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MECHANICAL CHARATERIZATION OF MEMS VIBRATION MEMBRANE WITH PLANAR SPRING DESIGN FOR ENERGY HARVESTER

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Abstract

In this paper, we report the study of the mechanical properties of the vibration sensor membrane implemented for energy harvester application. The study is done using Finite Element Method (FEM) analysis. The structure and geometry of the membrane with a planar spring arm design are the parameters of the analysis in this study. Some common MEMS materials, such as silicon, polyimide and PDMS (Polydimethylsiloxane) are also chosen for analysis. While the mechanical property of the membrane is analysed in terms of the resonance frequency, deflection height, surface deformation and the von-Mises-stress. The results show that the deflection height is proportional to the membrane material, thickness and applied pre-stress. It is shown that the thinner the membrane or the higher the pre-stress level is applied to the membrane the higher the membrane can be deflected. The PDMS is a promising material to be used as the flexible membrane material, as it has the highest deformation capability among other materials. It can be seen also that the higher elastic modulus of the material the higher membrane arm deflection could be achieved. These analyses will provide an insight into the mechanical property of a flexible membrane as the movable part of the electromagnetic energy harvester system.

Keywords: FEM analysis, Flexible membrane, MEMS sensor, Vibration energy harvester.

1. Introduction

Microelectromechanical systems (MEMS) has been an extra-ordinary technology in this decade. MEMS has transformed the whole industries to move away from a large conventional system to a miniaturized device and drive the next technological revolution to a more compact and energy-efficient system [1-5]. This micro scale system can be fabricated in large quantities using an IC like process hence replacing a large scale bulky actuators and sensors with a much smaller device size that reduces cost, and weight while increasing the performance, product density and functionality by orders of magnitude [6-10].

This has extended the potential application of MEMS device in the field of power generator system, especially for mobile system and rural area. Currently, mobile devices are widely used in broad range applications, such as handheld phone, medical diagnostics, GPS (Global Positioning System) unit and sensors, The ultimate power supply for these devices is the battery [11]. Unfortunately, the battery has a shortage of energy produced, which is limited, should often be charged or changed, high maintenance costs and short shelf life. Furthermore, there is an environmental issue for the waste product of the battery [12].

To address the problems encountered with battery usage, Tan et al. [13], studied an energy harvesting concept to collect the unused energy from the environment that could be an alternative solution in the future. Energy harvesting is a mechanism of capturing and converting of energy from one physical property, such as light, heat, wind and vibration to an electrical power output. Among all, the electrical power generated through a moving object is the most widely used method, as it is always available in our surrounding systems such as water flow, earth movement, automotive, heavy machine as well as human organs [12].

There are several methods that MEMS able to implement the membrane movement for sensing the mechanical motion or force that further produces the electric current generation, such as piezoelectric [14] and electrostatic energy converter [15]. These systems, unfortunately, cannot capture a broad range of vibration frequency and the system requires a considerable connection to delivered power, so it reduces the reliability when used in a portable and mobile instrument [16, 17].

On the other hand, electromagnetic (EM) power generator uses permanent magnetism to induce the voltage across the wire coil terminals. An electromagnetic power generator is the most efficient and reliable system because of its low impedance and low output voltage but high output current and especially high reliability when used in a constantly vibrating system [12].

The crucial issue of the mechanical part of the EM vibration energy harvester is the permanent magnet that is attached to the movable membrane [13]. Ideally, the membrane should be able to deform properly while its surface flatness is maintained. The inclusion of the permanent magnet to the membrane could affect the mechanical property of the membrane system. If the membrane could be able to deform with a resonance frequency matched to the frequency of the vibration sources, a large magnetic flux gradient change and large magnetic coupling to the coil could be delivered [18]. Therefore, the movable part of the energy harvester system including the membrane structure and material would be the most important part of the system.

