Impact Absorption System Based on MRE with Halbach Array

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Abstract

This paper presents impact absorption system based on magnetorheological elastomer with Halbach magnetic arrays used for tuning. Its design and results of experimental evaluation are presented together with proposition of a non-linear model to describe the system. In the end validation of the model is presented based on energy and power balance method for its parametrization. This paper presents both novel approach to impact absorption and to modelling of a system based on smart material such as magnetorheological elastomer.

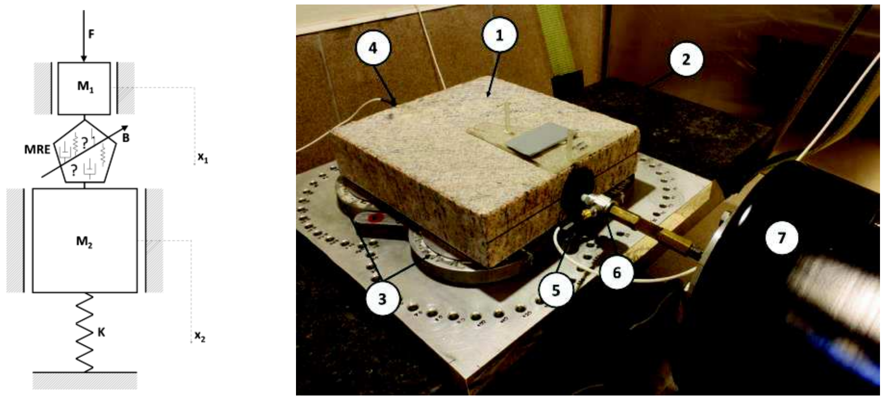
Keywords: Experimental mechanics, smart material, magnetorheological elastomer, magnetic field, modelling, parametrization, simulation

1. Introduction

Magnetorheological elastomer (MRE) is smart material that allows innovative approach to impact and vibration control in mechanical and civil structures. It is a composite material made out of rubber matrix and soft magnetic particles mixture. Application of magnetic field influences change of rheological and mechanical properties of the material as the particles try to arrange themselves into chain like structures inside of the material, along magnetic field vectors. Therefore material properties can be controlled with use of external magnetic field, what can be used in controllable impact and vibration control [1-4]. In the paper design and construction of the impact absorption system based on MRE material and Halbach arrays have been presented. Double dipolar circular Halbach array is an important element of this system as it is innovative method for low power consuming magnetic generator that can be used for stimulation of MRE absorbers and isolators [5, 6]. Testing of presented system have shown its potential for change of resonance frequency and its damping properties. On base of the experimental results a non-linear models of the system have been proposed. For its validation and parametrization energy and power balance method have been used [7, 8]. Results of the parametrization indicate need for search of another model as the results do not match with experiment.

2. Absorption system design

Presented impact absorption system is designed to absorb impact energy and mitigate vibrations occurring after impact. It was thought as single degree of freedom system, however for testing purposes second degree was added. The idea of the system is presented in Figure 1. a), where element between mass M_1 and M_2 is MRE material and spring K correspond to suspension the system is hanging on. The system is based on a magnetorheological elastomer working as damping material. For magnetic stimulation of the MRE material double dipolar circular Halbach arrays were designed and manufactured. Due to need for use of strong magnetic fields all elements used in the test rig are made out of non-magnetic materials, like marble, aluminium and brass. The test system is presented in Figure 1. b).



a) b)

Figure 1. Schematic idea of the absorption system a), picture of the absorption system, where: 1 - upper mass (4.25 kg), 2 - bottom mass, 3 - Halbach magnetic arrays, 4 - acceleration sensor, 5 - impact head, 6 - force sensor, 7 - shaker

For measurement purposes system is equipped with two sensors: accelerometer (353A33, PCB) located at the back of the upper mass and force sensor (208A02, PCB) between impact head and shaker. Signals were collected with use of DAQ board (U2355A, Keisight). It was also used to control shaker (2075E, The Modal Shop Inc.) powered by amplifier (SmartAmp Power Amplifier 2100E21 series, The Modal Shop Inc.). Modal shaker was used for controlled impact impulse generation. For programing purposes computer software (VEE 9.32, Keisight) was used [6].
Upper mass was placed on four magnetorheological elastomer dampers surrounded by double dipolar circular Halbach arrays. They were placed on CNC milled aluminium plate with locking holes for Halbach arrays. The base of the system was marble block with weight of almost 40 kg to provide low frequency swing of the system after each excitation.

