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Numerical Investigation of the Structural Frequencies Effects on Flow Induced Vibration and Heat Transfer

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Abstract
In this research, a numerical simulation, using ANSYS CFX 11, is used to study the flowinduced vibrations (FIV) and heat transfer in a heated circular cylinder subjected to a uniform cross flow with Reynolds number equals to 325. The cylinder is allowed to vibrate, both in in-line and in cross-flow directions. Results of the computations are presented for various values of the structural frequencies of the oscillator. Lock-in is observed for a fairly wide range of cylinder vibration frequencies centered around the vortex shedding frequency of the cylinder. The heat transfer rate is enhanced remarkably as the oscillating frequency of the cylinder approaches the natural shedding frequency. In one of cases, comparing with the stationary cylinder, the rate of heat transfer of the oscillating cylinder is increased by 13%.

*Keywords:*FIV, FSI, Heat transfer, Vibration, Cylinder

1. Introduction
The event of vortex shedding and Flow-Induced Vibration (FIV) by a flow passing over a cylinder is significant in engineering applications, for instance, in heat exchangers, nuclear reactor fuel rods and steel cables of suspension bridges. Flow past an oscillating cylinder was studied in the past few decades as well as the heat transfer mechanism of the cylinder which is also interesting and important in engineer applications related to the vortex shedding. Many researchers have studied Flow-Induced Vibration, because this kind of vibration can be very harmful. Solving the problems that involve fluid flow around the complex structure is not so simple. Therefore, by simulating the behavior of a simple structure such as a cylinder can help us to use the new methods in this field. Heat transfer is also important in many devices of this type such as the heat exchangers. In these applications, Flow-Induced Vibration can affect the heat transfer rate. For a flow crossing an oscillating cylinder, there are several numerical and experimental studies investigating this phenomenon [1-5]. Flow past cylinders subjected to forced in-line oscillations were studied by Griffin and Ramberg [6]. In their studies, two separate modes of vortex-shedding were observed. Chang and Sa [7] established these observations by using a numerical model. In another computational study, Mittal and Tezduya[8] observed that at a certain frequency, a cylinder subjected to in-line oscillations produces a symmetric mode of vortex-shedding. They noticed the phenomena of lock-in and hysteresis for a cylinder limited to cross-flow vortex-induced vibrations. Tanaka [9] studied the fluid-induced and fluid elastic vibration of the system under consideration. He calculated the critical velocity by measuring the unsteady fluid dynamic forces. He founded that the critical velocity in a low density fluid like air is to the power of one half relative to the mass damping parameter and in high density the critical velocity is less influenced by the latter. Also he studied the effect of detuning of natural frequency on critical velocity. Mittal and Kumar [10] studied vortex-induced oscillations of circular cylinder at low Reynolds number and also the effects of structural frequencies on induced vibrations. Mittal and kumar[11] again investigate the vortex-induced vibrations (VIV) of a light circular cylinder placed in a uniform flow at Reynolds number in the range of 10^3-10^4. Their Results were presented for various values of the frequencies of the oscillator. In certain cases they studied the effect of the mass of the