In this work we focused our study on the mechanical properties of the movable membrane incorporating the planar spring arm using Finite Element Method (FEM) analysis. The spring arms have the function to increase the deformation of the membrane in Z-direction and at the same time to enable the movement of the membrane in the X-Y plane. Hence, it is expected that the membrane will have reciprocating motion in the three degrees of freedom (X-Y plane and Z-Axis). Furthermore, the flexibility of the membrane is analysed by studying the appropriate material and structure of the movable part, such as arm length, and thickness, that could give the optimum deflection capability of the membrane for use as the vibration sensor in energy harvester system.

2. Electromechanical Principle of Vibration Energy Harvester

The principle of energy harvesting working through electromagnetic coupling in a moving system is derived from Faraday's law. The output voltage is generated through the interaction between electromagnetic wire coils and moving permanent magnetic. Faraday's law states that electro power is directly proportional to the change of magnetic flux links [6, 19]. Figure 1 shows a schematic diagram of electromagnetic vibration energy harvesting comprising of inertia mass M, suspended suspension with spring constant k and damper coefficient c.

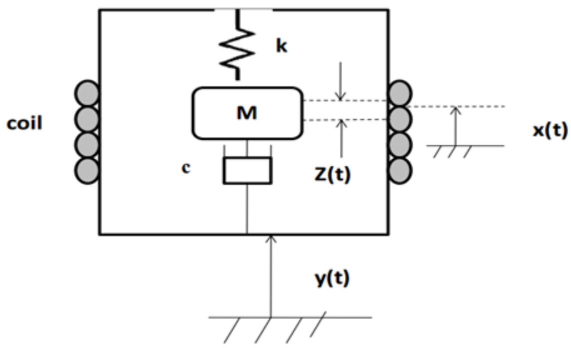

Fig. 1. The schematic of vibration energy harvester using electromagnetic coupling [4].

Following the Faraday's Law, if the moving magnet coupled to a coil, the magnetic flux line will be cut, and a potential difference is obtained at the end of the coil wire. The output electrical potential is given by Eq. (1):

$$V_{emf} = -n\frac{d\Phi}{dt} \quad (1)$$

where V_{emf} is electromotive force, n is the winding number of the coil and $d\Phi$ is the magnetic flux link through each winding. B is the magnetic field and the magnetic field degradation dB is due to the moving membrane, while A is the coil area affecting the magnetic coupling property that is changed with the moving membrane. The magnetic flux is, therefore can be considered as the total magnetic flux affecting the magnetic coupling between the permanent magnet and the planar coils in a moving condition, and is given as :

$$\Phi = \int_A (BdA + A\,dB) \tag{2}$$

where *B* is the magnetic field and the magnetic field degradation *dB* is due to the moving membrane, while *A* is the coil area affecting the magnetic coupling property that is changed with the moving membrane. By considering the Lenz's Law, the induced V_{emf} will be in the direction in which the magnetic field induced currents are opposite to the original magnetic flux that changes in the magnetic field. By replacing Eq. (2) into Eq. (1), Eq. (3) is obtained as follows:

$$V_{emf} = -n\frac{d\Phi}{dt} = -n\frac{d}{dt}(\int_A BdA + \frac{d}{dt}\int_B AdB) \tag{3}$$

3. Membrane Design

Following the Eq. (3), the movement of the membrane including the permanent magnet is the basic requirement in producing a magnetic field change in the magnetic chamber to induce the electromagnetic coil. The membrane with the spring arm model is therefore analysed in detail in this study using 3D structural analysis. Here, the membrane has a stiff and flat surface which is supported by four pre-stressed plated cantilever springs that are designed to enable a reciprocating motion in the 3 degrees of freedom (X-Y plane and Z axis), as shown in Fig. 2. The vibration of the membrane is assumed to be generated through a uniform pre-stress as high as 20 kPa acting on to the membrane surface.

