Design of patterned leaf spring for sensor-probe with stable reflectivity and high sensitivity

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\textbf{A B S T R A C T}

In sensors, integrated reflection mechanisms of the illuminating light to the reflection material on the proof mass require a strict single degree of motion because the accuracy almost entirely depends on the motion of the proof mass. Therefore, this paper describes the optimum design of a mass–spring structure that features high sensitivity and long linear elastic motion range of the leaf spring without rotation and lateral motion of the proof mass. Accordingly, finite element analyses were conducted to determine an optimal leaf spring pattern and to predict the probe performance. The optimum design of the leaf spring was determined by considering five criteria within the linear elastic region of the eight leaf spring models. Then, two types of leaf springs were manufactured, and the proposed mass–spring system integrated to the prototype was fabricated. The reliability of the FEA results and the performance of the fabricated mass–spring model were verified through the force–displacement curve test, the dynamic test, and the rotation test.

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1. Introduction

Single degree of freedom (SDF) structures can be considered as representative of the proof behavior of the vibrating structures [1]. Accordingly, SDOF systems have been widely adapted in sensor probes for acceleration, earthquake events, and tilt angle [2–7], as well as in actuators [8]. When this structure is applied to sensor probes for the quantification of physical parameters, the accuracy almost entirely depends on the motion of the proof mass. Generally, a cantilever design has been widely adopted as a spring or mass, because the minor lateral motion or the rotation of proof mass are typically permitted for normal operation in conventional capacitance and magnetic based sensor. However, under the laser or optical sensing principle [9–13] where a reflected signal from a reflective material of an object is exploited, microscopic rotation and lateral motion of the proof mass should be prevented for normal operation. In the case of the fiber optic sensor, in which optical fiber is used as a receiver of the reflected light, the accuracy almost entirely depends on the motion of proof mass due to a small numerical aperture. Furthermore, in terms of linearity, the cantilever design was limited in utilization for its narrow measurement range due to the nonlinearity at large deformation. In this regard, most SDOF systems in sensor probes require strict SDOF motion for high accuracy.

To enhance the reliability of this sensing principle, an advanced mass (M)–spring (K) model, which keeps stable reflectivity of the illuminating light to the reflective material on a proof mass, is necessary to ensure safe operation without lateral and rotational motion of the proof mass. To this end, two circular leaf plates may be employed as a spring. The proposed M–K model has a cylindrical form with a circular leaf spring because most reported and developed sensors such as accelerometers and tiltmeters [5,7,14–16] feature cylindrical appearances for convenience during installation and small size sensor. Therefore, appearances of the leaf spring and proof mass have circular shapes [17]. A circular leaf spring, which has an embedded hole at the center, is particularly useful in supporting the mass for strict linear motion of the proof mass. Furthermore, these are placed on both the top and bottom sides with horizontal symmetry in order to minimize the eccentricity error effect and unbalancing weight error during vibrated operation.

The proposed M–K model is intended for application to sensor probes for the monitoring of acceleration or tilting based on the reflection principle of the illuminating light to the reflection material on the proof mass. Therefore, a significant concern is stable reflectivity induced by the motion of the proof mass with a high sensitivity. Consequently, in order to determine the optimal design, the priority of criteria is rotation angle, which was admitted to a three decimal point, because the rotation of the proof mass does not guarantee stable reflected signal acquisition without distortion in reflection mechanism sensors. The second and third criteria

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are respectively defined as a sensitivity and linearity in this paper although these two criteria depend on the operation requirement of the sensor probe. Therefore, this paper investigated the optimum design of the M–K structure that features a large range of linear motion of the leaf spring and miniscule rotation of the proof mass. Static and dynamic analyses were conducted for the design of the optimal leaf spring pattern and to predict the probe performance through a parametric study. First, in order to provide flexibility to the circular leaf spring, it was divided into \( P \) equal parts. Parametric studies were then carried out on the arm length (AL) and thickness of the leaf spring as well as the moment balancing design (MBD). The leaf spring patterns of eight models were employed to verify the effect of the four parameters. Through a comparison of the finite element analysis (FEA) results, the optimal pattern of the leaf spring was determined over the rotation angle and lateral motion of the proof mass, along with the linearity, sensitivity, and linear motion range of the \( F \) (force)–\( S \) (displacement) curve within the elastic region of the leaf spring. Finally, the best pattern for the leaf spring was developed using commercial software, ABAQUS 6.7. The results of the FEA were applied to the fabrication design of the leaf spring.

