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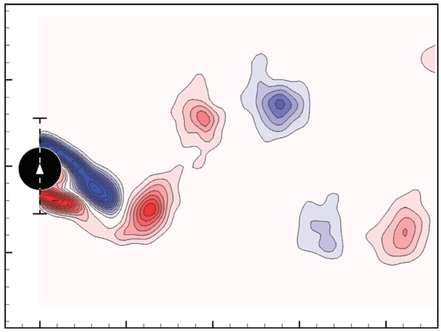
Focus on Fluids

Understanding and predicting vortex-induced vibrations



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Vortex-induced vibration of solid structures has been known since ancient times, and remains a very important problem of fluid mechanics. Experimental studies of the vortex-induced vibration of circular cylinders have provided many fundamental insights. Recent extremely carefully controlled forced vibration experiments by Morse & Williamson (*J. Fluid Mech.*, 2009, this issue, vol. 634, pp. 5–39), generating finely resolved data sets, are providing a fresh understanding of the mechanisms involved, especially for ocean structures with very low mass and damping.

Keywords. Flow-structure interactions, vortex streets, shedding

1. Introduction

Morse & Williamson (2009, this issue, vol. 634, pp. 5–39) have published the results of an extensive experimental study of the forced vibration of a circular cylinder that provides new insights into vortex-induced vibration (VIV). VIV of circular cylinders is a long established field of study and we know that the ancient Greeks used the concept in the design of the Aeolian harp to transform wind energy into musical sounds. In the nineteenth century, the Czech physicist Vincent Strouhal experimented with long slender circular cylinders to explain the singing of overhead telegraph wires and concluded that when the frequency of vortex shedding coincided with the natural frequency of a wire, transverse oscillations developed. Later von Kármán formulated an elegant theory to describe the form of the wake. However, VIV is largely an unwanted phenomenon particularly when it leads to the wind-induced vibration and possible fatigue failure of lightly damped cylindrical structures. Much of the early work on VIV relates to structures in air but as the number of applications in liquids increased, particularly with the development of offshore oil fields, it became clear that serious gaps in understanding were appearing. In addition to damping, an important parameter is the mass ratio, the ratio of the structural mass to the mass of displaced fluid, and for structures in water this is two to three orders of magnitude smaller than that typically found in air. With a smaller mass ratio the interaction between the fluid and the structure can be more pronounced leading to larger amplitudes of vibration over a wider range of flow speeds. Also, for large amplitudes, greater than one diameter, the mode of vortex shedding is not always the same as that described by the von Kármán vortex street model with one vortex of each sign shed per oscillation cycle of the structure.

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As the oil industry moved into deeper and deeper waters, the riser pipes used to transport oil took the form of flexible circular cylinders with aspect ratios of 5000 or more, exposed to varying currents. An exact numerical simulation is presently out of the question, as is a controlled experiment that matches all the key similarity parameters. Such a situation highlights the need for a fuller understanding of the basic mechanisms generating VIV, particularly if the accuracy of response prediction methods is to be improved. In addition to being of great practical importance, VIV raises questions of fundamental interest and the study described by Morse & Williamson (2009), directly addresses this challenge.

2. Overview

As in many other branches of fluid mechanics, an important requirement in VIV research is to simplify the problem to consider only those variables that have a significant effect. In common with a number of other investigators, Morse & Williamson (2009) use a rigid length of circular cylinder mounted on a lightweight carriage constrained to move transverse to a water flow. To study VIV, investigators have either allowed the cylinder to vibrate freely by attaching springs or, as in the present case, forced the cylinder to oscillate. With free vibration, a small increase in flow speed can result in large changes in cylinder oscillation amplitude, possibly accompanied by a change in the mode of vortex shedding. Such jumps, or transitions, are difficult to study under conditions of free vibration. On the other hand, with forced vibration a large number of runs have to be carried out in order to map precisely the conditions under which energy transfers from the fluid to the cylinder. Pioneering VIV research using forced vibration was conducted by Bishop & Hassan (1964) who observed that the fluid behaved like a nonlinear oscillator and that the frequency of vortex shedding could become locked to the frequency of the forced vibration. Other early circular cylinder experiments using forced vibration were conducted by Sarpkaya (1978) and Staubli (1983).

Morse & Williamson (2009) performed 5680 runs in a water flume, varying cylinder amplitude and frequency, at two constant Reynolds numbers, $Re = 4000$ and $12\,000$, taking a total of 2000 hr of running time, made possible by automating the experiment so that it could proceed unattended. They measured the transverse force acting on a cylinder forced to perform sinusoidal motion and present plots of the components in phase and out of phase with this motion. The part in phase with the cylinder velocity, often referred to as the excitation, sustains oscillations if it is positive and the out of phase part acts as an inertia force and influences the oscillation frequency of a freely oscillating cylinder. Using this data bank, and assuming that the flows around a cylinder undergoing free and forced oscillations are identical under otherwise similar conditions, they are able to predict closely the response of freely vibrating cylinders. Similar exercises were undertaken by Sarpkaya (1978), Staubli (1983) and Hover, Techet & Triantafyllou (1998) but due to the much finer amplitude and frequency resolution, the fits to free vibration response data presented by Morse & Williamson (2009) are significantly and convincingly closer.

