Augmentation of VIVACE by means of Thermal Buoyancy

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Abstract. The present numerical simulation is carried out to evaluate the effect of Richardson Number on cylinder displacement and in turn the power extraction from the movement of cylinder. An in-house code based on arbitrary Lagrangian Euler scheme is used to tackle fluid structure interaction. The following fluid parameters is used in a present study Reynolds Number (Re) = 100, Prandtl Number (Pr) = 7.1 and Richardson number (Ri) = [-1, 0]. Structural parameters are as follows Reduced velocities (Ured) = 3 and 8, Reduced mass (Mred) = 2, damping coefficient (ξ) is set to be zero. With the aid of thermal buoyancy there is significant increase in power is obtained.

Keywords: VIVACE, vortex shedding, thermal buoyancy.

1. Introduction

Vortex-induced aquatic clean energy (VIVACE) is a new proven approach to extract energy from water currents and vortex-induced vibration. Vortex Induced vibration finds its application in many engineering fields such as heat exchanger, wind engineering tall structures and oil rigs. The life of the structure is reduced because of VIV, for suppressing the vortex induced vibration there are several passive and active methods that have been employed in the past. Suppression of VIV have been reported in research article of Rashidi et al. [1]. Vortex induced vibration of bluff bodies also helps to extract energy from fluid energy. Soti et al. [2] in their numerical study discussed the energy extraction from vortex induced vibration of circular cylinder. Lee et al. [3] proposed VIVACE, that uses the flow stream kinetic energy to generate electricity. In addition, the VIV of finned cylinder helps in thermal augmentation of cylinder, as described by Izadpanah et al. [4]. The VIV of a circular cylinder with Reynolds number ≤ 200 has been studied by many researchers. Anagnostopoulos and Bearman [5] conducted an experiment of VIV of a circular cylinder which was mounted elastically in a water channel at Reynolds Number = 90-150. They were the first researchers to report that the maximum oscillation is observed at the beginning of the lock-in region in a low Reynolds number VIV of circular cylinder. Prasanth and Mittal [6] numerically investigated the characteristics of VIV for the flow on a circular cylinder. The cylinder was free to oscillate in the direction of the transverse flow for a range of Reynolds Number = (60-200) and with a relatively low mass ratio, m = 10. They reported that there are "initial" and "lower" branches at low Re, which correspond to vibrations of low ("initial") and high ("lower") amplitude. They investigated the effect of the blocking ratio on the hysteresis behavior of the response of cylinder. In a follow-up study, Prasanth et al. [7] investigated the combined effect of blockage and mass ratio on hysteresis in the VIV of a circular cylinder for a range of Re = (60 -150). Details of physics involved in the Vortex Induced Vibration can be found in review articles from [8]–[10].

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Vortex shedding of bluff body is suppressed or agitated by means of thermal effect or thermal buoyancy \[11,12\]. We have considered a square cylinder for our numerical study to find out the energy extracted from enlarge vibration of the cylinder which has not been investigated so far to the best of author’s knowledge. From the literature review we can conclude that for harnessing the energy, cylinder displacement plays the major role. So in the present study, effect of negative thermal buoyancy on square cylinder displacement and in turn the power extraction from it has been investigated for two structural parameter \(U_{\text{red}} = \) and \(U_{\text{red}} = 8\). An in house code for capturing the fluid structure interaction (FSI) is used to simulate the motion of the cylinder submerged in the fluid medium. It was concluded from the numerical simulation, that there is substantial agitation found in the displacement of the cylinder when we change the Richardson Number from 0 to -1.

In the present study numerical simulation is conducted for the parameters given as: Richardson number (\(Ri\)) = \([-1, 0]\), at a interval of 0.25, Prandtl number (\(Pr\)) = 7.1, Reynolds number (\(Re\)) = 100, reduced velocity (\(U_{\text{red}}\)) = 3 and 8 and reduced mass (\(m_{\text{red}}\)) = 2.

![Fig. 1 Schematic diagram of an elastically mounted square cylinder](image)

The problem definition is depicted in fig. 1. The cylinder is allowed to vibrate in transverse direction to the incoming flow. Flow is coming from negative y-direction i.e, opposite to gravity vector and cylinder is free to move in x-direction only. The cylinder is elastically mounted with a single spring and damper connected in x-direction. The spring is assumed to be linear. The structural parameters; mass, natural frequency and damping coefficient are converted in to dimensionless forms; reduced mass (\(m_{\text{red}}\)), reduced velocity (\(U_{\text{red}}\)) and damping coefficient (\(\xi = 0\)). The Reynolds number of the flow depends on the cylinder diameter D.

