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A Meso-scale Accelerometer using a Hall-effect Sensor and a Displacement-amplifying Compliant Mechanism

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Abstract

This paper reports a novel, low-cost, moderately sensitive, meso-scale accelerometer fabricated with spring steel foil and equipped with a Hall-effect proximity sensor. The Hall-effect sensor is small in size, and is suitable for miniature proximity sensing applications. 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 ENJ42/AISI1080 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 proposed here can be miniaturized further and fabricated with silicon microfabrication processes for enhanced sensitivity and resolution.

Keywords: Accelerometers, Hall-effect sensor, wire-EDM, and displacement-amplifying compliant mechanism

1 Introduction

Accelerometers have a 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 an electrical signal using various transduction principles such as capacitive, electromagnetic, piezoelectric, piezoresitive, electron tunneling, laser interferometry, etc. Recent advances in silicon microfabrication technologies have led to the miniaturization of these devices with considerable enhancement in their performance [1-3]. However, these devices require silicon fabrication technologies and complex on-chip electronic circuitry. While low-resolution micromachined 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. Therefore, towards the goal of developing a low-cost, moderately sensitive accelerometer, in this paper we present a miniature (“small volume” because of its flatness) accelerometer. The material we have chosen is spring steel (ENJ42/AISI1080). The fabrication process is wire-cut Electro Discharge Machining (EDM). Wire-cut EDM is not an inexpensive process 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.

While capacitive sensing is not ruled out at the meso-scale, we have chosen Hall-effect sensing principle. At the meso-scale magnetic based Hall-effect proximity sensors provide a cost-effective, simple, and compact alternative method to sense displacements [4]. Although the Hall-effect sensor is small in size and simple to use, it has a very low sensitivity (about 370 V/m for Allegro A1231), thus limiting the resolution of the accelerometer. 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 complaint mechanism (DaCM) to the proof-mass of the accelerometer [5].

The rest of the paper is organized as follows. 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 tested 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. Concluding remarks are in Section 5.

2 Displacement-amplifying Compliant Mechanisms (DaCMs)

DaCMs are usually used in literature to amplify the displacement of actuators which have limited stroke [5]. 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 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 input load. The inertia of the DaCM is lumped at the input and output sides and is denoted by m_{ci} and m_{co} respectively. A mass m_{ext} is 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.

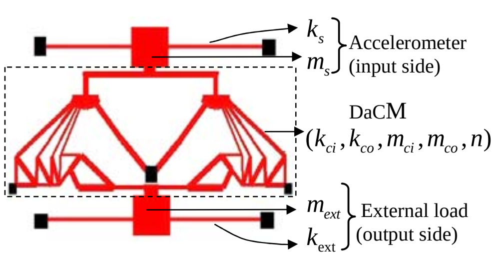

Figure 1: A DaCM and its lumped parameters. The accelerometer and the sensor side are also shown schematically. The input side shows the proof-mass and a suspension. The output side shows the external mass (magnet in the Hall effect sensor) and a suspension (which will be absent for a Hall effect sensor).

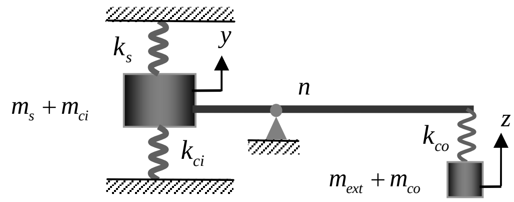

Figure 2: The spring-mass-lever model of DaCM.

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

$$z = \frac{m_s g}{k_s} \tag{1}$$

The output z_1 of the accelerometer with the DaCM is given by

$$z_1 = \frac{(m_{ext} + m_{co})\, g (k_s + k_{ci} + n^2 k_{co}) + n m_s g k_{co}}{k_{co}(k_s + k_{ci})} \tag{2}$$

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

$$NA = \frac{k_s \left\{ (m_{ext} + m_{co})(k_s + k_{ci} + n^2 k_{co}) + n m_s k_{co} \right\}}{m_s k_{co}(k_s + k_{ci})} \tag{3}$$

From Eq. (3), we can see that when $(m_{ext} + m_{co}) = 0$ and $k_{ci} << k_s$, the DaCM would approach a rigid lever because only then $NA = n$. Otherwise, $NA < n$. This 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 stiffnesses and inertias do matter. Furthermore, by computing the first two natural frequencies 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 and designed for the accelerometer application of this paper.