Two types of the leaf spring and proof mass were fabricated. Through a static loading test, the rotation angle of the proof mass and the \( F–S \) curve of the leaf spring were measured. Furthermore, the natural frequency of the proof mass is a significant parameter for the purpose of application as an accelerometer, as well as verification of the reliability of the FEA. The natural frequency was measured through a dynamic test. The reliability of the results of the FEA was verified through comparison with the experimental results. An optimal M–K model that can provide a minimized lateral motion and rotation angle to the proof mass was achieved as a sensor probe of high sensitivity.

In this study, Section 2 describes the FEA analysis according to parameters of the leaf spring pattern, and Section 3 describes the verification test for the proposed M–K model through force–displacement curve test, the dynamic test for the measurement of natural frequency, and the rotation test.

2. Finite element analysis

2.1. Description of parameters and models

Fig. 1 shows the configuration of the FEA model (96,261 nodes and 86,129 elements). The directions of \( u_1 \), \( u_2 \), and \( u_3 \) were defined in this figure. The sensor probe is composed of two leaf springs and a proof mass. The shell element of S4R and solid element of the C3D8R, supported by Abaqus/Standard, were used for the leaf spring and proof mass, respectively. A reflective material can be attached to the proof mass at the center. Six degrees of freedom were constrained at the border of each leaf spring. Concentrated load was applied at the center of the top surface of the proof mass. The leaf spring has a circular shape, as shown in Fig. 2. Control variables were an external diameter of 20.0 mm and an internal diameter of 10.0 mm. \( W \) refers to the arm width of the leaf spring, \( S \) refers to the arm gap of the leaf spring, and \( G \) refers to the gap between the parts, while \( P \) refers to the number of equal parts at each leaf spring (\( P = 3, 4, 5 \)). The root width on the arm, \( B \), was kept at the value of 1.0 mm during all FEAs. The length of the proof mass, \( L \), was maintained at a value of 23.0 mm. Although not shown here, through preliminary FEA results, it was found that the design with a smaller \( W \) and larger \( S \) should be avoided due to the increase in rotation angle and lateral motion of the proof mass. Furthermore, as \( G \) was increased, the rotation angle also increased. Therefore, \( G \) was kept at 0.3 mm. The materials of the proof mass, leaf spring, and reflective material were assumed to be aluminum (7075), copper beryllium alloy (CBA, C17200), and chrome, respectively. Based on this M–K design, FEAs were performed to determine the optimal pattern of the leaf spring.

The leaf spring was divided into \( P \) equal parts to provide flexibility to the spring (\( P = 3, 4, 5 \)). In addition, a MBD, in which positive moment on the \( u_3 \)-axis is offset by negative moment on the \( u_3 \)-axis, was employed to minimize the rotation of the proof mass: no MBD means all arms of the leaf spring headed out to a same direction. Lastly, in order to control the spring stiffness, the arm length (AL) and thickness of the leaf spring was varied with the aim of obtaining greater sensitivity, higher linearity, and a larger linear motion range within the elastic zone of the leaf spring.

Verification models for the effects of only the aforementioned parameters \( P \), AL, MBD, and thickness of the leaf spring were designed because the effects of the dimensions \( B \), \( L \), and \( G \) can be controlled by these parameters, while \( W \) and \( S \) depend on the AL. Therefore, only these four parameters were considered in the FEA.
as they are sufficient to control the intended performance. Fig. 3 describes the eight finite element (FE) models for verification of $P$, AL, MBD, and thickness of the leaf spring.

The notations and description of each FE model for the following FEAs are shown in Table 1. The notations referring to the FE models are used throughout this study. For convenience, AL was defined as the number of lines in each arm. For instance, 3N(2) and 4M2(3) have AL of two lines and three lines, respectively.

