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EFFECTS OF UNSTEADY SEPARATED FLOW PHENOMENA IN VORTEX-INDUCED VIBRATIONS

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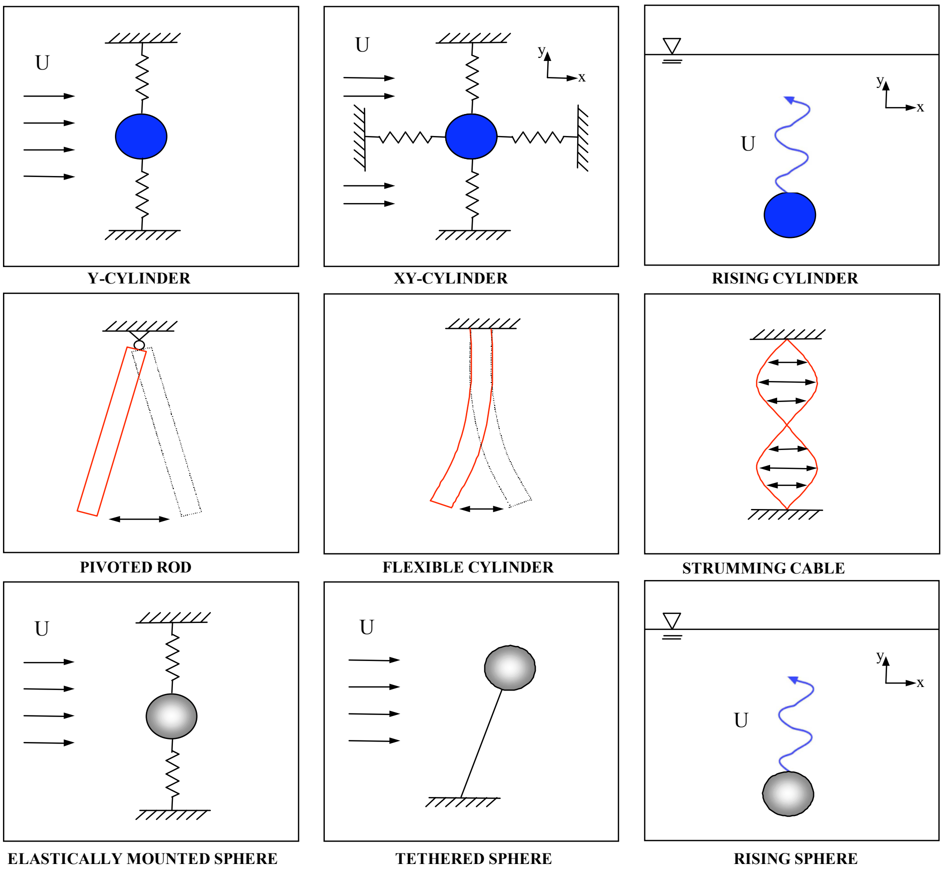
We shall review some of the recent discoveries concerning separated unsteady flows in the problem of vortex-induced vibration (VIV), that have been made over the last few years, many of which are related to the push to very low mass and damping (Williamson & Govardhan, *Annual Review of Fluid Mechanics*, 2004). We pay special attention to the vortex dynamics and energy transfer that give rise to modes of vibration. We present new vortex wake modes (see Figure 1), from several different flow-structure configurations, often in the framework of the Williamson-Roshko (1988) map of vortex modes compiled from forced (controlled) vibration studies.



Y-CYLINDER **XY-CYLINDER** **RISING CYLINDER**

PIVOTED ROD **FLEXIBLE CYLINDER** **STRUMMING CABLE**

ELASTICALLY MOUNTED SPHERE **TETHERED SPHERE** **RISING SPHERE**

Figure 1. Some of the VIV problems we have been studying with a view to finding universal or generic flow and response phenomena, which may occur in all such studies.

For a vibrating cylinder, positive excitation can be generated from the 2P (2 vortex pairs) and 2S (2 single vortices) wake modes, but the P+S mode yields negative excitation, and has therefore not been found experimentally in free vibration. For cylinders which are able to vibrate both in line and transverse to a flow, remarkably large peak amplitudes of around 3 diameters peak-to-peak are possible, if the mass is sufficiently low. This is made possible by energy transfer from a new vortex wake mode comprising vortex triplets; a 2T mode. For pivoted bodies, modes involving co-rotating vortex pairing (distinct from the well-known 2P mode) can yield similarly large amplitude vibration, despite the spanwise variation of vortex structure.

