**Design, fabrication, and testing of a meso-scale accelerometer made of spring steel**

Arun Balaji Baskar¹, Naveen Shamsudhin¹, Girish Krishnan² and G.K. Ananthasuresh²

¹Department of Instrumentation and Control Engineering, National Institute of Technology-Trichy, Tiruchirapalli, India
²Department of Mechanical Engineering, Indian Institute of Science, Bangalore, India
*E-mail : suresh@mecheng.iisc.ernet.in*

**Abstract:** This paper reports a novel, low-cost, moderately sensitive, meso-scale accelerometer fabricated with spring steel foil and equipped with either a Hall Effect-based proximity sensor or a capacitive sensor. Since the sensitivity of a Hall Effect sensor is low, we attach a displacement-amplifying compliant mechanism (DaCM) to the proof-mass of the accelerometer to increase the overall sensitivity without compromising on its natural frequency. The displacement of the output of the DaCM is measured using the Hall Effect sensor. The voltage-change in the sensor is calibrated for the applied acceleration. The device is fabricated using wire-cut electro-discharge machining (EDM) of EN J42/AISI 1080 spring steel resulting in an overall size of 60 mm × 60 mm × 10 mm including the Hall Effect sensor. Testing revealed that the accelerometer can detect acceleration signals as small as 14 mg. The measured sensitivity of the accelerometer is 71 mV/g. Finite element simulation of the accelerometer showed that its natural frequency is 50 Hz, which is around 40% greater than an accelerometer with similar sensitivity without a DaCM. The design of the DaCM proposed here can be miniaturized further and fabricated with silicon microfabrication processes for enhanced sensitivity and resolution. In a second embodiment of the sensor, the designs of the DaCM and the suspension were modified to make it suitable for differential capacitive sensing. This was also fabricated and tested. This sensor gives 1 mg resolution but shows nonlinear response to changing acceleration over 0-1 g range.

**Keywords:** Accelerometers, Hall Effect sensor, wire-EDM, and displacement-amplifying compliant mechanism.

**1. INTRODUCTION**

Accelerometers have a suspended proof-mass, which experiences an inertial force in the opposite direction of the acceleration that is to be measured. The deflection of the proof-mass caused by this force is determined by the suspension stiffness and is converted to a proportional change in electrical signal using various transduction principles such as capacitive, electromagnetic, piezoelectric, piezoresistive, electron tunneling, etc. Recent advances in silicon microfabrication technologies have led to the miniaturization of these devices with considerable enhancement in their performance [1-3]. See [4] for a review. However, these devices require silicon fabrication technologies and on-chip or off-chip electronic circuitry. While low resolution micro machined accelerometers are cheap, high-resolution ones are very expensive. The high cost becomes an issue in certain applications such as vibration monitoring in machine tools and in surveillance wherein an array of sensors of moderately high resolution are deployed to form a network. The fabrication of silicon accelerometers entails high overhead costs and access to a clean room. A micromachining foundry is not always an easy option because of fixed process flows and parameters. Furthermore, we feel that non-semiconductor materials should also be explored for miniaturization purposes. Ceramics and polymers are already being investigated. In this paper, we take the first steps in using metals-steel in particular and machining them using conventional macro manufacturing techniques.

Based on the foregoing, towards the goal of developing, a low-cost and moderately sensitive accelerometer using non-semiconductor materials, in this paper we present a miniature (small volume because of its flatness) accelerometer. The material we have chosen is spring steel (EN J42/AISI 1080). The fabrication process is wire-cut Electro Discharge Machining (EDM). Wire-cut EDM is not an inexpensive process for batch-production but the goal here is to demonstrate a spring steel accelerometer. Later on, other batch-fabrication techniques such as punching, extrusion, sheet-metal bending, etc., could be explored. Thus, a long-term goal of this work is adapting macro-machining processes to realize small features at the meso-scale (mm-cm) in excellent engineering materials such as steel.

