New nonlinear vibration energy harvesters based on PVDF hybrid uid diaphragm

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Résumé. A low resonance frequency piezoelectric energy harvesting using a hybrid fluid diaphragm (HFD) is presented. This paper describes the design, fabrication and measurement of such device for harvesting energy from environmental vibrations. The HFD consists in an incompressible fluid confined between two thin piezoelectric membranes. The output voltage and power of the PVDF HFD are studied based on experimental and simulation results. Compared with conventional vibration harvester, this proposed solution is very simple and suitable for miniaturization and integration.

1 Introduction

An increasing interest in wireless sensors networks has been growing up over recent years. The implementation of communicating sensors networks in industrial application, transport or buildings offers possible improvements : productivity gains, reliability and energy performance are feasible by the exploitation of the extensive collected information (temperature, humidity, electric consumption ...). With the rapid advancement of low-power wireless sensor nodes and MEMS technology, microscale energy harvesting has attracted worldwide research interests for powering [1]. Vibration-based energy harvesting has been exploited using transduction mechanisms including piezoelectric, electromagnetic and electrostatic [2, 3]. In order to extract the maximum power from the environment, the resonant frequency of a linear harvesting device has to match the dominant frequency of the excitation. Indeed frequencies of ambient available vibration sources are relatively low (normally less than 200 Hz) [4]. As a result, many vibration-based piezoelectric energy harvesters of centimeter scale have been demonstrated to operate at low frequencies [5]. This paper reports the modelling, fabrication and testing of a new piezoelectric fluid-membrane structure for vibration energy harvesting. Compared to classical cantilever architectures, this approach takes advantage of the mechanical stretch of circular diaphragms. However, when miniaturized, they present high resonance frequency [6] and it hinders their direct use. The concept of hybrid fluid diaphragm (HFD) consists in an incompressible fluid confined between two thin piezoelectric membranes, it allows the realization of low resonance frequency membranes. Moreover, Pressure fluctuation harvesting [7] can be especially targeted.

2 Piezoelectric HFD concept

We propose here, an innovative architecture for vibration energy harvesters. Fig.1 describes the geometry as well as the main geometrical parameters of the structure. The incompressible fluid is used as an inertial mass which allows a drastic reduction of the resonance frequency to effectively harvest ambient vibrations. The height of the structure can be easily tunned to provide more or less inertia effect. In a previously published work, the mechanical behavior of a HFD was presented [8]. As an example of the frequency reduction, the use of glycerin as the inertial fluid allowed the resonance frequency of Kapton® ($R = 10$ mm, $H = 10$ mm and $h = 100$ µm) membranes to decrease from 1200 to 180 Hz.

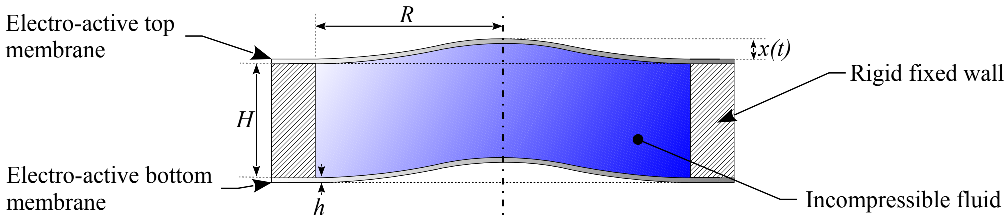

FIGURE 1. Architecture of the piezoelectric HFD

2.1 Theoretical model

A comprehensive theoretical model was proposed in [8]. Based on the Ritz method, approximate solutions for the fluid and the mechanicals diaphragms behaviours are set. This prior model is modified and extended here. Because, the final investigated dynamic behaviour of the HFD in the vicinity of its first resonance frequency is notably lower than the first natural frequency of a single diaphragm, it is thought that a simple static behaviour of the latter can be used for approximating the solution. By doing this, the model is simplified. Moreover, the electromechanical nature of the piezoelectric membranes is added in the model through the usual linear piezoelectric constitutive relations. The modelling strategy is developed using the following assumptions :

- Ideal geometry and homogeneous material properties
- Incompressible and inviscid fluid
- Elastic cylindrical diaphragms are considered
- The prestress effect of the diaphragms is taken into account
- Large amplitude deformation
- The analysis is restricted to axially symmetrical motions
- The analysis is restricted to in-phase motion of the top and bottom diaphragms

As a result, a simple lumped model can be derived presented by the schematic representation in Fig.2 and Eq.1-2. This system is constituted by a moving fluid mass (m_f) tied to a vertical spring ($k + n$) standing for the flexural diaphragm stiffness and two springs (b) standing for the non-linear stretching associated to large amplitude motions. The piezoelectric conversion (α) is associated with the latter (Fig.2a). The diaphragm deformationsinduce a voltage between the diaphragm electrodes. The input force is $m_i\gamma$ with γ the frame acceleration. The damping coefficient (c) embodies all the mechanical losses (the viscous losses within the membrane and the fluid dissipation). The piezoelectric generator behaves as a voltage source whose value is proportional to the product of the diaphragm bending and velocity (Fig.2b).

$$m_f\ddot{x} + c\dot{x} + (k + n)x + 2bx^3 + \alpha\frac{x}{h}V = m_i\gamma \tag{1}$$

$$\alpha\frac{x}{h}\dot{x} - C\dot{V} = I \tag{2}$$

If the displacement is small, the nonlinear behavior effects are minor. Because a single layer of PVDF is used, during a flexural motion, the same amount of PVDF film is compressed and

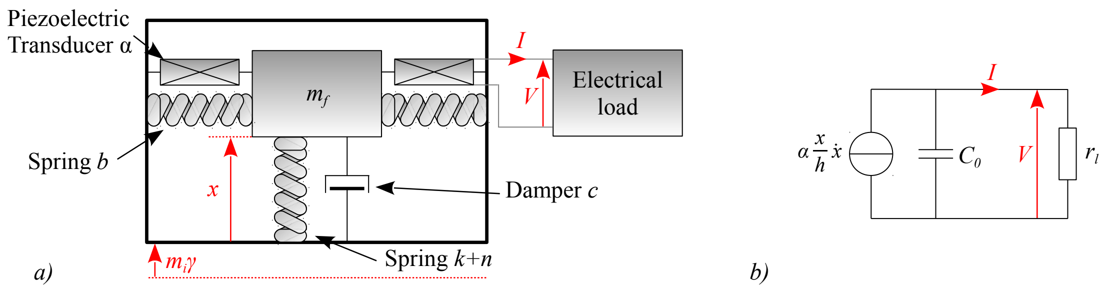

FIGURE 2. Non-linear inertial generator a) mechanical model and b) electrical model

stretched across the thickness so the global generated voltage is zero. From the previous equations, the voltage generation due to large deformation of the membranes is obvious.Is is related to the stretching of the whole section. Table 1 details the lumped parameters, their units and relationship to the geometry and material properties.

TABLE 1. Model Parameters

Parameter	Symbol	Value	Unit
Fluid inertial mass	m_f	See [8] $f(\rho, H, R)$	kg
Fluid excitation mass	m_i	$\frac{1}{3}H\pi\rho R^2$	kg
Flexural stiffness	k	$\frac{-16Eh^3\pi}{9R^2(1-\nu^2)}$	N/m
Large deformation stiffening coefficient	b	$\frac{Eh\pi(-7505-4250\nu+2791\nu^2)}{19845R^2(1-\nu^2)}$	N/m^3
Electromechanical coupling coefficient	α	$\frac{2d_{31}Eh\pi}{3(1-\nu)}$	N/V
Diaphragm capacitance	C	$\varepsilon_{33}\varepsilon_0\frac{\pi R^2}{h}$	F
Prestress flexural stiffness	n	Measured	N/m
Damping	c	Measured	N.m/s^2