oscillator on these frequencies. They observed lock-in for some ranges of structure's frequencies. Flow structure in the wake of a cylinder with forced oscillations has been investigated by many other researchers, e.g., [12-18]. In some of these studies, the cylinder is subjected to oscillations at frequencies that are sub- and super harmonics of the natural vortex-shedding frequency for a stationary cylinder.
For a flow passing over a stationary cylinder, alternating vortex shedding in the wake of a cylinder induces lift and drag forces on the cylinder and an unsteady flow is seen based on experimental observation and numerical predictions. There are many numerical and experimental investigations related to the heat transfer from cylinders in cross flow [19-25]. Due to unsteady flow and the resulting vortex shedding behind the cylinder, the heat transfer from the cylinder will be unsteady.
Sreenivasan and Ramachandran[26] have studied, by an experimental method, the effect of vibration on heat transfer of a horizontal cylinder normal to air stream and didn't observe significant changes in the heat transfer coefficient with the maximum velocity amplitude of 0.2. Saxena and Laird [27] for a flow at Re = 3500 measured heat transfer of a cylinder transversely oscillating in an open water channel and observed the increase in heat transfer rate to be about 60%. Leung et al. [28], Cheng et al. [29] and Gau et al. [30] experimentally investigated the heat transfer around a heated oscillating circular cylinder. The results indicated that the enhancement of heat transfer was relative to the magnitude of oscillating frequency and amplitude of the cylinder. Wu-Shung and Bao-Hong [31] studied the flow structures and heat transfer characteristics of a heated transversely oscillating cylinder in a cross flow. They studied the effects of Reynolds number, oscillating amplitude, oscillating speed on the flow structures and heat transfer characteristics and showed that the heat transfer of the cylinder in the lock-in regime is enhanced remarkably.
The subject of the present work is, therefore, investigation of the effect of structural frequencies on flow-induced vibration behaviors and heat transfer of a light heated cylinder. Study both of the induced vibrations and heat transfer can be near in fact. Cylinder is allowed to oscillate in both cross-flow and in-line directions so expected to undergo cross-flow and in-line vibrations. In general, the cylinder oscillations are predominantly in the cross-flow direction. The computations are restricted to two dimensions. The Reynolds number is 325 based on the free-stream speed and computations are carried out for various values of the structural frequency including the sub- and super-harmonics of the natural vortex-shedding frequency for a stationary cylinder. For a range of values of the structural frequency as expected, lock-in is observed. The results indicated that the heat transfer increased remarkably as the flow approached the lock-in regime; however, the heat transfer was almost unaffected by the oscillation of the cylinder outside the lock-in regime

2.The governing equations

Let $\Omega_t \subset \mathrm{IR}^{n_{sd}}$ and (0,T) be spatial and temporal domains, respectively, where n_{sd} is the number of space dimensions, and let Γ_t denote the boundry of Ω_t. The spatial and temporal co-ordinates are denoted by x and t. the navier-stokes equations governing incompressible fluid flow are:

$$\boldsymbol{\rho\left(\frac{\partial u}{\partial t}+u.\nabla u-f\right)-\nabla.\sigma=0 \text{ on } \Omega_t} \textbf{ for (0,T)} \qquad \textbf{(1)}$$

$$\boldsymbol{\nabla.u=0 \text{ on } \Omega_t} \textbf{ for (0,T)} \qquad \textbf{(2)}$$

Here ρ, u, f and $\sigma$are the density, velocity, body force and the stress tensor respectively. The stress tensor is written as the sum of its isotropic and deviatoric part:

$$\boldsymbol{\sigma=-pI+T\ ,T=2\mu\varepsilon(u),\varepsilon(u)=\frac{1}{2}((\nabla u)+(\nabla u)^T)} \qquad \textbf{(3)}$$

Here p and μ are the pressure and viscusity.
The local heat transfer coefficient and surface-averaged (mean) Nusselt number are computed from:

$$\boldsymbol{Nu_\theta=\frac{Q_{wall}\times D}{(T_c-T_0)K_F}} \qquad \textbf{(4)}$$

$$\boldsymbol{Nu=\frac{1}{A}\int_{\Gamma cyl} Nu_\theta\, d\,\Gamma} \qquad \textbf{(5)}$$

Where$Q_{wall}$is the heat that transfers from the cylinder surface;$Nu_\theta$and$Nu_\theta$are the local heat transfer coefficient and surface-averaged (mean) Nusselt number, respectively.
The boundary conditions are:
at the upstream far field
$u=u_\infty\ ,T=T_0$
at the downstream far field
$P_{stat\ out=0}$

at the surface of the cylinder
$u.n = u_{cy}.n\, , T = T_c$
and on the upper and lower boundaries: adiabatic wall with free sleep
where u_{cy} is the velocity of the cylinders, n is the unit normal vector and T_c is temperature of the surface of cylinder.
The circular cylinder is modeled by a spring-damper-mass system, which is representative of the location of maximum amplitude of vibration at the mid-span of a long cylindrical structure mounted with fixed ends. Thus, the cylinder motions can be accounted for by solving a two degree-of-freedom dynamic equation as:

