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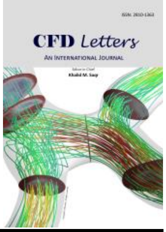

Numerical Simulation and Investigation of Flow Patterns Around Three Side-by-Side Cylinders Arranged in Line with an Oscillating Central Cylinder

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ABSTRACT

A flow past three cylinders arranged in a vertical row in a side-by-side configuration in which both side cylinders were kept fixed and an oscillatory movement provided to the middle cylinder was simulated. This particular configured setup holds significant importance in engineering and presents a compelling resemblance to numerous real-world scenarios especially in electricity production using oscillatory motion. In the present study, free-stream flow across three side-by-side cylinders with a transversely oscillating middle cylinder, was simulated using the commercial CFD software tool ANSYS 2021 R2 at a low Reynolds number (Re) = 100, with non-dimensional cylinder spacing (s/d) = 2;. For the middle cylinder, non-dimensional amplitude (amplitude ratio), A/d = 0.5 and a frequency ratio of f_e/f_o=0.8, 1 and 1.2 were considered (f_e/f_o, where f_e is the cylinder oscillation frequency and f_o is the corresponding vortex shedding frequency for stationary cylinders). In this study, re-meshing was done using the dynamic mesh technique, and pre-defined oscillatory motion was provided with the help of an additionally hooked User Defined Function (UDF) in the commercial CFD software tool. The objective of the present study was to investigate the effect of governing parameters on flow physics and wake nature, as well as the effect of the flow transition on engineering parameters. The interesting finding to report here that for oscillation frequency f_e/f_o= 1 there exist synchronous flow confirmed from wake diagram having comparatively more drag with that of other two higher f_e/f_o= 1.2 and lower oscillation frequency ratio f_e/f_o= 0.8 for cylinder spacing (s/d) = 2.

1. Introduction

Designing a structure consisting of bluff bodies is a critical engineering challenge. It will anticipate even more complex when that bluff body vibrates. Also, the analysis of a vibrating bluff body wake pattern that forms on the downstream side is an important aspect. In the engineering field, flow instability in the wake zone leads to vortex shedding, which results in flow induced vibration (FIV)

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and may further cause structural failure. The interaction of the wakes generated behind bluff bodies leads to complex time-varying forces, but most practical engineering scenarios involve structures that have multiple bluff bodies' configuration rather than a single bluff body, like the configuration commonly observed at offshore structures such as suspension bridges and further in nuclear reactors, multi-tube exchangers, and flow over rod tube bundles. Many literatures are available on both stationary and forced oscillatory motion of single and multiple cylinders. However, very little work is available on the configuration considered in the present study, which is a combination of stationary and oscillating ones that mimic most real-world situations. So the current investigation attempts to comprehend and report the flow characteristics over a transversely oscillating body in the vicinity of other adjacent stationary bluff bodies.

Earlier researcher Kang *et al.,* [1] studied the effect of cylinder spacing (s/d < 5) on three side-by-side stationary cylinders at a Reynolds number of 100 and reported five different types of flow patterns. Kumar *et al.,* [2] numerically investigated the flow over a row of nine side-by-side square cylinders at Re = 80 and various cylinder spacing's ranging from 0.3 to 12 and observed synchronized, quasi-periodic, and chaotic flow regimes. Guilmineau *et al.,* [3] studied flow across a single transversely oscillating cylinder at Re =185 for a frequency ratio of 0.80 to 1.2 with a maximum amplitude of 0.20D in which the effect of oscillation on the vortex switching mechanism was studied. Lee *et al.,* [4] studied two side-by-side transversely oscillating two cylinders at Re = 185 with a frequency ratio ranging from 0.8 to 1.2 and a maximum oscillation amplitude of 0.20 D and found that drag coefficient is affected by the oscillation frequency ratio, cylinder spacing, and root means square (r.m.s.) value of lift coefficient, which increases drastically when the frequency ratio is greater than 1. Sewatkar *et al.,* [5] studied row of transversely oscillating square cylinders using the lattice Boltzmann method and observed that the wake interaction behind the cylinders weakens with increase of governing parameters.

Sewatkar *et al.,* [6] studied combine effect of low Reynolds number ranging from 30 to 140 and cylinder gap spacing from 1 to 4. It was discovered that as the gap ratio rises, the critical Reynolds number for the onset of vortex shedding rises as well. Sewatkar *et al.,* [7] studied the impact of cylinder oscillation on flow regimes, engineering parameters, and energy transfer in relation to the cylinder spacing, oscillation amplitude, and low Reynolds number equal to 80.

The earlier various other researchers [8-11] *et al.,* studied the effect of forced vibration, tandem arrangement, gap spacing, and orientation on flow physics in the wake zone for a low Reynolds number using different methods, like LES and LSM. Using a dual cylinder system configuration like one stationery and another oscillating, different gap spacing and angle of attack were studied by Bao *et al.,* [12]. Williamson *et al.,* [13] experimentally investigated vortex formation in the wake of an oscillating cylinder. Chen *et al.,* [14] and Dutta *et al.,* [15] also used LSM method to simulate the flow past an oscillatory square cylinder. Placzek *et al.,* [16] studied effect of forced and free oscillations at low Reynolds number and its impact in wake zone. Sudhakar *et al.,* [17] used oscillating wake splitter plate to investigate flow structure. Rajpoot *et al.,* [18] studied wake structure for the Reynolds number = 100 in tandem square cylinders arrangement. Yogeswaran *et al.,* [19] studied effect of free vibrations at low Reynolds numbers on elliptic cylinder. Qiu *et al.,* [20] studied Vortex-induced vibration of two tandem square cylinders with different restraint conditions. Zhao *et al.,* [21] studied with numerical simulation of vortex-induced vibration for a single square cylinder at a low Reynolds number = 100 with various flow approach angles (α). Ishak *et al.,* [22] studied effect of crosswind flow angle (Ψ) around a generic train moving on different bridge Configurations and investigated two flow regime namely slender body flow at a smaller range of Ψ and bluff body flow behaviour at a higher range of Ψ.

