NUMERICAL INVESTIGATION OF A COUPLING PROBLEM IN MAGNETORHEOLOGICAL ELASTOMER FEM SIMULATIONS

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Abstract

Magnetorheological elastomers contain carbonyl iron particles of diameter of several microns each which are dispersed in the polymer resin. These particles are grouped in structures like chains. Properties of such materials can be changed by applying an external magnetic field and they can vary in a wide range. When the magnetic field intensity rises, the effective elastic module increases. The resulting modulus increase is rapid, continuous, and reversible. For a relatively high-modulus elastomer matrix such as natural rubber, the fractional modulus increase with magnetic field can exceed 50%, while it can be even larger for low-modulus host materials. Thanks to this property MREs are used in constructions like controlled vibration dampers, absorbers (TVAs), clutches, actuators, stiffness tunable mounts and suspensions, variable impedance surfaces, automotive suspension bushings, valves, brakes, safety restraint systems, semi active control systems, building vibration isolation, etc.

The magneto rheological elastomers (MRE) based on carbonyl iron particles-filled polyurethane resin were investigated. Their stiffness can be changed easily by magnetic field. Such a property can be useful in construction of active vibration damping structural elements. The problem of magneto-mechanical coupling was investigated. The coupling was performed in the 2 different ways. Both of the methods were iterative. The first one was performed in the two loops: external loop was performed over forces that loaded internal rows of iron particles (dipoles) and internal where the remaining external rows of dipoles were loaded by displacement that were induced by the forces.

The second method used single loop performed over magnetic forces that were applied to external rows of dipoles and were recalculated in subsequent iterations accordingly to the change of distances between rows of dipoles. Iterations were performed until the state of balance was reached. The compliance of results confirms the correctness of applied numerical methods of MRE behaviour under applied magnetic field.

Keywords: *magneto rheological elastomer, FEM modeling, magneto mechanical coupling*

1. Introduction

Magnetorheological elastomers are the so called smart materials. They contain carbonyl iron particles of diameter of several microns each which are dispersed in the polymer resin. These particles are grouped in structures like chains. Properties of such materials can be changed by applying an external magnetic field. They can vary in a wide range. While the magnetic field intensity arises the effective elastic module increases. The resulting modulus increase is rapid, continuous, and reversible. For a relatively high-modulus elastomer matrix such as natural rubber, the fractional modulus increase with field can exceed 50%, while it can be even larger for low-modulus host materials.

Thanks to this property MREs are used in constructions like controlled vibration dampers, absorbers (TVAs), clutches, actuators, stiffness tunable mounts and suspensions, variable impedance surfaces, automotive suspension bushings, valves, brakes, safety restraint systems, semi active control systems, building vibration isolation, etc. [1-5].

Most models of (MR) material behaviour are based on the magnetic dipole interactions between adjacent particles. These interparticle interactions are then averaged over the entire sample to yield a model of the bulk magnetostrictive behavior. Magnetisable materials exhibit strongly nonlinear behaviours such as paramagnetism and ferromagnetism.