$$\ddot{X} + 2\pi\xi F_s\dot{X} + (\pi F_s)^2 X = \frac{C_D}{M_r} \tag{6}$$

$$\ddot{Y} + 2\pi\xi F_s\dot{Y} + (\pi F_s)^2 Y = \frac{C_L}{M_r} \tag{7}$$

Where the reduced natural frequency of the oscillator is , F_s and ξ is the structural damping coefficient, M_r is the non-dimensional mass of the body while C_L, C_D are the instantaneous lift and drag coefficients for the structure respectively. The free-stream flow is assumed to be along the x −axis. $\ddot{X}$, $\dot{X}$ and X indicate the normalized in-line acceleration, velocity and displacement of the cylinder respectively, while $\ddot{Y}$, $\dot{Y}$ and Y represent the same quantities associated with the cross-flow motion, e.g., normal to x direction. In the present study, the displacement and velocity are normalized by the radius of the cylinder and the free-stream speed respectively. The reduced natural frequency of the system, F_s is defined as $F_s = 2f_s a/U_\infty$, where f_s is the actual frequency of the oscillator, a is the radius of the cylinder and U_∞ is the free-stream speed of the flow. The non-dimensional mass of the cylinder is defined as $M_r = M/\rho a^2$, where M is the real mass of the oscillator per unit length and ρ is the density of the fluid. The drag and lift force coefficients are computed as:

$$C_D = \frac{1}{\frac{1}{2}\rho U_\infty^2 2a}\int_{\Gamma_{cyl}} (\sigma n).n_x d\Gamma \tag{8}$$

$$C_L = \frac{1}{\frac{1}{2}\rho U_\infty^2 2a}\int_{\Gamma_{cyl}} (\sigma n).n_y d\Gamma \tag{9}$$

Where n_x and n_y are the Cartesian components of the unit vector, n which is normal to the cylinder boundary Γ_{cyl}. These coefficients include the fluid dynamic damping and the added mass effect.

The equations governing fluid flow are solved in conjunction with those for motion of the cylinder. By integrating the flow variables on the cylinder surface, the forces acting on the structure is calculated. The resulting drag and lift coefficients are used to calculate the displacement and velocity of the cylinder and then these variables are used to update the location of the body.

In the calculation of fluid-structure interaction problems, it is essential to resolve the structural dynamics, the flow field and, most important, fluid-structure interactions in every time steps. The calculated flow-induced forces and hence the structural dynamics will be in error if this last behavior is not resolved properly. During solving the problem, the fluid domain acts as a boundary for the structure and after solving the structural problem which produces motion, velocity and/or deformation of the boundary, the new conditions obtained from the structure is chosen for fluid domain. This interactionis performed in every time step.In the followings, first the solution of the flow is described, then the structural dynamics model, the resolution of the fluid-structure interactions and their feedback to the flow and structural dynamics solutions are presented. Finally the results obtained with this technique are discussed. For facilitating the analysis, the following assumptions are made: (a) fluid is water, (b) flow field is twodimensional and laminar, (c) fluid properties are constant, (d) effect of the gravity is ignored,(e) the no-slip condition is held on the interfaces between the fluid and cylinder, and (f) the light mass is used to support in-line oscillations.

3.Simulation domain

The cylinder is assumedto be in a rectangular computational domain such that upstream and downstream boundaries are located at 8Dfrom the left, top and bottom and 22.5D from the right side of the domain where D stands for the diameter of the cylinder as shown in Fig. 1. The Reynolds number is 325 based on the diameter of the cylinder, free-stream velocity and the viscosity of the fluid. The non-dimensional mass M_r of the cylinder is 4.7273 and the structural damping coefficient is assumed to be 3.3×10^{-4}.The same parameters for the oscillator and fluid have been used by Mittal and kumar [11]. In this study afinite element mesh with 18842 nods and 10934 elements is used. Themesh near cylinder is shown in Fig. 2.

