Hybrid fluid diaphragm structures for vibration energy harvesting applications

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***Abstract*—**This paper deals with the design of a compact, generic membrane structure suitable for vibration energy harvesting (VEH). A hybrid fluid diaphragm architecture is proposed. It allows the resonant frequency to match the classical low frequencies ambient excitations to be harvested. A semi analytical model has been developed and validated so the proposed structure can be easily tuned for a given application. The next step will consist in designing a piezoelectric structure which will be integrated to the HFD.

Keywords—Vibration energy harvesting, membrane, fluid-structure

I. INTRODUCTION

Diaphragm geometries are interesting structures for VEH. Numerous sensors are based on diaphragms. Moreover, they are advantageous for in vivo energy harvesting applications [1]. The VEH from air flow streams usually uses membrane structures [2].

However, most of the proposed membrane energy harvesters present high resonance frequencies which prevent these systems to be used in common applications [3]. Indeed, the later show frequencies lower than a few hundred hertz whereas the membrane geometry generally induces high resonance frequency. We propose here a new concept of a hybrid fluid diaphragm (HFD). It consists in an incompressible fluid confined between two thin membranes. This architecture aims to be easily manufactured with standard microelectronics methods.

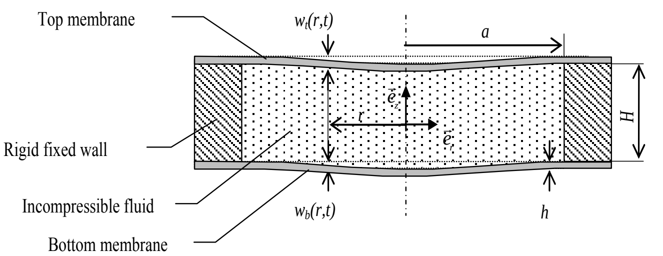

Figure 1: Hybrid fluid diaphragm schematic

Figure 1 described its main features as well as its geometric parameters. The inertia effect of the fluid allows obtaining operation frequencies significantly lower than for a single membrane. Moreover, in addition to the membrane mechanical parameters (geometrical and material properties) the fluid characteristics (height of the cavity, density) can be used as design parameters for optimization.

Fluid structure interaction problems are extensively studied in engineering. The particular case of two circular plates vibrating in contact with fluid has recently been studied by Jeong [4]. Weak solutions can be found for these problems [5]. The accuracy of the solution is related to the number of function used for approximation. As an example, the solution is sought using Bessel decomposition in [4]. In the present application, only the first in phase mode (IPM) also called the piston mode is of interest and a reduced simple model can be deduced. In addition, the filling of the container can be performed at a given pressure which induces static deformations of the membranes. For thin membranes this prestress is associated to tension effect and raises the natural frequencies. This can be seen as an additional control parameter for frequency tuning.

In this paper, a simple fluid structure model is proposed. The model is compared to experimental results for which the static prestress effects due to the fluid filling process have been taken into account. Finally a piezoelectric structure to be added to the HFD is presented.

II. MODELLING

A. Fluid model

The modeling of the fluid structure problem is based on potential fluid flow theory. The filling fluid is assumed to be an incompressible and inviscid liquid. With the liquid motion assumed to be irrotational, the fluid velocity is defined as: $\vec{U} = \vec{\nabla}\phi(r,z,t)$ in which $\Phi(r, z, t)$ is the velocity potential. At the side wall, the velocity of the fluid is parallel to the wall and at the bottom and the top of the cavity, the fluid velocity matches the diaphragm's one.

B. Diaphragm model

Elastic cylindrical diaphragms are considered here and prestress from static deformations of the diaphragms are taken into account. Moreover, we consider large amplitude vibrations of the mechanical structures. The main assumptions used for the modeling of the membrane are the following:

- Membranes are submitted to mechanical solicitations such as their strains are axisymmetric only.
- Plane stress is considered (shear stress is neglected).
- Rotational kinetic energy is neglected.
- The midplane displacements are in the *z* direction and denoted $w_b(r,t)$ for the bottom and $w_t(r,t)$ for the top diaphragms (see Fig. 1).
- Top and bottom membranes are supposed to be identical.
- The diaphragm is clamped at the wall.

