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Damping effects on vortex-induced vibration of a circular cylinder and implications for power extraction

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HIGHLIGHTS

- The damping effects on VIV of a circular cylinder were studied experimentally.
- A simple and tuneable eddy-current-based passive damping mechanism was constructed.
- Different VIV response branches of the cylinder are identified at higher damping.
- A fitting is proposed for the peak amplitude data as a function of mass–damping and Re.
- The flow power extraction efficiency of the cylinder is 20% at the highest Re considered.

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ABSTRACT

The effect of damping on vortex-induced vibration (VIV) of a circular cylinder with a fixed mass ratio ($m^* = 3.0$) was studied through water-channel experiments. An eddy-current-based damping mechanism was constructed to provide controlled and adjustable damping values. It consisted of a permanent magnet connected to the cylinder that moves parallel to a copper plate at some predetermined gap, which determines the damping in the system. Increased damping was found to reduce the reduced-velocity range of the upper and lower branches, thus reducing the synchronization region. As the damping is increased, the lower branch remains easy to identify from the amplitude response curves, but the boundary between the initial and upper branch becomes less clear. However, the frequency response under higher damping shows similarities to that at the lowest damping and these similarities, for the first time, were used to delimit the different response branches. The existence of the upper branch was found to continue down to $A^* \approx 0.2D$. The experimental data was assembled to plot the peak amplitude response as a function of the mass–damping parameter in a "Griffin plot". Due to a restricted variation in Reynolds number in the experiments, the measured data shows negligible scatter compared to the assembled literature data. Three sets of experiments using different sets of springs were conducted to quantify the Reynolds number effect previously established by Govardhan and Williamson (2006). An exponential fitting function was then used to successfully fit the data on the Griffin plot. Under higher damping, it was found that the total and vortex phases are no longer at either 0°or 180°, and take intermediate values throughout the response branches. The power extracted by the damping mechanism was also calculated. Maximum power extraction occurs for a combination of optimal damping and reduced velocity. The

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power was also found to increase with Reynolds number, correlated with the increase in vibration amplitude. At the highest Reynolds number examined, the dimensionless energy conversion ratio is 0.2, indicating that approximately 20% of the flow energy approaching the cylinder frontal cross-section can be converted to useful electrical energy. This factor increased substantially with Reynolds number from approximately 15 to 20% over the Reynolds number range considered ($Re \sim 1700$–5900). The fit devised for the peak vibration amplitude was extended for expressing the average extracted power as a function of mass–damping and Reynolds number.

Nomenclature

c	Damping coefficient
C_A	Added mass coefficient of circular cylinder
C_v	Vortex force coefficient
C_y	Lift coefficient
D	Cylinder diameter
f_n	Natural frequency of the system in air
f_N	Natural frequency of the system in fluid
F_v	Vortex force
F_y	Lift force
G	Gap between the magnet and copper plate
k	Spring stiffness
L	Immersed length of the cylinder
m	Total mass of the cylinder-magnet assembly
m_f	Mass of the displaced fluid
m^*	Mass ratio
P	Instantaneous power
$\overline{P}$	Average power
$\overline{P}_{max}$	Maximum average power
Re	Reynolds number
U	Free stream velocity
U^*	Reduced velocity
y	Transverse displacement of the cylinder
$\dot{y}$	Transverse velocity of the cylinder
$\ddot{y}$	Transverse acceleration of the cylinder
μ_m	Magnetic dipole moment of the magnet
ν	Kinematic viscosity of the fluid
ϕ_{total}	Phase difference between lift force and displacement
ϕ_{vortex}	Phase difference between vortex force and displacement
ρ	Fluid density
ζ	Damping ratio

1. Introduction

Vortex-induced vibration may occur when a bluff body, having some degree of freedom, is placed in a fluid stream. Stationary bluff bodies experience vortex shedding above a critical Reynolds number. In this state, vortical structures form at the rear of the bluff body and are typically shed in an alternating fashion. This causes fluctuations in the lift and drag forces experienced by the body. An elastically mounted body can vibrate due to these fluctuating forces, which is known as *vortex-induced vibration* (VIV). Indeed, VIV is encountered in many important situations, for example, marine risers, bridges, transmission lines, buildings, heat exchangers, etc. Often the flexibility of the structure can be modelled as a linear spring for simplicity. Such a simplified model focuses on the resonant vibration of an elastically mounted bluff body with one or two degrees of freedom (DOF) of movement due to the oncoming fluid flow.

Vortex-induced vibration (VIV) of a circular cylinder has been studied extensively by many researchers; for example, see the reviews by Khalak and Williamson (1999), Williamson and Govardhan (2004), Sarpkaya (2004), Gabbai and Benaroya (2005) and Bearman (2011). The focus of many of these studies has been to identify the maximum cylinder response by minimizing the structural damping. This is important because of the possible structural failure that may occur due to large