The models of 3N(2), 4N(2), and 5N(2) were designed to investigate the effect of parameter, $P$, in no MBD. All dimensions are the same in the radial direction. To investigate the effect of the MBD, two strategies in particular were adopted for the structural configuration: employing the MBD in each leaf spring (models of 4M1(2) and 4M2(2)) and reversing the direction of the upper and lower leaf spring (model of 4M3(2)). The MBDs of 4M1(2), 4M2(2), and 4M3(2) were appointed type 1, 2, and 3. The models of 4M1(2) and 4M2(2) were employed for the other moment offset design in each spring: the two arms of four arms headed out to a clockwise direction, while the remaining two arms headed out to counterclockwise direction. The arm-root locations are central vertical axis symmetry in the model of 4M1(2), while the arm-root locations are central horizontal axis symmetry in the model of 4M2(2). In the designs of 4M3(2), the arms of the upper leaf spring headed out to a positive direction, while the arms of the lower leaf spring headed out to a negative direction. Lastly, 4M2(2) and 4M2(3) were designed to predict the effect of the parameter AL. Furthermore, 4M2(3) and 4M2(6) were designed and compared to investigate the relationship between the thickness and AL of the leaf spring. The 4M2(6) has AL of six lines and the thickness of the leaf spring was 100 $\mu$m: the six lines of this model was determined to bring the identical sensitivity of 4M2(3). Except for 4M2(6), all of the models were designed with a thickness of 60 $\mu$m.

Fig. 4 shows the static and dynamic analysis results. Fig. 4(a) describes the stress distribution at the leaf spring of the 4M2(6) model. Maximum stress occurs at each edge of the pattern arm. Fig. 4(b) describes the deformation behavior of the M–K structure. The rotation angle of the proof mass was calculated at the marked node, which was placed on the center of the reflection material.

### 2.2. Results of FEA

The results of the eight model designs are shown in Fig. 5. The data was summarized within the yield strength (287.5 MPa) of CBA. Fig. 5(a) and (b) shows the moving displacement of the proof mass in the $u2$ and $u3$ directions, respectively. Fig. 5(c) shows the rotation angle on the $u3$–axis of the proof mass within the elastic region of the leaf spring. The evaluation criteria were rotation angle, linearity, linear motion range, and sensitivity, as well as lateral motion. The lateral motion was entirely estimated by the results of the moving displacement in the only $u2$ direction due to negligible moving displacement of nano scale in the $u1$ direction.

The results of the FEA within the elastic zone of the leaf spring are summarized in Table 2. The linearity was estimated by value through linear curve fitting analysis according to the results of Fig. 5(b). Furthermore, the sensitivity, inferred from the inverse slope of the $F$–$S$ curve, was also investigated.

When $P$ was increased in no MBD, the linearity was also increased, while rotation angle, lateral motion and sensitivity were reduced, and also natural frequency was higher. To prevent microscopical rotation in the proof mass, the three types of MBD (4M1(2), 4M2(2), and 4M3(2)) need to be employed. In these MBD, the $F$–$S$ curve in $u3$ direction featured non-linear function, and linear motion range and sensitivity were reduced in comparison with the result of 4N(2). In the case of 4M3(2), which MBD type of 3 was integrated, the rotation angle was the largest among the three different types of MBD models. However, in the case of 4M2(2), which MBD type of 2 was integrated, the rotation angle was the smallest among them. Furthermore, In the case of 4M1(2), movement in the $u2$ direction occurred, as shown in Fig. 5(a). In order to apply optical and laser sensing mechanism, which use reflected signal from the

