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Experimental and numerical studies of MR damper with prototype magnetorheological fluid

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Analysis and modelling

ABSTRACT

Purpose: Results of experimental studies of a prototype magnetorheological damper at various magnitudes of control current as well as the manner of modelling electromagnetic phenomena occurring in the damper are presented in this paper.

Design/methodology/approach: Model MR fluid was prepared using silicone oil OKS 1050 mixed with carbonyl iron powder CI. Furthermore, to reduce sedimentation, as stabilizers was added Aerosil 200. The observations of the surface morphology of carbonyl iron and fumed silica were carried out using Digital Scanning Electron Microscope SUPRA^{TM}25 ZEISS. The effect of magnetic field on magnetorheological fluid is modelled by the finite element method.

Findings: The presented model meets the initial criteria, which gives ground to the assumption about its usability for determining the dynamics properties of mechanical systems, employing the finite element method using ANSYS software.

Research limitations/implications: The elaborated model can be use for modelling the semi active car suspension dynamics.

Originality/value: The actual-non-linear characteristics of magnetisation identified experimentally were used as the values of relative magnetic permeability of the piston housing material. The possibility of application, e.g. real characteristics of material magnetisation and faster and faster calculation machines make possibility the creation of more precise models and more adequate ones to reality.

Keywords: Computational material science; Finite Element Method; Smart materials; Magnetorheological materials; MR damper

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1. Introduction

Magnetorheological fluids belong to a group of non-Newtonian fluids, i.e. such that do not meet Newton's law of fluid friction (the η kinetic viscosity coefficient is variable). They also represent a group of purely-viscous fluids with the liquid limit and the controllability of their properties by means of a magnetic field [1-4].

In the recent several years magnetorheological dampers have been widely investigated both, due to their interesting phenomenological characteristics as well as potential possibilities to use them for controlling vibrations in pneumatic systems. They are especially important in the automotive industry, where improved driving conditions are inherent to a driver's safety [5-7].

MR dampers are semi-active devices that contain magnetorheological fluids. After application of a magnetic field the fluid changes from liquid to semi-solid state in few milliseconds, so the result is an infinitely variable, controllable damper capable of large damping forces. MR dampers offer an attractive solution to energy absorption in mechanical systems and structures and can be considered as "fail-safe" devices [8-13].

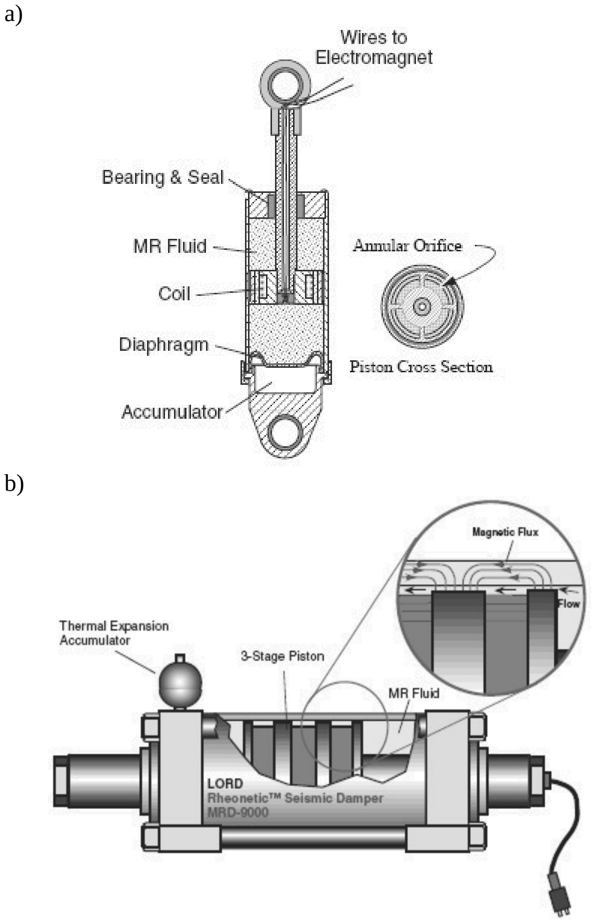

Fig. 1. Schematic diagram of the MR fluid dampers a) small-scale SD-1000 MR fluid damper, b) the prototype 20-ton large-scale MR fluid damper [14,15]

