bodies immersed in fluid flow and is known as Vortex Induced Vibration (VIV). Vortex energy extraction is of interest to this work. This paper presents the results of a 2D numerical simulation of the wake interaction of two circular cylinders at low Reynolds number using ANSYS Fluent Workbench. The upstream cylinder is stationary, while the downstream elastic cylinder can be affected by the vortices in the wake of the first cylinder. The paper reports the behaviour of the elastic cylinder through a CFD model, with a focus on harnessing the vortical energy. Also discussed is the theoretical maximum energy that can be harvested by this method. For validation purposes, the modelled amplitude of the oscillation is compared to published data in literature. The results show that the motion of elastic cylinder can be modelled as a simple mass spring damper model.

Introduction

Flow induced vibration is a phenomenon which is related to interaction of fluid forces and elastic forces in the structures [9]. These phenomena are related to the response of the structure which is immersed in fluid flow and are known as Vortex Induced Vibration (VIV). The vibration induced on structures by vortices is of importance because of its potentially destructive effect of structures. In these phenomena a non-stationary excitation force is exerted on the structures by vortices, which depending on the Reynolds number can be periodic. The vortex shedding behind a cylinder is known as a vortex street and the behaviour of the vortices in the wake of the structure is similar, regardless of the geometry of the structure. Blevins [6] showed that the vortex shedding in a steady subsonic flow is a function of the Reynolds number. Zdravkovich [11] presented the detailed information of the exerted forces on the stationary circular cylinder in different regimes. The results reveal that by increasing the Reynolds number from laminar to transitional regimes, Re=10^4-10^5, the lift force on the cylinder can increase significantly.

Vortices energy can be harnessed and used as a renewable, friendly energy. A study of the flow around a pair of cylinders as a tandem body might a simple model to harness the vortices energy by downstream cylinder.

This paper investigates numerically the flow interaction between two circular cylinders to explain a new concept of renewable generation energy due to VIV. In this model the upstream cylinder is stationary while the downstream has one degree of freedom and can oscillate freely in the normal to the mean flow direction.

Mathematical model

A simple schematic of the arrangement of two cylinders is shown in Figure 1. The moving rigid cylinder is mounted on an elastic base with one degree of freedom in y-direction. Therefore, the elastic cylinder is a simple mass-damper-spring system [4] and the equation of motion can be defined as

$$m_{osc}\ddot{y} + c\dot{y} + ky = F_y(t). \quad (1)$$

In the equation above, m_{osc} is the total oscillating mass of system, y is the normal direction of flow, $\dot{y}$ and $\ddot{y}$ are velocity and acceleration of cylinder, respectively, c is damping coefficient, k is spring stiffness and F_y is the fluid force which is exerted on the cylinder boundary perpendicular to the flow.

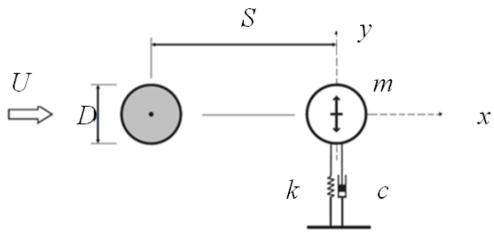

Figure 1. Schematic of two cylinders in cross flow, the upstream is rigidly mounted; the downstream is free to move

In Equation (1), it is appropriate that non dimensional parameters such as mass ratio and damping factor are considered instead of mass and damping constant. The mass ratio can be defined as the total oscillating mass of system over the specific mass of fluid, $m^* = 4\, m_{Osc}/\rho\pi D^2 l$ and damping factor is $\zeta = c/2\sqrt{k.\, m_{Osc}}$. In former equation, ρ is the fluid density, D is the diameter of cylinder and l is the length of the cylinder. In this research, the mass ratio and damping factor were $m^* = 2.6$ and $\zeta = 0.007$ based on the assumptions of Carmo [8] and the experiments of Assi [2] to validate the results. The Reynolds number, Re $=U_\infty.D/\vartheta$, is 1500 based on the diameter of the upstream cylinder D where U_∞ is free stream velocity and ϑ is kinematic viscosity of fluid. For this Reynolds number, the non-dimensionalised frequency which is defined as Strouhal number $St = f_s.D/U$ (f_s is the vortex frequency). The Strouhal number for the selected Reynolds number is close to 0.2 [6].