In this work, we have chosen the Hall Effect and capacitive sensing principles. At the meso-scale, Hall Effect-based proximity sensors provide a cost-effective,
simple, and compact alternative method to sense displacements [5]. Although the Hall Effect sensor is small in size and is simple to use, it has a very low sensitivity (about 370 V/m for Allegro A1231), thus limiting the resolution of the accelerometer. Therefore, to increase the sensitivity of the accelerometer, the mechanical sensitivity needs to be increased. In conventional accelerometers with just a proof-mass and a suspension, increasing the mass and decreasing the suspension stiffness increases the mechanical sensitivity. This, however, decreases the natural frequency and thus the bandwidth of the system. In this paper, we propose adding a displacement-amplifying compliant mechanism (DaCM) to the proof-mass of the accelerometer. This mechanism increases the sensitivity of the device [6]. In Section 2, we discuss the effect of adding a DaCM to an accelerometer. Systematic selection of the most suitable DaCM from the literature is also discussed. The detailed analysis and dimensional design is in Section 3. Section 4 contains a description of the fabrication process of the accelerometer. The fabricated accelerometer is calibrated by applying known weights. It was found to measure an acceleration signal as small as 14 mg, which is found to be consistent with the analysis. The fabricated model is found to have a range of 0-3 g. Section 5 has the brief description of the implementation of the capacitive sensing principle. The capacitive accelerometer is found to have a resolution of 1 mg but with a nonlinear response. Concluding remarks are in Section 6.

2. DISPLACEMENT-AMPLIFYING COMPLIANT MECHANISMS (DaCMs)

Displacement-amplifying compliant mechanisms are usually used in literature to amplify the displacement of actuators which have limited stroke [6]. They are equivalent to mechanical levers, but amplify displacement due to elastic deformation. Thus, these mechanisms have some stiffness, which can be modeled by two springs at their input and output sides in conjunction with a lever. Therefore, when a DaCM is added to an accelerometer (see Fig. (1)), the increase in sensitivity does not depend only on the amplification of the DaCM but on a few other quantities. These are shown in Fig. (2) in lumped parameter form. The inherent or the unloaded amplification of the DaCM is denoted by \( n \). This is the ratio of the output and input displacements when a force is applied at the input but no load is applied at the output. The mass and the stiffness of the proof-mass and the suspension are indicated by \( m_s \) and \( k_s \) respectively. This stiffness is in parallel with the input stiffness of the DaCM denoted by \( k_{ci} \). The DaCM has a different stiffness, \( k_{co} \), at the output. This is the stiffness felt when an output load is applied in the absence of the input load. The inertia of the DaCM is lumped at the input and output sides, which are denoted by \( m_{ci} \) and \( m_{co} \) respectively. The quantity \( m_{ext} \) is the mass at the output of the DaCM, which in the present application, is that of a magnet attached at the output as required by the Hall Effect sensor. These quantities are computed by the finite element analysis (FEA) of the DaCM for static and modal analyses cases.

![Fig. 1: A DaCM and its lumped parameters. The accelerometer and the sensor side are also shown schematically. The input side shows the proof-mass and a suspension. The output side shows the external mass (magnet in the Hall Effect sensor) and a suspension (which will be absent for a Hall Effect sensor).](image)

The static sensitivity of the accelerometer without the DaCM is simply:

\[
z = \frac{m_s g}{k_s} \tag{1}
\]

The output \( z \) of the accelerometer with the DaCM is given by

\[
z = \frac{m_{ext} + m_{co}}{k_{co}(k_s + k_{cl} + n^2k_{co})} + \frac{nm_{ext}gk}{k_{co}(k_s + k_{cl})} \tag{2}
\]

The net amplification, \( NA \), i.e., the ratio of the output displacement with the DaCM and the output displacement without the DaCM, is given by

![Fig. 2: The spring-mass-lever model of DaCM.](image)
\[ NA = \frac{k_v \left\{ (m_{\text{ext}} + m_{\text{co}})(k_v + k_s + n^2k_{\text{co}}) + nm_{\text{ext}}k_v \right\}}{m_{\text{ext}}(k_v + k_s)} \]

From Eq. (3), we can see that when \((m_{\text{ext}} + m_{\text{co}}) = 0\) and \(k_v << k_s\), the DaCM would approach a rigid lever because only then \(NA = n\). Otherwise, \(NA < n\). Clearly, we need to have \(NA > 1\) to justify the use of a DaCM. The fact that \(NA < n\) is an important point because when we are choosing or designing a DaCM, the inherent amplification is not the only one to be considered. The input and output side stiffness do matter. Furthermore, by computing the natural frequency of the spring-mass-lever model, it can be shown that the fundamental natural frequency of the accelerometer-DaCM system is higher than that of the fundamental natural frequency of the accelerometer. Next, we discuss how a suitable DaCM topology is selected for the accelerometer application.

