RENEWABLE ENERGY FROM FLOW-INDUCED VIBRATION

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Summary
This paper presents results investigating two flow-induced vibration phenomena, vortex-induced vibration and aeroelastic galloping. Both of these occur when a slender structure, such as a cylinder, is elastically mounted in a free stream, and allowed to oscillate in the cross-stream direction. Both can result in large amplitude oscillations that have the potential to drive a generator, to produce renewable energy. It is shown that simple, passive geometric features can have a significant impact on the flow structure and the structural response, and can be used to increase the efficiency of energy generation.

The wake of a circular cylinder immersed in a free stream is one of the most well-studied problems in fluid mechanics. Typically, vortices are shed alternately from one side of the cylinder, then the other, into the wake periodically, forming the Kármán vortex street. The flow is characterized by a single parameter, the Reynolds number $\mathrm{Re} = UD/\nu$, where U is the free stream velocity, D is the cylinder diameter, and ν is the kinematic viscosity. Periodic vortex shedding of some form is evident for essentially all $\mathrm{Re} \geqslant 47$.

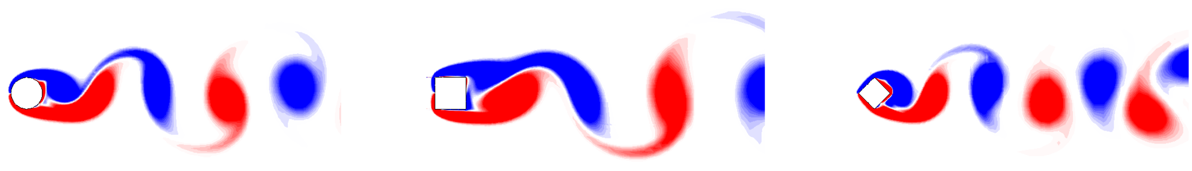
If the structure can vibrate, the behavior of the system becomes far more complex. The simplest model of such a system is that of a rigid, yet elastically-mounted cylinder (with linear springs), that is constrained to oscillate transversely (in the cross-stream direction) only. The spring stiffness k, mechanical damping c, and sprung mass m are introduced as dimensional parameters. Typically (and in this paper) these are formed into the following nondimensional groups: the reduced velocity $U^* = U/f_nD$, the damping ratio $\zeta = c/4\pi f_n$, and the mass ratio $m^* = m/m_f$, where $f_n = sqrt(k/m)/2\pi$ is the natural structural frequency, and m_f is the mass of fluid displaced by the body.

For a circular cylinder, large amplitude oscillations, with the potential to drive a generator, are caused only by the phenomenon of vortex-induced vibration (VIV). Essentially, if the vortex shedding frequency from the cylinder is close to the natural structural frequency f_n, synchronization or lock-in occurs (similar to resonance, but where the vortex shedding frequency can be changed to synchronize to, or close to, f_n, due to the fluid-structure coupling), resulting in resonant, large amplitude oscillations. Experiments have shown amplitudes of oscillation of over $1D$ for $\mathrm{Re} \simeq 10^4$ [1]. Simulations at $\mathrm{Re} = 200$ have found amplitudes of around $0.6D$ [3].

If the body is not circular, a second phenomenon, galloping, becomes possible. Galloping occurs due to the changes in force on the body due to changes in angle of attack. For the system constrained to oscillate transversely, an effective angle of attack is induced by the vector addition of the free stream velocity and the body velocity. If an initial positive displacement (with positive velocity) generates a positive lift force, the system is aeroelastically unstable, and large amplitude, typically low frequency, oscillations can occur. A successful quasistatic theory of such transverse galloping has been developed by [4].

The results presented in this paper are from a series of direct numerical simulations, using a well established spectral element code, investigating both VIV and galloping. The primary focus has been to investigate the impact of the geometry, namely changing the cross-section of the body, to try to identify the passive geometric features that can be used to generate large amplitude oscillations suitable for exploitation for renewable energy.

Three base geometries are presented for comparison; a circular cylinder, a square cylinder presenting a flat side to the oncoming flow (the "square" case) and a square presenting a corner to the oncoming flow (the "diamond" case). When rigidly mounted, all three geometries result in flows with very similar structures, essentially the Kármán vortex street. Examples of these three flows are presented in figure 1.