Fig. 1 shows schematic example of MR fluid dampers. It can be seen that the operation of this device is fundamentally different from that of brakes and clutches, in that MR fluid is forced through annular orifices rather than being directly sheared [14].

In the SD-1000 MR fluid damper (Fig. 1a), magnetorheological fluid flows from a high pressure chamber to a low pressure chamber through an orifice in the piston head. The damper is 21.5 cm long in its extended position, and the main cylinder is 3.8 cm in diameter. The main cylinder houses the piston, the magnetic circuit, an accumulator, and 50 ml of MR fluid. The damper has a ±2.5 cm stroke. The magnetic field, which is perpendicular to the fluid flow, is generated by a small electromagnet in the piston head. Forces of up to 3.000 N can be generated with this device [15].

The damper shown in Fig. 1b, uses a particularly simple geometry in which the outer cylindrical housing is part of the magnetic circuit. The effective fluid orifice is the entire annular space between the piston outside diameter and the inside of the damper cylinder housing.

Movement of the piston causes fluids to flow through this entire annular region. The damper is double-ended. The advantage of this arrangement is that a rod-volume compensator does not need to be incorporated into the damper, although a small pressurized accumulator is provided to accommodate thermal expansion of the fluid. In this damper maximum damping force of 200.000 N can be generated.

2. Experimental

In order to prepare the prototype magnetorheological fluid the carbonyl iron powder was selected (CI, reduced penta-carbonyl iron, SiO_2 - coated, BASF, Germany) as for a model particle suspended system.

The carbonyl iron particles are coated with silica which provides an effective stabilization against aggregation. CI is magnetically soft material characterized by high saturation magnetisation. The average particle size and tap density was 7.0 μm and 4.3 g/cm^3, respectively.

The concentration of CI was fixed at 40 wt%. In the aim of reduction of sedimentation process of the CI particles additional components (1 against CI amount) were added to the fluids. For the silicon oil the fumed silica (Aerosil 200, Degussa, Germany) was chosen.

The function of a carrier liquid is primarily to provide a liquid in which the magnetically active phase particulates are suspended.

The carrier liquid should also be largely non-reactive towards the magnetic particles. Similarly, the carrier liquid should be non-reactive toward the components/materials used in the device.

When selecting a carrier liquid, it is important to consider the boiling temperature, vapour pressure at elevated temperatures and freezing point.

For that reasons magnetorheological particles were dispersed in colorless silicone oil (SO, type OKS, Germany).

Metallographic examinations of the material structure were made on the SUPRA^{TM}25 ZEISS scanning electron microscope with EDAX energy dispersion X-ray spectrometer with 20 kV accelerating voltage.

A prototype of the MR damper was designed and produced as part of own work (Fig. 2).

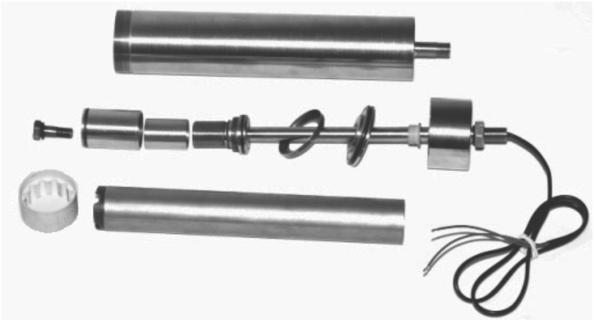

Fig. 2. Prototype MR Damper

3. Results and discussion

Metallographic microscopic research that was carried out permitted to observe morphologies of the carbonyl iron (CI) and applied stabiliser of the magnetorheological fluid – fumed silica (Aerosil 200).