Hassim *et al.,* [23] The effect of Wake-Induced Vibration (WIV) at Low Reynolds Number 1000 were taken for various gap spacing in tandem arrangement from 2D to 5D in which 2.5D found to optimum to produced higher lift force. Blackburn *et al.,* [24] simulated oscillating circular cylinder for Reynolds number 500 and oscillation amplitude 0.25 to understand the wake structures, flow dynamic in stationary and in simple harmonic cross-flow oscillation. The findings imply that the conclusion of a competition between two vorticity generating systems causes the abrupt change in vortex shedding phase. Jamal *et al.,* [25] studied two interlocked square cylinders for Reynolds number 150 and found that there was an early contact between the shear layers behind the wake of the two overlapping squares cylinders at the downstream sharp corner, where the flow separation was delayed.

Thus, it is noticed from the literature survey that the flow behavior of a combination of oscillatory and stationary cylinders was not well studied. So purpose of this study is to investigate non-reported research parameters and understand fluid flow behaviour with the help of a wake pattern generated in the downstream.

2. Methodology

2.1 Physical Description and Computational Domain

In the present study, free-stream flow across three side-by-side cylinders with a transversely oscillating middle cylinder is done. Figure 1 shows the computational domain and boundary conditions used for the study. The middle cylinder is oscillated transversely, with the expression for the transverse position of the cylinder given as

$$Y = A \sin(2 \Pi \, St \, \tau) \quad (1)$$

Where, A is the maximum amplitude of oscillation (= 0.5d), d is the diameter of the cylinder, $\tau = d/U_\infty$ is non-dimensional time, $St = f_e d/U_\infty$ is Strouhal number of the oscillating cylinder, frequency ratio = f_e/f_0 is he excitation frequency, and f_0 is the natural vortex shedding frequency. The domain, grid, and time independence study is done thoroughly. (Not reported here.)

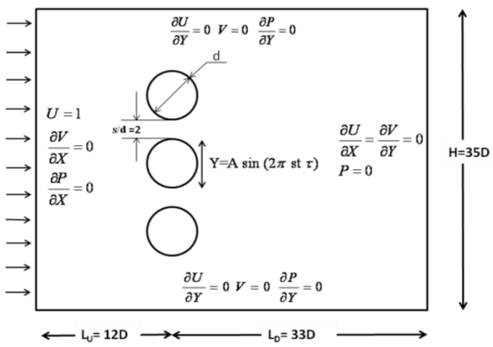

Fig. 1. Computational domain and boundary conditions

2.2 Governing Parameters

The present study is done for a constant Reynolds number (Re), cylinder spacing, amplitude of oscillation, and various frequency ratios. The values of the governing parameters considered are: Re = 100, cylinder spacing s/d = 2, amplitude of oscillation A = 0.5 d, frequency ratio f_e/f_0 = 0.8, 1, and 1.2.

2.3 Flow Solver

The simulations are performed using the finite-volume method-based commercial software ANSYS FLUENT, using the dynamic-mesh technique and the moving grid motion macro of the User Define Function (UDF) for the moving boundary problem. The laminar model is taken with a convergence criterion of 10^{-6}. The flow field is solved with a staggered, unsteady pressure-based solver. The convective and diffusive terms are obtained using the third-order accurate QUICK (Quadratic Upstream Interpolation for Convective Kinetics) scheme and the second-order accurate central-difference scheme (CDS), respectively. The pressure-velocity coupling is achieved using the PISO (Pressure Implicit Solution by Split Operator Method) algorithm. Least squares node-based discretization is used for the gradient term. For calculating pressure on the face, PRESTO (Pressure Staggering Option) is used.

2.4 Grid Details

There are two types of 2D mesh elements selected: the structured portion of the 2D quad and the triangular element in the unstructured zone, which collectively total almost 86,000. The computational domain was divided into three sub-domains using Hybrid Multi Block (HBM) meshing strategy. As shown in Figure 2 and Figure 3, sub-domain 1 consists of a fine Cartesian mesh of $\Delta X = \Delta Y = 0.01$ at the surface of all cylinders to capture the boundary layer and gradient effect precisely. Further sub-domain 2 consists of an unstructured tri-pave mesh enveloping sub-domain 1, in which grid size varies from 0.03 to 0.05. This subdomain 2 helps to get rid of negative volume issues often faced in dynamic meshing. Sub-domain 3 shown in Figure 3 is a Cartesian stretched mesh zone in the remaining domain, with the grid size varying from 0.05 to 0.25 at the outer boundaries.