### Table 1

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3N(2)</td>
<td>4 divided equal parts, AL of 2 lines, and thickness of 60 $\mu$m</td>
</tr>
<tr>
<td>4N(2)</td>
<td>4 divided equal parts, AL of 2 lines, and thickness of 60 $\mu$m</td>
</tr>
<tr>
<td>5N(2)</td>
<td>5 divided equal parts, AL of 2 lines, and thickness of 60 $\mu$m</td>
</tr>
<tr>
<td>4M1(2)</td>
<td>4 divided equal parts (type of 1), AL of 2 lines, and thickness of 60 $\mu$m</td>
</tr>
<tr>
<td>4M2(2)</td>
<td>4 divided equal parts (type of 2), AL of 2 lines, and thickness of 60 $\mu$m</td>
</tr>
<tr>
<td>4M3(2)</td>
<td>4 divided equal parts (type of 3), AL of 2 lines, and thickness of 60 $\mu$m</td>
</tr>
<tr>
<td>4M2(3)</td>
<td>4 divided equal parts (type of 2), AL of 3 lines, and thickness of 60 $\mu$m</td>
</tr>
<tr>
<td>4M2(6)</td>
<td>4 divided equal parts (type of 2), AL of 6 lines, and thickness of 100 $\mu$m</td>
</tr>
</tbody>
</table>
sensor head, the rotation angle is significant parameter by priority. Therefore, the basic MBD of type 2 in 4M2(2) model, which has even-numbered equal parts in the leaf spring, was recommended as the preferred design. However, the linearity of 4M2(2) was significantly poor. This can be overcome through the extension of AL. When AL was increased, the linearity was better and the linear motion range expanded more under higher applied load in 4M2(3) than those of 4M2(2) model, as shown in Fig. 5(b) and Table 2. In terms of the linear motion range, linearity, and sensitivity, the models 4M2(3) and 4M2(6), shown in Fig. 3(g) and (h), respectively, provided the best performance due to their high sensitivity. The priority criteria is the rotation angle, which was admitted to a three decimal point, because the rotation of the proof mass does not guarantee the stable reflected signal acquisition without distortion in

![Static and dynamic analysis in FEA model of 4M2(6).](image)

**Fig. 4.** Static and dynamic analysis in FEA model of 4M2(6).

<table>
<thead>
<tr>
<th>Type</th>
<th>Model</th>
<th>Rotation angle (°)</th>
<th>Natural frequency (Hz)</th>
<th>Linearity $R^2$</th>
<th>Sensitivity (mm/N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No MBD</td>
<td>3N(2)</td>
<td>1.22129</td>
<td>35.7</td>
<td>0.979</td>
<td>8.47</td>
</tr>
<tr>
<td></td>
<td>4N(2)</td>
<td>0.52950</td>
<td>64.3</td>
<td>0.996</td>
<td>3.82</td>
</tr>
<tr>
<td></td>
<td>5N(2)</td>
<td>0.35034</td>
<td>99.3</td>
<td>0.998</td>
<td>1.65</td>
</tr>
<tr>
<td></td>
<td>4M1(2)</td>
<td>0.00011</td>
<td>64.0</td>
<td>0.979</td>
<td>2.99</td>
</tr>
<tr>
<td></td>
<td>4M2(2)</td>
<td>0.00002</td>
<td>64.0</td>
<td>0.935</td>
<td>1.43</td>
</tr>
<tr>
<td></td>
<td>4M3(2)</td>
<td>0.01236</td>
<td>64.3</td>
<td>0.938</td>
<td>1.52</td>
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<tr>
<td></td>
<td>4M2(3)</td>
<td>0.00141</td>
<td>38.7</td>
<td>0.999</td>
<td>12.50</td>
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<tr>
<td></td>
<td>4M2(6)</td>
<td>0.00049</td>
<td>39.3</td>
<td>0.999</td>
<td>12.05</td>
</tr>
</tbody>
</table>

Table 2
Comparison of the results of each analysis within elastic zone.
reflection mechanism sensors. The second and third criteria of priority are the sensitivity and linearity, respectively. In addition, the comparison between 4M2(3) and 4M2(6) indicates that when the spring stiffness varied due to different Young’s moduli, thicknesses and other parameters used material in the experiment, only needs to be controlled to obtain larger linear motion and higher sensitivity. Consequently, it was found that the MBD of type 2 in the form of 4M2(2) should be employed as a basic design because this shape

Fig. 5. FEA results from nonlinear static analysis.

Fig. 6. Fabricated leaf spring patterns for verification test.
Table 3
Comparison of natural frequencies for each model.

