SELF-EXCITED OSCILLATIONS OF VERTICAL AND HORIZONTAL CYLINDERS IN PRESENCE OF A FREE-SURFACE[*]

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MOTIVATION AND AIMS

Practical systems in the area of ocean engineering involve self-excited vibrations of cylindrical structures (cables, risers, platform support components) in presence of a free-surface. The inflow may be approximated as a deep water wave, a steady current, or a combination of them. In addition to the inflow, the orientation of the cylinder with respect to the free-surface, e.g., horizontal versus vertical, will strongly influence the fluid-structure coupling, and thereby the nature of the limit cycle oscillation of the cylinder. These self-excited vibrations are expected to exhibit a number of distinctive features, relative to classical cases of fully-submerged structures in absence of free-surface effects.

The present research programs aim to clarify the physics of this class of flow-structure interactions by simultaneous consideration of: (i) unidirectional and bidirectional oscillations, including the possible types of limit cycle trajectories (orbital, figure-eight); (ii) wholefield representations of the flow structure in terms of patterns of instantaneous and averaged velocity, vorticity, and streamline topology interpreted with the aid of critical point theory; and (iii) either direct measurement or indirect deduction of the corresponding instantaneous forces acting on the cylindrical structure.

APPROACHES

Two basic classes of inflow are considered. A steady current with a nominally quiescent free-surface is generated in a large-scale free-surface water channel. A deep water wave, which has an exponentially decaying amplitude beneath the free-surface, is generated in a wave tank with a paddle that is actively controlled by a force feedback system. Both of these classes of flow systems are custom designed to allow three-dimensional optical access.

The trajectories of the self-excited cylinder motion are determined from a high-sensitivity orthogonal -axis laser system, which allows characterization of, for example, elliptical and figure-eight trajectories of bidirectional oscillations. Several types of unidirectional and bidirectional elastic support systems have been designed to have extremely low damping ratios, thereby allowing values of mass-damping ratios $m^*\zeta$ of the order of 10^{-4} to 10^{-3}. The bidirectional system has circumferentially invariant stiffness and damping.

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Instantaneous, wholefield patterns of vortex formation are acquired during unidirectional and bidirectional oscillations of the cylinder via either one or two synchronized CCD cameras, the latter of which precludes shadow effects during large amplitude oscillations. Both systems acquire images in the cinema mode at a sufficiently sampling rate to allow accurate correlation of quantitative representations of the flow structure with the trajectories of the cylinder oscillation.

INTERACTION OF A DEEP WATER WAVE WITH A VERTICAL, ELASTICALLY-MOUNTED CYLINDER

For the case where a deep-water wave interacts with a vertical cylinder, variations of the Keulegan-Carpenter number KC are achieved by increasing values of wave height at a constant value of wave frequency. The wave frequency is tuned to the natural frequency of the bidirectional system. Depending on the value of KC, sequences of in-line, inclined orbital, and figure-eight motions of the cylinder are excited. The transient (startup) trajectory that eventually leads to the steady-state limit cycle is examined by abrupt activation of the elastic system in a steady-state wave. This development towards the steady-state trajectory occurs in two stages. The first stage involves an elongated spiral in the in-line direction; a limiting amplitude is attained within a few cycles. The second stage of the transient development involves either direct attainment of an in-line limit cycle, or gradual departure, over a large number of cycles, to either an inclined elliptical trajectory, or a figure-eight trajectory. In fact, at a given value of KC, more than one class of steady-state trajectory can be generated. Imaging of the uni- and bidirectional trajectories of the cylinder, in conjunction with the aforementioned dual laser system, leads to definition of the cylinder displacement and velocity as a function of time, and thereby determination of: (i) the relative velocity of the wave motion with respect to the cylinder; and (ii) the phase shift between the wave velocity and the cylinder displacement and velocity. These features are essential for proper interpretation of the vortex shedding throughout a cycle of the cylinder oscillation, and its consequences for the vorticity-based loading of the cylinder.

