# DEVELOPMENT OF AN ACCELERATION SENSOR INCORPORATING A MAGNETO-SENSITIVE ELASTOMER

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**Abstract**

The present paper introduces an operating principle and concept of an acceleration sensor with an adaptable measuring range and sensitivity basing on the adjustability of the material properties of magneto-sensitive elastomers. The development of such a sensor requires a comprehensive understanding of the behaviour of the utilized material. Therefore, the magnetic field dependent behaviour of magnetic hybrid elastomer (MHE) with embedded magnetically soft and hard particles is investigated. Free vibrations of MHE beams are executed and hereafter, the frequency and damping behaviour are established. It is shown that the change of the magnetic field caused by a vibrating MHE beam contains detailed information about its deflection. Basing on the revealed results, the acceleration sensor concept incorporating a functional MHE element is presented. The possibility to adjust the material properties of this element with an externally applied magnetic field is used.

## 1 INTRODUCTION

Magneto-sensitive elastomer is a smart material whose material behaviour is alterable by an applied magnetic field. This manner is achieved by embedding magnetic particles in an elastomeric matrix. Current research basing on experimental investigations of magneto-sensitive elastomers containing exclusively magnetically soft [1, 2, 3] as well as exclusively magnetically hard particles [4, 5] points out that the stiffness and damping properties of the material are adjustable depending on an external magnetic field. Latter facilitate the premagnetization of the material which constitutes an additional parameter to influence the material behaviour at the time of production. Regarding this, other possibilities are particle and matrix properties as well as their mixing ratio. Magnetic hybrid elastomers (MHEs) which incorporate both kind of particles are rarely investigated until now [6, 7, 8]. Other related materials with field-depending properties are magnetorheological and electrorheological fluids which are nowadays well examined and used in applications like fast acting hydraulic valves [9] and shock absorbers [10, 11]. In the case of magneto-sensitive elastomers, applications like vibration isolation and damping [12, 13], shock absorption regarding prosthetic and orthotic devices [14] as well as sensor and actuator systems [15, 16] are subjects of current research.
In this paper, a concept of an acceleration sensor with an adaptable measuring range and sensitivity incorporating an MHE is presented. The development of such a sensor requires a comprehensive understanding of the material behaviour. Especially, the variation of the eigenfrequency and damping ratio depending on an external magnetic field is an important criterion. For this reason, experiments with MHE samples are carried out. Moreover, the magnetic field distortion is used

 

to determine the bulk deflection of the acceleration sensor. Further experiments are executed to analyse the potential of this method.

## 2 EXPERIMENTAL

### 2.1 Test setup

Free bending vibrations of MHE beams fixed at the top and featuring a free end under the influence of a magnetic field are investigated. The experimental setup is shown in figure 1. A Helmholtz coil generates in the relevant region a nearly uniform magnetic field in the range of 0...60 mT with an homogeneity of 96.5% [17]. To adjust a defined deflection of the beam, a release mechanism is utilized. The deflection at the free end as well as the change of the magnetic flux density along the horizontal axis are measured by a laser triangulation sensor and a Hall probe. The latter is positioned under the sample.

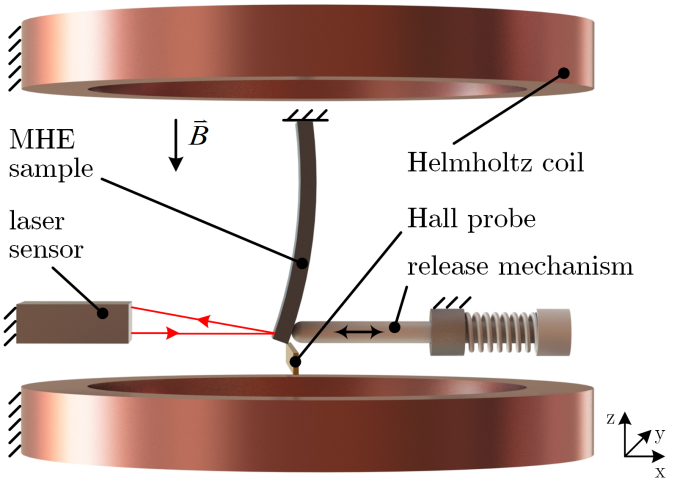


Figure 1: experimental setup to investigate the free vibrational behaviour of MHE beams fixed at the top and featuring a free end under the influence of an applied magnetic field