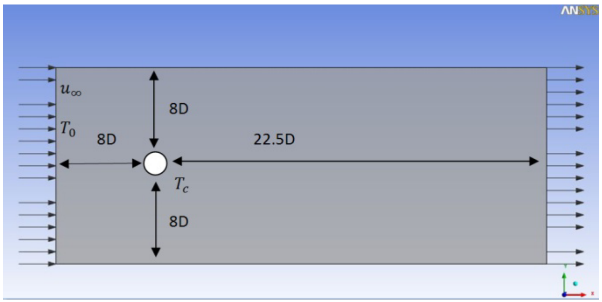


Figure 1 Simulation domain

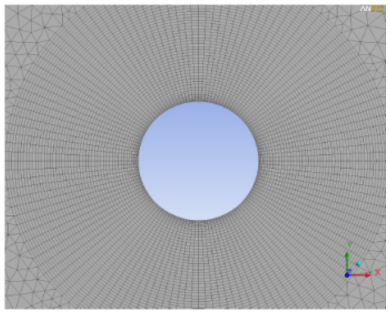
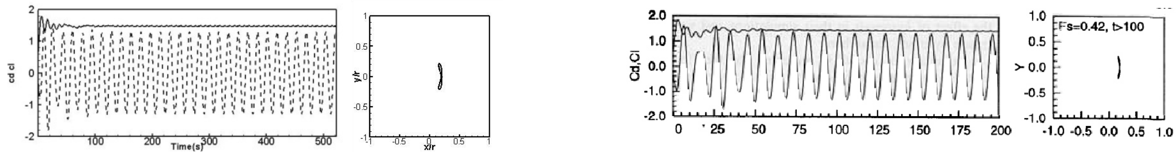


Figure 2 Mesh near the surface of the cylinder

4.Validation of the method

The validity of the proposed numerical method for fluid-induced vibration is examined by making a thorough comparison between the present calculations and previously reported numerical results. The numerical results of Mittal and kumar[11]are selected for this purpose.Use is made of the time history ofC_L, $C_D$coefficients and the trajectory of cylinder results fromMittal and kumar [11]Their studies have been carried out for the similar conditionswith boundary conditions as free-stream velocity, while in this study the top and bottom boundaries are chosen solid walls. However, their results can be used to validate the present solution for the structure under consideration.Figure 3 presents the results forF_s =0.42 where the letter (a) represents the result from Mittal and Kumar[11] and (A) shows the present results. These results were obtained for cylinder with two degrees of freedom and Reynolds number equal to 325. In both top and bottom figures, the vibration amplitude is normalized withthe cylinder radius.



(A) (B)

Figure 3 Left; the time histories of , ----- C_L, ______C_D coefficients and right; _______the trajectory of cylinder. (A) present study and (a) Mittal and Kumar (2001) with $F_s = 0.42$, $\xi = 3.3 \times 10^{-4}$, M_r=4.7273 and Re=325

5. Results

5.1.Results for flow-induced vibration

At Re = 325, first the steady state solutions and then the unsteady solution for the flow past a stationary cylinder were computed. The steady state resultswere used as the initial condition which is used for unsteady solution of the fluid calculations.These results arethen used as initial conditions for the cases involving the elastic cylinder motion which is free to move in cross flow and in line directions.Figure 4 shows the time histories of the drag and lift coefficients for stationary cylinder. For the flow passing over a stationary cylinder, the natural frequency of vortex shedding is about 0.2 in the range of Reynolds number $2 \times 10^2$to 10^4Wu-Shung and Bao-Hong [31]. In the present study,the same natural were also obtained.