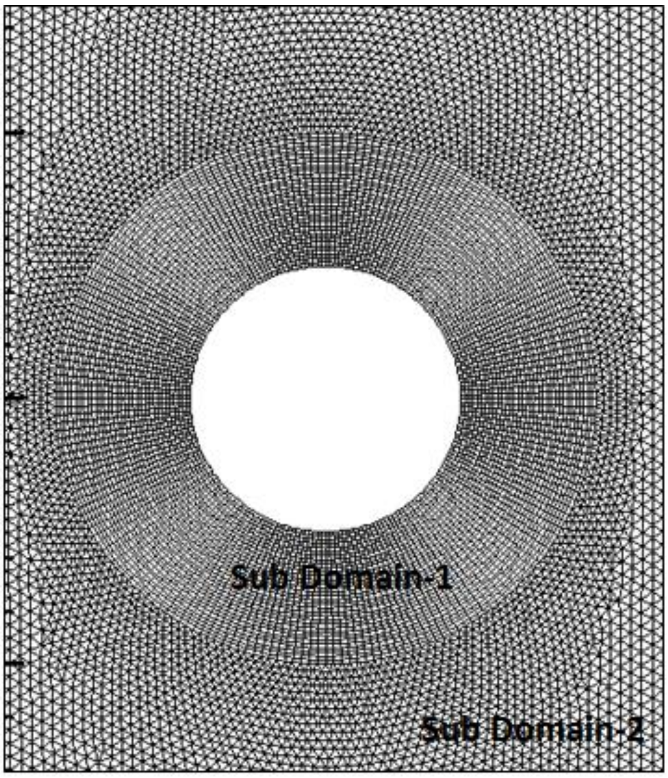

Fig. 2. Exploded view of Sub-Domain 1, 2

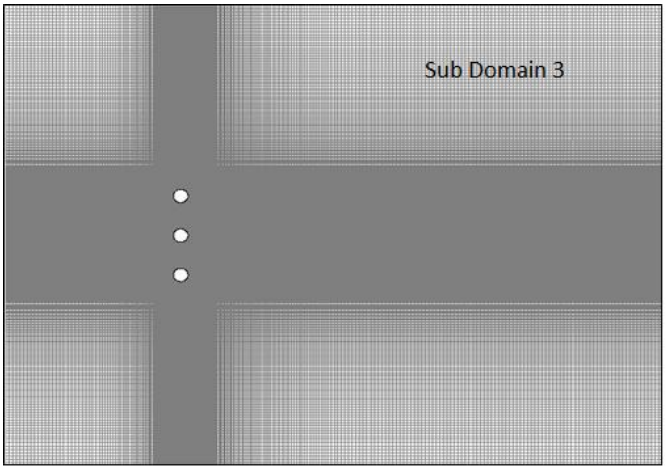

Fig. 3. Exploded view of Sub-Domain 3

2.5 Validation

A validation of the present computational methodology is done by comparing the present with the earlier published results. Two different problems on free stream flow across transversely oscillating cylinders are considered: first for single and second for two cylinders (with anti-phase oscillation) at f_e/f_0 = 0.8, 1 and 1.2 and Re = 185. The computational domain with boundary conditions is shown in Figure 4 for the first problem and Figure 6 for the second problem. The results shown in Figure 5 for the single oscillating cylinder and Figure 7 for the dual oscillating cylinder problem show excellent agreement between the present and published [3, 4] results.

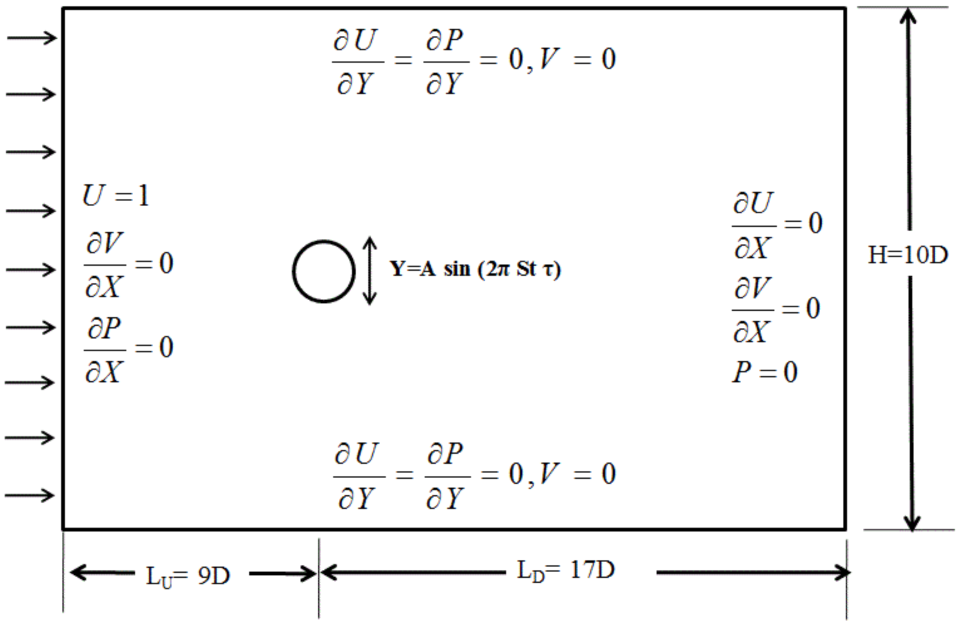

Fig. 4. Computational domain with boundary conditions

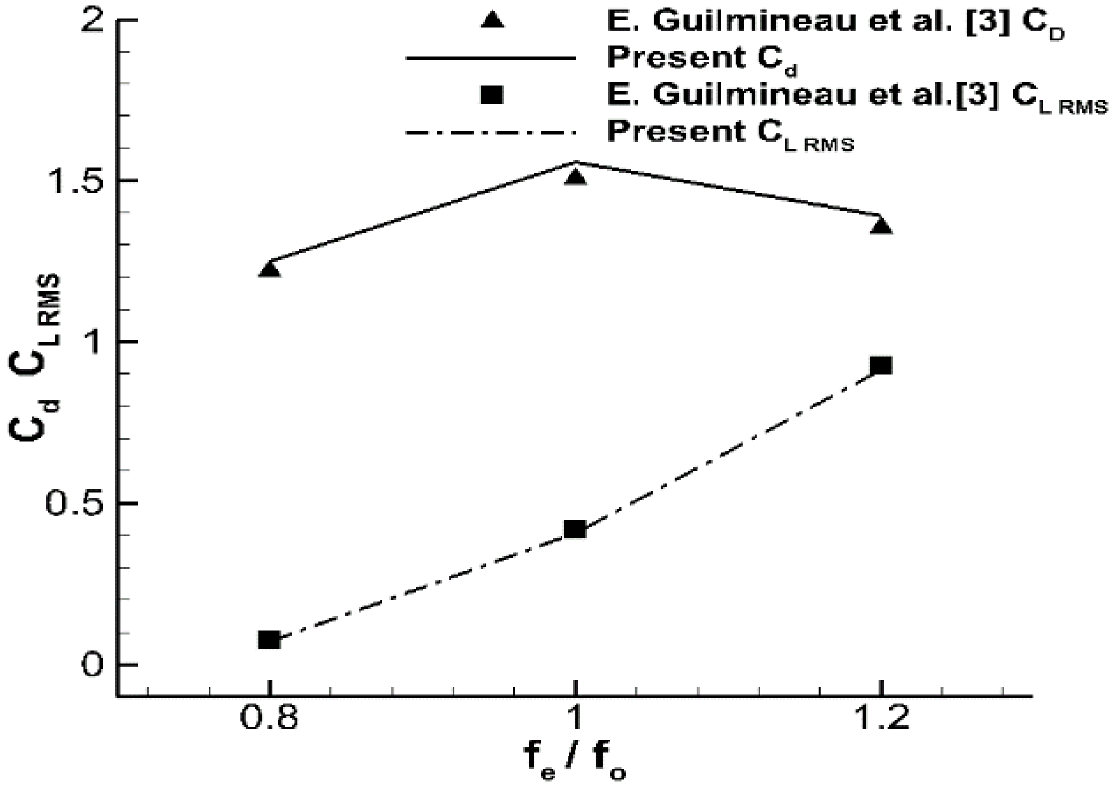

Fig. 5. Comparison of present and published results for mean drag and root mean square (*rms)* value of lift for transversely oscillating single cylinder for different frequency ratio at Re=182

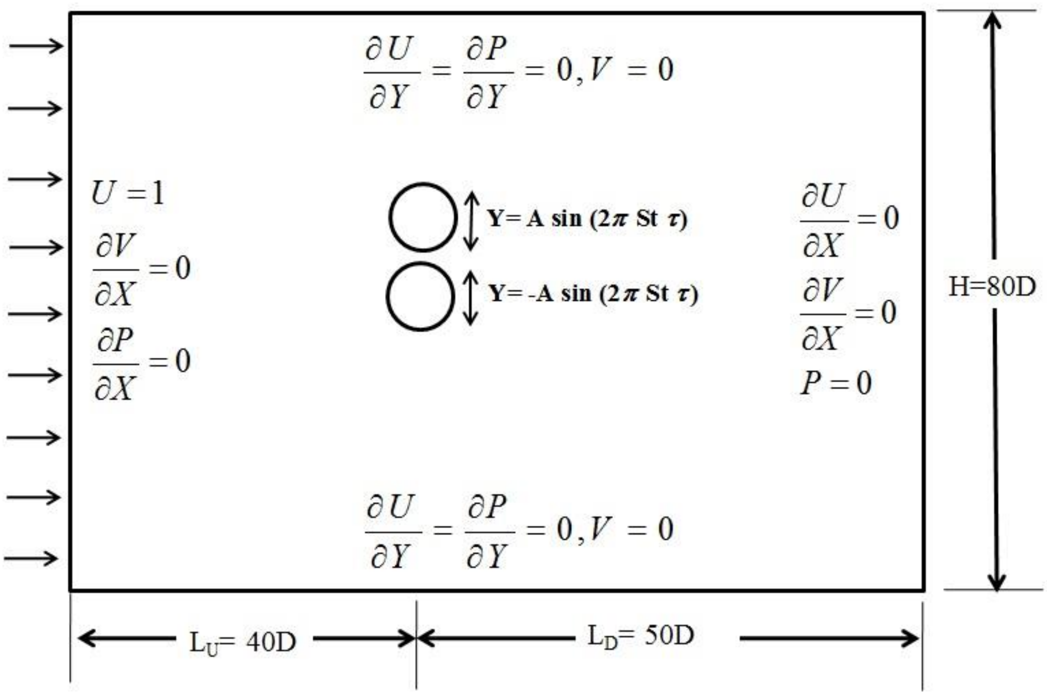

Fig. 6. Computational domain and boundary condition for dual oscillating cylinder

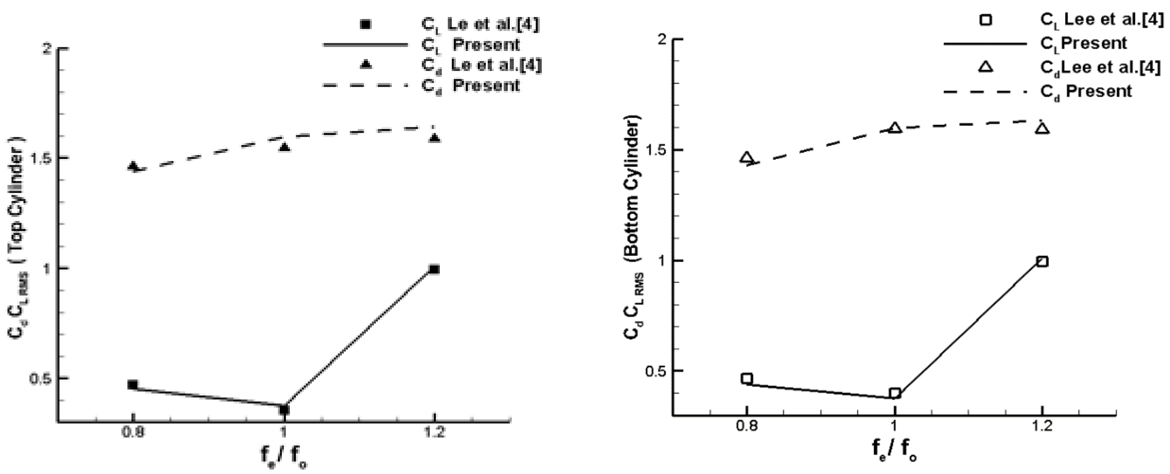

Fig. 7. shows comparison of present and published results for mean drag and *rms* value of lift coefficient respectively for transversely oscillating two cylinder for different frequency ratio at *Re=185*

3. Results

In the present study, the effect of frequency ratio for s/d = 2, A/d = 0.5, and Re = 100 is taken under study and simulated. Variations in engineering parameters such as C_D, C_L, and flow pattern of wake are discussed in the following section.