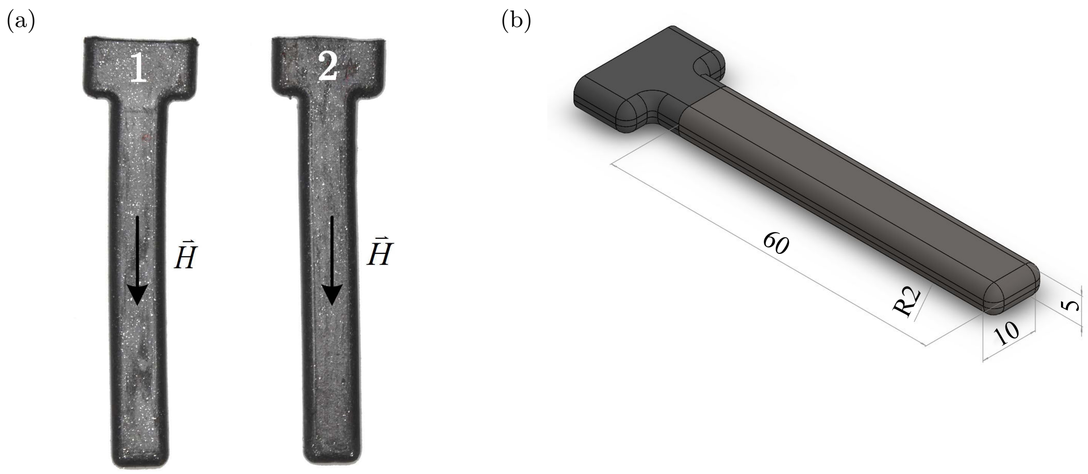


Figure 2: (a) investigated MHE samples magnetized along the length axis; (b) geometry and dimensions of the MHE samples in mm

### 2.2 MHE samples

Two identical MHE samples consisting of a polymeric matrix and magnetically soft carbonyl iron (Fe) and magnetically hard neodymium iron boron particles (NdFeB) are investigated. The beams are made from the material with a total filler volume concentration of 30 vol% with a ratio of magnetically hard and soft particles of 4:1. Their sizes are 40-100 $\mu$m and 3-10 $\mu$m, respectively. The elastic matrix is composed of the two component resin 'SIEL'. After the curing process of the resin including the embedded particles, the sample is magnetized with a large magnetic field of a flux density of 2 T. The orientation of this magnetic field relative to the sample is shown in figure 2a.
The sample geometry is shown in figure 2b. The investigated MHE beams have a length of 60 mm as well as rounded corners to reduce magnetic field distortions. Additionally, the dimensions are specifically chosen to gain a lower section modulus in the direction of vibration than in the perpendicular direction to avoid undesired oscillations.

### 2.3 Results

The time-dependent deflections of sample 1 with and without the influence of an external magnetic field are shown in figure 3. It illustrates the adjustability of the vibrational behaviour of beams consisting of MHE, which gives an initial assessment of the controllability of the material characteristics. Additionally, the corresponding periods decrease throughout the oscillation. In the shown example with a magnetic flux density of $B_e = 60$ mT the eigenfrequency increases by 1.92 Hz or rather 15.7 %. Therefore, the vibration can be classified as non-linear.

