# VORTEX-INDUCED VIBRATION OF A DIAMOND CYLINDER AT DIFFERENT MASS RATIOS

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*Summary* This paper presents the results of experiments on the dynamic response of a diamond cylinder experiencing vortex-induced vibration at different mass ratios. In contrast to what is seen in the classic circular cylinder geometry, the results here show the mass ratio can suppress the desynchronization region.

## INTRODUCTION

Flow-induced vibration (FIV) of bluff bodies has been intensively studied in the last 40 years because of its engineering applications, such as in offshore structures, civil bridges and buildings, and heat exchanger tubes. FIV has been documented in depth by [1] and [2]. Two typical body oscillators of FIV are vortex-induced vibration (VIV) and galloping. VIV occurs when an elastic or elastically mounted bluff body experiences vortex shedding that exert fluctuating forces on the body. An important phenomenon known as synchronization or "lock-in" can occur in VIV when the oscillating fluid force frequency matches the oscillation frequency of the body, departing from its normal constant Strouhal frequency function trend, $St = f_{St}H/U$, where $f_{St}$ is the vortex shedding frequency of a fixed body, $H$ is the characteristic length, and $U$ is the free-stream velocity. Within the lock-in regime, the body experiences large-amplitude oscillations, or resonance, if the frequencies are close to the natural frequency of the system. Galloping, on the other hand, is a movement-induced excitation, caused by the aerodynamic instability of structures. It is well known that a circular cylinder in a free stream is immune to the galloping instability. However, all non-circular cross-sectional structures are susceptible to galloping. Galloping occurs when the reduced velocity is above a critical value [1]. Oscillations associated with galloping have much larger amplitudes than VIV, but their frequencies are found to be much lower than the vortex shedding frequency.

Extensive work has been undertaken to study the fundamental characteristics of VIV of a circular cylinder. Reviews are presented by [1, 2]. Experiments [3, 4] of a circular cylinder with low mass and damping ratio experiencing VIV have shown that a three-branch amplitude response (termed as "Initial", "Upper" and "Lower" branches) occurs over a range of reduced velocity. The "lock-in" regions extend to significantly higher reduced velocities compared to cases with high mass and damping ratio. Considerable attention has also been given to the galloping instability of square cylinders, typically at an angle of attack of $\alpha = 0°$. In contrast to the above cases, much less research has been conducted into the VIV response of a diamond cylinder (a square cross-sectional cylinder placed at an angle of attack of $\alpha = 45°$ with respect to the free stream). This is perhaps surprising given that in many of the applications mentioned above the incoming flow direction can vary, altering the effective angle of attack.

The present study focuses on the cross-flow VIV response of a smooth rigid diamond cylinder. The governing differential equation of motion of the body is given by

$$m\ddot{y} + c\dot{y} + ky = F_y(t) \tag{1}$$

where $m$ is the mass of the system, $c$ is the structural damping, $k$ is the spring constant, $y$ is the cylinder's transverse displacement and $F_y(t)$ is the transverse lift force on the body.

### Experimental Details

The experiments were conducted in a free-surface recirculating water channel. The test section has dimensions of 4 m in length, 0.6 m in width, and 0.8 m in depth. The free stream velocity can be varied continuously in a range of $0.048 < U < 0.456$ m/s. The cylinder model used had a square cross-sectional shape with a side width of $D = 25$ mm and an immersed length of 620 mm, giving a displaced mass of water fluid of $m_d = 373.2$ g. The cylinder was vertically supported by a low-friction air bearing system that constrained the cylinder to oscillate linearly in the cross-flow direction. The mass ratio of the system, defined as $m^* = m/m_d$, was adjusted in a range of $2.6 \leqslant m^* \leqslant 15$. The stiffness of the system was controlled by a number of extension spring pairs, depending on the system's total mass. The structural damping ratio, defined as $\zeta = c/2\sqrt{k(m + m_A)}$, where $m_A$ is the added mass, was measured to be in a range of $1.31 \times 10^{-3} \leqslant \zeta \leqslant 2.54 \times 10^{-3}$. The amplitude and frequency responses of the cylinder were investigated over a normalized reduced velocity (defined as $U^* = U/(f_{nw}H)$) range of $2 < U^* < 20$, where $f_{nw}$ is the system's natural frequency measured in still water and $H$ is the frontal projected length of the cylinder.

The displacement of the cylinder was measured using a non-contact linear variable differential transformer (LVDT). The lift and drag forces acting on the cylinder were measured simultaneously using a two-component force balance based on strain gauges configured in Wheatstone bridge.