3.1 Variation of C_D and C_L

Figure 8 shows the temporal variation of CD and CL for the frequency ratios studied. As it can be seen from the figure, a modulation in the signal is obtained only for f_e/f_0 = 0.8, whereas for other frequency ratios, a periodic variation is obtained. For all the frequency ratios, the CD of the middle oscillating cylinder is larger than that of the side stationary cylinders. Moreover, CD for side cylinders is of the same order and in anti-phase mode. Further, it is observed that the magnitude of CL for the middle cylinder lies in between that of the side cylinders, whereas the magnitude of the side cylinders is of the same order. Also, CL for side cylinders is in in-phase mode. Moreover, it can also be seen that the magnitudes of both CD and CL are larger for f_e/f_0 = 1 as compared to other frequency ratios.

Figure 9(a) and Figure 9(b) show the variation of the mean drag and root mean square (*rms*) values of the lift coefficient w.r.t. various frequency ratios for the present study. For the middle oscillating cylinder, Figure 9(a) shows that mean drag increases with an increase in frequency ratio up to f_e/f_0 = 1 but with further increases in frequency ratio, it decreases. Whereas, for the side cylinder, mean drag increases with an increase in frequency ratio. Also in the range of frequency ratio studied, the middle cylinder has a larger mean C_D than the side cylinders this well confirms there exist synchronous flow [6] which was well defined by earlier researchers.

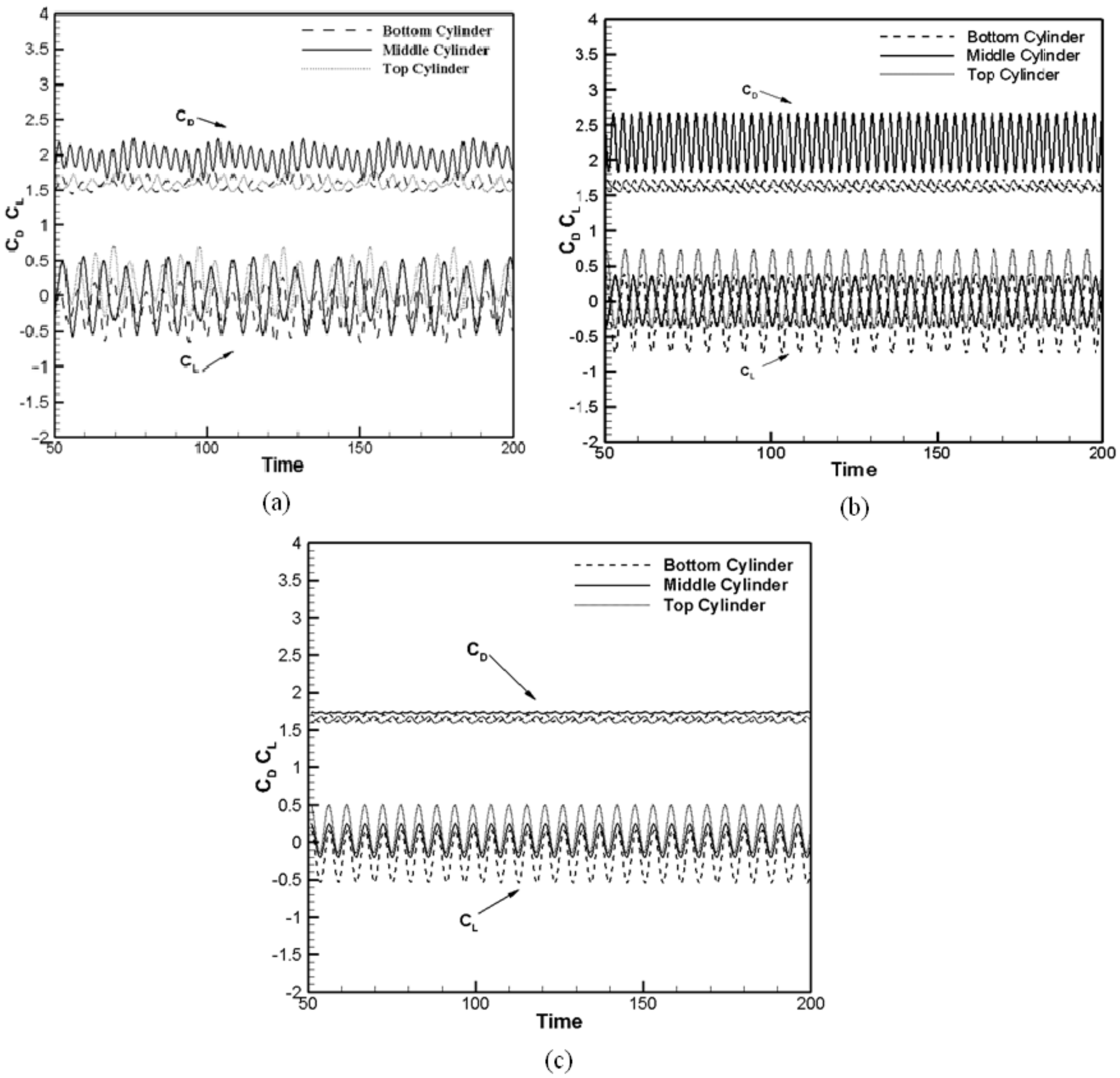

Fig. 8. Temporal variation of coefficient of drag (CD) and coefficient of lift (CL) for (a) f_e/f_o= 0.8, (b) f_e/f_o = 1 and (c) f_e/f_o = 1.2 at Re=100

Figure 9(b) shows the variation *rms* value of lift coefficient (C_L) w.r.t. frequency ratio. For a stationary side cylinder, Figure 9(b) shows that the *rms* value of lift increases with an increase in frequency ratio up to f_e/f_0=1 but with further increases in frequency ratio, it decreases. Whereas, for the middle oscillating cylinder, the *rms* value of lift decreases with an increase in frequency ratio. Also in the range of frequency ratio studied, side cylinders have a larger *rms* value of lift than middle cylinders, except for f_e/f_o = 0.8. It is to be noted here from Figure 9 that the mean drag and *rms* value of lift for an oscillating middle cylinder is lowest for f_e/f_o = 1.2, i.e., for the largest frequency ratio.