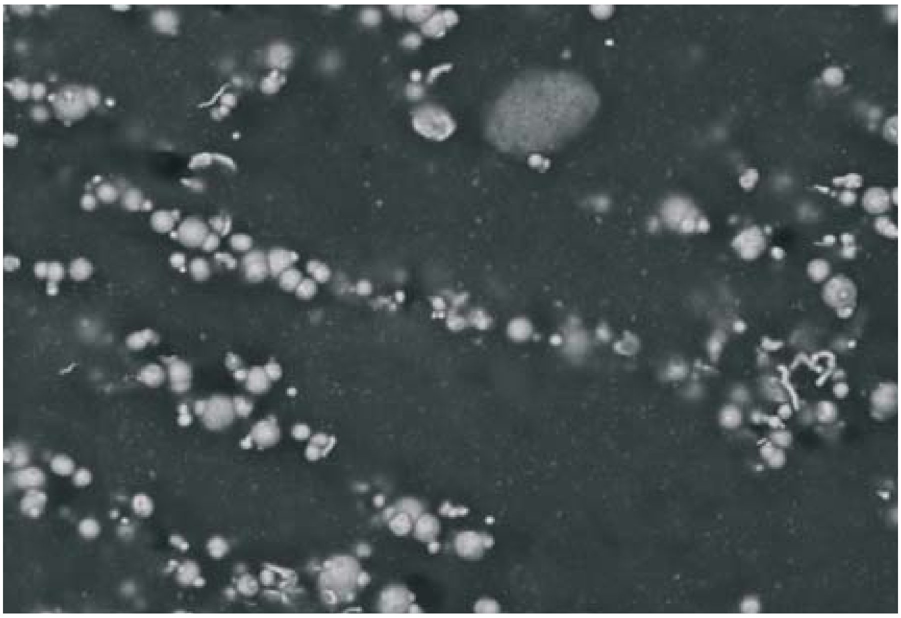

Fig. 1. Microphotograph of a MRE's structure: chains of carbonyl particles

2. Magneto mechanical coupling problem

Numerical calculations were performed on the MSC Nastran platform. The Neo Hookean material model was used to describe properties of the resin matrix. Magneto-mechanical coupling was taken in consideration with the use of iterative method.

Magnetic and mechanical phenomena coupling in MREs acts as follows:

- placing a MRE in magnetic field induces forces between dipoles of carbonyl iron particles,
- these forces change the distances between the dipoles and try to change their orientation (when the directions of chains and direction of magnetic field forces are different)
- the change of distances between the dipoles changes the induced magnetic forces,
- such a coupling acts until the state of equilibrium is reached.

There are compared two different iterative methods of the magneto-mechanical coupling simulation in case of leak of appropriate numerical package that offers adequate finite elements library to built models of MRE structures placed in the magnetic field (such possibilities offers ANSYS).

3. Magnetic force between two dipoles

Influence of of the magnet onto a single dipole is formulated as:

$$F_x = \boldsymbol{\mu}\,\mathrm{grad}(B_x)\ , \tag{1}$$

where $\boldsymbol{\mu}$ is the magnetic moment of a single dipole, B_x magnetic induction in an arbitrary distance from the magnet pole.

Magnetic induction in an arbitrary distance from the magnet pole is described as:

$$B_x = \frac{b}{\sqrt{b^2 + x^2}} B_0\,, \tag{2}$$

where B_0 is the magnetic induction generated by the single electromagnet, b is the width of the magnet pole. The gradient of the induced field is:

$$\mathrm{grad}(B_x) = \frac{-b\,x}{(b^2 + x^2)^{3/2}} B_0 \,. \tag{3}$$

The mass of the dipole is given as:

$$m_k = \rho_{Fe} V_k = 1.736 \cdot 10^{-9} \text{ g}, \tag{4}$$

where ρ_{Fe} is the iron density and V_k the volume of the dipole.

Magnetic moment for the single gram of substance is given as:

$$\boldsymbol{\mu}_{[\mathrm{g}]} = 0.2353 \frac{\mathrm{J}}{\mathrm{T} \cdot \mathrm{g}} \,. \tag{5}$$

From (4) and (5) we can obtain magnetic moment for the single dipole:

$$\boldsymbol{\mu} = \boldsymbol{\mu}_{[\mathrm{g}]} m_k = 4.0852 \cdot 10^{-10} \frac{\mathrm{J}}{\mathrm{T}} \,. \tag{6}$$

Finally, magnetic force value between the two dipoles is obtained as:

$$F_x = 408.52 \frac{-b\,x}{(b^2 + x^2)^{3/2}} B_0 \left[\mathrm{pN}\right]. \tag{7}$$

4. Characteristics taken for calculations of magnetic for ces

The following assumptions were taken into considerations for the needs of calculations of magnetic forces acting between two dipoles:

1.26 E-6	H/m	- magnetic permeability of free space,
7860	kg/m^3	- density of iron,
0.2353	Am^2	- magnetic moment of a 1g of iron in the full saturation state,
0.1	T	- magnetic field intensity,
10.0		- relative permeability of the iron,
1.0 E-6	m	- normalised radius of the dipole sphere,
4.1888 E-18	m^3	- volume of the model dipole,
2.4699 E-14	kg	- mass of the model dipole,
5.8117 E-14	Am^2	- static momentum of the model dipole.

Areas of the model that correspond to the polyurethane resin had properties adequate to the Neo-Hookean material model:

1.03	g/cm^3	- density,
22069,2	Pa	- C_{10} ratio.

