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A numerical investigation on piezoelectric energy harvesting from Vortex-Induced Vibrations with one and two degrees of freedom

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HIGHLIGHTS

- Energy harvesting from 1-dof and 2-dof VIV.
- Mathematical models for systems.
- In-line oscillations increase the energy harvesting efficiency.

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ABSTRACT

This paper presents numerical investigations into the dynamics of a rigid cylinder, mounted on elastic supports fitted with piezoelectric harvesters and subjected to the Vortex-Induced Vibrations (VIV) phenomenon. Hydrodynamic loads are considered by wake-oscillators models, whereas linear constitutive equations are adopted aiming at coupling the solid and electric oscillators. The main objective is to highlight the influence of an additional structural degree of freedom (namely, in-line oscillations) on the dynamics of the fluid–solid-electric system.

For a particular set of dimensionless parameters that define the harvester circuits, oscillation amplitudes, electric tension and harvested power are obtained for different reduced velocities. Among other findings, the simultaneous presence of in-line and cross-wise oscillations can be emphasized to lead to a marked increase in the maximum energy harvesting efficiency.

In addition to this analysis, a sensitivity study with respect to the influence of the dimensionless quantities that characterize the piezoelectric harvesters is carried out. The study shows that the energy harvesting efficiency can be increased by up to 50% for a particular reduced velocity.

1. Introduction

Flow-induced vibrations phenomena (FIV) cover a comprehensive class of generally non-linear problems that lead to self-excited oscillations. Examples of FIV phenomena include galloping, flutter and vortex-induced vibrations (VIV), the latter being the focus of this contribution. The textbooks written by Blevins (2001), Naudascher and Rockwell (2005) and Païdoussis and de Langre (2011) are examples of surveys on this topic.

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Nomenclature

$\omega_{n,y}$ and $\omega_{n,x}$	Cylinder's natural frequencies
m_s, m_f and m_d	Structural mass, potential added mass and mass of fluid displaced by the cylinder
U_∞	Free-stream velocity
ω_f	Vortex-shedding frequency
D, L	Cylinder diameter and length
ρ	Fluid density
k_y and k_x	Spring stiffnesses
c_y and c_x	Damping constants
R_y and R_x	Electric resistances
$C_{P,y}$ and $C_{P,x}$	Capacitances
θ_y and θ_x	Electro-mechanical coupling constants
t	Dimensional time
Y and X	Dimensional displacements
V_y and V_x	Dimensional electric tensions
V_0	Reference electric tension
q_y and q_x	Wake variables
τ	Dimensionless time
y and x	Dimensionless displacements
v_y and v_x	Dimensionless electric tensions
ϵ_y, A_y, ϵ_x and A_x	Parameters of the wake-oscillator models
m^* and C_a	Mass parameter and potential added mass coefficient
ζ_y and ζ_x	structural damping ratios
U_r	Reduced velocity
St	Strouhal number
$C_{y,v}$, $C_{x,v}$, $C_{L,v}$ and $C_{D,v}$	Force coefficients due to vortex-shedding
$\hat{C}_L^0$ and $\hat{C}_D^0$	Amplitude of the lift and drag coefficients observed for a stationary cylinder
$\overline{C}_D^0$	Mean drag coefficient observed for a stationary cylinder
$\sigma_{1,y}$, $\sigma_{1,x}$, $\sigma_{2,y}$ and $\sigma_{2,x}$	Dimensionless quantities related to the piezoelectric harvesters
$\eta_{el,y}$ and $\eta_{el,x}$	Dimensionless electric power harvested at cross-wise and in-line harvesters

VIV is a very interesting fluid–structure interaction problem commonly found in several engineering applications. Its self-excited and self-limited character has attracted attention from both the industrial and the academic communities in the last decades. Fundamental aspects of flow around cylinders can be found, for example, in the reviews by Bearman (1984, 2011), Parkinson (1989), Williamson and Govardhan (2004), Sarpkaya (1979, 2004). Besides these reviews, a series of investigations have focused on different aspects of the phenomenon has been published since the 1970s. Examples of studies include those related to the cylinder response to oscillatory flows (Sarpkaya, 1977, 1986; Sumer and Fredsøe, 1988), the wake patterns (Williamson and Roshko, 1988; Williamson, 1996), reduced-order modeling approaches (Hartlen and Currie, 1970; Iwan and Blevins, 1974; Skop and Griffin, 1975; Skop and Balasubramanian, 1997) and the dynamics of flexible cylinders (Lyons and Patel, 1986; Hover et al., 1997; Pesce and Fujarra, 2000; Fujarra et al., 2001; Chaplin et al., 2005b, a; Huera-Huarte and Bearman, 2009a, b).

Even though the aspects aforementioned are important, we focus on the fundamental problem of a rigid cylinder mounted on an elastic support free to oscillate only in the cross-wise direction (direction orthogonal to the free-stream velocity). For this condition (herein named 1-dof VIV), it is well known that relevant oscillations (with maximum amplitude close to one diameter D) are observed in the range of reduced velocities $3 < U_r = U_\infty/f_{n,y}D < 12$, being U_∞ the free-stream velocity and $f_{n,y}$ the natural frequency obtained with the cylinder submerged in a still fluid. In this range of reduced velocities, the vortex-shedding frequency f_f is close to $f_{n,y}$ and the lock-in phenomenon is observed.

Experimental results presented in Khalak and Williamson (1999) revealed the existence of distinct response branches depending on the mass-damping parameter $m^*\zeta_y$, where m^* is the mass parameter, defined as the ratio between the oscillating mass and the mass of fluid displaced by the cylinder and ζ_y is the damping ratio. The latter reference also discussed the dependence of the hydrodynamic force coefficients as functions of U_r, as well as distinct vortex-shedding pattern.

Since the early 2000s, focus has also lain on the problem of a rigid cylinder free to oscillate in both in-line (parallel to the free-stream velocity) and cross-wise directions, referred to throughout this paper as 2-dof VIV. As verified, for example, in Jauvtis and Williamson (2004), Stappenbelt and Lalji (2008), Blevins and Coughran (2009), Freire and Meneghini (2010) and Franzini et al. (2012) there are marked differences between 1-dof and 2-dof VIV. Among these differences, we can highlight the dependence of in-line oscillations magnitude with $m^*\zeta$, the increase in cross-wise response due to in-line oscillations and a new vortex-shedding pattern.