Abstract

MEMS actuators are widely used in modern industry. Their main advantage is the concentration of desired mechanical characteristics in a limited space. This paper presents a design and optimization of a flat solid MEMS actuator. The optimization is based on the selection of material properties needed for the achievement of the actuator mechanical characteristics required for good performance. The main goal is to reach necessary output mechanical force with minimal side force effects. The output mechanical force is evaluated by modeling and simulation of the magnetic field and its parameters by the use of FE Analyses. In order to make proper simulations, a finite element model of the complete actuator structure is made up suggested).

Another problem that has been solved in the paper is checking of actuator’s geometry and its dimensions in order to evaluate the effective use of the material. As a result of the study, the optimal output function of the mechanical force versus the stage position has been determined. This has been done on the basis of updated material specifications. The optimal design of a flat solenoid MEMS actuator is proposed.

Keywords: mini actuator, magnetic field, FEA, MEMS

1. Introduction

This study is a part of a series of micro-electro-mechanical-systems (MEMS) examined and designed by the authors [1] in CAD/CAM/CAE Laboratory at the Technical University of Sofia. Because of their micrometer scale and some advantages in their strength, polarity and distance of actuation, they have great potential for use in science and industry [2-11]. As the explored magnetic MEMS are based on electromagnetic interactions, they are an area of possible optimisation too.

The subject of the study presented is a newly developed design of a magnetic mini actuator – flat solenoid whose behaviour and output parameters are studied and optimized at design stage.

There are recently many studies describing the role of new materials in the development of magnetic sensors and actuators [5,8,12]. The application of different materials and their combination are explored and in result, a desired output mechanical force as a function of stage displacement is achieved. In addition, any slide negative effects are minimized or avoided.

2. Design of a flat solenoid MEMS

The conceptual design of the examined magnetic MEMS actuator is presented in Fig.1. The actuator is assembled of two major parts: a static coil (stator) and a movable stage (traveler). The magnetic field produced by the current in the coil C causes the stage to be loaded by mechanical force which also depends on current stage distance to the coil marked as Z in Fig.1. The stage consists of two hexagonal volumes (marked as S1 and S2) which are tied together. Each volume could be produced with different materials.

The goal is to obtain maximal mechanical force at movement direction (Z) and minimum mechanical vertical output force. That is assured by two subsequent steps that are performed in order to find the needed design configuration and materials and to evaluate actuator’s geometry:

a) Selection of materials for volumes S1 and S2;

b) Optimization of design parameters.

Material properties

The materials examined for the explored flat solenoid are for:

- Coil. The magnetic property for the coil material corresponds to copper – i.e. $\mu=1$.
- Stage volumes S1 and S2

The most important feature of the materials used for this design is their magnetic grade. Three different materials are used for the examined design variants: mild silicon steel AISI grade M-19 (it corresponds approximately to M350-65A [13]), NdFeB magnet grade N38 [14], and a non-magnetic material (6061-T6 aluminum for example). The soft iron M-19 used has nonlinear magnetic property and its magnetic characteristic is shown in Fig.2. The other materials used have linear characteristics and their parameters (Coercive force and permeability) are listed in Table 1.
Table 1 Properties of the materials used

<table>
<thead>
<tr>
<th>Property</th>
<th>Material</th>
<th>NdFeB N38</th>
<th>Non-magnetic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coercive force, $H_c$, kA/m</td>
<td>500</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Permeability, $m$</td>
<td>1.049</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2 Soft iron M19 – $B$-$H$ curve

Study objectives and steps

As it was described above, the study is developed in two steps:

First step: Material selection. Several possible combinations of material couples have been performed in order to choose the optimal material for the stages. They are summarized in Table 2:

Table 2 Variants of the materials examined

<table>
<thead>
<tr>
<th>Design</th>
<th>Volumes</th>
<th>S1</th>
<th>S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>M19</td>
<td>M19</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>NdFeB N38</td>
<td>NdFeB N38</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>M19</td>
<td>NdFeB N38</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>NdFeB N38</td>
<td>M19</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>NdFeB N38</td>
<td>6061-T6</td>
<td></td>
</tr>
</tbody>
</table>

Second step: Geometry optimization. The design is reviewed under the chosen materials to achieve more effective saturation of the stage. A higher value of current will result in higher force acting upon the movable stage.

The function stage position versus output mechanical force at Z direction will be calculated for the final design variant. Initially, only the closest positions of the stage to the coil will be examined.