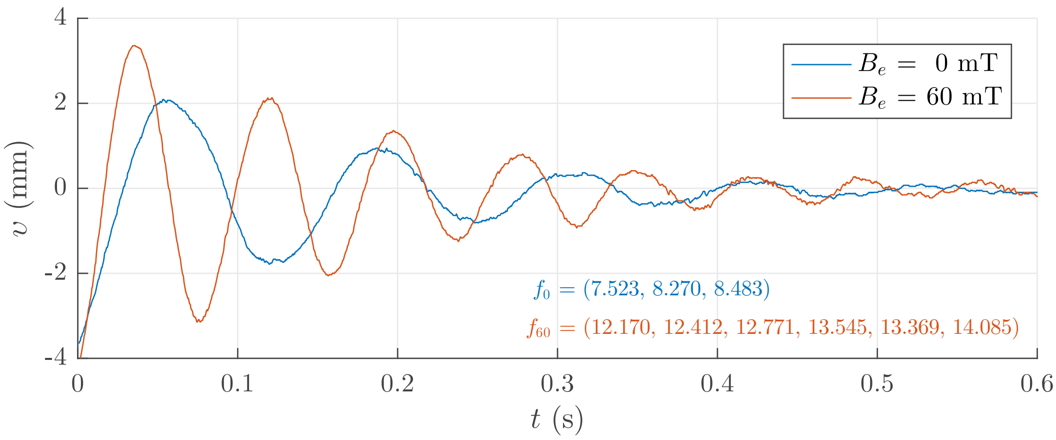


Figure 3: vibrational behaviour of MHE sample 1 for $B_e = 0$ mT and $B_e = 60$ mT characterized by its deflection versus time curves; the corresponding increasing eigenfrequencies $f_0$ and $f_{60}$ of the oscillations are given in Hz

Figure 4a and 4b show the frequency behaviour of both investigated samples under the influence of a magnetic flux density $B_e$ between 0 and 60 mT. These frequencies are determined using the measured deflection and the resulting period durations based on six repetitions for both orientations. The median values of the frequencies rise with an increasing magnetic flux density. The relative increase of the first eigenfrequencies can be achieved up to 58.9% for both samples.
Furthermore, in the range of the adjusted external magnetic field, the vibration shows a weakly damped behaviour, see figure 4c and 4d. The damping ratio $D$ of the deflection versus time curves can be calculated using the logarithmic decrement $\Lambda$, which is determined using the amplitude $\hat{v}$

 