<table>
<thead>
<tr>
<th>Model</th>
<th>FEA (Hz)</th>
<th>Experiment (Hz)</th>
<th>Relative error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4M2(3)E</td>
<td>25.1</td>
<td>24.0</td>
<td>4.4</td>
</tr>
<tr>
<td>4M2(6)E</td>
<td>12.1</td>
<td>12.5</td>
<td>3.0</td>
</tr>
</tbody>
</table>

guarantees the miniscule rotation of the proof mass. Furthermore, if the thickness or stiffness of the leaf spring is varied, the high sensitivity can be easily controlled by adaptable Al, as can be seen in the comparison between the FEA results of 4M2(3) and 4M2(6). In the aspect of priority, the leaf spring pattern of 4M2(6) is the best due to its rotation angle of 0.00049° within the elastic region of the leaf spring.

3. Experiment

3.1. Fabrication of M–K system

To verify the simulation results, the optimal leaf spring patterns of 4M2(3) and 4M2(6) were fabricated under the notations of “4M2(3)E” and “4M2(6)E”, respectively. The leaf spring patterns are composed of phosphor bronze (PB) with a thickness of 60 μm, as shown in Fig. 6. For convenience in manufacturing, the design was slightly different because the fabricated spring could be easily assembled with the proof mass through the integrated hole. After assembly between the proof mass and leaf springs, the constraint conditions and design were the same with the FEA models including the optimal leaf spring patterns of 4M2(3) and 4M2(6). Although the fabricated M–K system is the same with the ones of the FEA in Section 2, the notations of the fabricated leaf spring pattern is different to distinguish the results of the FEA in Section 2 from that of the FEA implemented in this section due to different material properties and thickness. Electric spark machining was employed for the fabrication of the leaf spring.

The M–K model, which has a size of total length L of 23 mm and leaf spring diameter of 20 mm, was fabricated, as shown in Fig. 7(a). That shows 4M2(3)E embedded structure, and a mirror was attached to the proof mass for rotation angle measurement. The total mass of this structure was 2.42 g. A schematic diagram of the prototype for static and dynamic test is shown in Fig. 8(b). Like the FEA conducted, the same boundary conditions can be applied to that as well.

The prototype was weighted with lead, as shown in Fig. 8(a). A laser displacement sensor (LK-081, Keyence, Co., Japan), which features a high resolution of 0.003 mm, was used for the measurement of the vertical moving displacement of the proof mass. Free vibration was also implemented to identify the natural frequency. The rotation angle was tested by using a visible He–Ne laser (05-LPL-340-005, Melles Griot, Co., USA) far from the mirror in the proof mass, as shown in Fig. 8(b). The distance between the visible laser and the mirror was kept at 3.1 m. The emitted light from the red visible laser (632.8 nm) was reflected from the mirror on the proof mass. The reflected red light was marked on the section paper.

3.2. Experimental results

To use this M–K model as an accelerometer sensor probe, the natural frequency is a significant parameter in determining the measurement frequency range. Table 3 shows the natural frequencies for each model. The natural frequencies of each model were experimentally determined as 24.0 Hz and 12.5 Hz, respectively, from three repetitions. In order to obtain reliable natural frequencies of the FEA, the elastic modulus of PB was measured through a nano indentation–experiment with a loading rate of 0.305 (μN/s), which was applied with a standard deviation of 0.241 from eight repetitions, and a sampling frequency of 5 Hz. The measured average of Young’s modulus was 92 GPa, and the standard deviation was 4.244 from eight repetitions. These material properties were used and reanalyzed for the FEAs. The experimental results coincide with that of the FEA within relative error of 5%. These results support the reliability of the FEA. For a wide frequency-measuring range, 3-line was preferred as a sensor probe.