3. DESIGN AND ANALYSIS OF THE ACCELEROMETER WITH THE DaCM

The net amplification \((NA)\) decides the sensitivity of an accelerometer, which is the theoretical change in the output voltage of the sensing element for unit acceleration, where as the acceleration due to gravity equal to 9.81 m/s\(^2\). Apart from the sensitivity and the natural frequency, a DaCM should also withstand stress under large loads and should have sufficient stiffness in the cross-axis direction so as to be insensitive in that direction. However, these two quantities cannot be directly predicted from the lumped model of Fig. (3). Thus, detailed finite element analysis of all the candidate DaCMs is needed. Figure (3) shows five DaCMs taken from the literature. There are many more, but these are the ones that give a net amplification greater than one [6]. The figure shows, in the right column, the deformed profiles of the five DaCMs. All these were size-optimized to fit in the same area and have the same out-of-plane thickness to make the comparison fair. Size-optimization entails the adjustment of the widths and orientations of the beam segments using gradient-based optimization algorithms so as to maximize \(n\). Now, in order to select the best one for the present accelerometer, we use a weighting method because we have two additional criteria (maximum stress and cross-axis stiffness) apart from the net amplification and natural frequency. All the four criteria are normalized to make the largest among each of them equal to one. This is shown in the top-half of Table 1. Now, we give weights to these multiple criteria and see which DaCM topology fares well. As can be seen in the bottom half of Table 1, M2 emerges as the best if we give the highest weight to \(NA\). Thus, we chose M2 for further scrutiny.

![Fig. 3: Five DaCM topologies (a-e), which have a net amplification of more than one, taken from the literature. The deformed profiles of the symmetric halves of (a-e) are shown in (f-j), respectively.](image)

4. ANALYSIS OF THE CHOSEN DaCM TOPOLOGY

The spring steel accelerometer of this work is made using wire-cut EDM (Mechanica, Maxicut\textsuperscript{\textregistered}). This machine is found to reliably give a minimum in-plane width of a beam to be 0.2 mm. Therefore, the DaCM topology M2 was modified such that the in-plane width of each member is fixed to 0.2 mm. This does not compromise the design significantly because the topology matters more than the actual shape when we consider the criteria listed in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
<th>M5</th>
</tr>
</thead>
<tbody>
<tr>
<td>(NA_n)</td>
<td>0.42</td>
<td>1.00</td>
<td>0.25</td>
<td>0.57</td>
<td>0.29</td>
</tr>
<tr>
<td>(FS_n)</td>
<td>1.00</td>
<td>0.09</td>
<td>0.31</td>
<td>0.11</td>
<td>0.43</td>
</tr>
<tr>
<td>(f_n)</td>
<td>0.45</td>
<td>0.15</td>
<td>0.74</td>
<td>0.30</td>
<td>1.00</td>
</tr>
<tr>
<td>(K_{\text{cross}})</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Score</td>
<td>0.41</td>
<td>0.77</td>
<td>0.28</td>
<td>0.46</td>
<td>0.44</td>
</tr>
</tbody>
</table>

Weights: \(0.75\) \(0.05\) \(0.10\) \(0.10\)

Table 1: Weighted analysis of the normalized metrics of five DaCMs labeled M1-M5. DaCM M2 is the best when the net amplification is given the highest weight.
The DaCM, the proof-mass and its folded beam suspension, and the magnet (for the Hall Effect sensor) are shown in Fig. (4). The thicknesses of all the beams, including those of the folded-beam suspension, are equal to 0.2 mm. The folded beams are 18 mm long and are 0.3 mm wide. The proof-mass is chosen to be 20 mm × 20 mm with a thickness of 10 mm. As noted earlier, the big proof-mass helps increase the sensitivity. The thickness of the proof-mass was determined as explained next.