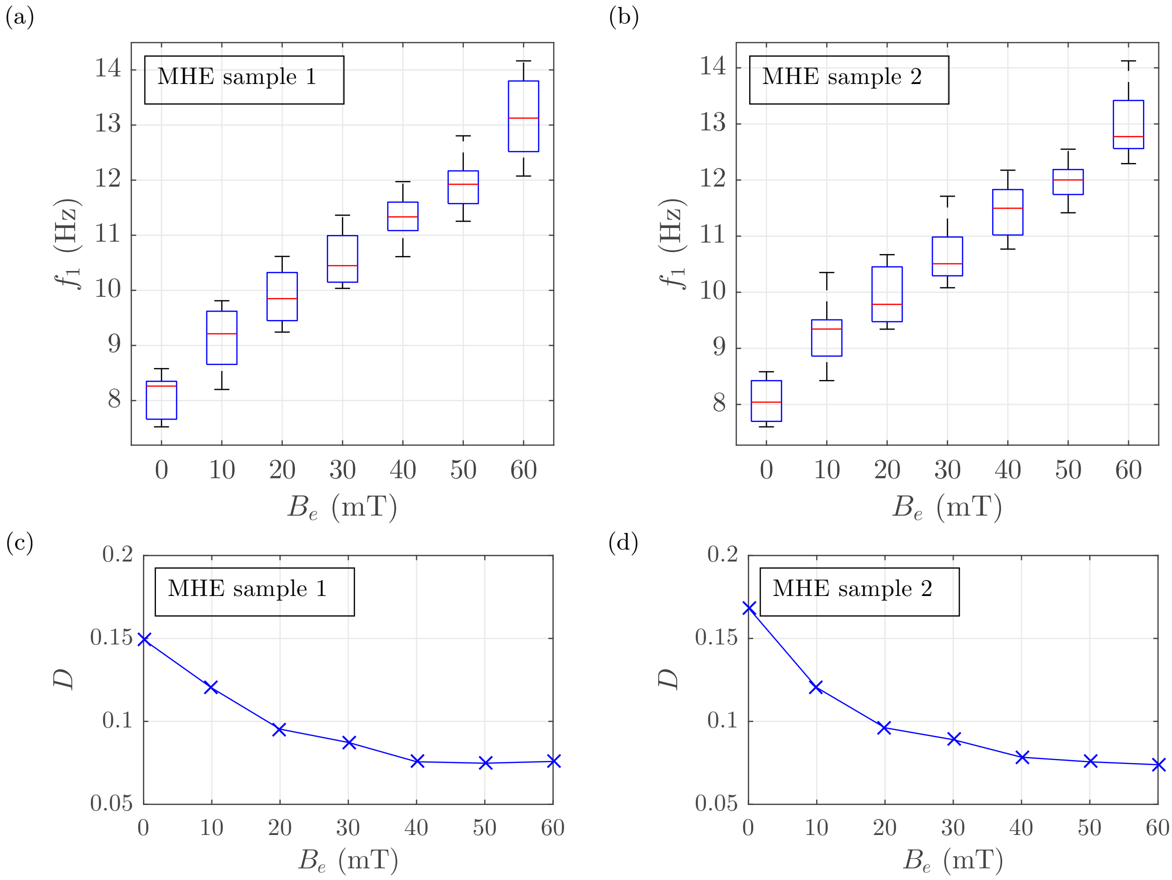


Figure 4: the first eigenfrequencies $f_1(B_e)$ as a function of the external magnetic field: (a) MHE sample 1, (b) MHE sample 2; the box demonstrating the 25th and the 75th percentile as well as the median values; the damping ratios $D(B_e)$ as a function of the external magnetic field: (c) MHE sample 1, (d) MHE sample 2.

of the oscillation at the time $t_1$ and $t_3$:

$$D = \frac{\Lambda}{\sqrt{4\pi^2 + \Lambda^2}}, \tag{1}$$

$$\Lambda = \frac{1}{2} \ln \left( \frac{\hat{v}(t_1)}{\hat{v}(t_3)} \right). \tag{2}$$

The damping ratio $D$ is monotonically decreasing with the applied field magnitude and reaches values from 0.1684 to 0.0738.
Figure 5b and 5d show the deflection as well as the magnetic flux density measured under the sample versus time with an external magnetic field of $B_e = 0$ mT and $B_e = 60$ mT. The oscillations of the beam and of the meausured magnetic flux densitiy boast the same frequency characteristics with no phase shift. So, it can be seen that the flux density contains detailed information about the position of the vibrating beam. Figure 5a and 5c point out the interrelationship between the measured magnetic flux density and the beam deflection. It is observed that the former can be unambiguously determined from the latter. In addition, a linear relation exists in a specific range of deflection. The measurement exhibits an approximate sensitivity of 1.4 mT/mm or rather 2.1 mT/mm for the different external magnetic fields of 0 and 60 mT in the linear section.

