Microfabrication of hybrid fluid membrane for microengines

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Abstract. This paper describes the microfabrication and dynamic characterization of thick membranes providing a technological solution for microengines. The studied membranes are called hybrid fluid-membrane (HFM) and consist of two thin membranes that encapsulate an incompressible fluid. This work details the microelectromechanical system (MEMS) scalable fabrication and characterization of HFMs. The membranes are composite structures based on Silicon spiral springs embedded in a polymer (RTV silicone). The anodic bonding of multiple stacks of Si/glass structures, the fluid filling and the sealing have been demonstrated. Various HFMs were successfully fabricated and their dynamic characterization demonstrates the agreement between experimental and theoretical results.

1. Introduction

Microengines based on the pistons mostly suffer from friction losses and leaks due to the cylinder-piston gap which is detrimental to the engine operation [1]. Therefore, membranes are preferred when microminiaturizing. However their natural frequency is a critical aspect for optimization, since low values matching the characteristics times of the micromachine cycle are required [2]. In this paper, we propose and demonstrate an alternative solution to the piston, which is called a Hybrid Fluidic Membrane (HFM), to provide a technological solution for low frequency microengines.

1.1 Geometry description

The architecture of the HFM is based on the work of [3], which demonstrates the possible use of fluid-membrane interaction to achieve membranes with a low resonance frequency. It consists in an incompressible fluid confined between two thin membranes. The incompressible fluid is used as an inertial mass which allows a drastic reduction of the resonance frequency to match dynamic requirements of microengines. The height of the structure can be easily tuned to provide more or less inertia effect. Additionally, a spiral spring can be added to the membrane, thus allowing stiffness control. This additional structure is also used to aim at an optimized flexural shape to increase the swept volume. One other advantage of this architecture is the uncoupling between stiffness and sealing. The latter can be achieved using soft material such as RTV silicone. The chosen fluid has to fulfil the trade-off between high density to enhance the fluid inertia effect and low viscosity to limit the mechanical dissipations. Figure 1a describes the HFM geometry as well as its geometrical parameters.
The 5 mm (= 2R) diameter spiral spring geometry is shown in Figure 1b. It consists in four intertwined logarithmic spiral shapes defining two planar springs. It is worth noting that their width vary proportionally with the spiral angle to aim at uniform stress distribution along the structure. A rigid 2 mm diameter central disk increases the swept volume compared to a simple plane membrane.

Table 1. Geometrical and material parameters.

| Geometry       | Fluid      | Frame          |
|----------------|------------|----------------|
| $h = 200 \mu m$ | Vaseline   | $1.6 \text{ mm} < H < 6 \text{ mm}$ |
| $R_{cd} = 1 \text{ mm}$ | Glycerine | $R = 2.5 \text{ mm}$ |
| $E = 1.5 \text{ MPa}$ | $\rho_f = 800 \text{ kg/m}^3$ |               |
| $\nu = 0.49$ | $\rho_m = 1100 \text{ kg/m}^3$ |               |
| $\rho_m = 1100 \text{ kg/m}^3$ | $\rho_f = 1200 \text{ kg/m}^3$ |               |

1.2 Analytical modelling approach

An analytical fluid-structure model was proposed in [3]. The modeling strategy is based on the Ritz method to obtain approximate solutions for the fluid motion and the mechanical diaphragm deformation amplitude. Additionally, the study is limited to axisymmetric in phase motions of the membranes (i.e. first eigenmode of the HFM) and the fluid is assumed to be inviscid.

Each membrane is considered as a plain annular diaphragm and an additional linear spring. Consequently, a simple model can be established and while capturing the complexity of the spiral spring behaviour in a single stiffness parameter. It is also important to notice that FEM can be used to design the spiral spring to aim at the desired stiffness value (Figure 2a).

The flexural deformation $w(r)$ of the diaphragm is the first natural mode shape obtained through modal analysis of the annular diaphragm and is expressed from Bessel’s functions [4]. The accuracy of the approximate shape is deemed well enough as can be seen in Figure 2b when compared to FEM result Figure 2a. The dynamic equilibrium of the HFM is obtained from the energy method applied to the global structure (top and bottom membranes and fluid). From the model, the resonance frequency of the HFM can be analytically expressed provided that the material properties and central disk diameter are set.