2.1. Magnetorheological elastomer

Magnetorheological elastomer is a smart material that changes its mechanical and rheological properties under influence of external magnetic field. It is rubber material filled with soft magnetic particles that tend to create chain like structures in the direction of the magnetic field that stimulates the material. MRE material used in the test stand is made out of three components: thermoplastic elastomer matrix Tefabloc TO..222 (Mitsubishi Chemical Performance Polymers), iron particles ASC 300 (Höganäs) and paraffin oil Onida 934 (Shell) in weight ratio 83 : 14 : 3. This material was previously developed and described in papers [9, 10]. Material was prepared using in mixing chamber of Plasti-Corder Lab-Station (Brabender). Samples were made by extrusion pressing. Figure 2. presents picture of the samples and their cross-section showing its uniform structure. Each sample was 15 mm high and had diameter of 25 mm.

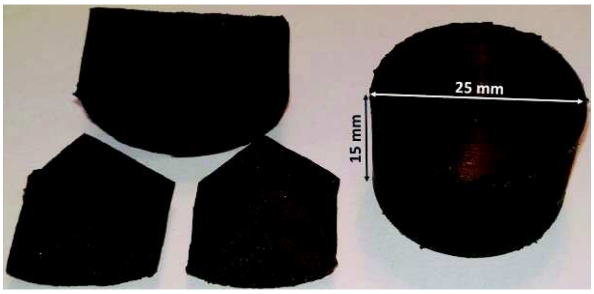
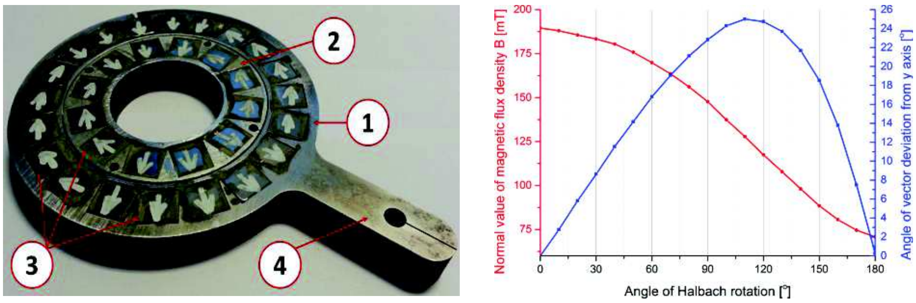


Figure 2. Magnetorheological elastomer sample

2.2. Magnetic field generator

To stimulate magnetorheological elastomer enquired is magnetic field, the stronger it is the bigger change of the materials properties. Therefore for the purpose of the test stand double dipolar circular Halbach arrays were designed and fabricated. Figure 3. a) presents picture of one of the arrays. The circular Halbach array is a set of magnets oriented is a specific way that can generate dipolar magnetic field inside of its opening. By setting two or more such arrays around one another it is possible to change generated magnetic field by rotating them around one another.



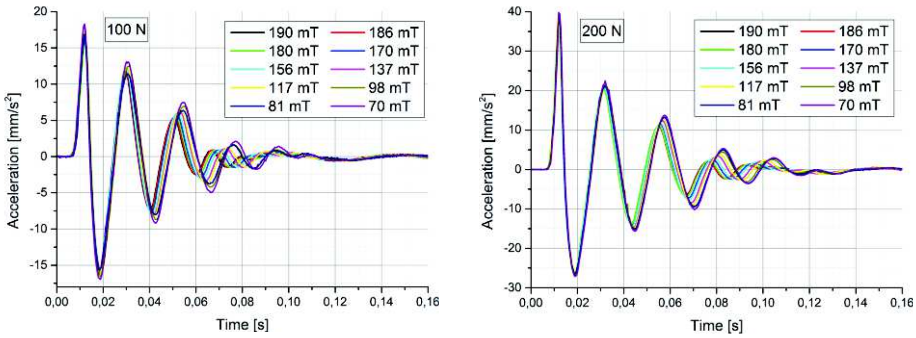
a) b)