The predictions of responses in free vibration experiments are interesting but it is equally important to consider what these new data sets can reveal about the flow that accompanies VIV. Figure 1, schematically shows vorticity fields, captured using PIV images, in various regions of A^*: λ^* parameter space, where the amplitude A^* and the wavelength λ^* are normalized by the cylinder diameter. Four modes of vortex shedding are observed: P+S; 2S; 2P and $2P_o$. S refers to a single vortex and P a

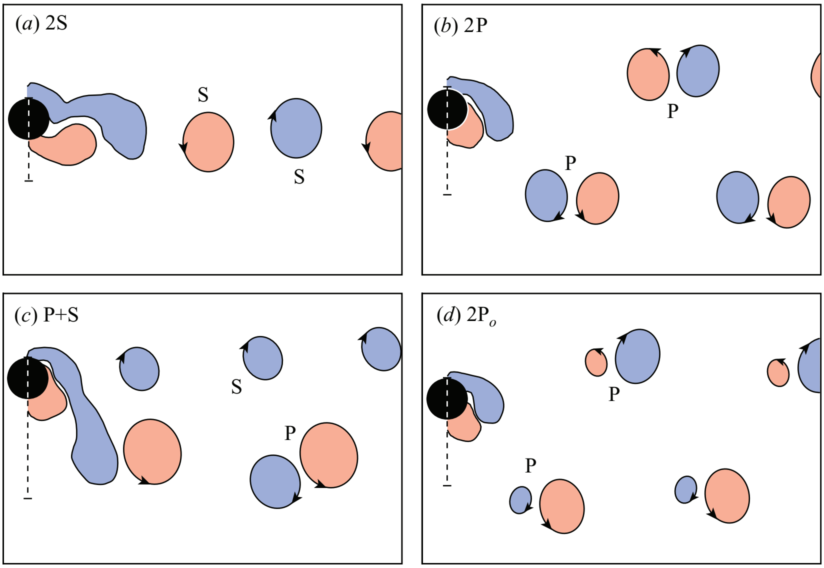

FIGURE 1. Vorticity fields for the vortex shedding modes: P+S, 2S, 2P, 2P$_o$.

counter-rotating vortex pair. 2S is the familiar von Kármán vortex street mode with vortices of opposite sign shed alternately from each side of the cylinder and is the mode found behind stationary cylinders but only in certain regions of $A^*:\lambda^*$ space for oscillating cylinders. The other three modes are only associated with the wakes of oscillating cylinders, and the 2P$_o$ mode is identified for the first time by Morse & Williamson (2009). The 2P mode consists of an arrangement of roughly equal strength vortex pairs whereas the P+S mode has a single vortex shed from one side and a pair shed from the other. The force measurements by Morse and Williamson show that in the P+S mode energy is transferred to the fluid from the cylinder (i.e. the fluid excitation is negative) and hence it would not expect to be found in the wake of a freely vibrating cylinder. The new 2P$_o$ mode is similar to the 2P mode except that the vortices making up the pair are of significantly different strengths. Since it occurs in a region of $A^*:\lambda^*$ where other modes are possible it has been named the 2P overlap mode (2P$_o$). Morse & Williamson (2009) show that the vortex wake modes can switch intermittently and for a freely vibrating cylinder this can result in amplitude changes without the flow speed changing.

With the exception of the 2P$_o$ mode, these vortex wake states have been observed previously by Williamson & Roshko (1988) using flow visualization. Using their force data, Morse & Williamson (2009) are now able to relate these modes to regions of $A^*:\lambda^*$ where the fluid excitation by the forced oscillation is positive, negative or zero. For a circular cylinder with low mass and damping, undergoing VIV, plots of transverse amplitude versus velocity exhibit three main regions, or branches. These branches are commonly referred to as initial, associated with lower velocities, and upper and lower, associated with higher and lower amplitudes respectively. The high-amplitude upper branch is now shown to be associated with the 2P$_o$ vortex mode. Using data from Morse & Williamson (2009) it is now possible to understand how the response switches between the various branches.

3. Future

There have been debates in the literature about whether the flows generated by freely oscillating and forced oscillated cylinders can be the same and questions regarding the importance of flow history and the role of harmonics in the displacement trace of a freely vibrating cylinder have been raised. Also the influence of possible nonlinearities in structural quantities such as stiffness and damping cannot be ruled out. However, Morse & Williamson (2009) have convincingly demonstrated that under carefully controlled conditions there is a very close correspondence between these flows if the parameters are correctly matched. This opens the way for their highly resolved data sets to be used to investigate further the fluid/structure interaction processes that occur during VIV. An obvious direction for future study is to explore further the influence of Reynolds number on the unsteady fluid forces and on the modes of vortex shedding. It should be noted that the data of Morse & Williamson (2009) are for a constant Re whereas in a free vibration experiment it is normal to fix the structural parameters and vary the flow speed, and hence Re. For a freely vibrating cylinder with low mass and damping Re can change appreciably as the flow speed is varied through the range where VIV occurs. In the comparisons presented by Morse & Williamson (2009), it appears that the sensitivity of the vortex shedding modes to changing Re is very small. Does this result hold for all Re?

What other modes of vortex shedding from an oscillating cylinder are waiting to be discovered? In practical situations it is unusual for cylinders only to have flexibility in the cross-flow direction and generally a cylinder is free to vibrate due to vortex shedding in all directions normal to its axis. It responds to vortex shedding in the in-line direction, albeit at a significantly lower amplitude, at roughly half the flow speed for transverse vibration since a fluctuation in drag is produced every time a vortex is shed whereas a fluctuation in the transverse force requires vortices to be shed from both sides of the cylinder. Indeed, a long flexible cylinder such as a riser pipe has many modes of vibration and at a given flow speed it is possible to have simultaneous VIV in the in-line and transverse directions, but with different structural modes excited. Following Morse & Williamson (2009), it should be possible to study this problem although there are now two amplitudes and two wavelengths, as well as a phase angle between the motions.

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