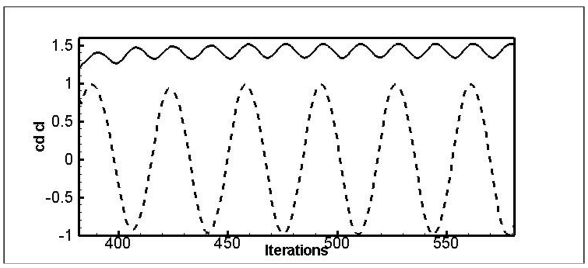
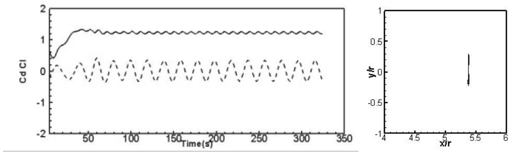
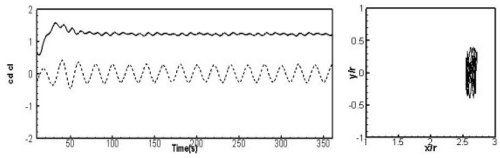
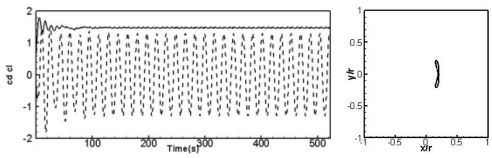


Figure 4 Time histories of----- $C_L$and______$C_D$coefficients for stationary cylinder.

In this section, to begin with, a summary of the results is presented for the flow-induced vibrations of the cylinder when the structural frequency is sub- and super-harmonics and also is equal to the natural vortex-shedding frequency for the stationary cylinder. Fig. 5 shows the time histories of the drag and lift coefficients and the cylinder trajectory for sub- and superharmonics for various values ofF_S.
For all these cases (suband super harmonic frequencies) the mean drag coefficient is about 1.2. The lift coefficient amplitudes for super-harmonic frequencies are larger than those for sub-harmonic frequencies. While, the amplitude of cylinder vibration in cross flow direction for sub- frequencies is larger than for super-harmonic frequencies. This is related to non-dimension frequencies in each case.


(a)


(b)


(c)

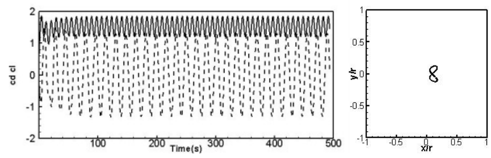

(d)

Figure 5 Left; time histories of, ----- C_L, ——— C_D coefficients and right; ——— trajectory of cylinder. (a) F_s =0.07, (b)$F_S = 0.1$, (c)$F_S = 0.42$, (d)$F_S = 0.53$ with $\xi = 3.3 \times 10^{-4}$, M_r=4.7273 and Re=325

It can be noticed that the static in-line deflection of the cylinder increases as the structural frequencydecreases. This value is about 5.5 times the radius of the cylinder forF_S =0.1, while it is about 0.2 times forF_S =0.53. Exceptfor the non-dimensional frequencyF_S =0.1, in all frequencies used, the cylinder has a distinct trajectory such that in super-harmonic frequencies this trajectory takes the shape of figure6. In these cases, the lock-in (vibrations with large amplitude) cannotbe seen.

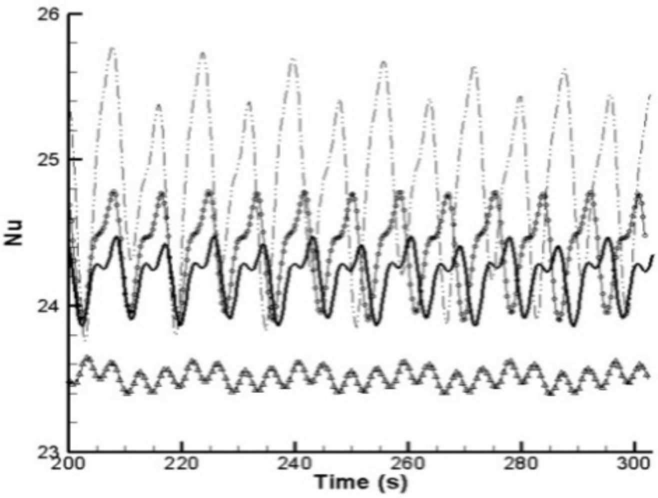
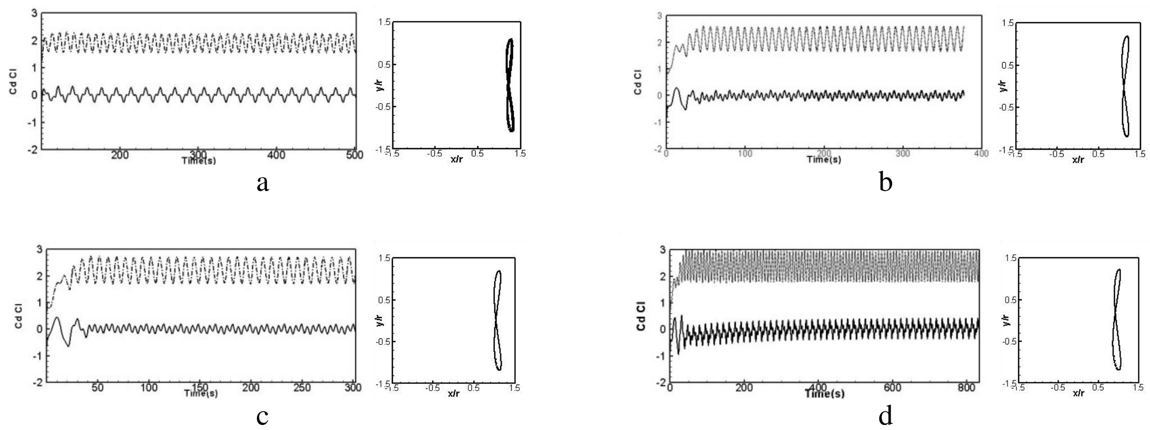