The carbonyl iron particles possess in general spherical shape (Fig. 3).

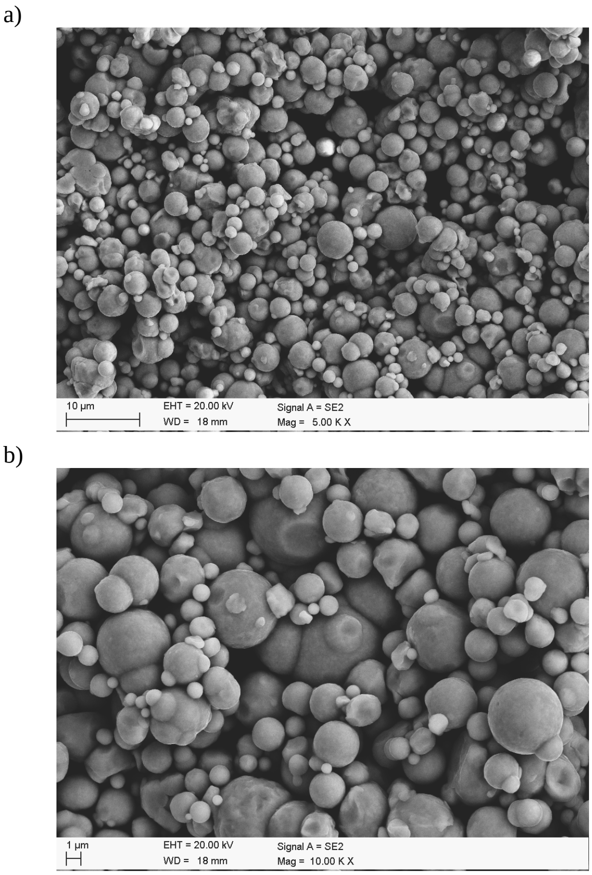

Fig. 3. Scanning electron micrograph of carbonyl iron particles used to preparation of model MR fluids

Initially constructed chain structure of these particles can be transformed into an assembled structure of individual chains through the chain rupture and reformation process by shear deformation under an applied magnetic field.

The surface of CI is coated by silicon dioxide layer with the purpose of protection carbonyl iron particles against agglomeration.

On the base of metallographic observations it was found that analysed silica (Aerosil 200) was characterized by irregular shape (Fig. 4). The silica surrounds the spherical CI particles, ensuring better protection against their agglomerations in suspension.

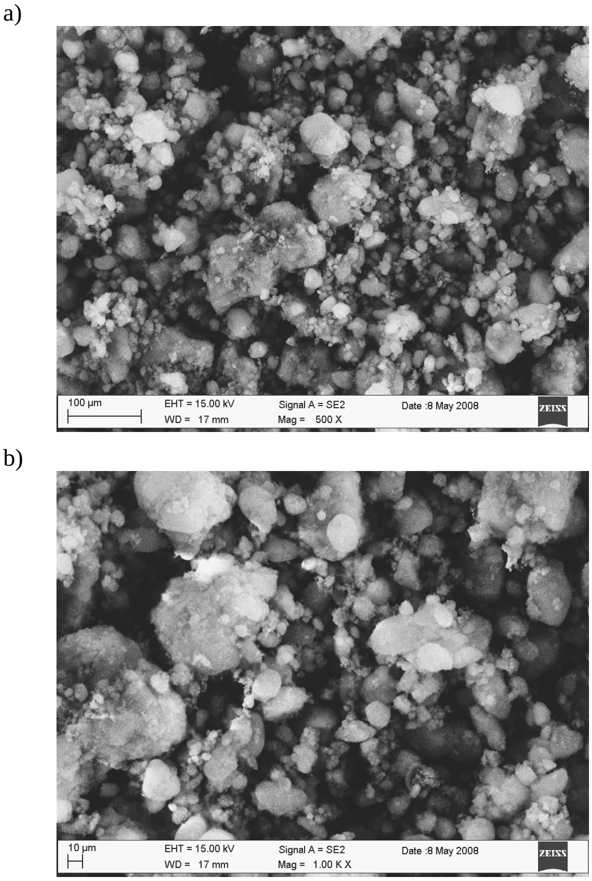

Fig. 4. Scanning electron micrograph of silicon dioxide (Aerosil 200)

A piston rod of the prototype magnetorheological damper was the subject of a numerical analysis concerning electromagnetic effects. The following calculation modules were chosen for the process of electromagnetic phenomena modelling in the prototype MR damper:

- a mechanical module responsible for strength properties,
- a magnetic module that allows to accomplish a field distribution characteristic based on a colour flat model or a spatial model created by revolving a 2-D model around a vector located on the left-hand side,
- a dynamic module showing fluid behaviour relative to the displacing piston.

An axisymmetric damper model (Fig. 5.) was created with a special focus on the elements where the distribution of the magnetic field has the largest effect. The coordinate values defining the location of the individual constituent parts and their geometry were introduced for this purpose.

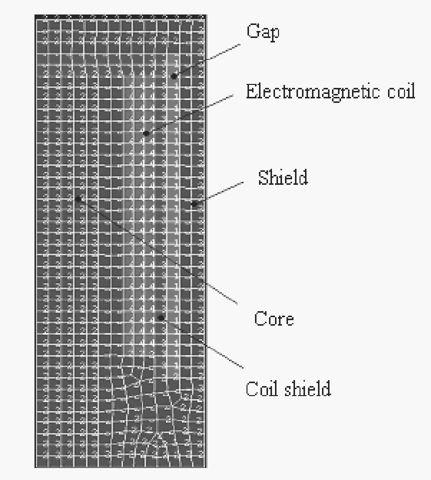

Fig. 5. Piston division into finite elements – the calculation areas

All the surfaces were divided into finite elements using quadrilateral, octanodal elements with the four degrees of freedom in the PLANE 53 type node described with a low order polynomial. The used option allows us to divide the grid in a coarse manner, but allowing to achieve the required field distribution at the expense of shortening the calculation time.

Materials were chosen for the adopted damper areas and their material properties were defined, in particular magnetic permeability (Table 1).

Table 1.
The relative magnetic permeability of the materials making up the piston rod

Diamagnetic materials	μ_r
Copper	0.9999999
Ferromagnetic materials	μ_r
Carbon steel (E295)	50-220
Prototype magnetorheological fluid	5
Paramagnetic materials	μ_r
Air	1.0000004

The magnetic permeability μ_r is a value characterising the behaviour of a given material body as a result of the magnetic field's activity. It depends on the magnetic induction vector $\vec{B}$ the magnetic field intensity vector $\vec{H}$ (1):

$$\vec{B} = \mu_0 \cdot \mu_w \cdot \vec{H} \tag{1}$$

where:

$\mu_0 = 4 \cdot \pi \cdot 10^{-7} \left[\frac{H}{m}\right]$ denotes the magnetic permeability of vacuum,

$\mu_w = \frac{\mu_r}{\mu_0}$ is relative magnetic permeability.

One can distinguish in dependence of magnetic permeability values:

- ferromagnetic materials ($\mu_w >> 1$),
- paramagnetic materials ($\mu_w > 1$),
- diamagnetic materials ($\mu_w < 1$).

All the piston's surfaces were limited with a line beyond which the magnetic field's distribution is of negligible importance. This process once again permits to simplify the calculation stage and to observe the line of forces of the piston port.

