New linear vibration energy harvesters based on bimorph PVDF hybrid fluid diaphragm

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***Abstract*—A low resonance frequency piezoelectric energy harvesting using a hybrid fluid diaphragm (HFD) is presented. This paper describes the design, fabrication and characterization of such a device for harvesting energy from 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. This device resonates at about 100 Hz for low acceleration (10 m/s²). The simulations showed the power production of about 10 µW.**

***Keywords*—Energy harvesting; Vibration; Piezoelectric; Membrane; Fluid-structure.**

I. 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, energy harvesting has attracted worldwide research interests [1]. Vibration-based energy harvesting has been exploited using transduction mechanisms including piezoelectric, electromagnetic and electrostatic [2]. 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) [3]. As a result, many vibration-based piezoelectric energy harvesters of centimeter scale have been demonstrated to operate at low frequencies. 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 strain of circular diaphragms. However, when miniaturized, they present high resonance frequency [4] 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 system as the fluid is used as an inerttial mass. Moreover, pressure fluctuation harvesting [5] can be especially targeted.

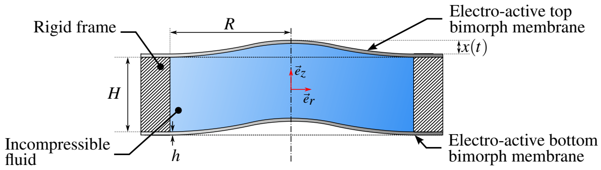

Figure 1: Architecture of the piezoelectric HFD

II. Inertial piezoelectric HFD generator

A. Architecture

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. The height of the structure can be easily tunned to more or less inertia effect. In a previously published work, the mechanical behavior of a HFD was presented [6]. As an example of the frequency reduction, the use of glycerin allowed the resonance frequency of Kapton® membranes ($R = 10$ mm, $H = 20$ mm and $h = 100$ µm) to decrease from 1200 to 180 Hz.

B. Theoretical model

A comprehensive theoretical model was proposed in [6]. 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. 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:

- Incompressible and inviscid fluid
- Elastic cylindrical diaphragms are considered
- The diaphragm prestress is taken into account
- Axially symmetrical motions
- In-phase motion of the top and bottom diaphragms

As a result, a simple lumped model can be derived and presented by the schematic representation in Fig.2 and Eq.1-2. It consists in 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 stretching associated to large amplitude motions. The piezoelectric conversion (β) is associated with the flexural stiffness. The diaphragm deformations induce a voltage between the diaphragm electrodes. The input force

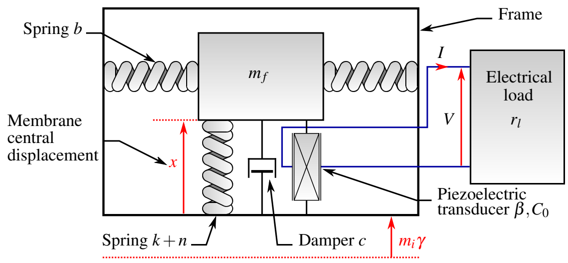

Figure 2: Linear inertial generator electro mechanical model

is $m_i\gamma$ with γ the frame acceleration. The damping coefficient (c) embodies all the mechanical losses (the losses within the membrane material and the fluid dissipation). The piezoelectric generator behaves as a voltage source whose value. $\beta\dot{x}$ is parallel to a capacitance (C_0) induced by the piezoelectric element.

In the case of small displacement, the non-linear behavior effects are minor and the non-linear stretching (b) can be neglected. If a single layer of PVDF (monomorph) is used, during a flexural motion, the same amount of PVDF film is compressed and stretched across the thickness so the global generated voltage is zero. To extract energy in linear behavior, a double layers of PVDF (bimorph) is to be used.

$$m_f\ddot{x} + c\dot{x} + (k+n)x + bx^3 + \beta V = m_i\gamma \quad (1)$$

$$\beta\dot{x} - C_0\dot{V} = I \quad (2)$$

C. Prototype

A HFD prototype has been realized aiming at the validation of the proposed model (Fig.3a). 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 ensure flat surfaces producing mechanical prestress (coefficient n in Eq.1). The next step is to put the two half-HFDs together immersed in a fluid to get a fluid-filled HFD without bubbles to ensure incompressibility. The tightness between the half-HFDs is assured by a o-ring. It is also possible to adjust the internal pressure, and consequently the flatness of the diaphragms, with a small tuning screw.

For this type of generator, P(VDF-TrFE) has been used for the membranes. This material is more flexible than a conventional PVDF and has similar piezoelectric properties. The electrodes geometry are complex (Fig.3b). During flexural motion, there is the same amount of piezoelectric material compressed and stretched in the thickness and in the radius, while the voltage is zero. So to extract energy, it is necessary to include an electrode on the neutral surface deformation splitting. Consequently, a membrane is composed of electro-active films with a common central electrode. The films are assembled with their polarity reversed. For differentiating the compression and the stretching on the radius, two areas have been delimitated, a disk and a ring . The model showed that the optimum radius of central electrode is $r_1 = R\sqrt{1/3}$, and the inner radius of the external electrode is $r_2 = R\sqrt{2/3}$. With these dimensions, the electrode surfaces are identical resulting in a same capacitance.

Table I: HFD model properties

Geometrical properties		Material properties	
R	10 mm	E_{PVDF}	1 GPa
H	40 mm	ρ_{fluid}	1260 kg/m^3
h	125 µm	d_{31}	−5 pC/N

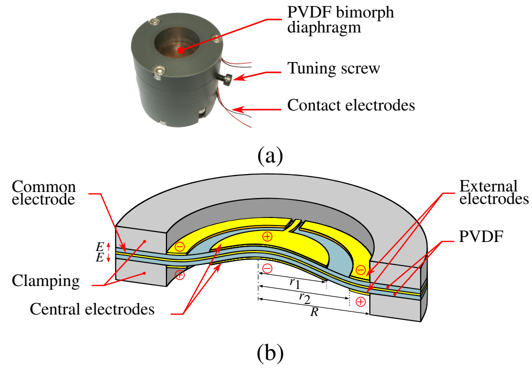

Figure 3: (a) Diaphragm structure and (b) HFD prototype

III. Results

The first results of simulation show that the generator (with geometrical and material from Table.I) will have to resonate at 89 Hz for 10 m/s^2. The power delivered by the generator is 4.5 µW for a load resistance of 11 MΩ by membrane, so about 10 µW for the device. An Experimental approach is in progress to validate the results

IV. Conclusion

A complete model of a piezoelectric inertial generator has been developed and a prototype realized. The preliminary results show low performance, but the device resonates near 100 Hz for a low acceleration (10 m/s^2). Experimentation will validate the model, can be used as a design tools to aim at a set requirements from a given applications. With a market extraction and storage energy circuit adapted, it is possible to improve the performance and allow the power entry of a node sensor.

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