Figure 3. a) Double dipolar circular Halbach array, where 1 - outer array frame, 2 - inner array frame, 3 - neodymium magnets, 4 - rotation arm with locking pin hole, b) relation of normal value of magnetic flux density B generated by Halbach array and its angle of deviation from y axis to the angle of rotation of outer array to inner one

Magnetic Halbach arrays used in the study was made out of 32 N48 grade neodymium magnets 12 mm x 12 mm x 12 mm. It allowed to generate magnetic field in range from 190 mT to 70 mT. In Figure 3. b) is presented graph showing change normal value of magnetic flux density B generated versus rotation of the outer array around inner one and change of deviation angle of the magnetic field vector from y axis.

3. Experimental evaluation

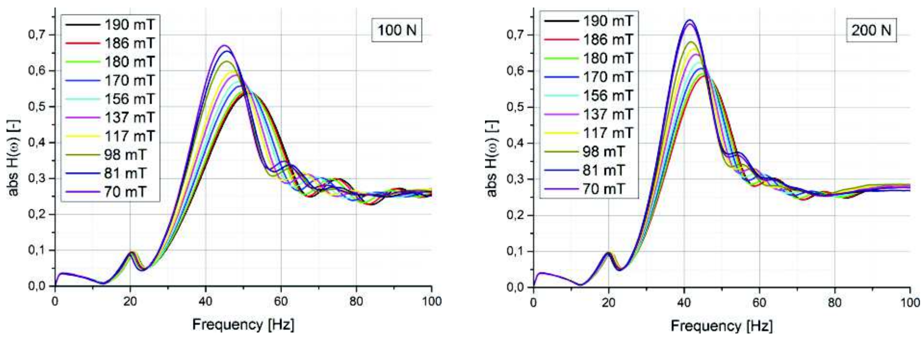
Experimental investigation of impact absorption and vibration damping with use of the test stand was conducted for set of impact force and magnetic flux density values. Tests were run in series for different values of magnetic field. After each test setup there was a 20 minute brake that allowed mitigation of vibration caused by the suspension of the system (refer to Figure 1. a)). In the paper are presented results of acceleration time traces for two representative values of impact force and corresponding frequency response functions.



a) b)

Figure 4. Time traces of acceleration of the upper mass for range of magnetic field values for two representative values of impact force: a) 100 N and b) 200 N

Figure 4. presents time traces of acceleration collected with acceleration sensor mounted on the upper mass of the test system. For both values of impact force presented it is visible that the stimulation with stronger magnetic field caused faster damping of the vibrations occurring after impact.



a) b)

Figure 5. Frequency response functions for range of magnetic field values for two representative values of impact force: a) 100 N and b) 200 N

Figure 5. show frequency response functions for range of magnetic fields and two representative values of impact force. It was calculated on base of acceleration and force signals with use of the double channel signal analysing method [6, 11]. On base of presented results it is clearly visible that magnetic field can significantly influence properties of the MRE material and therefore increase its damping properties what can be used for better reduction of vibration in civil and mechanical structures.

4. Parameter estimation

To analyse obtained results a non-linear constitutive model have been proposed. It is four parameter model with one elastic element (C_0) connected with viscous element (K_0) in series and they are connected in parallel with elastic non-linear element (C_1) and viscous element (K_1). For parametrization of this model energy and power balance method is used [7, 12, 13]. Figure 6. presents schematic representation of the model.

