FINITE ELEMENT COMPUTATION OF UNSTEADY FLOWS PAST CIRCULAR CYLINDER

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A review of our work on computation of flows past cylinders and their flow induced vibrations is presented. A circular cylinder, mounted on lightly damped springs, is allowed to to vibrate in both in-line and cross-flow directions. The flow is modeled by the incompressible Navier-Stokes equations while the motion of cylinders follows the Newtons laws of motion for rigid bodies. Computations have been carried out for Reynolds number in the range $300 - 10^4$. In most of the cases the trajectory of the cylinder corresponds to a *Lissajous* figure of 8. *Lock-in* is observed for a range of values of the structural frequency (F_s). Over a certain range of F_s, the vortex-shedding frequency of the oscillating cylinder does not match F_s exactly; there is a slight *detuning*. This phenomenon is referred to as *soft-lock-in*. Our computations show that this detuning disappears when the mass of the cylinder is significantly larger than the mass of the surrounding fluid it displaces. It appears that the detuning of the vortex-shedding frequency from the structural frequency is a mechanism of the oscillator to self-limit its vibration amplitude. In certain cases the oscillations of the cylinder result in a change in the vortex shedding mode and sometimes in a competition between the various modes. Figure 1 shows the vorticity field for $Re = 1000, F_s = 0.60$.

Flow past a pair of cylinders in tandem and staggered arrangements is studied for cases when the spacing between the two cylinders is beyond the critical value for proximity interference. The $Re = 100$ flow leads to a very organized wake and large amplitude motion is observed for the downstream cylinder. For the tandem arrangement, the two cylinders move along a figure of 8. However, for the staggered arrangement the trajectory of the rear cylinder resembles a tilted oval. The wake looses its temporal periodicity, beyond a few diameters downstream of the front cylinder, for the $Re = 1000$ flow. The upstream cylinder continues to respond as an isolated single cylinder while the downstream one undergoes slightly more disorganized motion. *Soft-lock-in* is observed in almost all the cases. Figure 2 shows the vorticity field for one of the cases studied.

Next, results for control of flow past a circular cylinder using small rotating cylinders are presented. Several values of the *gap* between the main and control cylinders are considered. When the control cylinders rotate at high rates, such that the tip speed (U_c) is five times the free-stream speed (U), the flow at $Re = 100$ achieves a steady state. At higher Reynolds numbers ($Re = 10^4$), even though the flow remains unsteady, the wake is highly organized and narrower compared to the one without control. A significant reduction in the overall drag coefficient and the unsteady aerodynamic forces acting on the main cylinder is observed. This study brings out the relevance of the *gap* as a design parameter for such flow control devices. Compared to the drag coefficient of 1.4 for a single cylinder, the case with $U_c/U = 5$ and *gap*$= 0.1D$ results in average value of 0.25, approximately. Figure 3 shows the vorticity field for flow past a cylinder with and without control.

Next, results are presented for numerical simulation of three-dimensional unsteady flows past finite cylinders of low aspect ratio. The cylinder end-conditions are specified to model the effect of a wall that may correspond to the flow in a wind tunnel, water channel or a tow-tank experiment with a cylinder having large end-plates. The computations confirm that it is the end conditions for the finite cylinder that determine the mode of vortex shedding (parallel or oblique). The $Re = 100$ and 1000 flows exhibit oblique mode of vortex shedding. The flow for $Re = 100$ is very organized, devoid of any vortex dislocations and is associated with only one cell along the cylinder span. The flow at $Re = 1000$ is interspersed with vortex dislocations and the vortex shedding angle varies, both, temporally and periodically. The presence of vortex dislocations is responsible for the breakdown of spanwise coherence of vortex structures. The arrangement of the streamwise vortex structures resemble the Mode B pattern of vortex shedding. Flow at $Re = 300$ results in flow patterns that correspond to the wake transition regime. Mode A and Mode B patterns of vortex shedding in addition to vortex dislocations are observed at different time instants. Figure 4 shows the z-component of vorticity at the $x - z$ plane for $Re = 1000$ flow at $t = 180$.

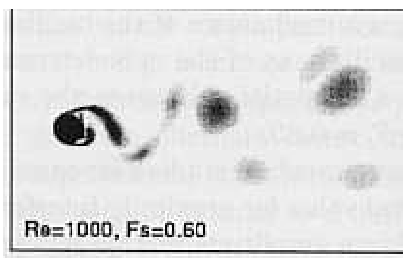

Figure 1: Flow induced vibration of a single cylinder.

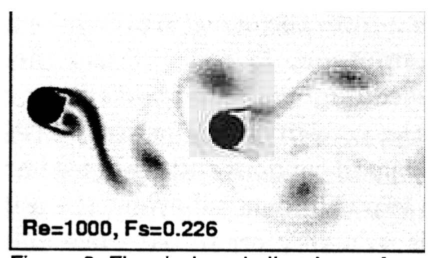

Figure 2: Flow induced vibrations of two cylinders in staggered arrangement.

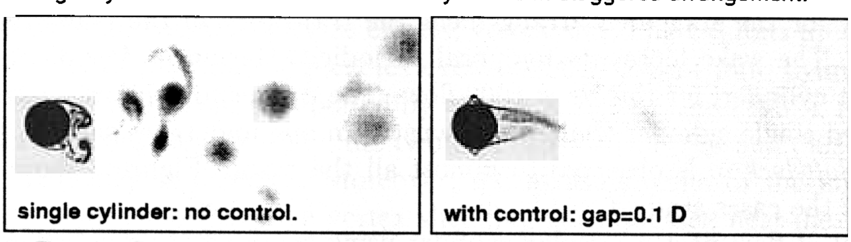

Figure 3: Flow control using rotating control cylinders. Re=1000, Uc/U=5.

Figure 4: 3D flow past a circular cylinder of aspect ratio 16. Top wall is no-slip and