Figure 6 Mean Nusselt number for —△—$F_S = 0.18$, ———$F_S = 0.2$, —o—$F_S = 0.21$, ...—...—$F_S = 0.23$, $\xi = 3.3 \times 10^{-4}$, M_r=4.7273 and Re=325.

The time histories of the drag and lift coefficients and cylinder trajectory for thecomputations with$F_S = 0.18$, 0.20, 0.21 and 0.23 are shown in Figure7. These frequencies are close enough to the vortex shedding frequency for stationary cylinder, i.e., 0.2.Lock-in and the well-known Lissajoufigure6are observed for all these cases. Like the cases of sub- and super- harmonic frequencies, with increase in cylinder frequency, the static in-line displacement is decreased. Amplitude of lift coefficient for these cases is smallandthe displacement in cross flow direction is large; corresponding to sub- and super- harmonic frequencies. Mean

drag coefficients in vortex shedding frequency domain is about 2.1, which is increased a small amount with the increment of frequency. The lift coefficient has two peaks in each cycle which is caused by the modes of vortex shedding.The cross-flow vibration frequency of the cylinder corresponding to the vortexsheddingfrequency is twice the vibration frequency value for the case of in-linedirection.
The same observations have been made earlier by researchers during laboratory experiments and study of vortex shedding in cross flows.



(a)$F_S = 0.18$, (b)$F_S = 0.2$, (c)$F_S = 0.21$, (d) $F_S = 0.23\xi = 3.3 \times 10^{-4}$, M_r=4.7273 and Re=325.

Figure 7 Left; time histories of, - - - - - C_D, ——— $C_L$coefficients and right; ——— trajectory of cylinder.

5.2. Results for heat transfer

For all various values ofF_S, the surface-averagedNusselt number were calculated. The mean Nusselt number calculated for stationary cylinder is about 22. These values for sub and super harmonic frequencies are shown in one figure and the heat transfer result for frequencies that experiment lock-in are shown in another figure. From Fig. 8, it is observed that the meanNusselt number for these natural frequencies (0.07, 0.1, 0.42 and 0.53) does not have distinct variations compared to stationary cylinder heat transfer results. Hence, as seen in Figure 8, the mean Nusselt number for a cylinder with $F_S = 0.1$ decreases relative to the same value for stationary cylinder. Maybe the erratic trajectory causes this behavior. The results for F_S which represent lock-in are shown in Figure 6. The heat transfer rate is enhanced, obviously, as the oscillating frequency of the cylinder approaches the natural shedding frequency.
The rate of heat transfer in lock-in for F_S= 0.18 increases about %10 compared with the stationary cylinder, and this value is about %13.6 forF_S=0.23. Cylinder approaches the natural shedding frequency. The rate of heat transfer in lock-in for F_S= 0.18 increases to about %10 compared with the stationary cylinder, and this value is about %13.6 forF_S= 0.23.For F_S=(0.18, 0.20, 0.21 and 0.23), table 1 shows the non-dimensional vortex shedding frequency F_{SS} and the xnon-dimensional.