The geometric and electromotoric parameters of electromagnetic coil were defined:

- space underneath the electromagnetic coil,
- copper wire for electromagnetic winding was chosen,
- the active coil field was identified considering the completing coefficient,
- current's value was defined based on the system's resistance,
- current's density necessary to determine the magnetic fields' intensity was defined.

The images of magnetic field line distribution were produced when selecting the relative magnetic permeability (acc. to Table 1.) for the elements.

The actual characteristics of magnetisation identified experimentally were used as the values of relative magnetic permeability of the piston housing material (E295) – Fig. 6.

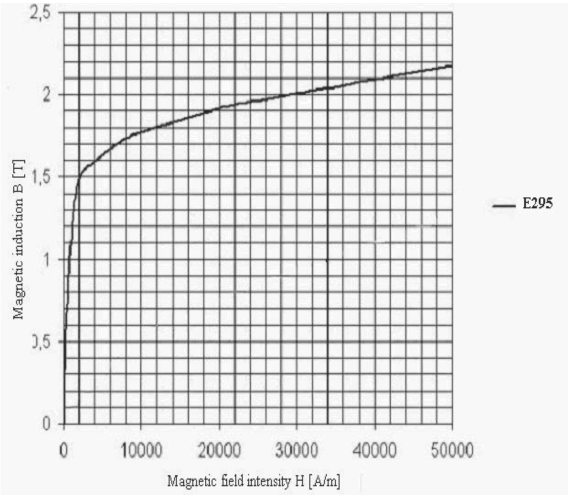

Fig. 6. The actual characteristic of magnetisation for the selected constituent parts of the magnetorheological damper

An analysis of the non-linear model and the distribution of magnetic field line reveals that the lines along which the forces of this field are active change their inclination angle insignificantly thus being closer to the required straight angle improving the working conditions.

The activity of magnetic forces occurs to the largest extent at the beginning and at the end of the active part of the port.

It was stated that the largest effect of concentration occurs at the height of the start and the end of the coil winding, and it is falling when nearing its centre (Fig. 7).

Distribution of the magnetic field lines, values of magnetic flux density and corresponding magnetic field strengths have been obtained in the form of maps and in the form of a vector field, which enable determination of dynamic damping forces that occur in the model of magnetorheological fluid (Figs. 8-12)

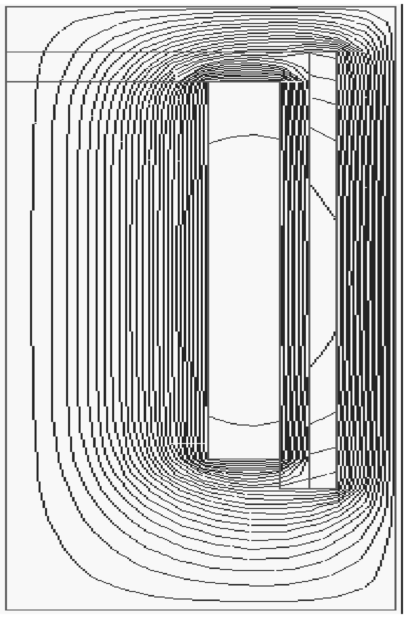

Fig. 7. Distribution of magnetic field line

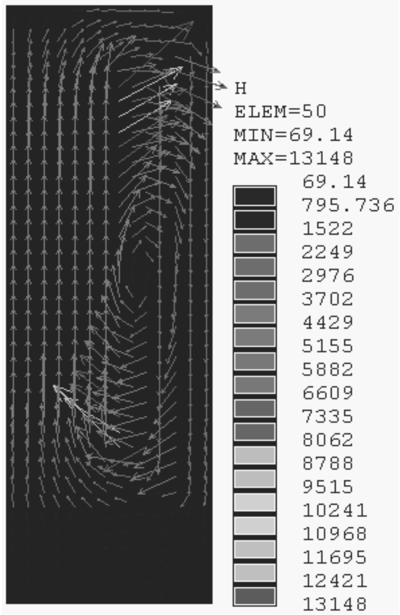

Fig. 8. The concentration of the magnetic field represented with vectors

On the base of the investigations it was revealed that the flux density increases linearly from the start of gap length to the point where coil winding starts. It then decreases nonlinearly down to zero in the middle of the total gap length (Fig. 13)

An identification experiment was carried out in the next stage of the modelling process for a semi-active suspension system where the dynamic characteristic of the prototype MR damper was produced.