C. *Fluid structure model*

A Ritz method is used to find approximated solutions to the coupled fluid-structure problem. Provided that the spectral basis is limited to the first mode, this approach gives an analytical model of the nonlinear fluid coupled dynamical behavior. In the case of one single mode, and assuming small deflection, the first IPM frequency of the HFD was calculated as (1), where :

$$f = \frac{1}{2\pi}\sqrt{(k_1 + n_1) / (m_1 + m_{fluid})} \qquad (1)$$

In which k_1 and m_1 are the generalized mechanical stiffness and mass respectively. Eq. (1) underlines the inertia effect of the fluid m_{fluid} is a function of its density, the height and diameter of the cavity. The prestress (n_1) increases the effective stiffness.

III. Model Validation

Experimental validation was performed. Prototypes of HFD were made from a 25 µm thickness Kapton® film glued on a rigid aluminum frame. The cavity was filled with water and sealed. The aluminum frame is 9.2 mm height. Two cavities diameters were tested (7 and 8 mm). The HFD can be clearly seen on the picture of the experimental mockup given in Fig. 2. The HFD is excited by an electrodynamical shaker and the displacement of the top membrane is measured using an embedded laser optical sensor.

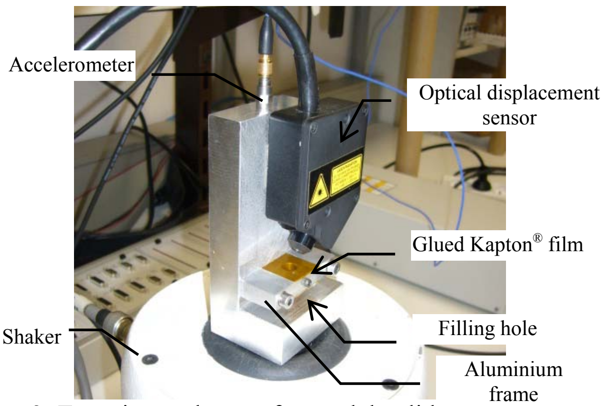

Figure 2: Experimental setup for model validation

The experimental identified resonance frequencies values are reported in Table 1. The fluid inertia effect is very important and allows the natural frequencies to dramatically lessen by a factor of about 10. As expected, the frequencies decreases when the HFD diameters is larger.

Though high quality factor of the HFD was not sought, these tests exhibited pretty sharp resonance peaks, which is favorable for vibration energy harvesting purpose. With optimized assembling process, the quality factor is expected to increase.

diaphragm	diameter (mm)	Natural frequency (kHz)	Mech. quality factor Q
	7.32	6.47	≈ 50
HFD	exp. freq. (Hz)	theo. freq. (Hz)	Discrepancy (%)
	1000	702	29
diaphragm	diameter (mm)	Natural frequency (kHz)	Mech. quality factor Q
	8	4.63	≈ 30
HFD	exp. freq. (Hz)	theo. freq. (Hz)	Discrepancy (%)
	421	495	17.6

Table 1: experimental vs. theoretical results

IV. Conclusions and Perspectives

A HFD concept suitable for micro fabrications techniques has been proposed. Based on fluid-structure interaction, a comprehensive model was proposed and validated. It is able to predict the important frequency characteristics for the first IPM relevant for VEH applications. Experimental prototypes have been obtained and tested. First results are in accordance with the model predictions. Based on this structure, electromechanical conversion will be integrated.

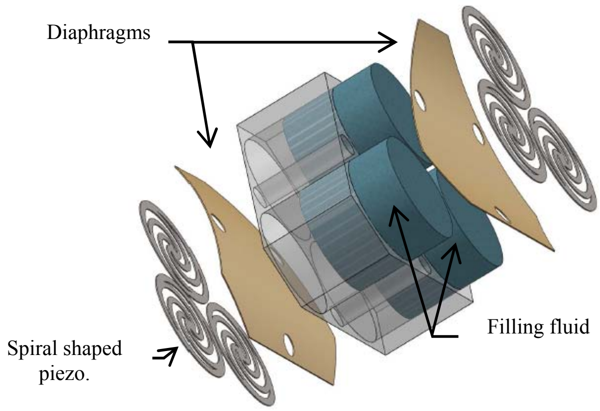

Figure 3: Array of HFD generators

Preliminary designs of spiral shaped piezoelectric material to be glued on the membranes are identified as potential favorable geometries. Figure 3 presents the concept of HFD generators clusters which would be obtained through batch-process fabrication.

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