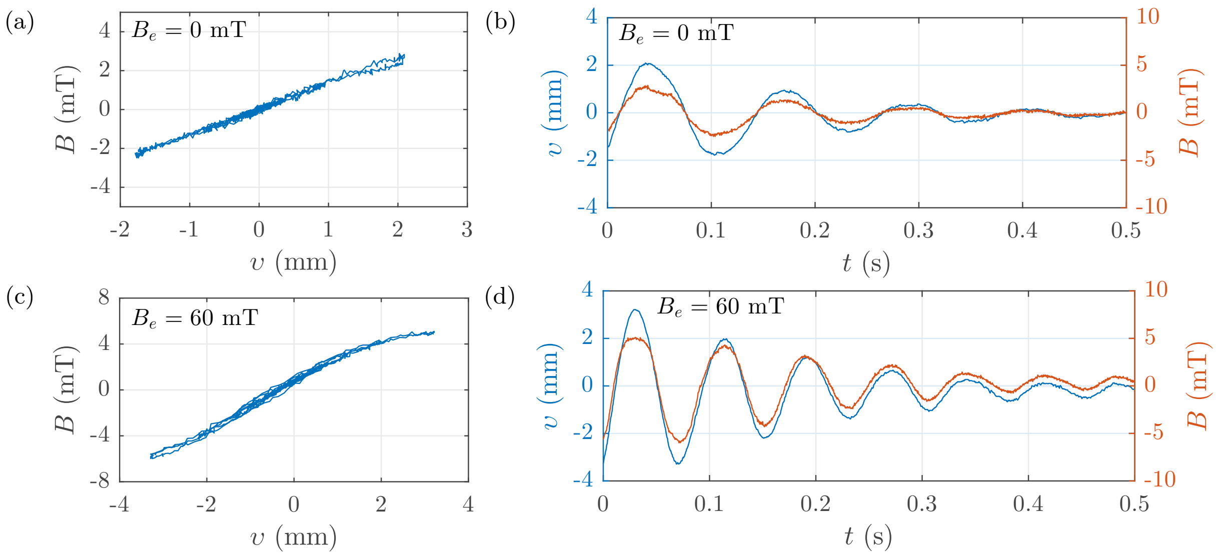


Figure 5: relationship between beam deflection $\upsilon$ at the end of MHE sample 1 and the magnetic flux density $B$ measured by the Hall sensor for the external magnetic flux densities $B_e = 0$ mT (a, b) and $B_e = 60$ mT (c, d)

## 3 ACCELERATION SENSOR INCORPORATING AN MHE

In this section based on the revealed results of section 2, a concept of an acceleration sensor with an adaptive measuring range and sensitivity of the material properties of MHE is presented. For this reason, at first, the operating principle of state-of-the-art acceleration sensors and the influence factors on the calculation of the measuring range are explained. Secondly, the design of the sensor prototype is proposed.

### 3.1 Operating principle of an acceleration sensor

State-of-the-art acceleration sensors use the inertial force on a bulk caused by an applied acceleration. The bulk $m$ is elastically attached to the housing, see figure 6. The acceleration $\ddot{x}$ effecting the sensor causes a bulk deflection $y_R$ in relation to the housing. By measuring the latter, the acceleration can be determined. In this regard, the method of capacitive displacement measurement is usually used [18]. The oscillation system is described by equation (3) with the damping coefficient $k$, the spring constant $c$ and the deflection of the imposed harmonic excitation $x(t)$:

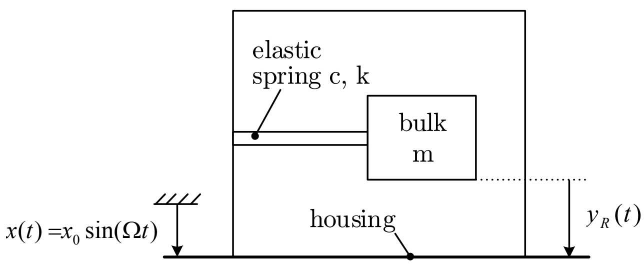


Figure 6: operating principle of an state-of-the-art acceleration sensor

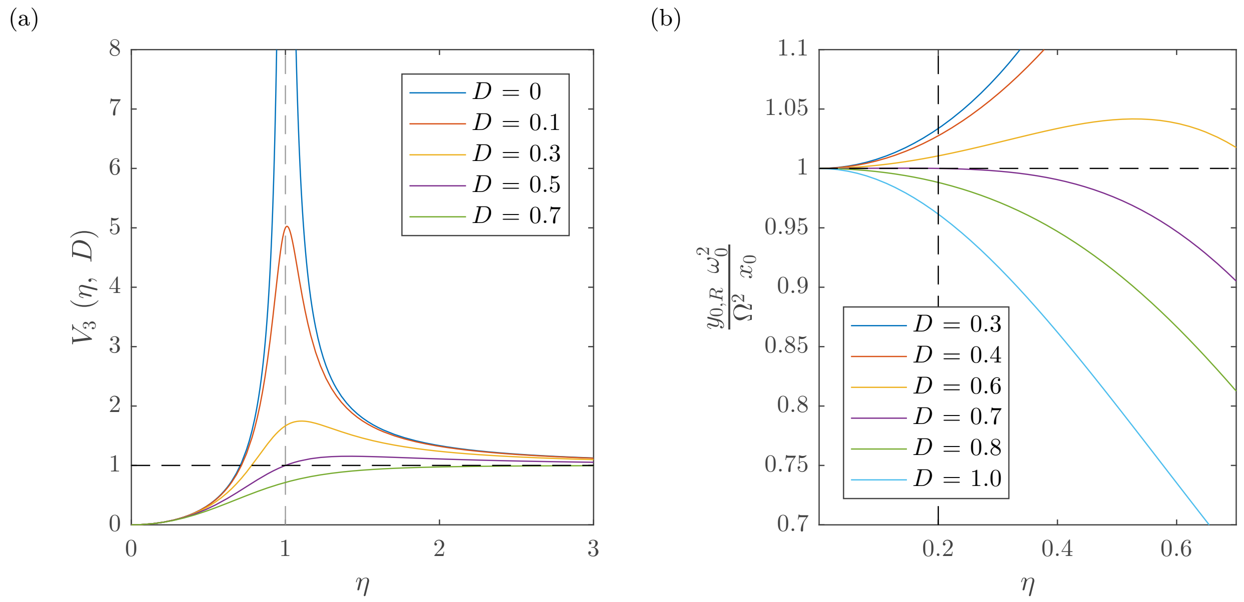


Figure 7: (a) amplification function; (b) ratio between mass deflection and acceleration

$$m\ \ddot{y}_R(t) + k\ \dot{y}_R(t) + c\ y_R(t) + m\ \ddot{x}(t) = 0. \tag{3}$$

The differential equation with a sinusoidal excitation of the housing with the frequency $\Omega$ and the amplitude $x_0$ is as follows:

$$m\ \ddot{y}_R(t) + k\ \dot{y}_R(t) + c\ y_R(t) = m\ \Omega^2 x_0\ \sin(\Omega t). \tag{4}$$

After the transient response, the steady-state movement of the bulk can be expressed as with the amplitude $y_{0,R}$ and the phase shift $\varphi$:

$$y_R(t) = y_{0,R}\ \sin(\Omega t + \varphi). \tag{5}$$

Here, the amplitude $y_{0,R}$ and the phase shift $\varphi$ are calculated as follows using the amplification function $V_3$, the damping ratio $D$ and the eigenfrequency $\omega_0$:

$$y_{0,R} = x_0 V_3(\eta, D), \quad V_3(\eta, D) = \frac{\eta^2}{\sqrt{(1-\eta^2)^2 + (2D\eta)^2}}, \tag{6}$$

$$\tan\ \varphi = \frac{2D\eta}{1-\eta^2}, \quad \eta = \frac{\Omega}{\omega_0}. \tag{7}$$

Furthermore, the eigenfrequency and the damping ratio are given by:

$$\omega_0 = \sqrt{\frac{c}{m}}, \tag{8}$$

$$D = \frac{k}{2m\ \omega_0}. \tag{9}$$

A visualization of the amplification function $V_3(\eta, D)$ boasting different damping ratios is shown in figure 7a. For small values of $\eta$, the denominator in the formula of $V_3(\eta, D)$ is nearly one. This results in a linear relationship between the amplitude of the mass deflection $y_{0,R}$ and the amplitude of the acceleration $a_0$:

$$y_{0,R} = \frac{x_0\ \Omega^2}{\omega_0^2} = \frac{a_0}{\omega_0^2}. \tag{10}$$

The acceleration of the sensor can be determined using this equation in connection with a measurement of the bulk deflection. The maximum measurable acceleration $a_{0,\ max}$ and hence also the measuring range is revealed by the achievable deflection $y_{0,R}$ limited by the installation space and the range of deflection in which the oscillation can be assumed as linear, see equation (10). Subsequently, the frequency range for which the used simplification is valid and with this a linear relation between the bulk deflection and the acceleration exists has to be identified. For this reason, the ratio between the mass deflection and the acceleration is formed in the following:

$$\frac{y_{0,R}}{\Omega^2\ x_0} = \frac{1}{\omega_0^2} \cdot \frac{1}{\sqrt{(1-\eta^2)^2 + (2D\eta)^2}}. \tag{11}$$

This correlation is visualized in figure 7b. In the case of a damping ratio accounting for 0.7, a frequency range with a sufficient accuracy of (0...0.2) $\omega_0$ results [18].