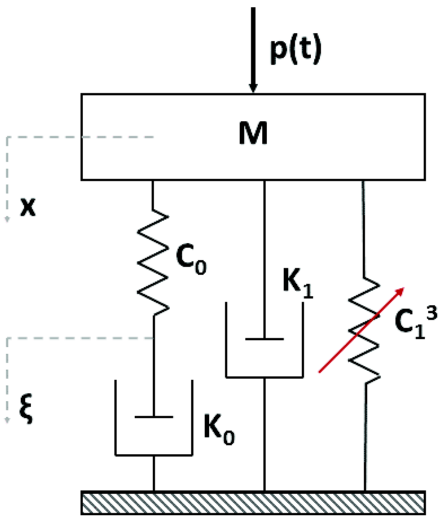


Figure 6. Four parameter constitutive models chosen for analysis of the obtained results [8, 14]

To describe the model following equations are used:

$$C_0 \cdot (x - \xi) = K_0 \cdot \dot{\xi} \tag{1}$$

$$p(t) = C_0 (x - \xi) + C_1 \cdot x^3 + K_1 \cdot \dot{x} + m \cdot \ddot{x} \tag{2}$$

$$p(t) = C_1 \cdot x + \frac{K_0 \cdot C_0 + K_0 \cdot C_1}{C_0} \cdot \dot{x} + K_1 \cdot \dot{x}^3 + M \cdot \ddot{x} + \frac{3 \cdot K_0 \cdot K_1}{C_0} \cdot \dot{x}^2 \cdot \ddot{x} + \frac{M \cdot K_0}{C_0} \cdot \dddot{x} - \frac{K_0}{C_0} \cdot \dot{p} \tag{3}$$

$$\alpha_x^p = \left(K_1 + K_0\right) \cdot \alpha_x^{\dot{x}} + \frac{K_0 (C_1 + C_0)}{C_0} \cdot \alpha_x^{\dot{x}} + 3 \frac{K_0 \cdot C_1}{C_0} \cdot \alpha_x^{x2\dot{x}} + \frac{M \cdot K_0}{C_0} \cdot \alpha_x^{\dddot{x}} - \frac{K_0}{C_0} \cdot \alpha_p^{\dot{x}} \tag{4}$$

$$\alpha_{\dot{x}}^{p} = C_1 \cdot \alpha_{\dot{x}}^{x^3} + \frac{K_0 \cdot K_1}{C_0} \cdot \alpha_{\dot{x}}^{\ddot{x}} + M \cdot \alpha_{\dot{x}}^{\ddot{x}} + 3\frac{K_0 \cdot C_1}{C_0} \cdot \alpha_{\dot{x}}^{x^2\dot{x}} - \frac{K_0}{C_0} \cdot \alpha_{p}^{\ddot{x}} \quad (5)$$

Equations (1) and (2) describe dynamic equilibrium state of the model with non-linear elastic element. On their base equation (3) is created to eradicate ξ from those equations and join them in one. On base of this uniform equation two formulas for the energy and power balance are formulated and are presented in equation (4) and (5). In those equations $\alpha_{\dot{x}}^{x}$ represent area of the hysteresis loop created from displacement x and velocity $\dot{x}$. With use of multiple linear regression parameters of the model are determined and are presented in Table 1. Parameters are presented in form of function where B is normal value of magnetic field used for stimulation of the MRE material.

Table 1. Results from parametrization, where B is value of magnetic field

K_0	K_1	C_0	C_1	Mean squared error
$0.0108\ B^3 - 4.5659\ B^2 + 636.23\ B + 3.34 \cdot 10^4$	$-0.0108\ B^3 + 4.5388\ B^2 - 631.45\ B + 3.29 \cdot 10^4$	$4 \cdot 10^7\ B - 3 \cdot 10^{11}$	$-10^4\ B + 2 \cdot 10^7$	0.999969

On base of those parameters simulation have been done with initial parameters matching those from experiment. The unexpected result was that scatter instead of tending to zero what means that the model does not match presented results and therefore presented parameters are wrong. Nevertheless presented method gives a promising approach for modelling and parametrization of the presented system, with use of different model.

5. Conclusions

This paper presents design, construction and an approach to modelling of the system. The impact absorption system is based on magnetorheological elastomer is and active smart magnetic material that presents controllable damping properties. To control its properties double dipolar circular Halbach arrays have been designed and fabricated. They allow to change generated magnetic field in a range from 70 mT to 190 mT. Experimental testing of the system have proven its possibility to shift frequency resonance by more than 10 Hz and to effectively reduce vibrations occurring in the system after impact. An approach to modelling with use of the energy and power balance method have been made, however obtained results do not match with experimental results and indicate need for search of a different model.

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