5. 2D Model a of a MRE

The Model A was built on the MSC PATRAN platform (Fig. 2). The calculations were performed with the use of the MARC solver. Spheres of carbonyl iron were treated as rigid material in comparison to the polyurethane resin, which had hyper elastic properties due to the Neo Hookean material model enabled. Carbonyl spheres were modeled as sets of MPCs (multipoint constraints) consisting of RBE2 rigid bar elements. The top as well as bottom external edges of the model were constrained with the use of MPCs to remain straight. The area of interest where the most accurate results are obtained is showed at the Fig. 2.

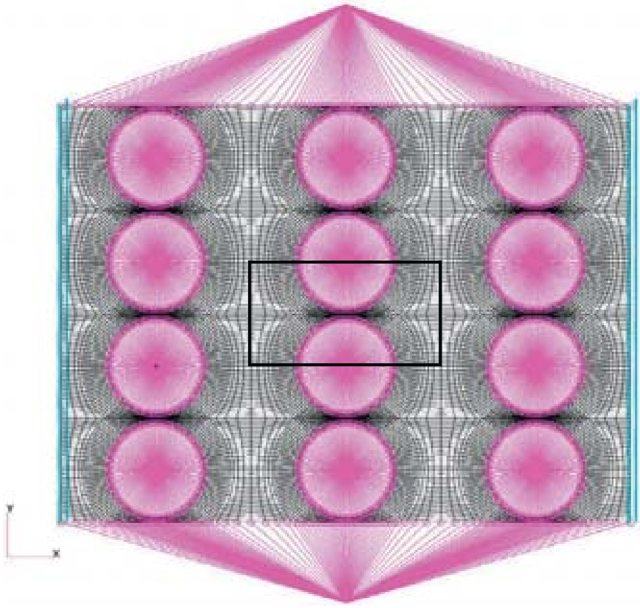

Fig. 2. 2D Model A of MRE

6. Algorithm of the considered method of magneto mechanical coupling simulation

The considered method is based on iteration which are performed in the 2 loops:
- external loop: over the forces,
- internal loop, over the displacements.

Forces that are calculated externally from appropriate formulas, are applied to the two internal rows of the dipoles. External rows of the dipoles as well as upper and lower free edges of the model are loaded by the displacements that are calculated from the those induced between the two internal rows of the dipoles. Iterations are performed until the balance is reached.

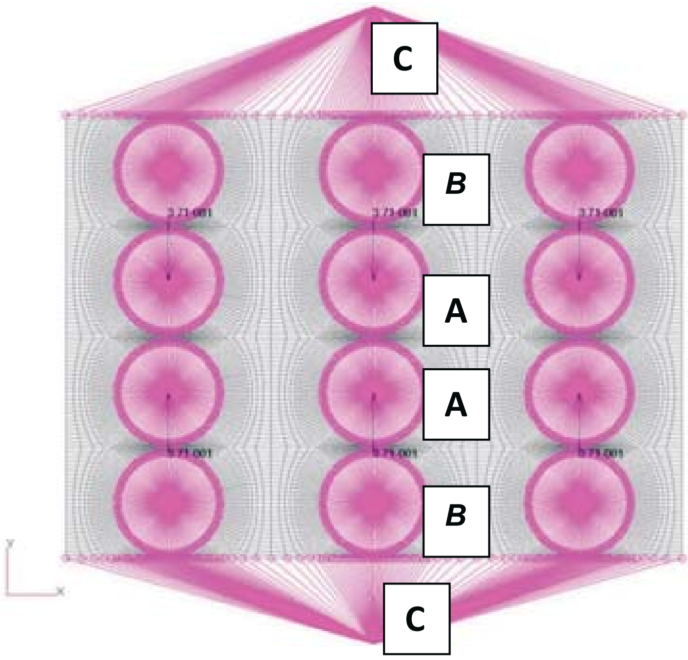

Fig. 3. Model A: the first step of the loop over forces - the internal rows of the dipoles (A) are loaded by magnetic forces

7. Model a - results

The results obtained from the Model A with the use of the considered iterative method of the magneto mechanical coupling phenomenon implementation are presented in Fig. 5.

Repeatability of displacement, strain and stress distributions patterns is the visible proof that the balance state is reached with the use of considered method.