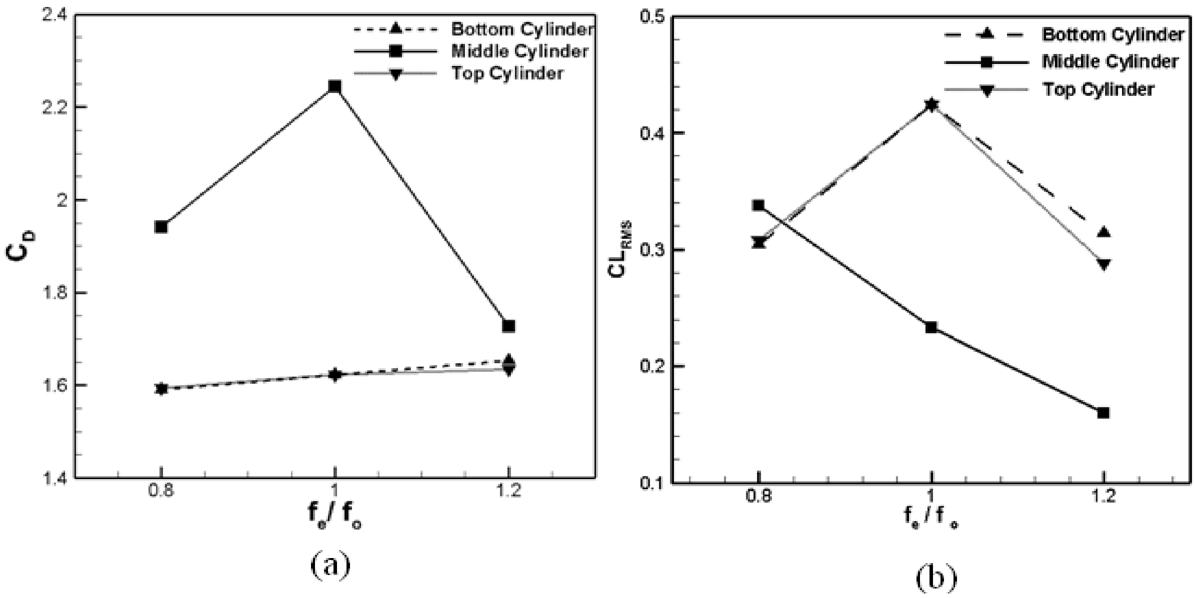

Fig. 9. Variation of engineering parameter C_D (a) and C_L (b) with frequency ratio 0.8, 1 and 1.2 for present study s/d =2 and at *Re=100*.

3.2 Wake and Vorticity Contours

Figure 10 shows the variation of the single modulation cycle of CL for the middle cylinder for f_e/f_0 = 0.8. Here, points a–j represent different instances of time at which wake and vorticity contours are shown in the following section.

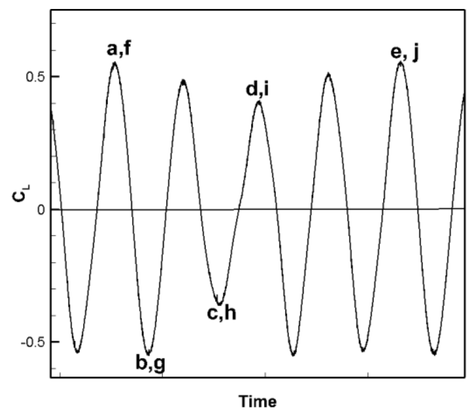

Fig. 10. Single modulation cycle for f_e/f_0=0.8 representing different salient points

Figure 11 shows the wake and vorticity contours for s/d =2 and f_e/f_o = 0.8. The figure shows an interaction between the wake and vortices, with a periodic variation of a wake-merging length in the top as well as the bottom gap, as well as a periodic variation of the phase difference between the vortex shed by the oscillating middle and stationary side cylinder.

Figure 12 shows the variation of the single oscillation cycle of C_L for the middle cylinder for f_e/f_0 = 1 and 1.2. Here, points a–j represent different instances of time for which wake and vorticity contours are shown in the following section.