2.2 Prototype

A HFD prototype has been realized aiming at the validation of the proposed model. Fig.3a introduces a section of the HFD design. Fig.3b shows the prototype realized in PVC. The first step for the assembly procedure is the clamping of the cylinders to obtain two equal halves of the final HFD. This operation is realized without fluid. When tightening, the membranes are stretched over a low shoulder to get a flat surface producing mechanical prestress (coefficient n in Eq.1). The next step is to put the two half-HFDs together plunged in a fluid to get a fluid-filled HFD without bubbles to ensure incompressibility of the cavity. The tightness between the half-HFDs is assured by a seal that can be seen in Fig.3a. It is also possible to adjust the internal pressure, and consequently the flatness of the diaphragms, with a small tuning screw on one half-body (Fig.3b). The film used to make the diaphragms was home-made from a solution of Poly(VinyliDeneFluoride-co-TriFluoroEthylen) also noted as P(VDF-TrFE). It is a copolymer with 70 % of VDF and 30 % of TrFE with piezoelectric property. The mechanical and piezoelectric properties of the fabricated films are similar to industrial ones. The main advantage of this choice is the tailor-made structures. The thickness h of the films is 80 µm with variations of some microns. For the fluid, we used glycerin for its high density.

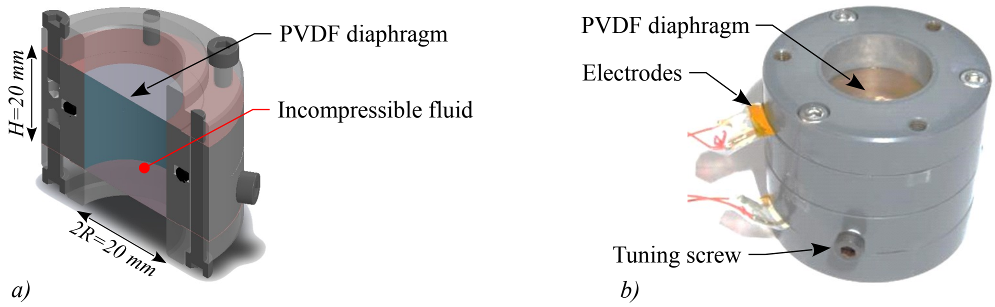

Figure 3. HFD a) design and b) prototype

3 Experimental and theoretical results

The piezoelectric HFD was tested on an electro-dynamic shaker driven with a slow varying increasing frequency sweep from 80 Hz up to 140 Hz. The first resonance frequency of the system is 119.6 Hz. Using an accelerometer and a dedicated control unit, the shaker is driven using a closed-loop control to ensure constant acceleration amplitude throughout the frequency range. The displacement and the velocity of the top diaphragm center are measured using a differential laser vibrometer. In parallel, the control unit drives a set of electrical load resistances (r_l). The generated power can be rigorously assessed varying the load between 0.8 MΩ and 14 MΩ. Several tests were performed for different acceleration levels (around 40 m/s^2) allowing the nonlinear behavior to be triggered.

3.1 Temporal results

The model highlights a frequency doubling voltage, which is clearly visible comparing Fig.4a (displacement of the diaphragm center at 119.6 Hz) and Fig.4b (voltage). Two dominant harmonics are shown performing the Fourier transform of the voltage signal (Fig.4c). The first is at the excitation frequency and the second is about the double (224.2 Hz). This first frequency shows the voltage produced by the membrane bending and the second from the nonlinear behavior. This observation highlight a non-homogeneity in the membranes thickness,which was not taken into account in the model.