Wholefield distributions of instantaneous velocity obtained from high-image-density particle image velocimetry are employed to determine patterns of instantaneous and phase-averaged vorticity and streamline topology, which can be visually interpreted with the aid of contours of instantaneous in-line and transverse velocity. In view of the fact that the instantaneous loading of the cylinder is directly related to the time rate change of instantaneous moments of vorticity about the cylinder, representation of the so-called vortex shedding in terms of patterns of vorticity is central to understanding the types of limit cycle trajectories described in the foregoing. These patterns of vorticity are interpreted simultaneously with instantaneous streamline topology, which allows identification and tracking of critical points during the cylinder motion. For the case of purely in-line oscillations of the cylinder, which can exist up to KC = 6, highly organized patterns of vorticity do not exhibit mirrored-symmetry with respect to the plane of symmetry of the cylinder. This means that the forms and phase relationships of the vorticity patterns occur in a fashion that allows the in-line motion to persist to relatively large amplitudes. On the other hand, when the cylinder undergoes self-excited oscillation in a bidirectional, e.g., orbital, trajectory, patterns of elongated vorticity rotate about the periphery of the cylinder, while forming successive rings, the outermost of which decay rapidly. Evaluation of the corresponding instantaneous force vectors is currently underway, taking advantage of the very low system damping to deduce the forces from knowledge of the characteristics of the mechanical system.

SELF-EXCITED OSCILLATIONS OF A HORIZONTAL CYLINDER ADJACENT TO A FREE-SURFACE

Limit cycle oscillations of a horizontal cylinder at and beneath a quiescent free surface are distinctly different from those described in the previous category. The nature of the oscillation is strongly influenced by the nominal elevation of the cylinder beneath the free-surface. The first phase of this program therefore considers the case of a steady inflow with a quiescent free-surface, with eventual extension to an actual deep water wave.

When the cylinder undergoes limit cycle oscillations in the crossflow direction, the nature of the oscillation is dramatically altered when piercing of the free-surface occurs during a very small fraction of the cycle. In such cases, the steady state response takes the form of a modulated trajectory, which can be represented by two distinct branches on the classical plane of amplitude A/D versus reduced velocity V_r. When surface piercing does not occur, but the oscillation occurs in close proximity to the free-surface, the width of the locked-on response on the plane A-D versus V_r is a strong function of the level of nominal submergence beneath the free-surface. It is demonstrated that these types of responses are closely connected to the static stiffness of the elastically-mounted cylinder prior to, and upon cessation, of the oscillation. A further distinguishing feature of this class of oscillations, relative to the classical case of the fully-submerged cylinder, is the occurrence of new types of hysteresis, which can be observed by increasing and decreasing flow velocity and observing the amplitude response. This type of hysteresis is distinctly different from that observed for jumps between response branches of the fully-submerged cylinder system.

Using the same imaging approaches as in the aforementioned investigation, the flow structure at successive stages prior to the onset of fully-evolved limit cycle oscillations is characterized. New modes of vortex shedding are represented by time sequences of vorticity patterns. When the horizontal cylinder is very close to the free-surface, the onset of oscillation involves a single-sided vortex shedding, then for increasing values of nominal submergence beneath the free-surface, the patterns of vorticity, which are originally shed from either side of the cylinder, undergo various rates of attenuation, depending on whether they interact with the free-surface and the degree to which they form counterrotating vortex pairs.

These features of the flow physics are linked to the variation of the oscillation frequency with reduced velocity. When the nominal submergence beneath the free-surface is such that surface piercing does not occur during the oscillation cycle, the oscillation frequency exhibits the classical lock-on to the frequency of the mechanical system. On the other hand, when the nominal submergence falls within a range where even a small degree of surface piercing occurs, such lock-on does not occur, and the form of the frequency versus reduced velocity curve is very similar to that for a fully-submerged oscillating cylinder having very low mass ratio.

LINKS TO MODELS AND SIMULATIONS

Efforts are currently underway to make the foregoing results readily available to colleagues engaged in modeling and numerical simulation of elastic cylinders and structures in presence of a free surface. Links have been established with universities and laboratories in this country and abroad, including the MARNET consortium. In order to facilitate these interactions, a new website www. lehigh.edu/~influid provides overviews of the foregoing investigations, as well as a range of related experiments centered on quantitative imaging.

A particularly promising approach is representation of the coupled flow-structure systems described herein with a low order model. Progress in this direction has already been made in a joint effort with the group of Professor George Karniadakis at Brown University. The first phase involves the case of a stationary cylinder in a deep water wave. This approach is driven by quantitative experimental imaging of the type described in the preceding sections, and is based on a proper orthogonal decomposition (POD) approach formulated by the Brown group. Eigenmodes are extracted from laboratory images. Construction of the low-dimensional model involves use of a penalty method to address the unsteady boundary conditions. Accurate modeling can be achieved with only ten degrees of freedom and, furthermore, such a model is asymptotically stable without use of artificial dissipation. This general approach has substantial promise for simulation of the types of limit cycle oscillations described herein, as well as related classes of flow-structure interaction.