For the system under investigation, vortex shedding in the wake of upstream cylinder exerts harmonic forces on the elastic downstream cylinder. The asymmetric distribution of pressure acts on the surface of elastic cylinder and generates the translational motion. This motion has been simulated using the ANSYS Fluent Workbench 14.0. To model the behaviour of elastic cylinder a User Define Function as a UDF file has been loaded in the Fluent and it has been coupled by a dynamic mesh setup. In this interaction the sinusoidal response of the cylinder causes the fluctuating transverse amplitude and force. Therefore, harmonic displacement, velocity and lift coefficient equations of the cylinder can be considered respectively as

$$y = y_{max}.\sin(2\pi f_s t), \quad (2)$$

$$\dot{y} = (2\pi f_s)\dot{y}_{max}\cos(2\pi f_s t) \quad (3)$$

$$c_L(t) = C_L.\sin(2\pi f_s t + \varphi) \quad (4)$$

Here y_{max} is maximum amplitude of oscillation and φ is the phase angle between the fluid forcing and the displacement, c_L is time dependent lift coefficient and C_L is the amplitude of lift coefficient of the cylinder. The position and velocity of cylinder can be interpreted by Fluent for transient flow in each time step. The work generation by the downstream cylinder is obtainable utilising the total vertical force including the pressure and viscous forces on the surface of elastic cylinder. Therefore, Equations (3) and (4) can be used to calculate the work acting on the cylinder as the inner product of fluid force which is exerted on the cylinder during a vortex-induced vibration cycle by the displacement of cylinder as follows

$$W_{VIV} = \int_0^{Tcyl} F_y.\dot{y}.dt \quad (5)$$

In the Equation (5), $Tcyl$ is the one complete cycle of oscillation. By integrating the right hand side of Equation (5) and averaging over the cycle period the power due to VIV for a circular cylinder can be obtained as [5]

$$P_{VIV} = \frac{W_{VIV}}{Tcyl}. \quad (6)$$

Interaction of two stationary cylinders

The behaviour of shear layers around coupled stationary circular cylinders has been broadly categorized as six regimes [10] depending on the separation distance between the cylinders. Experimental and numerical analysis of these regimes have been conducted by Igarashi [10] and Carmo [8]. They found that critical separation is located somewhere between $S = 3.0 - 4.0$ which *S* is a separation distance between cylinders (see Figure 1) and the downstream cylinder can be significantly affected by shear layers. Considering to the regimes C and D illustrate that vortices after separation are symmetric and gradually they change as the asymmetric shear layers. Therefore, the more distance between cylinders causes asymmetric pressure distribution over the second cylinder. Assi [1] suggested that the vortex formation length of a coupled cylinder is directly dependent on the Reynolds number and it decreases by increasing the Reynolds number between 3000 and 13000. He also showed that turbulence intensity can also affect the angle of separation [2].

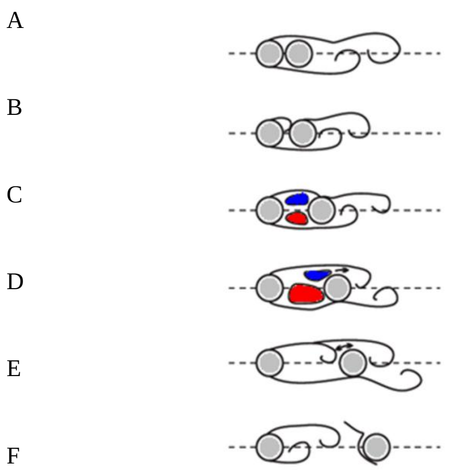

Figure 2. Patterns of flow regimes between two aligned cylinders [10]

Mixed effects of x_0 and y_0 (separation and lateral distance respectively) on the lift and drag coefficient of downstream body have been analysed by Bokaian et al. [7]. Their outcomes illustrate that the lateral distance to access the maximum lift coefficient is close to one diameter of the cylinder.

Numerical model

A numerical simulation was conducted to analyse the behaviour of the downstream elastic cylinder and to harness the energy of the vortices. The number and type of mesh elements have been selected in an iterative manner to give an accurate solution with minimal computational time. A finer mesh was incorporated near the boundary layers to capture the flow behaviour in this region in greater detail since the boundary layer flow patterns and its interaction with the free stream velocity are of major importance in this investigation. Figures 3 and 4 display the mesh for a pair of circular cylinders.