The obtained damping force curves were dependent upon the speed of the piston force and the fluid flowing in the coil of the prototype MR damper.

The identification experiment was made on the MTS testing machine (Fig. 14).

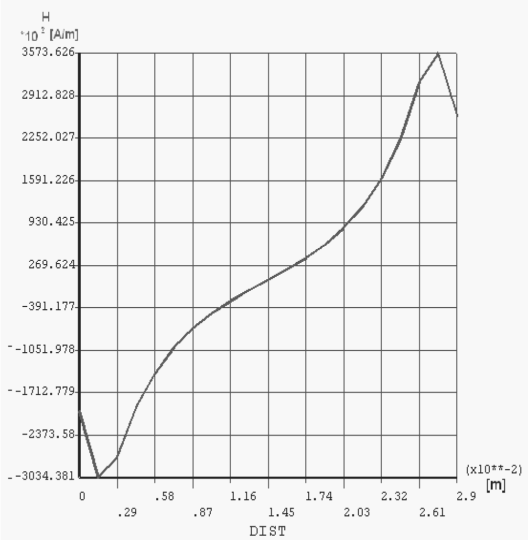

Fig. 9. The diagram of magnetic concentration relative to the port length

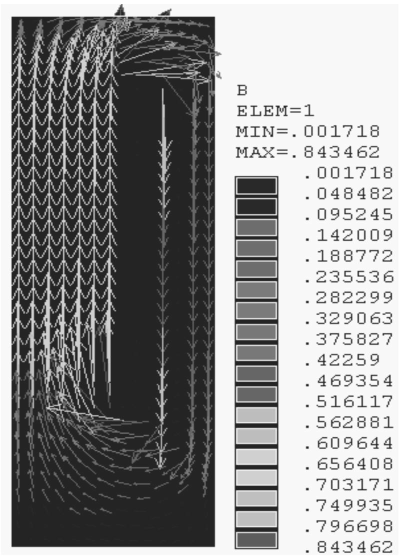

Fig. 10. The vectoral distribution of magnetic induction for non-linear analysis

Dynamic characteristics were identified in the tests by assuming:

- coil current of 0 [A] to 5 [A],
- piston rod speed of 0 [ms^{-1}] to 1 [ms^{-1}].