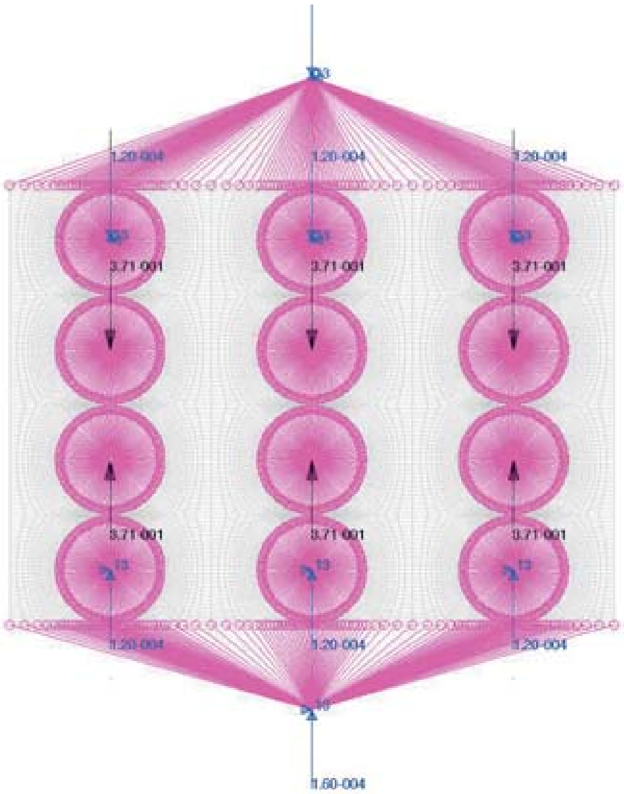

Fig. 4. Model A: internal loops over displacements - external rows of the dipoles as well as the free edges of the model are loaded by displacements calculated from that induced between the internal ows by the forces acting between them

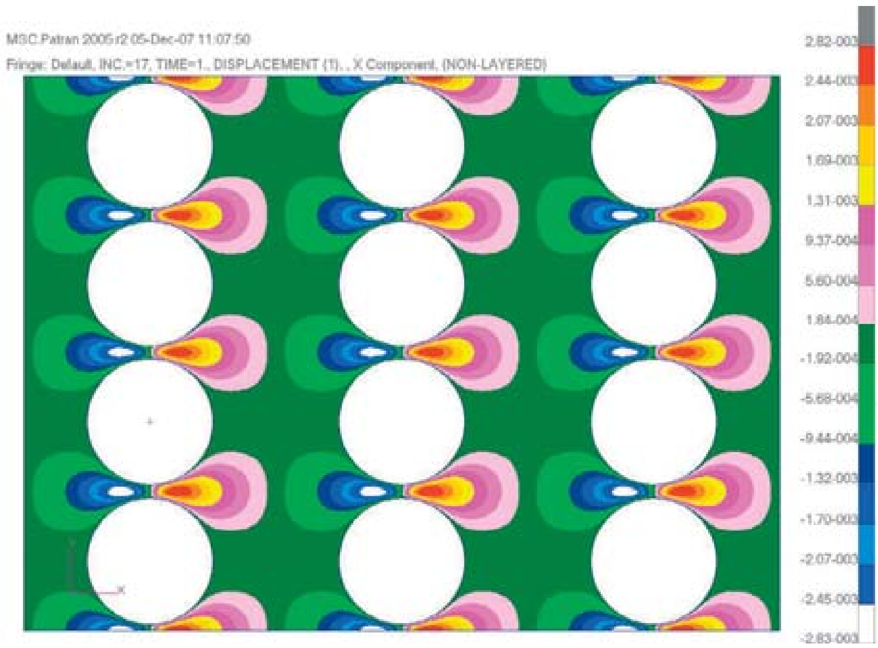

Fig. 5. Displacement component d_x

8. Model b - classic: loading conditions and results

Model B was built to use classic way of loading by magnetic forces. Here only the external rows of dipoles were loaded and only the loop over the forces was performed.