A 3D model of the accelerometer was made in SolidWorks [7] to generate a meshed model for the finite element analysis. This is shown in Fig. (5). Static, geometrically nonlinear, elastic analysis was done in COMSOL [8] by applying the inertial force as a body force throughout the structure. As can be expected, when the proof-mass is thick, most of the inertia force is dominated by it. The thickness of the proof-mass was increased incrementally in a parametric analysis by monitoring the stress limit of the folded beams and the desired natural frequency of the entire structure. This determined the proof-mass thickness to be 10 mm. The Finite element simulation of the accelerometer with and without the DaCM was done. The analysis revealed that the natural frequency of the accelerometer with DaCM is around 50 Hz which is about 40% greater than an accelerometer without DaCM. Figure (6) shows the deformed profile of the structure in COMSOL. A net amplification of about five can be clearly seen in this figure.

The simulated displacement of the accelerometer with and without the DaCM is shown in Fig. (7). The remarkable improvement in the output displacement can be seen in the figure. In the range up to 3 g, the linearity is also remarkable. We can go for higher g. However, the Hall Effect sensor does not remain linear beyond this range.

5. PROTOTYPING AND TESTING

A 0.2 mm thick spring steel (EN J42/AISI 1080) foil was machined using wire-cut electro discharge machining (EDM) to create the shape of the accelerometer. Several holes were drilled using a CNC machine prior to EDM in order to thread the wire. A 9.8 mm thick steel piece was cut to shape and was glued to the proof-mass area to give the thickness of the proof-mass to be 10 mm. An L-shaped aluminum bracket was attached to the output side of the DaCM and then
a magnet was stuck to it. This was then packaged between two polypropylene sheets and top of another polypropylene sheet. The Hall Effect sensor (Allegro A1231) was fixed at a pre-determined distance from the magnet. The details can be seen in Figs. (8-9).

![Figure 8: The assembled spring steel accelerometer with a DaCM and the Hall Effect sensor.](image)

Fig. 8: The assembled spring steel accelerometer with a DaCM and the Hall Effect sensor.

![Figure 9: The close-up view of spring steel accelerometer. The L-shape piece to which the magnet is attached and the Hall-Effect sensor can be seen in the figure.](image)

Fig. 9: The close-up view of spring steel accelerometer. The L-shape piece to which the magnet is attached and the Hall-Effect sensor can be seen in the figure.

5.1 Testing

The fabricated accelerometer assembly was tested mechanically by hanging known weights to the proof-mass and thus increasing the force due to the acceleration acting on it. Different accelerations were applied by setting the accelerometer at different angles to the vertical. When the assembly is vertically set, 1 g acts on it; and zero when it is horizontal. Thus, the voltage signal of the Hall Effect sensor was noted for different values of the applied acceleration. This is shown in Fig. (10). When it is vertically set without any weights, the measured voltage was 71 mV. Therefore, the accelerometer has a sensitivity of 71 mV/g. But the calculated sensitivity was 65 mV/g. The smaller calculated sensitivity is possibly due to the less stiff beams produced by the wire EDM technique, which would increase the sensitivity. A sensitivity of 71 mV/g under real conditions implies that it can resolve 14 mg because the voltage-measurement device has a noise of 1 mV. Table 2 shows the summary of the design and measured parameters of the accelerometer.

![Figure 10: Measured output voltage vs. equivalent acceleration experienced due to weight hung from the accelerometer.](image)

5.2 Discussion

Based on the preliminary testing done until now, we can see that the performance of the spring steel accelerometer compares well with that of the silicon micro machined accelerometers (see Fig. 11). Another thing to note in this figure is that with DaCM, both the bandwidth and the resolution improve. We describe the second embodiment using capacitive sensing.

6. CAPACITIVE SENSING

Capacitive sensing is usually used at the micro scale but here we show that it can be used at the meso scale too with some benefits. This alternative sensing mechanism serves as a point of comparison for the commercial Hall Effect-based sensors described above. Here, we take the same accelerometer mass, suspension, and the DaCM and add to it a differential capacitive sensing attachment. Differential capacitive sensing gives high sensitivity with good linearity [4]. The solid model of the entire device is shown in Fig. (12a). As seen in