In fig. 2 a non-orthogonal, O-type body fitted grid is shown that is wrapped around the cylinder. The outer domain of grid is set to be as 40 D. After the study of grid independence a grid of 305*375 is taken and time step of 0.0004 is taken for the present simulation.
Continuity:

\[
\left( \frac{\xi_x}{\xi_x} \frac{\partial}{\partial \xi_x} + \eta_x \frac{\partial}{\partial \eta_x} \right) U + \left( \frac{\xi_y}{\xi_y} \frac{\partial}{\partial \xi_y} + \eta_y \frac{\partial}{\partial \eta_y} \right) V = 0
\]  
(1)

X - Momentum:

\[
\left( \frac{\partial U}{\partial \tau} + (U^\xi - U^g_\xi) \frac{\partial U}{\partial \xi} + (U^\eta - U^g_\eta) \frac{\partial U}{\partial \eta} \right) = - \left( \xi_x \frac{\partial p}{\partial \xi_x} + \eta_x \frac{\partial p}{\partial \eta_x} \right) + \frac{1}{Re} \nabla^2 U
\]  
(2)

Y - Momentum

\[
\left( \frac{\partial V}{\partial \tau} + (U^\xi - U^g_\xi) \frac{\partial V}{\partial \xi} + (U^\eta - U^g_\eta) \frac{\partial V}{\partial \eta} \right) = - \left( \xi_y \frac{\partial p}{\partial \xi_y} + \eta_y \frac{\partial p}{\partial \eta_y} \right) + \frac{1}{Re} \nabla^2 V + Ri\theta
\]  
(3)

Energy:

\[
\frac{\partial \theta}{\partial \tau} + \left( U^\xi - U^g_\xi \right) \frac{\partial \theta}{\partial \xi} + \left( U^\eta - U^g_\eta \right) \frac{\partial \theta}{\partial \eta} = \frac{1}{Re.Pr} \nabla^2 \theta
\]  
(4)

Vibration equation:

\[
\frac{d^2 x}{dt^2} + \frac{4\pi \varepsilon_x'}{U_{red}} \frac{dx}{dt} + \frac{4\pi^2 x}{U_{red}^2} = \frac{1}{2M_{red}} C_x
\]  
(5)

The non-dimensionalized form of rigid body motion equation is shown in equation (5). The reduced mass of the cylinder is defined as \( M_{red} = \frac{m}{\rho_f D^2} \); where \( m \) is mass of the cylinder per unit length and \( \rho_f \) is the fluid density. \( C_x \) is the instantaneous transverse force coefficients of the body. \( U_{red} \) is defined as: \( U_{red} = \frac{U_\infty}{f_n D} \) where, \( f_n \) is a natural frequency of cylinder.
Validation:
The present numerical simulation has been carried out with help of in house code based on arbitrary Lagrangian-Euler scheme. The results are validated against published research papers and presented in Table 1 and found good agreement with the available research.

Table 1. Comparison of mean Nusselt number and mean drag coefficient of a square cylinder at Re=100, Pr = 0.71 and Ri = 0

| Literature                  | $\overline{C_D}$ | Nu  |
|-----------------------------|------------------|-----|
| Sharma and Eswaran [11]     | 1.559            | 4.070 |
| Sohanker et al. [13]        | 1.460            | -   |
| Present                     | 1.477            | 4.031 |

Results and Discussion:
The variation of Ri and cylinder displacement (x) is listed in Table 2 (a) and Table 2 (b) for two different reduced velocities, $U_{\text{red}} = 8$ and 3. It is clearly observed from the Tables 2 (a) and (b) that as Ri changes from 0 to -1, the displacement increases. The displacement also depends up on reduced velocity, $(U_{\text{red}})$. For $U_{\text{red}} = 8$, the cylinder displacement is 0.08 D at Ri = 0 whereas at Ri = -1 there is a significant change in cylinder displacement and it becomes 1.266 D. Similar results are obtained for $U_{\text{red}} = 3$ where at Ri = 0, x = 0.02 D whereas at Ri = -1, x = 0.08 D. This clearly shows that structural parameters have strong impact on the cylinder displacement for the same variation in the values of Ri.