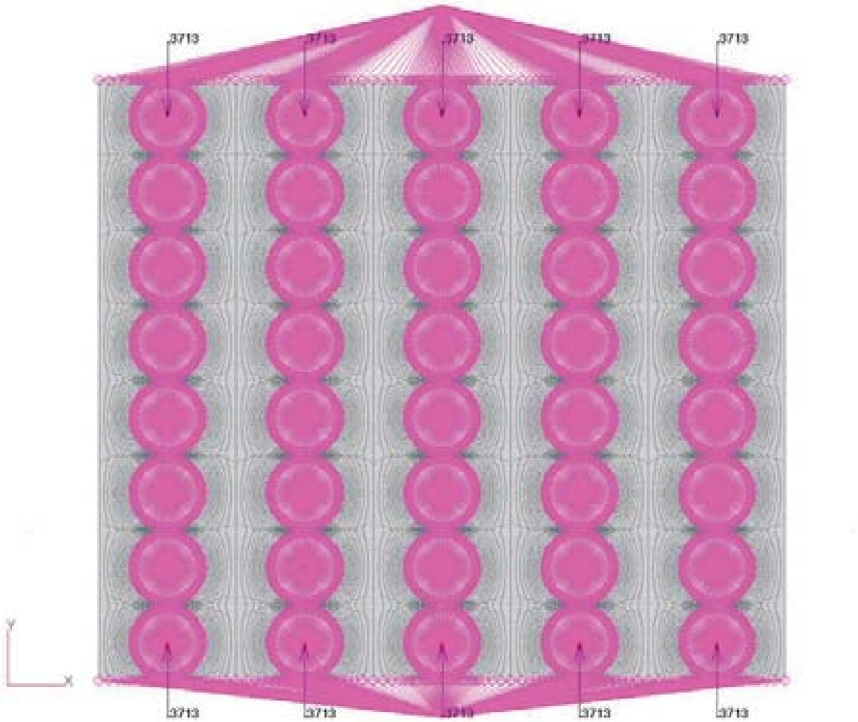

Fig. 6. Model B: magnetic forces were applied to the external rows of dipoles and modified in subsequent iterations accordingly to the change in the distance between dipoles

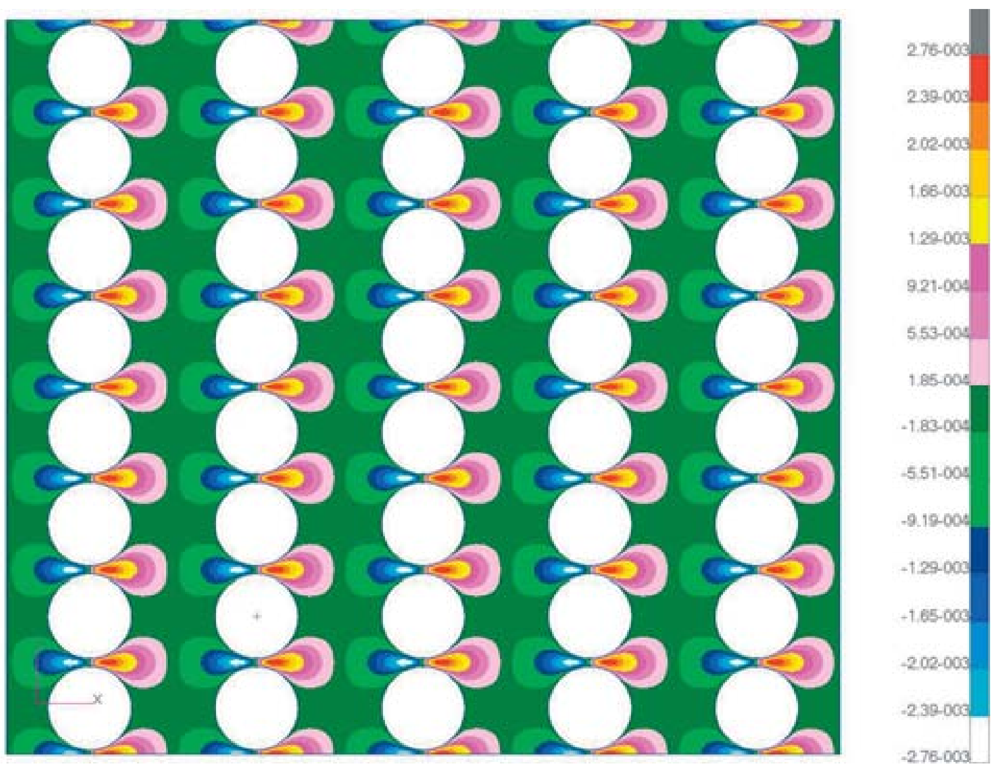

Fig. 7. Displacement component d_x μm

In each step the calculated value of displacements of dipoles was used to recalculate the value of magnetic forces which then were applied to the model in subsequent step of computations. Such a procedure was performed until the state of balance was reached.

The set of MPCs applied to the upper and lower free edges of the model enable to keep their rectilinearity.

9. Conclusions

The results obtained from the two different models with the use of the two different iterative methods of magneto mechanical coupling simulation in a MRE are comparable. This is self consistent proofs that the considered models, methods of boundary conditions definition and way of computations performing are correct.

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