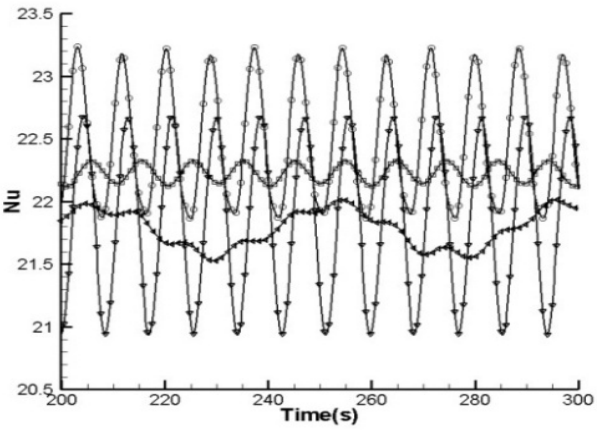


Figure 8 Mean Nusselt number for —□—□— F_S =0.07, —◁—◁— $F_S = 0.1$,—▽— $F_S = 0.42$, —○— $F_S = 0.53$ with $\xi = 3.3 \times 10^{-4}$, M_r=4.7273 and Re=325

vortex shedding frequencyF_{ss} and the non-dimensionalvibrationfrequency F_{sy} for cylinder in cross flow direction. As the difference between these two frequencies is reduced, the Nusselt number increases more. The time history of the lift coefficients are used to calculate the vortex shedding frequencies, and the trajectory of cylinder in cross flow direction is used for vibration frequency calculations of the cylinder.

Table. 1. Differences between the non-dimensional vibration and vortex shedding frequencies in cross flow direction.

Non-dimension frequency of cylinder	Non-dimension vibration frequency (F_{sy})	Non-dimension vortex shedding frequency (F_{ss})	different between$F_{sy} - F_{ss}$
$F_s = 0.18$	$F_{sy} = 0.1901$	$F_{ss} = 0.1883$	0.0018
$F_s = 0.20$	$F_{sy} = 0.2034$	$F_{ss} = 0.2025$	0.0009
$F_s = 0.21$	$F_{sy} = 0.2091$	$F_{ss} = 0.2098$	0.0008
$F_s = 0.23$	$F_{sy} = 0.2207$	$F_{ss} = 0.2214$	0.0007

Conclusions

A numerical simulation, using ANSYS CFX 11, is performed to study the effects of natural frequencies of the structure on flow-induced vibrations and heat transfer of a heated circular cylinder. The Reynolds number based on the free-stream speed is 325 and the computations are carried out for various values of the structural frequency including the sub- and super harmonics of the natural vortex-shedding frequency for a stationary cylinder. Some conclusions are summarized as follows:

1. For an elastic cylinder, the 'Lock-In' is observed in a large range of natural frequencies.
2. The range of frequencies was fixed for 'Lock-in' phenomenon, in an oscillatory cylinder, near the vortex-shedding frequency of stationary cylinder.
3. In 'Lock-In' condition, the frequencies of in-line vibrations are twice the cross-flow vibration frequencies. The trajectory of the cylinder corresponds to Lissajou figure 8.
4. As the difference between the non-dimensional vortex shedding frequency and the non-dimensionalvibrationfrequency is reduced, the Nusselt number increases more.
5. Compared with the stationary cylinder, the heat transfer rates from the oscillating cylinder are increased from about 10 to 13.6 percent, and there was not any sensible change in heat transfer for natural frequencies which do not show 'Lock-in' phenomena.

All these results for vortex–induced vibrations have been obtained in the earlier studies and experimentalobservations, and the heat transfer results were shown for cylinder with forced moving conditions in cross flow direction. In this study, the simultaneous solution of both of them can help to simulate the behavior of more complicated arrangements of the cylinders which are close to the real applications and are found in industries.

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