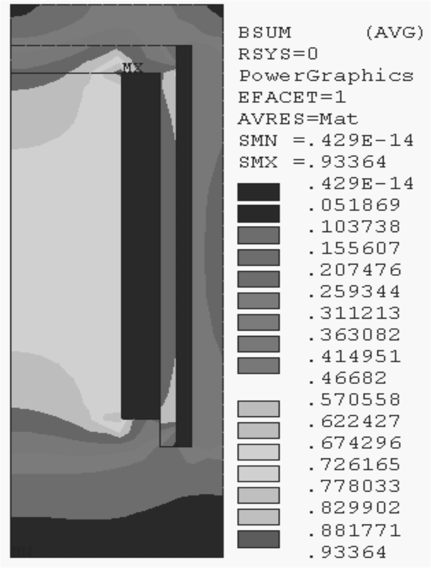

Fig. 11. A colour map of magnetic induction distribution – non-linear model

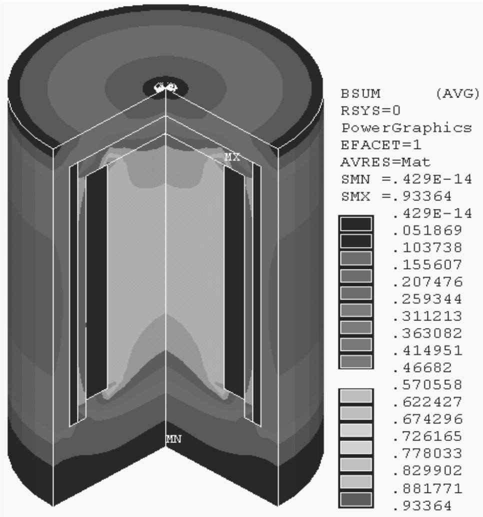

Fig. 12. A spatial view of magnetic induction distribution

The characteristics produced for the selected parameters of the adopted range are shown in the Figs. 15-17.

The damper's dynamic model was established in Simulink software on the basis of the characteristics describing the prototype MR damper's dynamics recorded in the experiment including their geometric form (piston rod's stroke).

The block identified as F(v,I) represents the damper dynamics (Fig. 18) identified in the experimental studies and recorded in Simulink.

The established dynamic MR damper model was used for performing numerical simulations to revise the adopted assumptions were correct. The simulations were made for the system with two degrees of freedom.

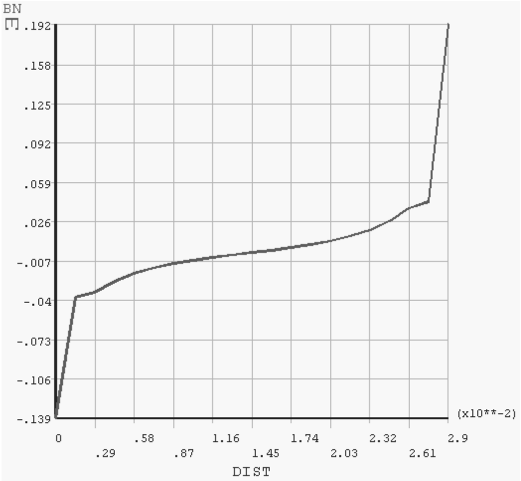

Fig. 13. Magnetic induction chart according to port length - non-linear model

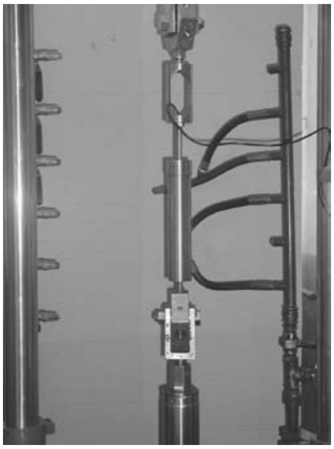

Fig. 14. A MTS test station for the evaluation of dynamic characteristics of the prototype MR damper

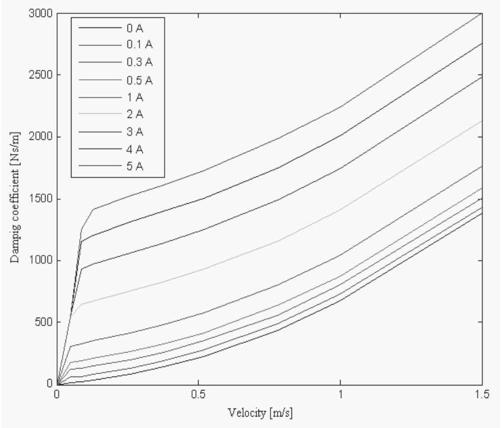

Fig. 15. A group of damping force characteristics according to speed and piston force for different coil current values of the prototype MR damper