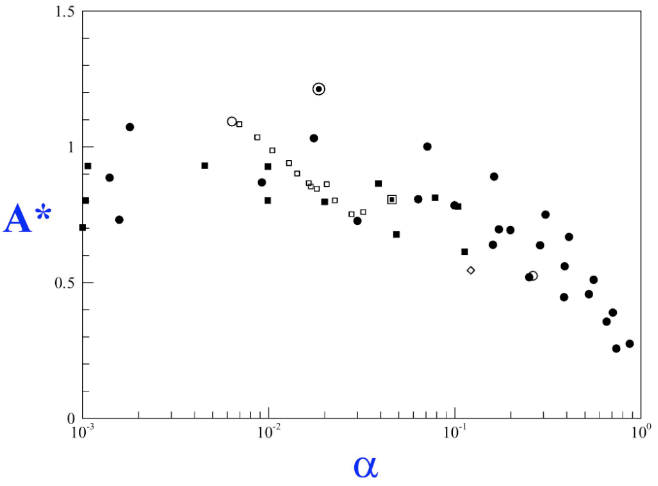
We have discovered, in several VIV problems, a new, and quite surprising, generic phenomenon whereby an elastically mounted body can continue to resonate even as the normalised flow velocity becomes infinitely large, i.e. as the vibration frequency, $f >>$ natural frequency, f_N, which is radically different from classical resonance, where $f \sim f_N$. This is only possible under the conditions where the mass of the structure falls below a special critical value. Corresponding with this result, an unrestrained body will not vibrate at all *unless* the mass is reduced below such a critical value, at which point the large vibrations will appear quite suddenly. We extend this work to the problems of rising and falling bodies - in this case we find that freely rising bodies (spheres and cylinders, for example) will only vibrate, as they rise, if their relative density falls below a special critical value, closely related to the critical mass in our VIV studies. Above the critical mass, bodies simply rise or fall in rectilinear motion, but not always vertically.

We shall shed light on the large unexplained scatter found in the classical Griffin plot (a plot of the peak vibration amplitudes (A^*) versus the product of mass-damping (α) over the last 30 years. We recently demonstrated a distinct trend of increasing peak vibration amplitude as Reynolds number (Re) increases. We also showed that the shape of the Griffin plot at different Re remain similar (Govardhan & Williamson, *Journal of Fluid Mechanics*, 2006), suggesting a form for the peak amplitude as:

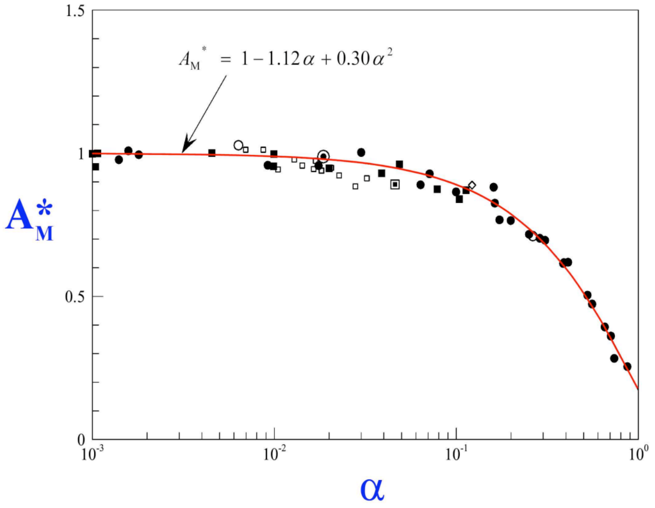
$$A^*_{PEAK} = f\{Re\} \,.\, g\{\alpha\}$$

If we go on to renormalise the axes of the plot to take account of Reynolds numbers in the different studies, then we find a beautiful collapse of peak amplitude data in a "modified" Griffin plot, in place of the large scatter classically presented.

Griffin Plot



“Modified Griffin” Plot



Data collapses onto a single curve !

Figure 2. Collapse of the otherwise scattered peak amplitude data when account is taken of the Reynolds number, in the Griffin plot. The Griffin plot illustrates the relationship of the peak amplitude of response (A*) versus the mass-damping parameter (α). From Govardhan & Williamson, *Journal of Fluid Mechanics*, 2006.

Our work with the rising and falling cylinder, and our work with tethered spheres, have combined to trigger the study of rising and falling spheres. Corresponding with our tethered sphere studies, we have discovered a critical mass of $m^*_{CRIT} \sim 0.60$ above which spheres simply rise to the surface with no vibration (Horowitz & Williamson, to be submitted, *Journal of Fluid Mechanics*, 2007). This contrasts with the known studies of rising and falling spheres, where it has generally been assumed that all rising bodies vibrate, and all falling bodies descend without vibration. The example shown below in Figure 3 is one where the vibration naturally occurs in a vertical plane, which is distinct from another possible mode where the body might rise in a helical trajectory. Our typical trajectories show remarkable periodicity at the low value of mass $m^* = 0.27$ (below critical).