(a) (b) (c)

Figure 1. Examples of the Kármán vortex street for the (a) circular cylinder, (b) square cylinder, and (c) diamond. $\mathrm{Re} = 200$ for all cases.

However, once the bodies are elastically mounted, their behavior, and the resulting flow, becomes a strong function of the geometry. Here, the response of the circular and diamond cylinder are compared. For both geometries, $\mathrm{Re} = 200$, the mass ratio is low at $m^* = 2$, and the mechanical damping is zero. This leaves the reduced velocity, U^*, as the only independent parameter.

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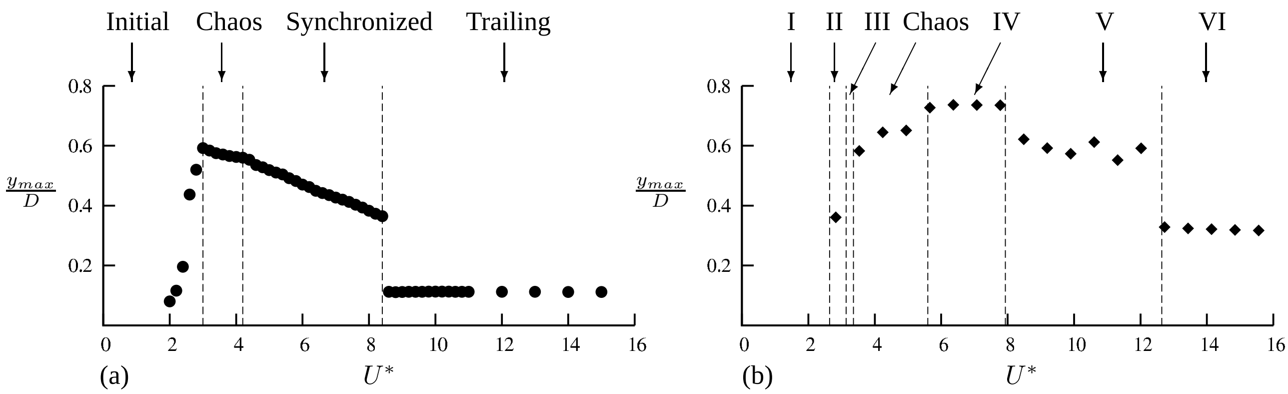

Figure 2. Maximum oscillation amplitudes for (a) the circular cylinder, and (b) the diamond case, as a function of U^*. For both cases, $\mathrm{Re} = 200$, $m^* = 2$, $\zeta = 0$. The vertical dotted lines and annotation at the top of the plot indicate different response regimes, each with unique spatio-temporal symmetries.

Figure 2 shows the maximum amplitude of oscillation for both geometries as a function of U^*. Also marked on these plots are the approximate boundaries of different regimes of response [3, 2]. The most striking feature of these plots is that the diamond geometry produces peak amplitudes of oscillation around 30% greater than the circular cylinder, and the range of U^* over which significant oscillations occur is greater. Both of these findings indicate that energy generation from VIV can be improved using simple, passive geometric features. Also, the number of flow regimes is greater for the diamond, with significant chaotic, quasiperiodic, and subharmonic response regimes present that do not occur for the circular cylinder.

The square cylinder is susceptible to transverse galloping because a small positive displacement with positive velocity results in a positive mean lift force. Galloping typically occurs for high values of U^*, with the amplitude of oscillation increasing with increasing U^*. Preliminary results, and the results of [5], show that even for $\mathrm{Re} = 250$, low frequency periodic oscillations with amplitudes of over $1D$ can be achieved. This alone presents great potential to use galloping for energy generation.

In a similar manner, some cross sections can be unstable to a rotational galloping mode, where a small positive angular displacement results in a positive moment being applied. The square cylinder is not unstable to this mode, however rectangular bodies, longer in the flow direction, are unstable to this mode. Further potential may be harnessed by finding cross sections that are unstable to both of these modes, or cross sections where instability in one mode increases the amplitude of oscillation in the other.

These results show that, for both VIV and galloping, an understanding of the flow structures involved, and their interaction with the geometric features of the body, is critical to developing the most efficient energy generation technologies.

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