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of the proof-mass</td>
<td>30E-3 kg</td>
</tr>
<tr>
<td>Length of the proof-mass</td>
<td>20 mm</td>
</tr>
<tr>
<td>Breadth of the proof-mass</td>
<td>20 mm</td>
</tr>
<tr>
<td>Thickness of the proof-mass</td>
<td>10 mm</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>71 mV/g</td>
</tr>
<tr>
<td>Resonant frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Net amplification of DaCM</td>
<td>5</td>
</tr>
<tr>
<td>Thickness of the DaCM</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>Overall size</td>
<td>60 mm ×</td>
</tr>
<tr>
<td></td>
<td>60 mm ×</td>
</tr>
<tr>
<td></td>
<td>10 mm</td>
</tr>
<tr>
<td>Measured resolution</td>
<td>14 mg</td>
</tr>
</tbody>
</table>

Table 2: Specifications of the accelerometer
the capacitance of the two parallel-plate capacitors changes and this is fed to a capacitance extraction circuit. Figure (12b) shows a different and close-up view of the DaCM and the capacitor arrangement using a meshed finite element model. The base capacitance was estimated to be 10.6 pF using the simulation. Figure (13) schematically shows the method capacitance extraction. We used the printed circuit board (PCB) implementation of continuous time voltage (CTV) method that uses modulation and de-modulation [19]. In this method, the differential capacitance is modulated by exciting the capacitors with a carrier frequency. The modulated waveform is then de-modulated, amplified, and passed through a low-pass filter to extract the change in capacitance as a measurable voltage.

The sensor element along with the differential capacitance beams was fabricated using wire-cut EDM. Electrical connections were made to connect the sensor’s capacitors to the PCB implementation of the universal capacitance sensor. The measure base

Fig. 11: Comparison of the performance of the accelerometer with the micromachined accelerometers from the literature. Note the reversed scale on the y-axis. After adding the DaCM, both the bandwidth and the resolution improve. Adapted from [18].

this figure, a rectangular frame with three beams is attached to the output of the DaCM. Underneath this frame, there are three corresponding beams that act like fixed electrodes. The beams on the moving frame and those on the fixed electrode are aligned such that two parallel-plate capacitors are formed. The gap between the capacitor plates was 3.5 mm. When the frame moves,
capacitance was 10.8 pF, which compares well with the estimated capacitance of 10.6 pF. The sensor was mounted on a cart-wheel type arrangement shown in Fig. (14). The cart-wheel arrangement helps tilt the sensor so that the proof-mass is vertical or horizontal. When it is vertical, no inertial force acts in the sensing direction. Hence, it will detect zero acceleration. On the other hand, in the horizontal position an acceleration of \( g \) is detected. Figure (15) shows the measured response. It can be seen that we got 1 V/g, which means that we can detect 1 mg considering that we have about 1 mV noise in our capacitance measurement system. Thus, while the Hall Effect-based sensor gave 14 mg resolution, the capacitive sensor gives an order of magnitude better resolution. However, the drawback is that the sensor's response is nonlinear. This needs to be rectified as linearity is preferred in sensors. This nonlinearity here is not due to the differential sensing but because of the large motion of the output of the DaCM. That is, the capacitance vs. acceleration is nonlinear as opposed to voltage vs. capacitance being nonlinear.

7. CONCLUSIONS

In this paper, we have designed, fabricated, and tested a spring steel accelerometer at the meso-scale. The use of a displacement-amplifying compliant mechanism (DaCM) and exploring the utility of metals in miniature accelerometer application are the contributions of this paper. The DaCM helps increase both the sensitivity and bandwidth of the accelerometer. The selection of a DaCM from the existing topologies and its optimization for this application were described in the paper. A wire-cut EDM of spring steel foil was used to prototype the accelerometer. Because we have used a Hall Effect sensor, the accelerometer has a size of 60 mm x 60 mm \( \times 10 \) mm packaged size. Calibration of the device made in this study indicates that the accelerometer can resolve up to 14 mg in the presence of the noise. We also designed and fabricated a capacitive-sensing based alternate embodiment. This showed a resolution of 1 mg-an order of magnitude improvement over the Hall Effect sensor-but has nonlinear response.

ACKNOWLEDGMENTS

The authors thank Mr. G. Balaji, Research Assistant, Department of Mechanical Engineering, IISc, Bangalore, for his technical assistance in fabricating the device. This work was partially funded by the DRDO Wireless Sensor Network project in IISc. This support is gratefully acknowledged.

REFERENCES

2. W. Yun and R. T. Howe, "Silicon micromachined accelerometers: a perspective on recent developments",