To keep the mesh size small and the solution time reasonable, the membrane is considered as a planar plate structure having two layers. It assumes that in the top and bottom layers, the plating process creates equal and opposite initial stresses. So it is easy to set the model. The purpose of the model is to elaborate on the use of pre-stresses in plated metal layers in order to create a desired move of a MEMS structure. The membrane is freely movable with 4 anchored points at the end of the arms

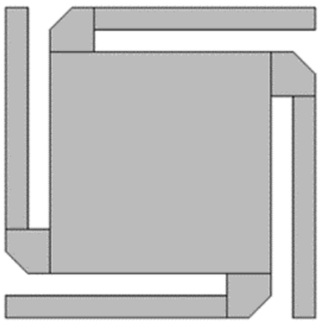

Fig. 2. Geometrical modelling of the membrane supported by four spring arms anchored at the end.

The deflection of the membrane system depends on the deformation capability of the spring arm. Here, we use the rectangular arm having various lengths starting from 10 μm and a fixed arm width of 100 μm. If we assumed that the membrane has a low mass, then the deformation of the arm having the arm size of the width *a* and length *b* can be considered as a beam with an applied pre-stress P_o at the center of the membrane. The maximum deflection a_{11} can be calculated using Timoshenko equation [20] as follows:

$$a_{11} = \frac{p_0 a^4}{4\pi^4 D}\left(\frac{1}{3+3\left(\frac{a}{b}\right)^4+2\left(\frac{a}{b}\right)^2}\right) \quad (4)$$

$$D = \frac{Et^3}{12(1-v^2)} \quad (5)$$

where *D* is the mechanical property of the material, *t* is the membrane thickness, *E* is material's Young's modulus and *v* is material's Poisson's ratio.

Tables 1 and 2 summarize the material parameters and variable analysis used in the study. The design parameters are chosen based on the consideration in the device dimension, while the three materials namely, Polyimide, PDMS and silicon, are chosen for their flexibility property and the common material, respectively, that are used in MEMS devices.

Table 1. Physical property of applied materials in the study.

Material	Young's modulus, E [Pa]	Poisson's ratio, *v*	Density [kg/m^3]
Silicon	170 x 10^9	0.28	2329
Polyimide	3.1 x 10^9	0.31	1300
PDMS	750 x 10^3	0.49	970

Table 2. Variable parameters in analysis.

Description	Details
Material	Polyimide, Si, PDMS
Applied pre-stress [kPa]	4, 6, 8, 10, 20 and 5000
Membrane thickness t [µm]	10; 50; 100
Membrane size [mm^2]	1 x 1
Arm length [µm]	10; 20; 60; 100; 1000
Arm width [µm]	100

4. Results and Discussions

Figure 3 (left) and (right) show the deformation characteristic of the PDMS membrane when a pre-stress of 20 kPa is applied onto the membrane surface. The membrane is able to deflect uniformly. It can be seen that a slightly flat surface can be kept while the maximum deformation appears at the end of the spring arm near the membrane shoulder. The thickness of the membrane seems to have an effect on the arm deformation.

Analysis of the membrane deformation in Fig. 4 shows that the membrane arm deflection height increases with the applied pre-stress. The membrane with a thickness of 10 µm obtains the highest shape change with a maximum height of 150 µm compared to that with a thicker membrane. Therefore, simulation results showed that the thicker the membrane reduces the flexibility hence affecting to the deformation height which can be referred to the Eqs. (4) and (5).

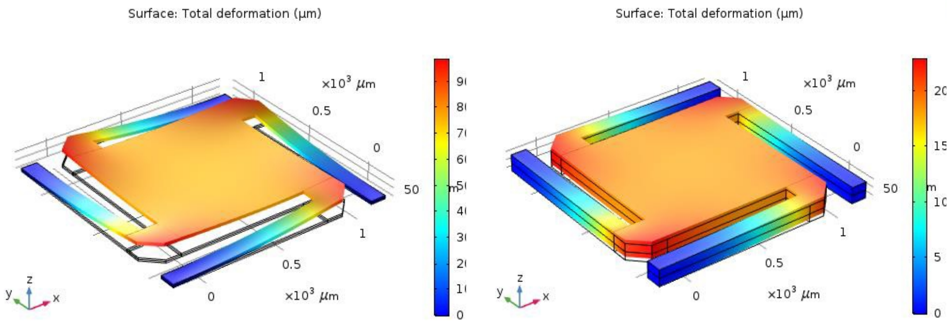

Fig. 3. The deformation height and surface changes of PDMS membrane and arms with the thickness of 10 μm (left) and 50 μm (right).