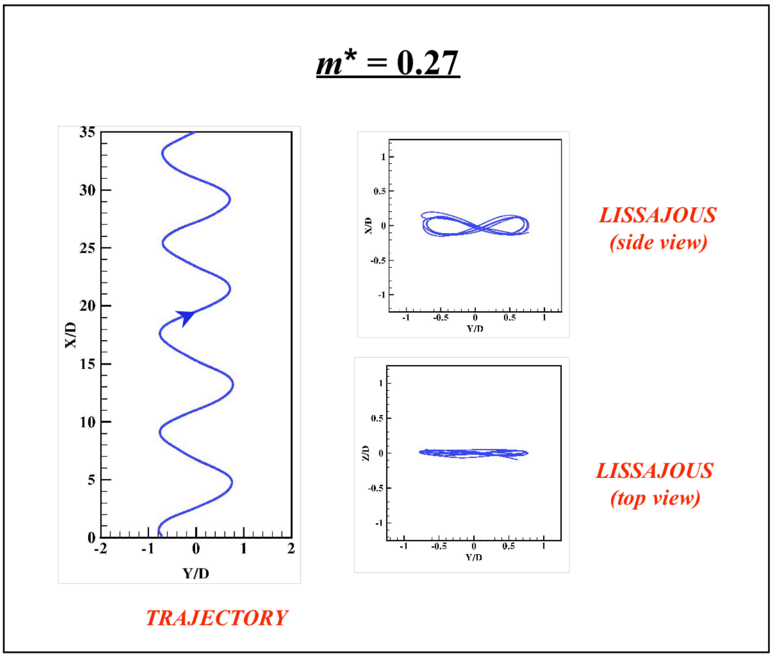


Figure 3. Trajectories for rising spheres, Re = 10,000.

In Figure 4, we demonstrate the double-sided vortex loop formation from a tethered sphere (Govardhan & Williamson, *Journal of Fluid Mechanics*, 2005), which one might expect to be similar to those modes found for a rising sphere. However, we shall show that such vortex formation modes for the rising sphere have a somewhat more complex structure when the body is completely unrestrained.

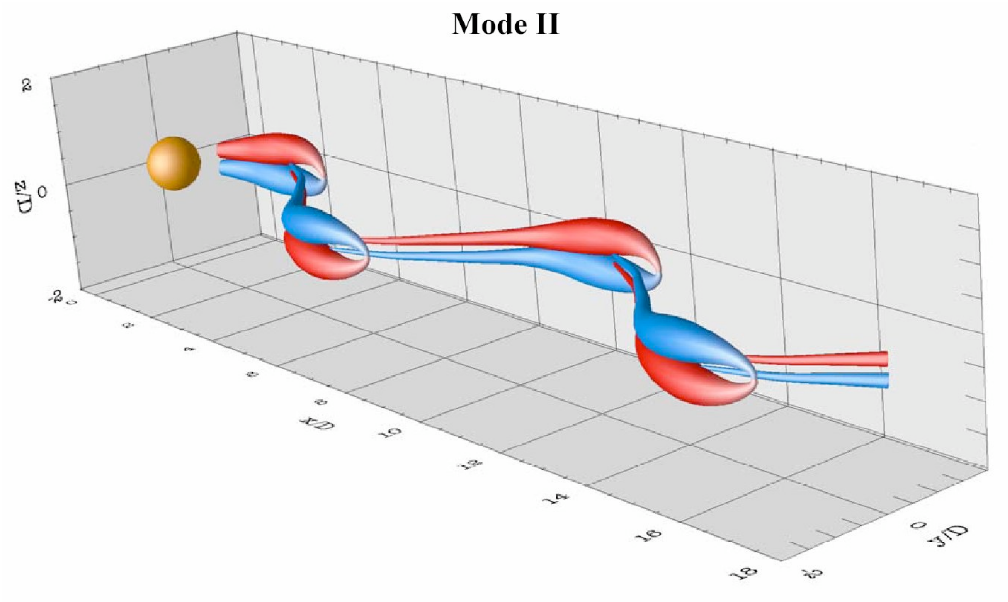


Figure 4. Dominant wake structure behind a tethered sphere - a chain of streamwise vortex loops (and the downstream pinching off of a system of vortex riings).

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