Govardhan, R.; Williamson, C. H. K.

Modes of vortex formation and frequency response of a freely vibrating cylinder. (English)

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The authors study transverse vortex-induced vibrations of an elastically mounted rigid cylinder in a fluid flow. To determine the vorticity field, for the first time in such free-vibration investigation the authors employ the DPIV technique simultaneously with force and displacement measurements. There exist two distinct types of response in such systems, depending on whether one has a high or low combined mass-damping parameter $m^*\zeta$. In the classical high-$m^*\zeta$ case, 'initial' and 'lower' amplitude branches are separated by a discontinuous mode transition, whereas in the case of low $m^*\zeta$, a further high-amplitude 'upper' branch of response appears, and there exist two mode transitions. To understand the existence of more than one mode transition for low $m^*\zeta$, the authors give two distinct formulations of the equation of motion, one of which uses the 'total force' while the other uses the 'vortex force' which is related only to the dynamics of vorticity. The first mode transition involves a jump in 'vortex phase' (between vortex force and displacement), φ_{vortex}, at which point the frequency of oscillation f passes through the natural frequency of the system in the fluid, $f \sim f_{N\text{water}}$. This transition is associated with a jump between $2S \leftrightarrow 2P$ vortex wake modes, and with a corresponding switch in vortex shedding timing. Across the second mode transition, there is a jump in 'total phase', φ_{total}, at which poin $f \sim f_{N\text{vacuum}}$. In this case, there is no jump in φ_{vortex}, since both branches are associated with the $2P$ mode, and therefore there is no switch in timing of shedding, contrary to previous situations. It is noted that for the high-$m^*\zeta$ case, the vibration frequency jumps across both $f_{N\text{water}}$ and $f_{N\text{vacuum}}$, corresponding to the simultaneous jumps in φ_{vortex} and φ_{total}. This causes a switch in the timing of shedding, coincident with the 'total phase' jump, in agreement with previous assumptions. For large mass ratios, $m^* = O(1)$, the vibration frequency for synchronization lies close to the natural frequency ($f^* = f/f_N \approx 1.0$), but as mass is reduced to $m^* = O(1)$, f^* can reach remarkably large values. The authors derive an expression for the frequency of lower-branch vibration, $f^*_{\text{lower}} = \sqrt{\frac{m^*+C_A}{m^*-0.54}}$, which agrees very well with a wide set of experimental data. This frequency equation uncovers the existence of a critical mass ratio, where the frequency f^* becomes large: $m^*_{\text{crit}} = 0.54$. When $m^* < m^*_{\text{crit}}$, the lower branch can never be reached, and it ceases to exist. The upper-branch large-amplitude vibrations persist for all velocities, no matter how high, and the frequency increases indefinitely with flow velocity. Experiments at $m^* < m^*_{\text{crit}}$ show the beginnings of this high-amplitude upper-branch, persisting to the limits of experimental facility, yielding vibration frequencies in excess of 4 times the natural frequency.

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