Numerical simulation of vortex induced vibration of cylinders with flexible splitter plates

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Abstract. Vortex induced vibration (VIV) of circular and square cylinders with flexible splitter plates is studied at low Reynolds numbers. Finite element based flow and structure solvers, coupled using a partitioned approach, are used for simulating the fluid-structure interaction. Effect of flexibility of an attached flexible plate on its ability to suppress the VIV of a circular cylinder is considered. Flexibility of the plate is found to adversely affect the reduction in amplitude of the vibration of the cylinder. Next, flow past two square cylinders with deformable splitter plates placed side-by-side is considered. Vibration response of the two plates is studied for different values of flexibility. Initially, the plates vibrate out-of-phase with each other, but eventually settle for an in-phase fully developed response. Large amplitude of vibrations in the fully developed response is observed when its dominant frequency is close to the first natural frequency of the plate vibrations.

1. Introduction
Vortex induced vibrations (VIV) of bluff bodies is a problem of great practical as well as academic interest. There has been a great effort in the direction of understanding and controlling this phenomenon. Splitter plates are a popular device used for modifying/controlling vortex shedding from cylinders and the associated vibrations. The effect of variations in geometry, especially length, of rigid splitter plates on the vortex shedding and cylinder oscillations has been investigated by a number of researchers in past [1, 2]. Kwon and Choi [1] found that the splitter plate length must exceed a critical value, depending on the value of the Reynolds number, to be able suppress the vortex shedding. Wu and Zhao [3] considered the effect of a rigid splitter plate hinged to the rear of a circular cylinder supported on springs. The effect of a flexible splitter on an elastically mounted cylinder is, however, much less explored.

The effect of splitter plates on multiple rigid bodies has also not received great attention. Kim and Durbin [4] studied the effect of a single splitter plate placed along the centerline between two circular cylinders in a side-by-side arrangement. They found the position of the plate required to make the wake steady. A number of researchers have studied the effect of flexible splitter plate on flow past a cylinder, for both circular and square geometries [5-7]. The objective of the present paper is to investigate the effect of flexible splitter plates on aeroelastic response of single and multiple cylinders. While the multiple cylinders are on rigid support, the single cylinder is on elastic support. Both circular as well as square geometries are considered. The effect of flexibility of the plate on the fluid-structure interaction is investigated. In particular, we study the phenomena of lock-in and galloping.
Lock-in occurs when observed frequency of vibration is close to the natural frequency of the structure. This phenomenon is particularly well known in case of vortex induced oscillations of isolated cylinders [8, 9]. Galloping is an instability that occurs with change in angle of attack of flow due to vibration of a radially asymmetric object.

2. Computational Methodology
The fluid-structure system is simulated by solving the coupled equations that govern the flow and structure. The Navier-Stokes equations for incompressible fluid are used to model the flow. The structure is modeled via the force balance along with St. Venant-Kirchhoff's constitutive relation. The characteristic non-dimensional parameters for the system are the Reynolds number \((Re)\), the ratio of the mass of the structure to that of the fluid it displaces \((m^*)\) and the reduced velocity \((U_p^*)\) calculated using the fundamental natural frequency of the plate vibrations. In the case of an elastically mounted cylinder, reduced velocity \((U_s^*)\) calculated using the natural frequency of the spring-mass oscillator is used for characterizing the compliance of the elastic support for a fixed value of \(m^*\).

The method of Deforming-Spatial-Domain/Stabilized Space-Time (DSD/SST) [10] is used for solving the fluid-flow problem over the deforming spatial domain. DSD/SST utilizes SUPG/PSPG stabilizations in a space-time framework. Mesh is deformed to conform to the evolving spatial domain by modeling it as a linear elastic solid. Smaller elements are made stiff to preserve the quality of mesh in the boundary layer region. The structure dynamics is handled by the open-source program Calculix [11]. It uses standard Galerkin descretization for a total Lagrangian formulation, while the time integration is performed using Newmark's scheme. Forces are transferred from the fluid mesh to the structure mesh using an algorithm that conserves the work done by the interface [12].

3. Results and Discussion
The flow past an isolated square cylinder with flexible splitter plate has been studied by a number of researchers in past [5-7]. We extend these studies to two cylinders placed side-by-side. We also consider the effect of flexibility on the vibration response of the plate, by varying the parameter \(U_p^*\).