3. FE model and boundary conditions

FE models are widely used for simulation of MEMS operation [1,5,9,15]. Our model has been developed by the use of ANSYS package. The finite element model is generated on the basis of the actuator geometry described above (Fig.1). The FE model is shown in Fig.3. It is made by the use of scalar potential elements. The model includes all bodies and surrounding fluid (air) as well. It is important to note that because of its geometry and load symmetry, only a half of the model is made. The mesh is generated in the way to allow different stage positions just by material properties change.

The solutions are performed for current through the wire of 63.5 mA. This means a total current of 16.5 A for 260 turns of 44GA according to the limited cross section of the coil and this corresponds to 25 A/m.

4. Simulations

First step: Selection of proper materials

The simulations have been performed for all possible combinations of materials presented in Table 2. The results of the simulations are shown in Table 3 where are the components in Z ($F_z$) and Y ($F_y$) directions of the output mechanical force. Additionally, they are compared graphically in Fig.4. The force component $F_z$ has to be maximum (this is the driving force) and $F_y$ component has to be minimum, because it is the friction force and it has a negative influence on the actuator functions.

Table 3 Results of the material combinations examined

<table>
<thead>
<tr>
<th>Design</th>
<th>Force</th>
<th>$F_z$, mN</th>
<th>$F_y$, mN</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.887</td>
<td>-0.003</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>18.827</td>
<td>-4.029</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>3.164</td>
<td>-1.985</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>17.630</td>
<td>-3.798</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>18.071</td>
<td>-2.396</td>
<td></td>
</tr>
</tbody>
</table>
The results show that the initial variant A is completely inapplicable as its output force is too small. Variant C is also not competitive with its low force values. The highest force is calculated for variant B, but its vertical component (F_Y) is the highest one too. Finally, it could be stated that variant E shows the best performance and will be studied further. Its (variant E) results are shown in detail in Fig.5 which indicates magnetic flux density field. It could be observed that there are some zones of the stage with low magnetic flux density and that the stage design could be optimized further by means of its geometry and dimensions.

This design variant is simulated for different stage positions in order to obtain the output mechanical force as function of the stage position. The stage position is changed in pitch 0.5mm and thus five positions are simulated, starting with Z=0.6mm (closer position of the stage to the coil) and ending at 2.1mm distance. This allows to evaluate better the design output and to have a good view over its performance. The function is presented in Fig.6.

The curve in Fig.6 shows that the local maximum of the force it at 1.2mm distance between the stage and coil. This is caused mainly by the back effect of the stage to the magnetic field generated by the coil. The diagram indicates also that the force will remain more than 10mN even at the largest distance between stage and coil that we examined.

**Second step: Optimization of design geometry**

The results of the magnetic flux density field show that there are zones with low concentration (Fig.5). The middle parts of the ends of stage S1 are not very well saturated. Because of that, the geometry of the model has been modified in order to reach higher magnetic flux density values. This will allow creating more “Load Balanced” magnetic/electric structure without changing the external dimensions of the system. Such an approach will cause also a change in the output mechanical force function in terms of its flattening. Thus, the design will be changed according to the scheme shown in Fig.7.

Further, FE model is built according to this scheme by keeping high mesh density near the stage enclosure interface surfaces. The results for the case in which the stage is closer to the coil are shown in Fig.8 In this case, the applied boundary conditions and current are the same as for the previously modeled initial geometry. The results for the acting mechanical forces on the stages for this case are as follows:

- \( F_Y = -3.232 \text{ mN} \) – vertical force;
- \( F_Z = 16.361 \text{ mN} \) – longitudinal force.

The useful longitudinal force is slightly decreased to 16mN, which is an acceptable value and the
negative vertical force is increased a little. Nevertheless, the values of the output mechanical forces are acceptable.

![Fig.8 Magnetic flux density field distribution (B, Tesla) in the solid parts for the modified design, based on previously explored design case E](image)

The mechanical output function is built again, based on several analyses in which the stage is placed in different distances to the coil. The results are summarized and shown in figure 9.

![Fig.9 Output mechanical force as a function of stage position – modified design geometry](image)

The results show that the function is flattened in the distances between 0.6mm and 1.6mm. This is the exact work stroke of the actuator. The desired forces are achieved in the interval between 1.6 and 2.1mm.

5. Conclusions

This paper proposes an approach for optimization of design and selection of proper materials for a MEMS actuator. The results achieved cover the requirements for the actuator’s application. The demonstrated approach shows good applicability to MEMS design and moreover it is applicable at the stage of design development. The contemporary simulation technologies make possible decreased time-to-market and reduce cost of the product development.

References: