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Energy harvesting with two parallel pinned piezoelectric membranes in fluid flow

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ABSTRACT

The pinned and clamped configurations of a single piezoelectric membrane placed in free stream flow were extensively compared in terms of energy harvesting performance and spatiotemporal variations in the membrane's displacement and curvature. The results convincingly show a considerable gain in the harvested energy of the pinned membrane due to the broad region with large curvature. The self-adaptive nature of the pinned membrane in response to different flow directions was also demonstrated. A comprehensive study at the reduced flow speed regime $U^* = 22.8$ to 38 was made of two parallel pinned membranes with different cross-flow separation distances ($D/L = 0.6$ to 2.2). The shapes of the two flapping membranes were visualized with a high-speed camera while the synchronous variation of the terminal load's voltage on each membrane was recorded. At small separation distance $0.6 \le D/L \le 0.8$, the membranes flapped with a phase difference of 0.5 π at $U^* = 22.8$ to 28.5; the increase in velocity resulted in a switch to the in-phase flapping mode. At $D/L = 1.0$ to 1.8, the two membranes flapped in the anti-phase mode for the entire velocity region $U^* = 22.8$ to 38.0, along with a considerable gain in the harvested energy over the other coupled modes. The results indicated that a large region ($D/L = 1.0$–1.8, $U^* = 22.8$–38) with the anti-phase coupling in the D/L-U^* plane was suitable for energy harvest. As the separation distance increases further to $2.0 \le D/L \le 2.2$, the membranes flapped at different frequencies. Finally, the influence of the terminal load on the power was determined for the separation distance $D/L = 1.2$; the anti-phase flapping membranes were connected into circuits with reversed electrode arrangements, reaching a peak power $P = 10.31$ mW at the optimal terminal load for $U^* = 36.1$.

1. Introduction

In a wireless sensor network (WSN), a large number of autonomous sensor nodes work collaboratively to monitor various quantities, e.g., mechanical stress for seismic and infrastructure safety, and humidity and temperature for agriculture (Akyildiz et al., 2002; Sirohi and Mahadik, 2011; Yang, 2014). The typical sensor nodes that usually integrate sensing,

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Abbreviations: ; FFT, Fast Fourier transformation; PVDF, Polyvinylidene Fluoride

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Nomenclature

A	Flapping amplitude [m]
B	Flexural rigidity [N·m]
C	Capacitance [F]
D	Cross-flow separation distance of parallel membranes [m]
e_{31}	Electromechanical coupling factor [C·m^{-2}]
f	Flapping frequency of membrane [Hz]
h	Membrane thickness [m]
h_p	PVDF layer thickness [m]
i_s	Source current [A]
I	Effective value of the source current [A]
L	Length of membrane [m]
m	Mass per unit surface [kg·m^{-2}]
M^*	Mass ratio, $M^*=\rho_f L/M$
P	Time-averaged electricity power of terminal load [W]
P_c	Membrane's reactive power [Var]
R	Terminal load resistance [Ω]
R_{12}	Dimensionless correlation coefficient
s	Arc-length of membrane from leading edge [m]
t	Time [s]
Z	Impedance of circuit [Ω]
U	Free-stream flow speed [m·s^{-1}]
U^*	Reduced flow speed, $U^*=LU\sqrt{m/B}$
V_{oc}	Open circuit voltage [V]
W	Span of membrane [m]
X	Streamwise coordinate [m]
X_c	Source impedance of PVDF layer [Ω]
Y	Longitudinal coordinate [m]

Greek symbols

α	Free-stream flow direction [°]
ε	Membrane curvature
ρ_f	Fluid density [kg m^{-3}]
τ	Time lag [s]
ϕ	Phase
$\triangle\phi$	Phase difference

computing, and wireless communication subsystems require reliable and continuous power from 100 μW to 100 mW (Priya and Inman, 2009; Vullers et al., 2010). Compared with conventional batteries, an autonomous power system with an embedded energy-harvesting device would be of great significance in terms of environmental friendliness and low-cost maintenance, especially in difficult-to-access ocean environments (Elvin and Erturk, 2013; Sudevalayam and Kulkarni, 2011). Among various mechanisms, the harvest of ambient fluid energy through the flow-excited fluttering motion of bimorph membranes and its conversion into electrical energy would make a great deal of sense (Truitt and Mahmoodi, 2013; Vatansever et al., 2011).

The flapping motion of a piezoelectric membrane in a fluid flow is a canonical fluid-structure interaction problem that results from an instability of the equilibrium among the flow force, membrane inertia, and flexural rigidity (Piñeirua et al., 2015). Piezoelectric materials subjected to flow-induced mechanical strain would result in the production of electricity on two electrodes (Akaydin et al., 2010b). As one of the foremost piezoelectric materials, polyvinylidene fluoride (PVDF) is flexible in response to wind and ocean flows and sufficiently durable for long-term deployment in WSNs (Hobeck and Inman, 2012). The vortex-induced and self-excited flutter (aeroelastic instability) or flapping motion of a PVDF membrane placed in a uniform flow is normally characterized by a periodic output voltage and relatively high power (Yu and Liu, 2015). A large body of studies (Doaré and Michelin, 2011; Elvin and Erturk, 2013; Tang et al., 2009) have delineated the energy harvesting performance and nonlinear dynamics. Table 1 summarizes the power densities of various PVDF-related configurations. From the viewpoint of practical applications, the power density is calculated as the total harvested power divided by the total harvester volume rather than just by the volume of the piezoelectric layer. The table reveals that the power must be further improved for high-performance sensor nodes. Most of the configurations are characterized by placing a single flexible membrane or plate in the fluid flow while keeping the leading edge clamped and the trailing edge free (Akcabay and Young, 2012; Piñeirua et al., 2015; Tang et al., 2009). Increasing the membrane's chord length gives rise to increase of its mass ratio to the fluid and the reduced flow speed; the membrane thereupon trends to flap from second

Table 1
Parameters of PVDF polymer harvesters.

Configuration	Excitation type	Maximum output (μW)	Energy density (μW cm^{-3})	References
Boundary layer–PVDF	Turbulence-induced	0.055	0.57	(Akaydin et al., 2010b)
Valve-PVDF	Turbulence-induced	93.6	124.40	(Vatansever et al., 2011)
Bluff body–PVDF array	Turbulence-induced	1.4	6.04	(Hobeck and Inman, 2012)
Bluff body–PVDF	Vortex-induced	4	41.67	(Akaydin et al., 2010a)
Bluff body–PVDF	Vortex-induced	193.54	161.28	(Yu and Liu, 2015)
PVDF membrane	Aeroelastic instability	178.16	148.47	
PVDF stalk–plastic leaf	Aeroelastic instability	615	388.01	(Li et al., 2011)
Bluff body–PVDF	Multiple (vortex, aeroelastic instability, and gravity)	10,000	346.73	(Robbins et al., 2006)
PVDF membrane array	Aeroelastic instability	10,310	3306.01	Present study