### 3.2 Sensor concept

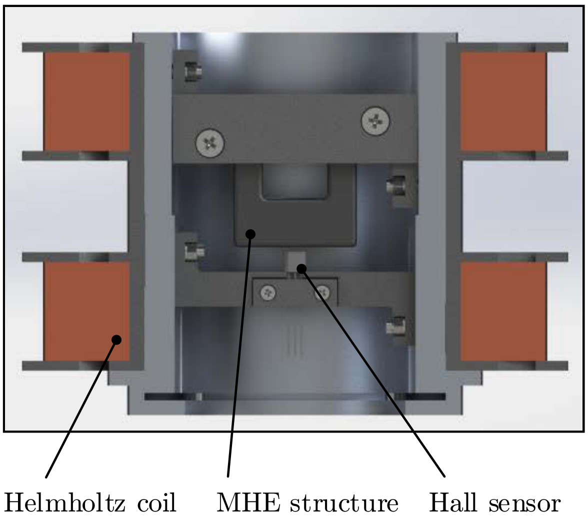


Figure 8: concept of an adaptive acceleration sensor incorporating an MHE structure

The measuring range and the sensitivity of acceleration sensors depend on the eigenfrequency of the oscillation system which is shown in equation (10). Furthermore, the suggestibility of the eigenfrequency of MHE under the influence of an external magnetic field is proven in experiments, see figure 4. This leads to the possibility of the realization of acceleration sensors with an adaptable measuring range and sensitivity using an adjustable magnetic field and an MHE bending spring. Figure 8 shows a possible technical implementation of such an acceleration sensor. The oscillation system consisting of MHE is fixed in the housing and boasts the geometry of two bending springs connected in parallel. The needed adjustable magnetic field is generated by a pair of Helmholtz coils. The external mechanical excitation leads to the vibration of this MHE structure. Its deflection is measured by a Hall sensor. As already stated in section 2.3, the magnetic flux density measured under the oscillating beam consisting of MHE contains detailed information about its position.
The selection of MHE instead of magneto-sensitive elastomers containing exclusively soft or hard

magnetic particles has many reasons:

- the possibility of pre-magnetizing which eases the measurement of the magnetic field distortions, that paves the way to obtain the bulk deflection
- the larger number of modifiable parameters, e.g. the mixing ratio of magnetic particles, the filler concentration, direction and strength of the magnetizing field, lead to a more extensive adjustability of the material properties at the time of production
- the strong dependence of the damping and elastic properties of MHE under the influence of an external magnetic field.

The desired functional principle of the proposed sensor concept incorporating MHE with an adaptive behaviour and operating sensitivity has great potential. However, for designing such intelligent devices, further research and engineering aspects should be put in relation to each other.

## 4 CONCLUSIONS

The present paper deals with the elastic and damping behaviour of two samples consisting of MHE which include soft as well as hard magnetic particles. The beams execute nonlinear bending vibrations and show an increase of the median values of the determined eigenfrequencies of 58.9% with an external magnetic field. The damping ratio monotonically decreases and reaches values from 0.1684 to 0.0738. Furthermore, experiments point out that throughout free bending vibrations of a beam consisting of MHE the magnetic flux density measured under the sample contains detailed information of the deflection. The latter can be unambiguously determined from the former, as a linear relation between them exists for small deflections of the beam.
An operating principle and concept of an acceleration sensor incorporating an MHE with an adaptable measuring range and sensitivity using the adjustability of the eigenfrequency are presented. It boasts an oscillation system consisting of two bending springs connected in parallel which are composed of MHE. An homogenous magnetic field is required to adjust the eigenfrequency of the functional MHE element according to the required sensitivity range. The deflection of the bulk can be unambiguously determined by magnetic field distortions. The specific aspect concerning this kind of sensors is the dependence of the damping properties on an external magnetic field. It is shown that a constant damping ratio of 0.7 is required to achieve a linear relation between external acceleration and bulk deflection.

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