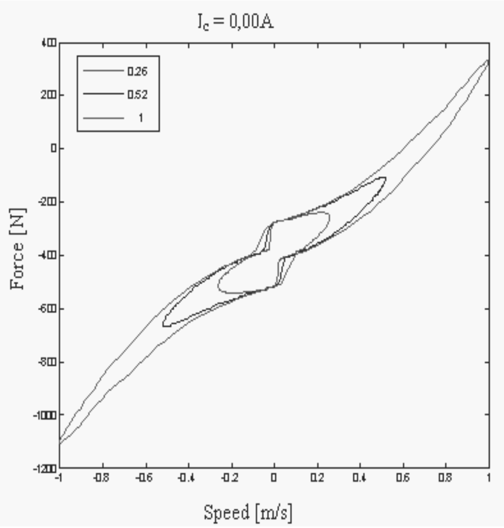

Fig. 16. A group of damping force characteristics according to three piston force speeds for the coil current of 0A

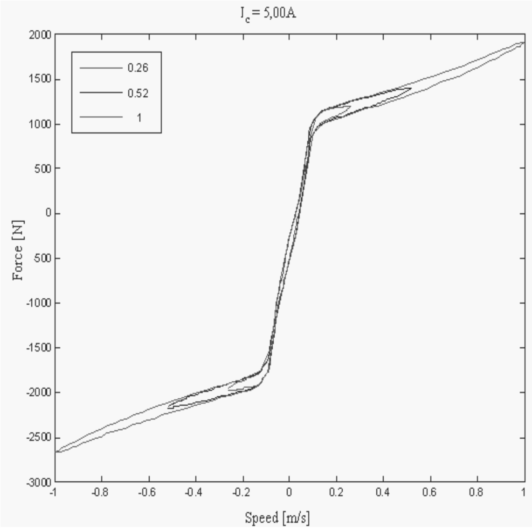

Fig. 17. A group of damping force characteristics according to three piston force speeds for the coil current of 5A

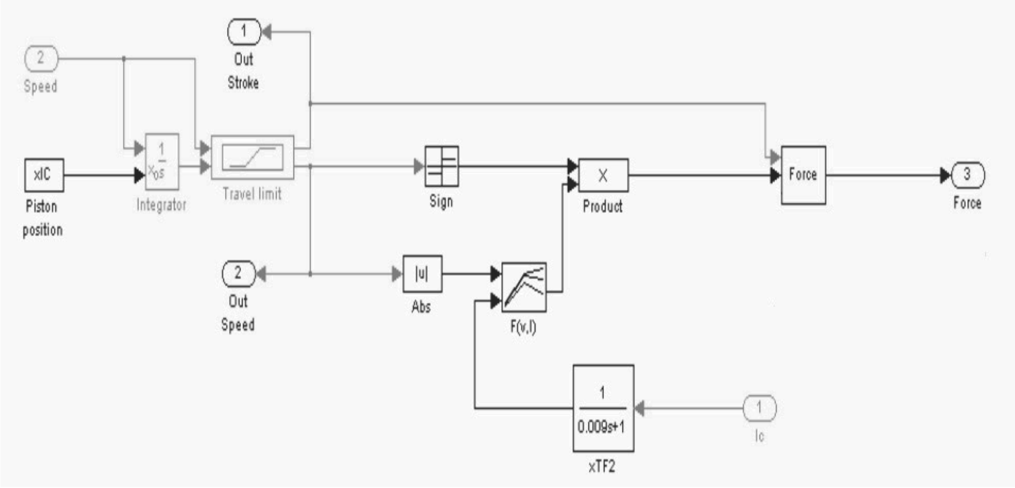

Fig. 18. The prototype MR damper model

4. Conclusions

The results presented in this paper show the good efficiency of vibration damping within the full range of excitation frequencies occurring while driving a car. The sprung mass' displacements for the Skyhook type control used and for all the studied excitation frequencies were lower than for the system with passive suppression.

One can observe a tendency of the active system's higher vibration isolation efficiency in relation to the passive system along with the growing excitation frequency.

Another characteristic of the established system is its much lower sensitivity within the range of resonance frequency.

Furthermore, active damping helps the vibrating object to reach its fixed state more quickly.

Acknowledgements

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