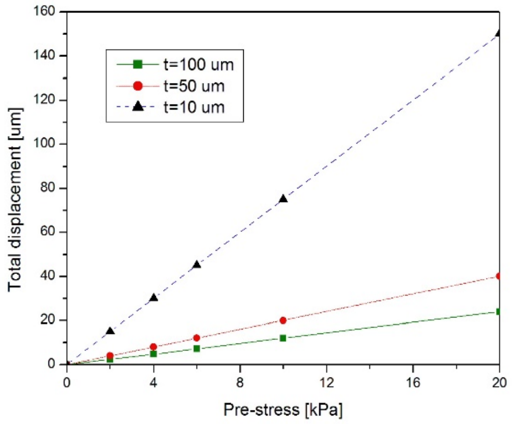

Fig. 4. The effect of the membrane thickness on the deformation capability of the membrane under various applied pressure.

For the vibration mechanism of the membrane, it is necessary to find the resonance frequency of the membrane system for efficient capture of the vibration energy [18, 20]. It is clearly shown in Fig. 5 that the length of the spring arm will affect to the resonance frequency of the membrane vibration. By reducing the arm length it is possible to increase the resonance frequency that will affect also to the captured vibration frequency of the membrane [21]. A resonance frequency as high as 90 Hz can be achieved which is within the range with the design of Zhang et al.[22], in which the resulting frequency value is <11 Hz, however with the membrane diameter of 2.5 mm.

Another important parameter of the moving membrane is the capability of the membrane against fracture due to the continuous press. The von-Mises-stress analysis in Fig. 6 shows that the critical point of the membrane is located at the end of the arm where the membrane arm is fixed to the static points. It can be seen that another critical point besides the arm end is the arm pit. This occurs because the arm pits have to bear the high load caused by the membrane.

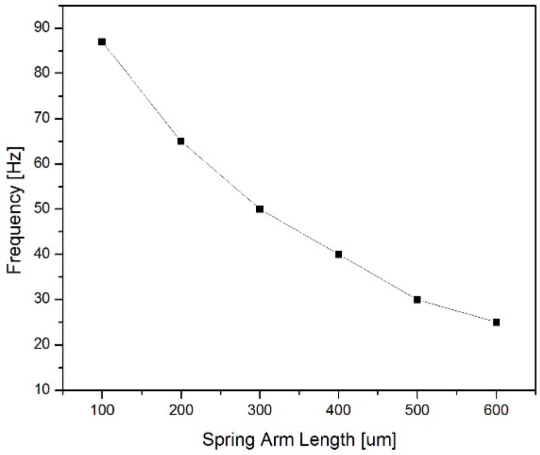

Fig. 5. The effect of the spring arm length to the resonance frequency.

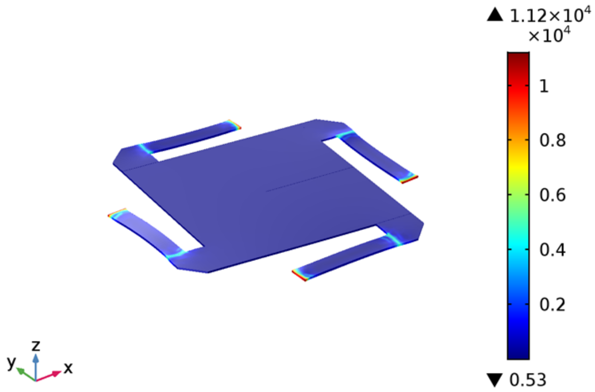

Fig. 6. Von-Mises-stress analysis of the membrane.