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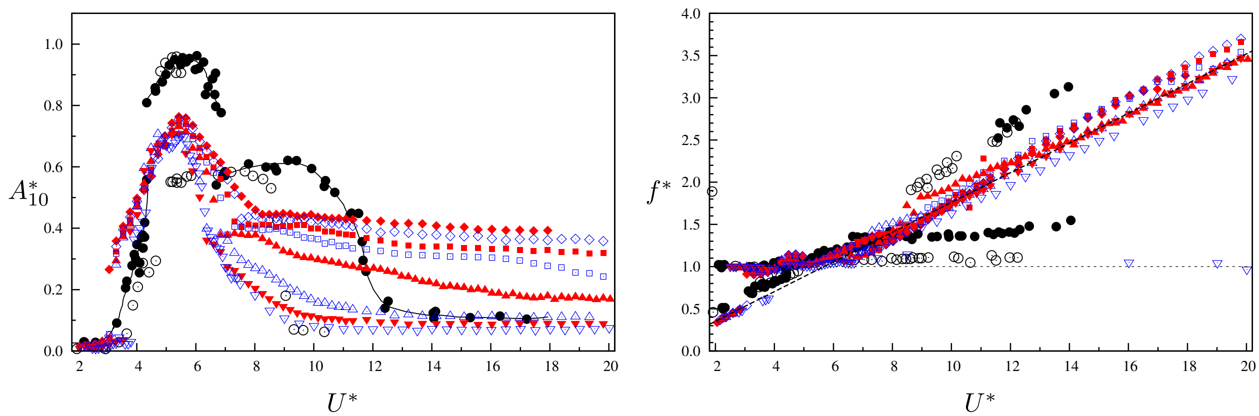


**Figure 1.** VIV response of a diamond cylinder with mass ratio variation: (a) the amplitude response, and (b) the frequency response. Solid diamonds: $m^* = 2.6$; open diamonds: $m^* = 3.0$; solid squares: $m^* = 3.5$; open squares: $m^* = 4.0$; solid up triangles: $m^* = 5.0$; open up triangles: $m^* = 7.5$; solid down triangles:$m^* = 10.0$; open down triangles: $m^* = 15.0$; solid circles: circular cylinder at $m^* = 2.4$ by [3]; open circles: circular cylinder at $m^* = 10.3$ by [3]. Note that the amplitude values of the circular cylinder cases were based the peak values of $A^*_{max} = A_{max}/H$.

## RESULTS AND DISCUSSION

The diamond cylinder results are compared to cases of a circular cylinder at $m^* = 2.4$ and $\zeta = 5.4 \times 10^{-3}$, and $m^* = 10$ and $\zeta = 1.65 \times 10^{-3}$ [3], in Figure 1. In the present analysis, the normalized amplitude, $A^*_{10}$, represents the mean of top $10\%$ amplitude maxima of $A^* = A/H$, and the oscillation frequency is normalized by the system's natural frequency, defined as $f^* = f/f_{nw}$. The amplitude response of the diamond cylinder over the investigated $U^*$ range displays a typical VIV response. Similar to a circular cylinder, its oscillations occur with very small amplitudes at $U^* \approx 2$, with the oscillation frequencies matching the vortex shedding frequency, $f^* = St \approx 0.176$. As $U^*$ approaches 3, the oscillation frequency jumps up close to the natural frequency, $f^* \approx 1$, and the amplitudes gradually increase. The largest amplitudes of the diamond cylinder occur at $U^* \approx 5.5$, where the frequencies are still close to the natural frequencies of the system. The maximum amplitude of $A^*_{10} \approx 0.76$ is found at $m^* = 2.6$, approximately $24\%$ less than that of a circular cylinder with a similar $m^* = 2.4$. As $m^*$ is increased, the maximum amplitude drops down to $A^*_{10} \approx 0.7$ with $m^* = 10$, approximately $30\%$ less than that of a circular cylinder with a similar $m^* = 10.3$. After the maximum amplitude, the amplitudes of the diamond cylinder at $m^* = 2.6$ drops gradually to lower amplitudes of $A^*_{10} \approx 0.43$ at $U^* = 8$, and the oscillation frequencies follow the Strouhal number function trend again at higher $U^*$ values, indicating the end of the synchronization region. This behaviour is different from the upper-to-lower branch transition of a circular cylinder, which has a distinct amplitude jump from $A^* \approx 1$ to $A^* \approx 0.6$ present in its "lock-in" region up to $U^* \approx 12$, followed by the desynchrization region at higher reduced velocities with oscillation amplitudes of $A^* \approx 0.1$ and frequencies following the Strouhal number function trend. As the mass ratio was further increased, the amplitude trends in the desynchronization region of the diamond cylinder were significantly suppressed from $A^* \approx 0.4$ at $m^* = 2.6$ to $A^* \approx 0.07$ at $m^* = 15$. Further, the upper limit of the"lock-in" region is reduced from $U^* = 8$ at $m^* = 2.6$ to $U^* = 7$ at $m^* = 15$, which is narrower than that of a circular cylinder.

## CONCLUSIONS

These experiments show that a diamond cylinder behaves in a typical VIV-response fashion, with no galloping observed, over the reduced velocity range of $2 < U^* < 20$. The maximum amplitude observed was approximately $24\%$ – $30\%$ less than that of a circular cylinder with a similar $m^*$. One possible cause of this is due to the fixed flow separation locations and the sharp afterbody of the body's geometric shape. The mass ratio significantly suppresses the amplitude response in the desynchronization region.

## References


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