Table 2. Comparison of Richardson Number (Ri) and Cylinder Displacement (a) $U_{\text{red}} = 3$ and $U_{\text{red}} = 8$ of a square cylinder at Re = 100

| $U_{\text{red}} = 8$ | $U_{\text{red}} = 3$ |
|---------------------|---------------------|
| Richardson Number (Ri) | Cylinder Displacement (x) | Richardson Number (Ri) | Cylinder Displacement (x) |
| Ri = -1.0           | 1.266 D            | Ri = -1.0           | 0.08 D              |
| Ri = -0.75          | 0.75 D            | Ri = -0.75          | 0.07 D              |
| Ri = -0.50          | 0.18 D            | Ri = -0.50          | 0.04 D              |
| Ri = -0.25          | 0.11 D            | Ri = -0.25          | 0.024 D             |
| Ri = 0              | 0.08 D            | Ri = 0              | 0.02 D              |

(a)  (b)

The power extraction from the cylinder movement due to the incoming flow is tabulated in Table 3. Table 3 (a) shows the power extracted for $U_{\text{red}} = 3$ at Ri = 0 and -1. It can be seen from the Table 3 (a) that with the aid of thermal buoyancy (Ri = -1), the power available is more as compared to no thermal buoyancy (Ri = 0). At Ri = -1 the power extracted is 0.24 watt whereas
Table 3. Power obtained for different $U_{\text{red}}$ (a) $U_{\text{red}} = 3$ (b) $U_{\text{red}} = 8$

| $U_{\text{red}}$ = 3 | $Ri = 0$ | $Ri = -1$ |
|-----------------------|----------|-----------|
| Displacement          | Velocity | Energy    | Power   |
| 0.04 m                | 0.016 m/s| 0.256 J   | 0.1 watt|
| 0.18 m                | 0.0352 m/s| 1.245 J   | 0.24 watt|

| $U_{\text{red}}$ = 8 | $Ri = 0$ | $Ri = -1$ |
|-----------------------|----------|-----------|
| Displacement          | Velocity | Energy    | Power   |
| 0.16 m                | 0.062 m/s| 3.93 J    | 1.54 watt|
| 2.52 m                | 0.56 m/s | 319.25 J  | 71.5 watt|

at $Ri = 0$ power extracted 0.1 watt for $U_{\text{red}} = 3$. Similar results are obtained in case of $U_{\text{red}} = 8$ as shown in Table 3 (b). The striking feature in case of $U_{\text{red}} = 8$ is that power extracted in case of $Ri = -1$ is much larger than that of $U_{\text{red}} = 3$. However, displacement of cylinder at $Ri = 0$ for $U_{\text{red}} = 3$ and $U_{\text{red}} = 8$, do not have significant difference. This clearly shows the dependency of thermal buoyancy on structural parameter reduced velocity ($U_{\text{red}}$).

Fig. 3 (a) and (b) shows the variation of x direction cylinder displacement with time for $U_{\text{red}} = 3$ and 8 at $Re = 100$. As we can see from the figure, cylinder displacement is increased as we change the value of Richardson number from 0 to -1. Therefore it is clearly observed that the effect of buoyancy helps the cylinder to move with larger displacement.
Fig. 3 shows the variation of x-direction cylinder displacement with time for $U_{\text{red}} = 3$ and $U_{\text{red}} = 8$ at $Re = 100$.

Fig. 4 shows the instantaneous vorticity contours for different Richardson number for $U_{\text{red}} = 8$. As we can clearly observe from the fig.4, wake region in the downstream of the cylinder is wider for $Ri = -1$ in comparison to $Ri = 0$. The vortex shedding mode for all Richardson number is found to be “2S”( two vortices are formed in one vibration period of the cylinder). At $Ri = 0$ vortices occur alternatively and in case of $Ri = -1$ vortices are formed wider. The vortex pattern for $U_{\text{red}} = 3$ at different $Ri$ was observed similar as shown in fig. 4, therefore its is not presented here. The stationary cylinder wake also becomes wider in case of $Ri = -1$ as reported by Sharma and Eswaran [11].
### Conclusions:

It is concluded that the higher negative value of Richardson number moves the cylinder with larger displacement. Hence power extracted is more with the aid of negative thermal buoyancy. The vortex shedding pattern for $\text{Ured}= 8$ at $\text{Ri} = [-1, 0]$ is obtained as 2S mode of vortex shedding.
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