Figure 2. a) FEM model of the membrane, b) Deformed shape used for the fluid-structure HFM model.
The effects of HFM height, type of fluid or additional stiffness can be easily studied. Figure 3 presents the evolution of the natural frequency with respect to the chamber height \((H)\) for the two different fluids of Table 1. In Red and blue lines are the natural frequency curves for Glycerine and Vaseline respectively whereas the initial membrane natural frequency is plotted in dashed line. A reduction ratio up to 1/3 can be obtained as shown in Figure 3b.

![Figure 3](image_url)

**Figure 3.** a) Theoretical effect of height of the HFM on \(f_0\), b) Reduction ratio.

2. Fabrication and realization of HFMs

The wafer-level fabrication approach of HFMs is constrained: all elements should withstand the required temperature for the machine operation and for the fabrication process itself. This includes high temperature (\(\geq 250^\circ C\)) anodic bonding (AB) steps which ensure hermitical sealing of wafers. RTV silicone elastomer, which can withstand 340°C, is used as the membrane material [5]. Glycerine and low viscosity Vaseline oil having boiling point \(\approx 300^\circ C\) are used for the fluid. They have been selected as incompressible fluid for the HFM.

![Fabrication flowchart](image_url)

**Figure 4.** Microfabrication steps from free suspended RTV silicone membrane to HFM structures.

The developed fabrication process flow is described in Figure 4. It starts with the patterning of 150\(\mu m\) deep silicon planar spring structure using DRIE. RTV silicone moulding allows hermetical membrane to be obtained (Figure 5a). Besides, it allows a drastic improvement of the Si spring robustness. The Si spirals are embedded in RTV silicone with an additional elastomer layer of 50 \(\mu m\) thickness. The latter is then etched from back side to suspend the embedded planer spring based RTV silicone membrane. In the next step, the RTV silicone membrane wafer was anodically bonded to the central thick multiple Si/glass based frame. The HFM structures are then filled with a fluid using the wafer level filling method described in Figure 4. The wafer-level filling process of the chambers was performed in a vacuum chamber, allowing the suppression of air bubbles left inside the chambers to guarantee the dynamic
characteristics of the HFM. Once the chamber connecting membranes were filled with fluid through a thin channel (500 µm diameter), HFM chips were diced. HFM with two different chamber heights (HFM1 and HFM2, with 1.6 mm and 6 mm chamber height respectively) were successfully fabricated (Figure 5b).

Figure 5. a) Silicone spiral spring plus RTV silicone membrane, b) HFM structures.

3. Experimental measurements, results and discussions

3.1 Dynamic characterization

Dynamic characterizations of HFMs were performed using a MEMS analyser (Figure 6a), in which a laser vibrometer measures the center disk displacement when the structure is submitted to low-level dynamic excitation using a PZT buzzer. Figure 6b shows the experimental spectral response for a membrane alone and a HFM filled with Vaseline oil, which shows the effective reduction of the HFM resonance in comparison to the membrane alone.

Figure 6. a) MEMS analyzer b) Experimental resonance frequencies.

Table 2 sums up the experimental results on selected samples.

| Frequency (Hz) | Membrane alone | HFM 1.6 mm | HFM 6 mm |
|---------------|----------------|------------|----------|
| 3793, 3605, 3716 | Vaseline: 2504, 2546, 2357 | Vaseline: 2504, 2546, 2357 | Vaseline: 2162, 2131, 2265 |
| 1570          | Vaseline: 1570 | Vaseline: 1570 | Vaseline: 1570 |

3.2 Model validation

Figure 7 presents theoretical as well as experimental results. The plain red and blue curves are theoretical results obtained for Glycerine and Vaseline when updating the stiffness value of the model using the mean value of the measured frequencies of the membranes. Red and blue dots lines represents the
scattering of the theoretical results based on the maximal and minimal measured frequencies and deduced stiffness. Though some dispersions are observed, the experimental results for the HFMs are in good agreement with the theoretical results. The maximal discrepancy between experimental and theoretical approaches is 6.6 %.

![Graph](image)

**Figure 7.** Experimental and theoretical result for $f_0$.

4. Conclusion

We have demonstrated the fabrication of low frequency MEMS membrane using the concept of HFM. In addition, characterizations of the fabricated HFM membranes show the expected dynamic features, namely the reduction of the membrane resonance frequency. The choice for materials and processes have been made targeting oscillating engines which operates with a moderate temperature of 200°C. Additional developments will aim at repeatability improvement, the evaluation of quality factor and the large amplitude behavior study. The integration of an electromechanical transduction will be a next step towards a fully integrated component for micro-engine concepts.

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