The inlet boundary and the free walls are set at 6*D* far away from the centre of cylinders. Here *D* is the diameter of both cylinders and is equal to 0.05 m. The outlet boundary has been selected sufficiently far away from the downstream body and it is equal to 25*D*. The separation distance between cylinders is *S* = 4*D*. The triangular mesh has been generated for flow domain as an unstructured mesh with 67,666 elements.

The location of the downstream cylinder is (0, 0) (relative to the position of the axes in Figure 1) and the location of the upstream cylinder is (0, 4*D*). The natural frequency of the elastic cylinder was f_n = 0.3 Hz, chosen to match the structural factors of the previous experiments [2]. The non-dimensionalised flow speed can be considered as $V_r = U/f_n D$. Consequently, according to the free velocity of the fluid, the reduced velocity for this simulation is $U/f_n D$ =2.0. It is obvious that the maximum amplitude of VIV occurs when the reduced velocity is close to $U/f_s D$. This means that the frequency of vortices is equal to the natural frequency of the structure.

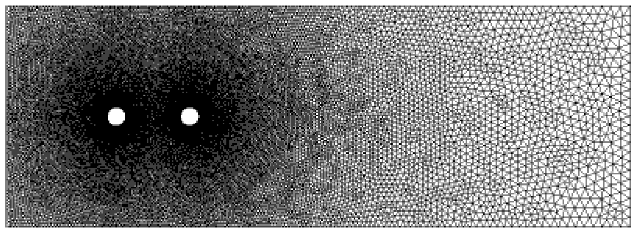

Figure 3. Triangular mesh and imposed boundary conditions of cylinders.

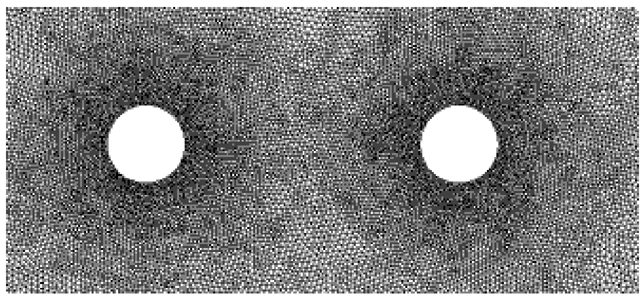

Figure 4. Unstructured fined mesh around cylinders.

The instantaneous flow field for the numerical results are shown in Figure 5. The image reflects the position of the upstream cylinder and vertical displacement of the downstream cylinder using plus sign in the centre of each cylinder.

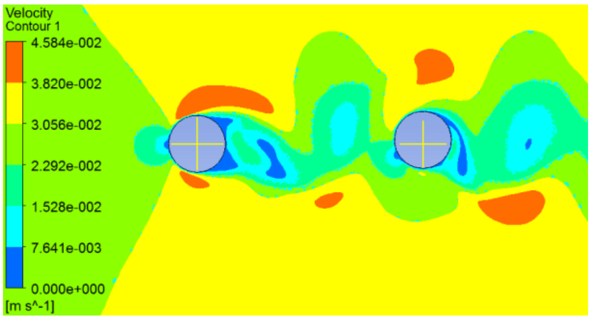

Figure 5. Instantaneous velocity contours (m/s) over two cylinders and vertical displacement of elastic downstream cylinder

Numerical results and discussion

The power which is produced by the elastic circular cylinder in normal direction to the fluid flow can be calculated using the velocity and lift coefficient history diagram of the downstream cylinder. Therefore, the force acting around the wet surface of the elastic cylinder (D) can be determined using the dynamic pressure over the cylinder surface. Figures (6-a) and (6-b) show the lift coefficient history for both the stationary upstream and elastic downstream cylinders, respectively. It is clear that the exerted lift force on the elastic downstream cylinder is almost three times bigger than the lift force exerted on the stationary cylinder due to effects of the produced vortices.