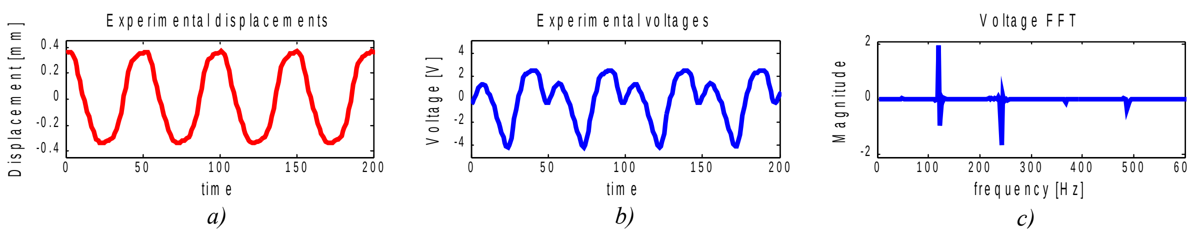

Figure 4. Experimental results a) displacements, b) voltages during the time for 119 Hz at 40 m/s^2 and c) voltage Fourier transform of the voltage signal

3.2 Experimental results and simulation comparison

Experiments using frequency sweep and various load resistances have been performed and the results (red grid in Fig.5) are compared to simulation results (color scale). Fig.5a shows the displacements with respect to the excitation frequencies and load resistances. The nonlinear effects associated with large displacement are very marked. The electric conversion has a negligible impact on the displacement, reflecting a weak electromechanical coupling.

The displacement amplitude at resonance frequency is 376 μm. Fig.5b shows the power, whose maximum is about 4.18 μW at the resonance frequency and for a load resistance of 2.88 MΩ. However the mechanical stiffening effect allows to have a high bandwidth, about 41.58 Hz. The simulations show a good correlation with the experimental results near the peak of power, however for other results furthest from the peak, we find the voltage error induced by the suspected membrane inhomogeneity.

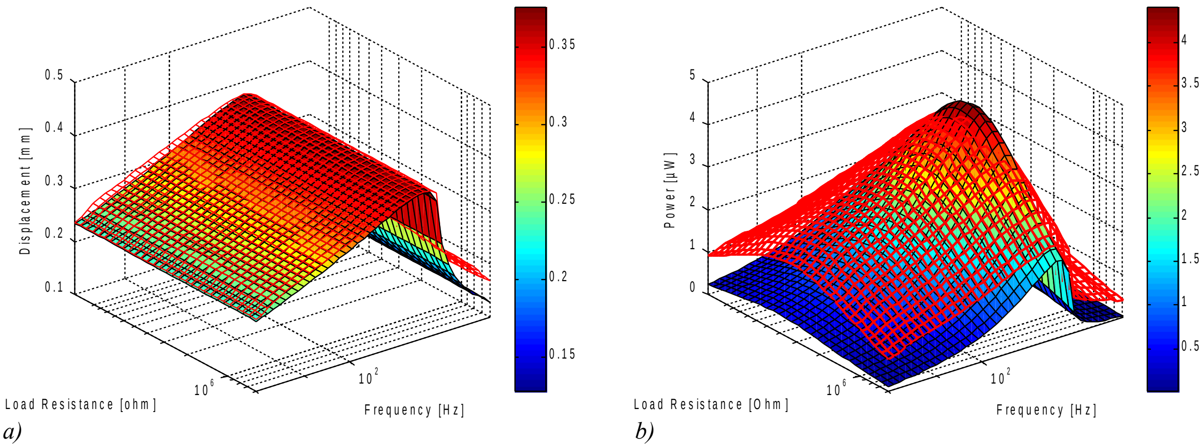

FIGURE 5. Experimental and simulation results comparison, a) displacements and b) power

4 Conclusion

A complete model of a piezoelectric inertial generator has been developed and a prototype realized. Simulation results showed that the voltage from the flexural mechanical effect is not negligible when the PVDF film is not perfect, but in the immediate area of the maximum power, the model is rather predictive and it correlates well. The generator performances are low but it has a very wide bandwidth and the first resonance frequency is about 100 Hz. Now the model can be used as a design tools to aim at a set requirements from a given applications. A future approach is to double the improved PVDF films. By reversing the polarity, this will fully exploit the voltage from the diaphragms flexion allowing performance gain.

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