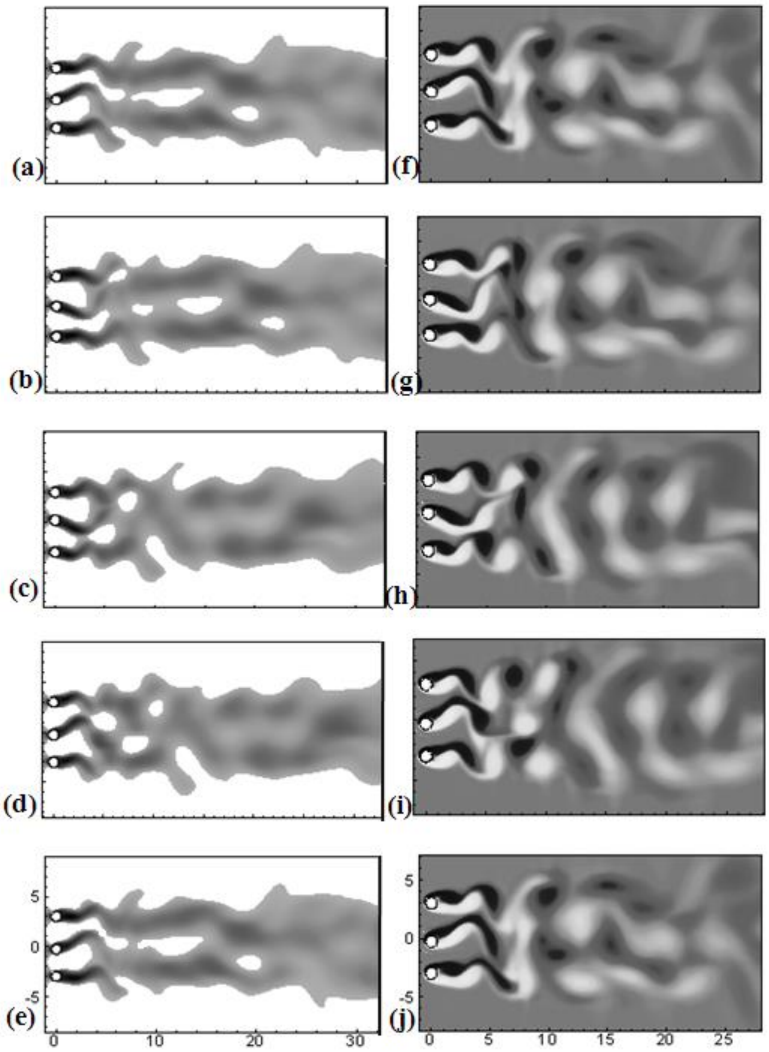

Fig. 11. Temporal variation of wake (a-e) and Vorticity (f-j) contours for s/d=2 and Frequency ratio (f_e/ f_o) = 0.8

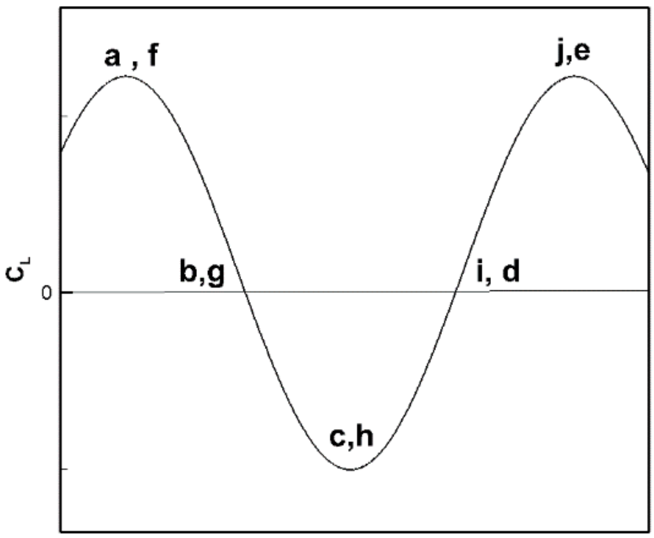

Fig. 12. Single oscillation cycle for f_e/f_0=1.0 and 1.2 representing different salient points

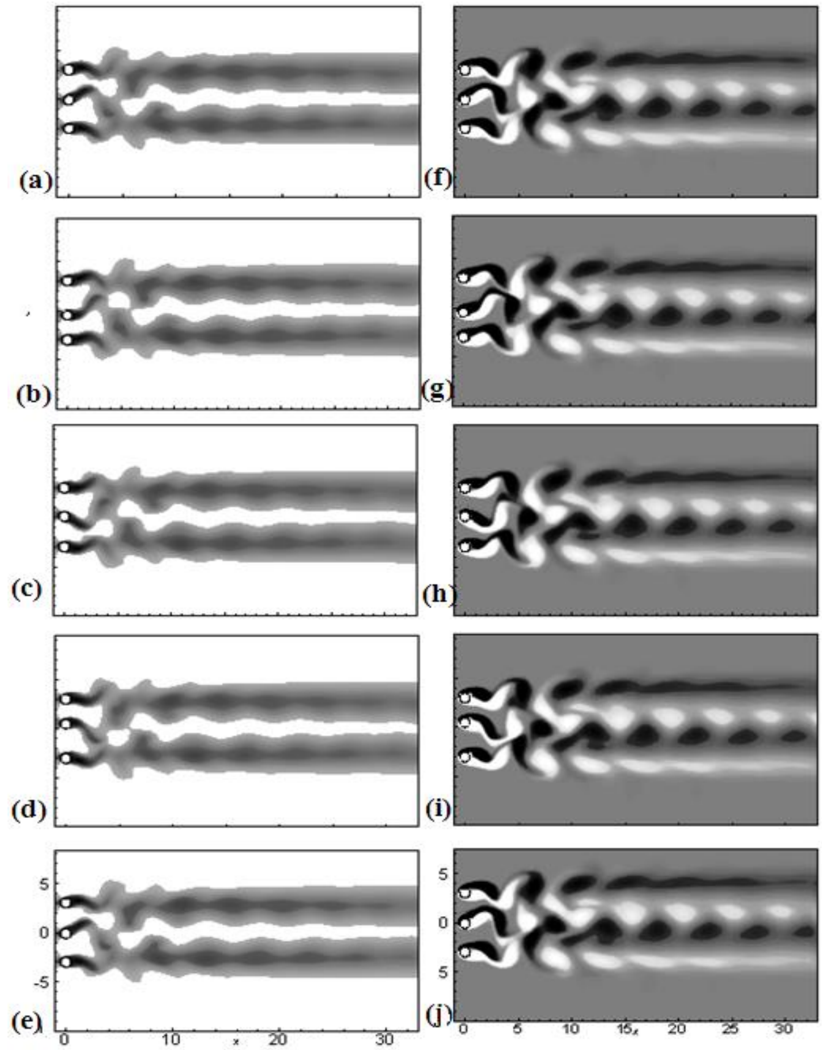

Fig. 13. Temporal variation of wake (a-e) and vorticity(f-j) contours for s/d=2 and frequency ratio (f_e / f_o) =1 at Re =100