Figure 7 shows the membrane arm deflection height when a pre-stress of 5 GPa at the center of the membrane is applied for various membrane materials. There is a significant difference in the flexibility of the membrane between PDMS and Silicon or Polyimide. It can be analysed from its Young's modulus property as shown in Table 1, where PDMS has much lower value compared to others. Therefore there will be a significant difference in the deflection capability of the membrane. The comparison results show clearly that the PDMS material obtains the largest shape change of the arm with a maximum deflection value of 1760 μm which is the highest among other studied materials.

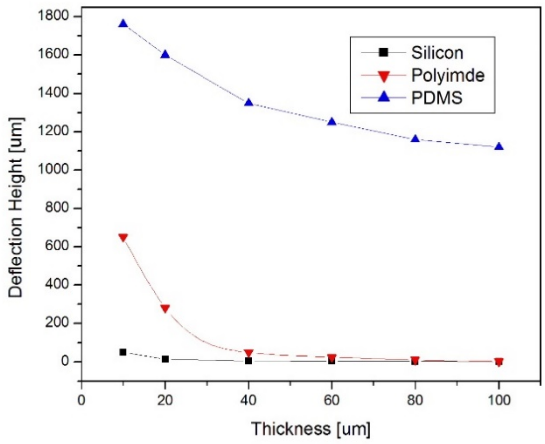

Fig. 7. The deformation characteristics of the membrane with various studied materials.

Based on the observations made by the FEM simulations, a PDMS based membrane with spring arm design is then characterized by including an attached NdFeB permanent magnet and compared with another membrane without magnet material. The NdFeB permanent magnet is included in the study to analyse the implementation of the magnet as the magnetic field generator for magnetic induction purpose. In Fig. 8, it can be seen that the effect of the attached magnetic material on the membrane affects only to the height of the deflection. The deflection height is slightly reduced due to the additional load made by the magnet. It can be concluded that the PDMS could be the better membrane material as the movable part.

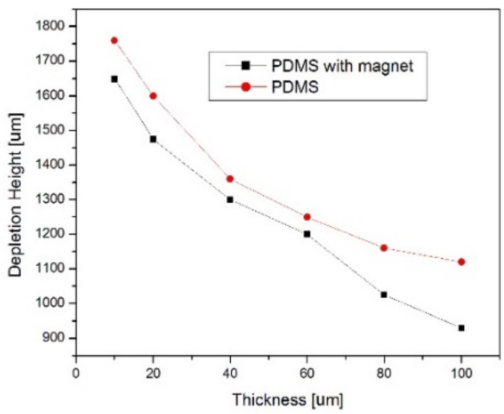

Fig. 8. The deformation characteristics of the PDMS membrane with attached permanent magnet.

5. Conclusions

An analysis of the mechanical property of the vibration sensor membrane with spring arm design has been done using FEM analysis. The results show that the membrane material, thickness and geometry of the spring arm and the pressure applied at the membrane affect significantly to the mechanical property of the membrane. The von-Mises-stress analysis shows that the critical point of the membrane is located at the end of the arm. The length of the membrane arm will determine the resonance frequency of the moving membrane. It can be also concluded that low mechanical properties can affect the shape change on the membrane, while the PDMS material has been found as the promising movable material for the vibration sensor. This study will provide insight into possible optimization of the membrane design used as the movable part of the vibration sensor for energy harvesting application.

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Nomenclatures

a	The width of the arm, m
a_{11}	Deformation height, m
A	Electromagnetic coil area, m^2
b	The length of the arm, m
B	Magnetic field , T
c	Damping coefficient
E	Young’s modulus
k	Spring constant
M	Inertial mass kg
n	Electromagnetic coil winding number
p_o	Applied pressure at the center of the membrane, Pa
v	Poisson’s ratio
V_{emf}	Electromotive force, v
$x(t)$	Movement of the sensor system, m
$y(t)$	Vibration, m
$z(t)$	Movement of the load, m

Greek Symbols

Φ	Magnetic flux, Tm^2

Abbreviations

FEM	Finite Element Method
GPS	Global Positioning System
MEMS	Microelectromechanical System
PDMS	Polydimethylsiloxane

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