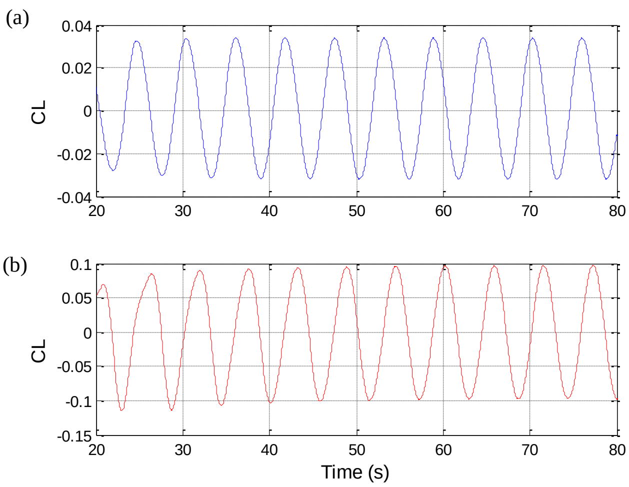

Figure 6. Lift coefficient history of cylinders: (a) stationary upstream cylinder, (b) elastic downstream cylinder.

The non-dimensionalised power can be defined as a power of VIV divided to the power of fluid [5]. Therefore, the efficiency of VIV can be written as

$$\eta_{VIV} = \frac{P_{VIV}}{P_{fluid}} \tag{7}$$

where,

$$P_{fluid} = F_y . U = \frac{1}{2}\, \rho U^2 . Dl . U . \tag{8}$$

Table 1 compares the maximum amplitude of the elastic cylinder in the normal direction with available experimental data [2]. It is observed that the numerical results correspond satisfactorily with the data obtained from previous experiments.

	Re	***S***	***V_r***	***y/D***	***Error***
Assi (2009)	1500	4D	2.0	0.061	~6%
Present study	1500	4D	2.0	0.065	

Table1. Comparison between the numerical results and experimental data

The power of VIV can be calculated using the normal velocity and lift force of downstream cylinder for one full developed cycle. The graphs in Figure 7 show the non-dimensionalised displacement (a), velocity (b) and force (c) history of the cylinder. These graphs reveal that the phase angle between velocity and force is zero. This means that the quantity of cos (φ) is maximum and it is equal to one. Hence, the power can be calculated using inner product of velocity and force. The efficiency of VIV power for one cycle of oscillation can be calculated using the Equation (7). The maximum efficiency of power for one cycle is 0.7%. Although, the value of efficiency is very small, these conditions have been selected only to validate the numerical simulation. Admittedly, by selecting appropriate parameters which involve mass ratio, damping factor, natural frequency, Reynolds number or reduced velocity and lateral distance of cylinders the extracted power can be increased. This method can be considered as a new technique for production of renewable energy which comes from ocean and shallow rivers.

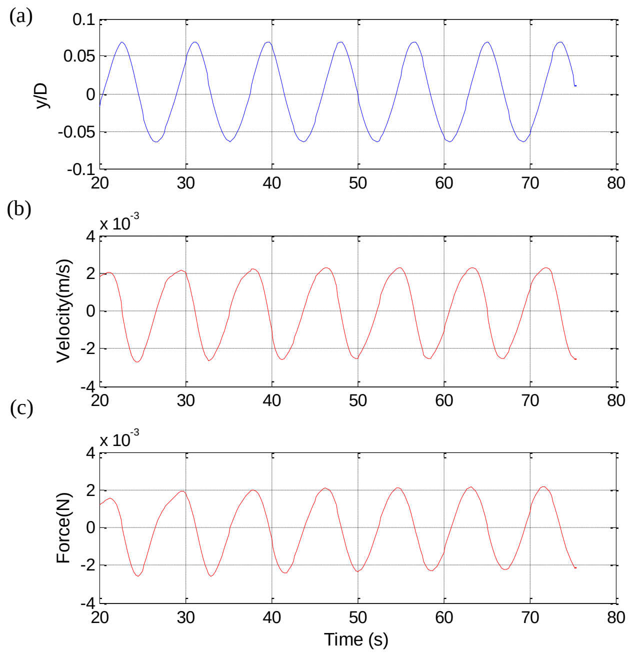

Figure 7. History of: (a) displacement, (b) velocity, (c) force for one cycle of oscillation

Conclusions

Two-dimensional numerical analysis of vortex induced vibration has been done to harness vortical energy which is produced from the wake of the upstream circular cylinder. Due to vortices formation, the downstream circular cylinder which is mounted on the elastic system can be oscillated perpendicular to the flow direction. This translation was modelled as a motion of simple mass-damper spring. Numerical simulation results for amplitude of oscillation have a sufficient agreement with previous experiments. The outcomes illustrate that the velocity of cylinder and normal force has the same frequency, and positive power can be generate due to this method.

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