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 output voltage of the sensing element for unit g acceleration. Apart from the sensitivity and 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 [5]. 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. 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 highest weight to NA. Thus, we chose M2 for further design.

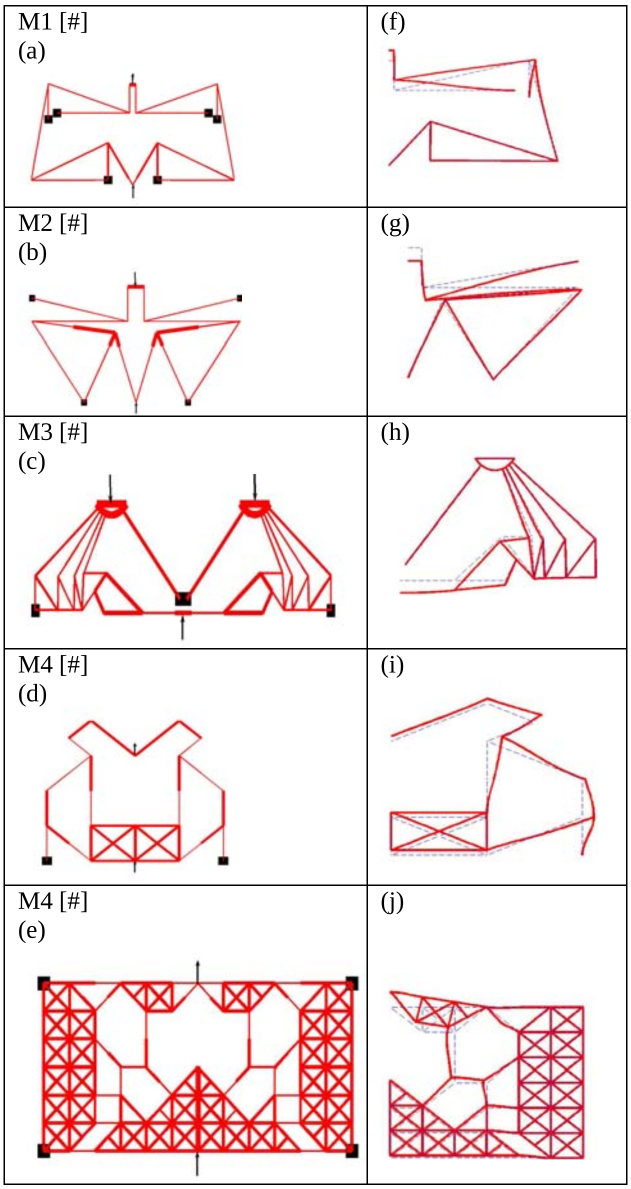

Figure 3: Five DaCM topologies (a-e), which have a net amplification of more than one, taken from the literature. The deformed profiles of the symmetric halves of (a-e) are shown in (f-j) respectively.

3.1 Analysis of the chosen DaCM topology

The spring steel accelerometer of this work is made using wire-cut EDM (Mechanica, Maxicut^e). 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 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.

	M1	M2	M3	M4	M5
NA_n	0.42	1.00	0.25	0.57	0.29
FS_n	1.00	0.09	0.31	0.11	0.43
f_n	0.45	0.15	0.74	0.30	1.00
K_{crossn}	0.00	0.00	0.01	0.00	1.00
Case 1	0.41	**0.77**	0.28	0.46	0.44

Weights	NA_n	FS_n	f_n	K_{crossn}
Case 1	**0.75**	0.05	0.10	0.10

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 all 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, a big proof-mass helps increase the sensitivity. The thickness of the proof-mass was determined as explained next.

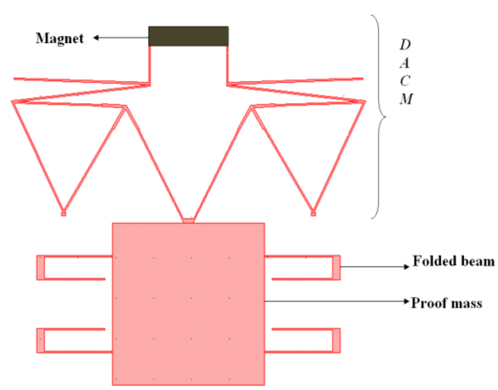

Figure 4: The accelerometer with the chosen DaCM in its modified form and including the magnet.