Figure 13 shows wake and vorticity contours s/d =2 and f_e / f_o =1. It is interesting to note here that there are only two separated wakes, as the wake from the middle cylinder completely merges with the top and bottom cylinders, causing only periodic variation in C_D and C_L. Figure 12(a) and Figure 12(f) represents the point at which the largest lift is obtained. As can be seen from Figure 13, a negative vortex is being shed from the top of the middle cylinder, thus causing a low pressure zone at the top of the cylinder, resulting in the largest C_L. Also, from the wake diagram, it can be seen that an accelerated flow region is seen at the top of the middle cylinder, thus signifying a low pressure zone, which also indicates a larger C_L. Similarly, in Figure 12(c) and Figure 12(h) represents the point at which the smallest lift is obtained, as can be seen from Figure 13, where a positive vortex is being shed from the bottom of the middle cylinder, thus causing a low pressure zone at the bottom of the cylinder, resulting in the smallest C_L. Also, from the wake diagram, it can be seen that an accelerated flow region is seen at the bottom of the middle cylinder, thus signifying a low pressure zone, which also indicates a smaller C_L. As opposed to the above discussed in Figure 12 (b, g, and d, i), contours are shown for the points at which C_L is zero. Also, it can be seen from Figure 13 (f) – Figure 13(j) that at these times, vortex formation is taking place; thus resulting in intermediate pressure zones of equal magnitude at the top and bottom of the middle cylinders. Furthermore, Figures 13 (b, g, and d,i) show that the wake contours of accelerated flow at the top and bottom of the middle cylinder are of equal intensity, thus resulting in zero C_L. It is interesting to note that for f_e/f_o = 1, a P + 2S type of vortex pattern is observed.

Figure 14 shows the variation in wake and vorticity pattern for the middle oscillating and side stationary for s/d =2 and frequency ratio (f_e / f_o) = 1.2. As we increase the frequency ratio, the merging length reduces and the flow becomes stable.

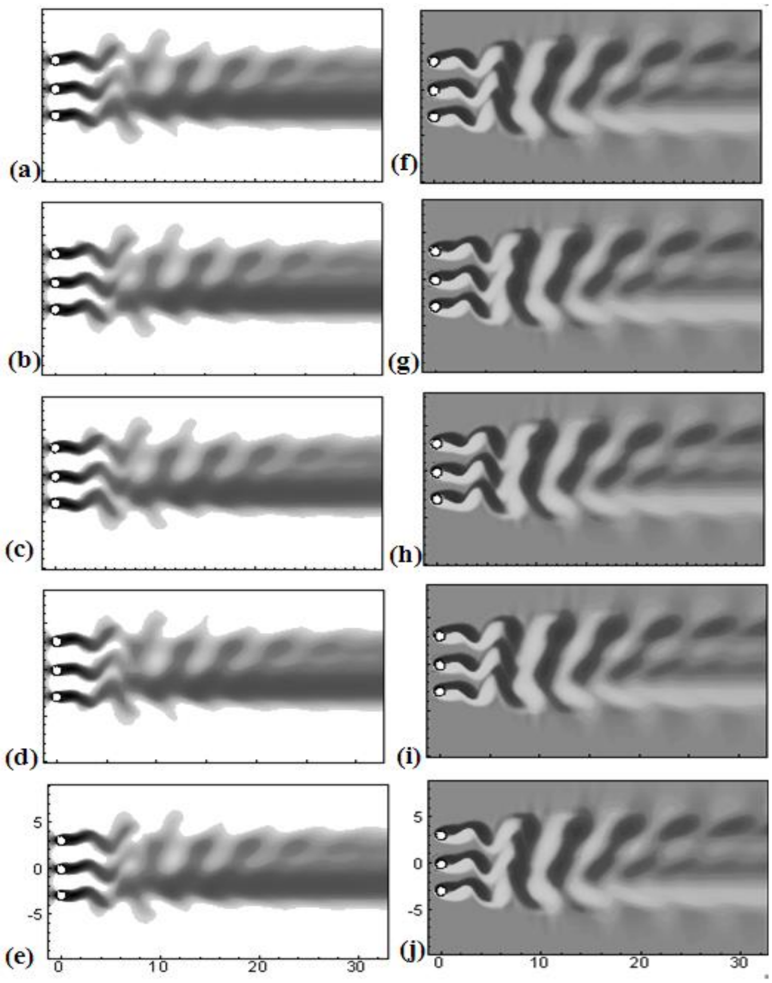

Fig. 14. Temporal variation of wake (a-e) and Vortices (f-j) contours for s/d=2 and Frequency ratio (f_e / f_o) = 1.2

4. Conclusions

The significance of this study is to understand flow physics and wake patterns, which find crucial application in many real-world places, like in heat exchangers, where oscillating cylinders can enhance heat transfer by promoting turbulence and disrupting the boundary layer, leading to more efficient heat exchange between the fluid and the solid surfaces. Secondly, oscillating cylinders can be used as components in underwater propulsion systems, where the oscillation generates thrust by interacting with the surrounding fluid, similar to the mechanism of fish or marine mammals. In biomedical engineering, oscillating cylinders could be utilized in devices where controlled fluid flow patterns are required for efficient drug dispersion.

In this paper, we have investigated the fluid-structure interaction of an oscillatory cylinder with stationary cylinders and its flow pattern at a low Reynolds number (Re) of 100. A commercial CFD software tool was used for the simulation of free-stream flow across three side-by-side cylinders with a transversely oscillating middle cylinder. The method was thoroughly benchmarked for free stream flow across one oscillating cylinder as well as two transversely oscillating cylinders, and it shows excellent agreement with the published results. Thereafter, the simulation for the present problem is done to study the effect of the frequency of oscillation (f_e/f_o = 0.8, 1, and 1.2) on the middle cylinder at a constant oscillation amplitude of A/d = 0.5, cylinder spacing of s/d = 2, and Reynolds number of 100.

The flow structure is quite different in the three different frequency ratios studied here. The vortices shed by the top and bottom (side) stationary cylinders are almost in-phase at all the time instants, for the various frequency ratios. Whereas, for the middle transversely oscillating cylinder, the vortices shed is in-phase at the largest f_e/f_o =1.2, anti-phase at f_e/f_o = 1.0, and periodically switch from in-phase to anti-phase at the smallest f_e/f_o =0.8, as compared to the vortices shed from the stationary side cylinder. This is discussed with the help of wake and vorticity contours here. It is found that C_D for the oscillating middle cylinder is greater than the side cylinders, whereas C_L is smaller for the middle cylinder in comparison with stationary side cylinders for the parameters under consideration.

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