An inspection of the F–S curve and rotation angle of the proposed M–K model was conducted through a static test. The results are shown in Fig. 9. For 4M2(3)E and 4M2(6)E, the FEA results are illustrated to demonstrate their reliability by comparison with the experimental results. In the FEA, the analysis was implemented within yield strength (287.5 MPa) of CBA. Therefore, in the prototype, in order to avoid plastic deformation of the leaf spring, the movable range of the proof mass was limited to 2.9 mm according to the FEA result of “4M2(3)E_FE A”. In Fig. 9(a), the results for linearity coincided with the tendency of the FEA. For the use as a sensor probe, the sensitivity is a significant parameter. Based on these graphs, the sensitivity and linearity were also increased. In the case of 4M2(6)E, the sensitivity was approximately four-times better than that of 4M2(3)E. The experimental results were almost the same with the one of FEA. Additionally,
the linearity was almost 1 at both the FEA and experiment through linear curve fitting analysis. Therefore, the reliability of the FEA results was verified based on the results of the FEA and the experiment. Rotation test of the proof mass was also conducted. Each leaf spring has four equal parts. Each part should have the same spring stiffness. However, in the experiment, it is difficult to fabricate the ideal spring pattern with same configurations of the FEA models although the leaf spring pattern should be fabricated with a higher degree precision manufacturing process because such small and sensitive measurements are required. Furthermore, it is difficult to measure the miniscule rotation angles up to 4 decimal points as calculated in the FEA although the leaf spring was fabricated with high degree precision. In terms of the rotation angle measurement, the experimental results did not exactly coincide with that of the FEA due to local plastic deformation and manufacturing error at the edge of the spring arm. Accordingly, to demonstrate the superiority of the MBD, the result in the FEA model of “4N(3)E, FEA” is illustrated and compared with that of “4M2(3)E, Experiment”, as shown in Fig. 9(b). 4N(3)E is illustrated in the inset of Fig. 9(b). The notation of 4N(3)E means that the FEA model, in which the measured material property was applied, that features 4 equally divided parts with no MBD, AL of 3 lines, and thickness of 60 µm. The FEA result of model 4N(3)E, a representation of the no MBD design, has a relatively large rotation angle up to 1 decimal point. However, the proposed models (4M2(3)E, 4M2(6)E) in this paper have a relatively miniscule rotation angle up to 2 decimal points in comparison to the FEA result of “4N(3)E, FEA”. This result indicates that an MBD design should be employed for miniscule rotation angles in comparison with a no MBD design. Therefore, MBD in the form of 4M2(3)E and 4M2(6)E should be employed as a basic design because such form guarantees the minor rotation of the proof mass.

Furthermore, in consideration of the second (sensitivity) and third criteria (linearity), 4M2(6)E is the best design. If the second criteria is the large measurement frequency range, 4M2(3)E is

<table>
<thead>
<tr>
<th>Model</th>
<th>FEA (mm/N)</th>
<th>Experiment (mm/N)</th>
<th>Relative error (%)</th>
<th>Linearity R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>4M2(3)E</td>
<td>17.19</td>
<td>18.76</td>
<td>8.4</td>
<td>0.9994</td>
</tr>
<tr>
<td>4M2(6)E</td>
<td>72.90</td>
<td>71.94</td>
<td>1.3</td>
<td>0.9990</td>
</tr>
</tbody>
</table>
better than 4M2(6)E due to its higher natural frequency of the M–K model.

4. Conclusion

This paper presents the optimal design of the mass–spring (M–K) model, composed of two leaf springs and a proof mass for the minimized rotation, maximal linear sensitivity and largest linear motion range of the proof mass. Through static and dynamic analyses, the performances of the M–K models, which depend on the leaf spring pattern, were inferred. For application to the sensor probe based on the reflection mechanism, the pattern should have a MBD in each leaf spring, which has even-numbered divided parts, like that of the aforementioned proposed shape. By considering second and third criteria as an option, an appropriate sensor probe should be adopted according to the operation requirements because most sensors have a tradeoff among the measurement dynamic range and sensitivity of the proof mass within the elastic motion range of the leaf spring. Finally, according to the priority in the performances of the sensor probe, the leaf spring pattern of 4M2(6), which has a negligible rotation angle and lateral motion of the proof mass in working, was determined as the optimum design, in terms of providing maximal linear sensitivity and linear motion range to the motion of the proof mass.

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References


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