A 3D model of the accelerometer was made in SolidWorks [6] 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 [7] 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 the DaCM is around 50 Hz which is about 40% greater than an accelerometer without DaCM. Fig. (6) shows the deformed profile of the structure in COMSOL. A net amplification of about five can be clearly seen in this figure.

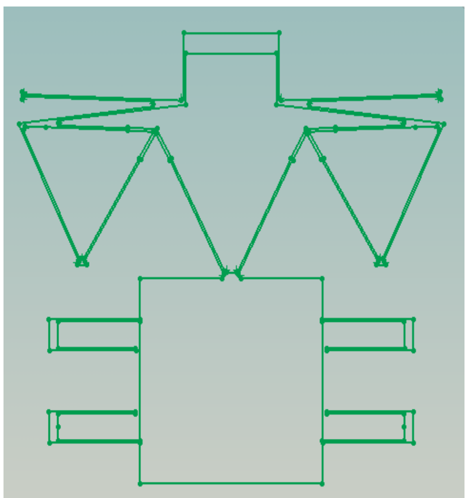

Figure 5: The solid model of the accelerometer with its proof-mass and folded-beam suspension and attached to a DaCM.

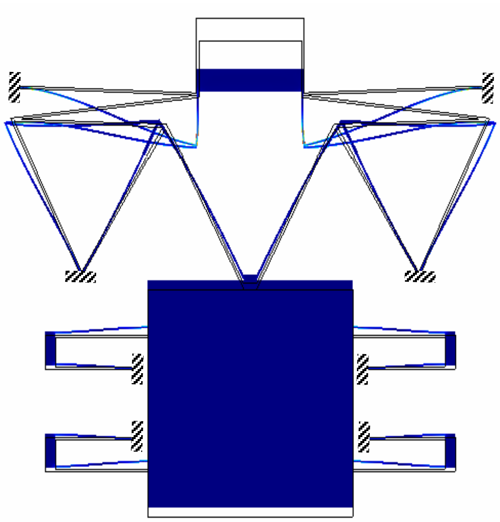

Figure 6: The deformed profile of the accelerometer and the DaCM under acceleration induced body force. The displacement amplification of about five is noticeable in the figure.

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.

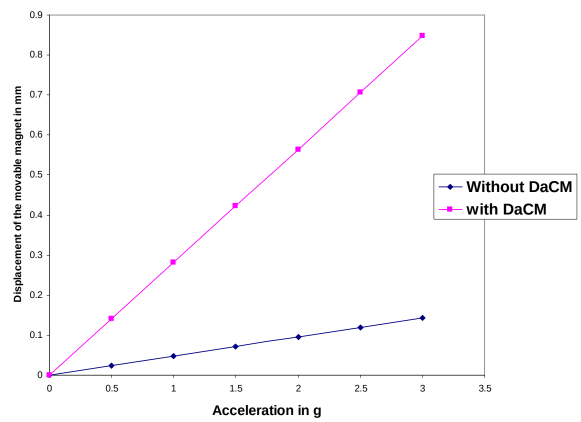

Figure 7: The simulated output displacements of the accelerometer with and without the DaCM for a range of applied accelerations.

4 Prototyping and Testing

A 0.2 mm thick spring steel (ENJ42/AISI1080) foil was machined using wire-cut electro discharge machining (EDM) to create the shape of the accelerometer shape. 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 aluminium piece 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).

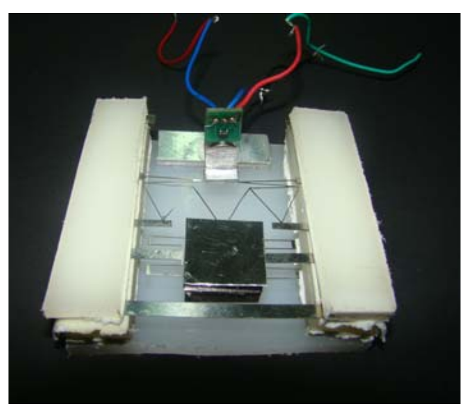

Figure 8: The assembled spring steel accelerometer with a DaCM and the Hall Effect sensor.