![Figure 1. Re = 100 flow past two square cylinders with flexible splitter plates: variation of frequency and amplitude of displacement with \(U_p^*\). The frequencies \(f\) (plotted on left y-axis) are non-dimensionalized using \(U_\infty/D\), while the amplitude \(A\) (plotted on right y-axis) is non-dimensionalized by \(L\).](image-url)
Two square cylinders are placed side-by-side with centre-to-centre separation equal to the twice of their edge length ($L$). Each plate is $4L$ long and $0.06L$ thick. The Reynolds number of the flow based on the edge length of the cylinder is 100. The flexibility parameter of the plate, $U_p^*$, is varied from 8.5 to 24, while $m^*$ is fixed at 84.746. For a fixed $m^*$, smaller values of $U_p^*$ imply greater stiffness of the plates. Larger is the value of $m^*$, weaker is the coupling between the dynamics of fluid and structure. Initially, the plates vibrate out-of-phase with each other, maintaining the symmetry of the flow field. This happens because, as the fluid is accelerated through the gap between the cylinders, the plates are impulsively pulled towards each other. This results into the vibration response of the plates dominated by their inertia. However, after a period of time, different for different values of $U_p^*$, the motion of the plates eventually becomes in-phase. The plates now vibrate in unison, more or less behaving like a single cylinder with splitter plate. Figure 1 shows the variation in amplitude and the most dominant frequency of the fully developed in-phase response with $U_p^*$. Solid circles show the amplitude values, while triangles are used for showing the corresponding frequencies. The variation of the first natural frequency of the splitter plate (beam) vibrations is indicated by the continuous red curve. The broken black line gives the value of vortex shedding frequency for the rigid plate case ($f_0$). The values of amplitude are normalized by $L$, and all the frequencies by $U_\infty/L$. Relatively large amplitude of vibration is observed when the dominant frequency in the response is close to the first natural frequency of the plates. This points toward the phenomenon of frequency ‘lock-in’. The cases with $U_p^* = 24$, 17 and 8.5 show lock-in of the dominant frequency in the plate’s response with the first natural frequency of the plate bending oscillations. Figure 2 shows the difference between the vorticity fields for a lock-in ($U_p^* = 24$) and a no lock-in ($U_p^* = 12$) case, when the plates are at their extreme positions. In contrast with the lock-in case, the shear layers separated from the outer edges of the cylinders, during no lock-in, do not interact with the splitter plates. The vortices are shed much downstream in the lock-in scenario as compared to the case of no lock-in.

Use of rigid plate for suppressing vortex induced vibration of circular cylinder is well known [13]. In this study, we now present the effect of a flexible splitter plate on the vortex induced vibrations of a circular cylinder mounted on a spring. The splitter plate has dimensions $3.5D \times 0.2D$, where $D$ is the diameter of the cylinder. The Reynolds number, based on $D$, is 150 while $m^*$ has a value of 10. The value of the parameter $U_\infty^*$ is taken as 6. Computations were carried out for an isolated cylinder, cylinder with a rigid splitter plate and cylinder with a plate having $U_p^* = 12.8$. The reduction in amplitude due to rigid plate is significantly larger than that due to the flexible one. This can be explained by the ability of the plate to better preserve the symmetry of the flow by restricting the interaction of the flow on the two sides, and thereby suppressing the asymmetric vortex shedding and associated vibrations. The use of rigid plate also reduces the frequency of oscillations appreciably. Figure 3(a-c) shows the differences in the vorticity field observed due to the presence of rigid and flexible splitter plates. The splitter plates, especially the rigid one, delay the shedding of vortices to a much downstream location. The rigid plate, thus, offers a better option for suppressing VIV. To study the effect of stiffness of the spring support, a simulation was carried out at $U_\infty^* = 22$. For same value of
Figure 3. $Re = 150$ flow past an elastically mounted circular cylinder: instantaneous vorticity field for (a) an elastically mounted isolated cylinder with $U_i^* = 6$, (b) a fixed cylinder with a rigid splitter plate with $U_r^* = 6$, (c) a fixed cylinder with a flexible splitter plate having $U_p^* = 12.8$ and (d) an elastically mounted cylinder with a flexible splitter plate for $U_i^* = 22$ and $U_p^* = 4.6$. 
smaller $U_p^*$ corresponds to greater stiffness of the plate. $U_p^*$ was taken to be 4.6, which corresponds to an almost rigid plate. The vorticity field corresponding to this case is shown in figure 3(d). The amplitude of cylinder vibration is quite large, even though it is quite small for the plate-tip vibrations. This shows that for a sufficiently compliant spring galloping may set in. Even though the magnitude of plate oscillations is very small and the near wake appears to be steady, the entire structure undergoes heaving motion. The vortices are shed at a location which is even more downstream as compared to the other cases.

4. Conclusions
A study is presented on the effect of flexible splitter plates on the vortex induced vibration of a single and multiple bluff bodies. The shear layer separated from the bodies interacts with the splitter plates to produce rich dynamical effects. For two square cylinders with splitter plates, initially the plates vibrate out-of-phase with each other. The fully developed response, however, consists of in-phase vibrations of the plates. Lock-in of the response frequency with the first natural bending mode frequency is observed for certain values of flexibility ($U_p^*$), leading to large amplitude of plate vibrations. For a single elastically mounted circular cylinder, the flexibility of the plate reduces its ability to suppress the vibrations.

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