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Flapping dynamics of a piezoelectric membrane behind a circular cylinder

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ABSTRACT

The flapping dynamics of a piezoelectric membrane placed behind a circular cylinder, which are closely related to its energy harvesting performance, were extensively studied near the critical regime by varying the distance between the cylinder and the membrane. A total of four configurations were used for the comparative study: the baseline configuration in the absence of the upstream circular cylinder, and three configurations with different distances (S) between the cylinder and the membrane ($S/D=0$, 1, and 2). A polyvinylidene fluoride (PVDF) membrane was configured to flutter at its second mode in these experiments. The Reynolds number based on the membrane's length was 6.35×10^4 to 1.28×10^5, resulting in a full view of membrane dynamics in the subcritical, critical, and postcritical regimes. The membrane shape and the terminal voltage were simultaneously measured with a high-speed camera and an oscilloscope, respectively. The influence of the upstream cylinder on the membrane dynamics was discussed in terms of time-mean electricity, instantaneous variations and power spectra of terminal voltage and membrane shape, fluctuating voltage amplitude, and flapping frequency. The experimental results overwhelmingly demonstrated that the terminal voltage faithfully reflected various unsteady events embedded in the membrane's flapping motion. For all configurations, dependency of the captured electricity on a flow speed beyond the critical status was found to follow the parabolic relationship. In the two configurations in which $S/D=0$ and 1, the extraneously induced excitation by the Kármán vortex street behind the circular cylinder substantially reduced the critical flow speed, giving rise to effective energy capture at a lower flow speed and a relatively high gain in power output. However, in the configuration in which $S/D=2$, the intensified excitation by the Kármán vortex street on the membrane considerably reduced the captured energy. Finally, a transient analysis of the membrane's flapping dynamics in the configuration in which $S/D=0$ was performed in terms of phase-dependent variations of the membrane segment's moving speed, membrane curvature, and terminal voltage; the analysis resulted in a full understanding of the energy harvesting process with consecutive inter transfer of elastic, kinetic, and electric energies.

Abbreviations: CMOS, complementary metal-oxide semiconductor; EIE, extraneously induced excitation; FFT, fast Fourier transformation; MEMS, micro-electro-mechanical system; MIE, movement-induced excitation; PET, polyethylene terephthalate; PVDF, polyvinylidene fluoride

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Nomenclature

B	flexural rigidity $[N \cdot m]$
C	capacitance [F]
D	cylinder diameter [m]
e_{31}	electromechanical coupling factor $[C \cdot \mathrm{m}^{-2}]$
f	frequency [Hz]
f^*	non-dimensional frequency
f_c	Kármán vortex street frequency [Hz]
f_0	flapping frequency [Hz]
h	thickness of membrane [m]
H	span of membrane [m]
H^*	aspect ratio
i_c	current intensity through capacitive source impedance of piezoelectric material [A]
i_R	current intensity through terminal load [A]
i_s	current intensity generated by piezoelectric material [A]
L	length of membrane [m]
m	mass per unit surface $[\mathrm{kg} \cdot \mathrm{m}^{-2}]$
M^*	mass ratio
n	frame number
P	time-averaged electricity power [W]
q	distance between electroactive layer and neutral layer of the membrane [m]
R	terminal load resistance [Ω]
Re_D	Reynolds number based on the diameter of the cylinder
Re_L	Reynolds number based on the membrane's length
s	arc-length of membrane from leading edge [m]
S	distance between cylinder and membrane [m]
t	time [s]
Δt	time interval [s]
U	free-stream flow speed $[m \cdot \mathrm{s}^{-1}]$
U^*	reduced flow speed
V	velocity of membrane $[m \cdot \mathrm{s}^{-1}]$
V_L	terminal voltage [V]
W	cylinder length [m]
x	streamwise coordinate [m]
y	longitudinal coordinate [m]

Greek symbols

ε^*	membrane curvature
ρ_f	fluid density $[\mathrm{kg} \cdot \mathrm{m}^{-3}]$
ρ_s	membrane density $[\mathrm{kg} \cdot \mathrm{m}^{-3}]$
χ^*	piezoelectric coupling coefficient

1. Introduction

The power consumption of micro sensors has been considerably reduced to the order of microwatts (μW) due to the rapid development of state-of-the-art MEMS and CMOS technologies in the past decade (Mitcheson et al., 2008). Compared with conventional batteries, integrating an autonomous power system into a micro sensor by means of an energy-harvesting device is of great significance in terms of environmentally friendly and low-cost maintenance, especially in difficult-to-access ocean environments (Priya, 2007; Sudevalayam and Kulkarni, 2011; Elvin and Erturk, 2013). Among various mechanisms, the harvesting of energy by exciting the flapping motion of a piezoelectric membrane or plate in a fluid flow has gained widespread attention across the fluid-mechanics community (Vatansever et al., 2011; Truitt and Mahmoodi, 2013). Accordingly, insights on the flapping dynamics of the piezoelectric membrane, which are closely associated with energy harvesting performance, are highly desirable.

A literature survey showed that a large number of studies have been made on the energy-harvesting mechanism of a cantilevered flexible plate placed in an undisturbed uniform free-stream flow, which was associated with movement-induced excitation (MIE) (Naudascher and Rockwell, 1994). A cantilevered flexible plate in fluid flow suddenly loses stability and attains an intensified flapping motion when the flow speed increases beyond a critical magnitude; this change is usually attributed to a broken compromise between the destabilizing pressure forces of the fluid and the stabilizing bending stiffness of the plate (Taneda, 1968; Païdoussis, 2004; Eloy et al., 2007, 2008; Tang, 2007). Tang et al. (2009) numerically investigated flapping modes and energy transfer of an MIE mechanism-based flutter mill in an early stage of the postcritical region in which the flow speed was 10% higher than the critical magnitude. The numerical results demonstrated better energy-harvesting feasibility at the second-order flapping mode of the plate due to the absence of the inflection point among the whole flapping process; the piezoelectric polymers flapping at higher modes needed to be particularly segmented to avoid the offset of electrical energy; otherwise, the sections with concave and convex deformations would generate opposite electric potential energies, resulting in reduced electricity output. Subsequently, nonlinear numerical simulations by Doaré and Michelin (2011) and Michelin and Doaré (2013) gave a full spectrum of energy-harvesting efficiency at various parameters, such as tuning ratio, flow velocity, mass ratio, and piezoelectric coupling coefficient, and concluded that the limit-cycle oscillation associated with steady-output current amplitude and frequency was particularly helpful for energy harvest. In addition, a flexible plate in fluid flow exhibited hysteresis behaviors of critical speed with a cyclic increase and decrease in flow speed (Eloy et al., 2008); a stable dynamic state of a flexible plate was reached when the flow speed was beyond the upper critical magnitude (postcritical region) or below the lower one (subcritical region) (Zhang et al., 2000). A changeover of a flapping motion to chaotic behavior was identified when the flow speed was far beyond the postcritical region (Alben and Shelley, 2008; Chen et al., 2014). This chaotic status was not appropriate for energy harvest in terms of the complexity introduced in circuit design. Thus, the intensified flapping motion in the postcritical region would