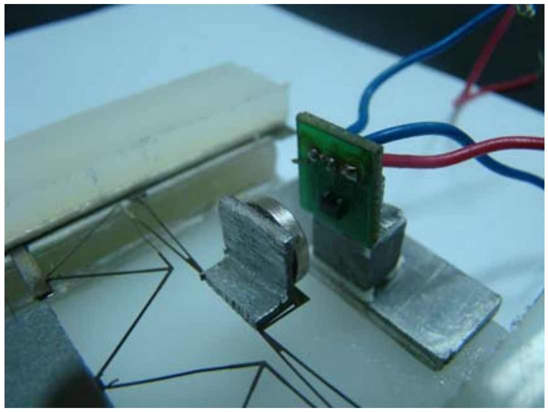

Figure 9: The close-up view of spring steel accelerometer. The L-shape piece to which the magnet is attached and the Hall Effect sensor can be seen in the figure.

4.1 Testing

The fabricated accelerometer assembly was tested mechanically by hanging known weights to the proof-mass and thus increasing the acceleration force acting on it. When it is vertically set, 1 g acts on it. Less than 1 g is obtained by setting it different known inclined angles. More than 1 g is obtained by adding weights. In all cases, equivalent acceleration and the voltage in the Hall Effect sensor were noted. These are 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 65mV/g. The smaller calculated sensitivity is possibly due to the less stiff beams produced by the wire EDM technique, which would have increased 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.

Table 2: Specifications of the accelerometer

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

4.2 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 micromachined accelerometers (see Fig. (11)). Another thing to note in this figure is that with DaCM, both the bandwidth and the resolution improve. Resolution shown in Fig. (11) is calculated from the lowest measured sensitivity and the bandwidth.

Our ongoing work includes using capacitive detection rather than the Hall Effect sensor. This will help in reducing the thickness of the assembled accelerometer. The same design can also be further miniaturized for silicon micromachining.

It should be noted that a DaCM improves the sensitivity (and hence resolution) beyond whatever other improvements are achieved with electronics, signal processing, or fabrication [9].

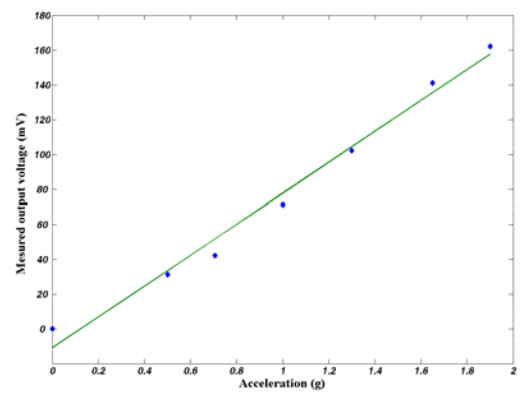

Figure 10: Measured output voltage vs. equivalent acceleration experienced due to weight hung from the accelerometer.

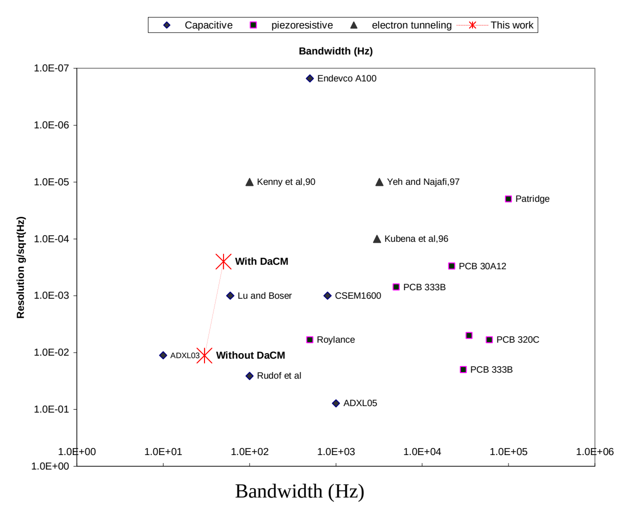

Figure 11: Comparison of the performance of the accelerometer with the micromachined accelerometers from the literature. Note the reversed scale on the y-axis. After adding the DaCM, both the bandwidth and the resolution improve. Adapted from [8] and modified with extra information.

5 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) in an accelerometer application is the main contribution of this paper. A DaCM helps increase both the sensitivity and the 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 × 60 mm × 10 mm packaged size. But it can be made smaller than this by using capacitive sensing. Current testing indicates that the accelerometer can resolve 14 mg.

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