

## ANALYSIS OF THE DEPENDENCE BETWEEN A TEMPERATURE AND WORKING PARAMETERS OF THE MR DAMPER

### SUMMARY

*In this paper detailed description of temperature influence on MR damper working parameters has been described. Prototype of such a device and its mathematical description taking into considerations a thermal balance, have been proposed. Basing on experimental results, a connection between temperature and operating parameters of tested MR damper has been revealed.*

**Keywords:** MR fluid, temperature, laboratory tests, MR damper, smart materials

### BADANIA WPŁYWU TEMPERATURY NA PARAMETRY PRACY TŁUMIKA MAGNETOREOLOGICZNEGO

*W pracy szczegółowo omówiono wpływ temperatury na charakterystyki dyssypacji energii amortyzatora wypełnionego cieczą magnetoreologiczną. Zaproponowano pewne rozwiązanie konstrukcyjne prototypowego amortyzatora MR oraz jego model matematyczny, uwzględniający bilans cieplny. Na podstawie wyników badań eksperymentalnych wykazano ściśle powiązanie parametrów eksploatacyjnych amortyzatora MR z jego temperaturą pracy.*

**Słowa kluczowe:** ciecz MR, temperatura, badania eksperymentalne, materiały inteligentne

### 1. INTRODUCTION

Deeply bibliographical studies related to controlled “smart” fluids and devices, which the operating base are such fluids, particularly (magnetorheological) [8–11], reveal that the main problem on which interests of researchers is focused, is possibility of controlling their physical features. The main controlling factor is in this case the passage of electric current through the solenoid. The influence of the current intensity on the fluids properties and in consequences on the properties of a whole device has the main importance from the controlling process point of view.

Hitherto existing, carried out on the basis of rheological models, analysis of properties of fluids and MR devices is basically focusing on the mathematical description of model's elements movements depending on their parameters, also on electric and mechanical properties. Simultaneously, almost always, during description of devices operation or analyzing their models, an attention to many other factors, which could influence on their properties is paid.

Results of experimental research, also an exploitation experience of devices working on the basis of MR fluids reveal, that one of the most important by-product of their operation is heating. This phenomenon reacts of a fluid, changing the working conditions of the whole device.

### 2. RESEARCH OBJECT, OBJECTIVES AND THE RANGE OF PAPER

This paper is devoted to discussion and a comprehensive analysis of the mutual dependences which are observed between fluid's temperature and the working parameters of MR devices. Presented experimental results will be connected with a prototype of the shock absorber, which had been developed in the Institute of Machines Design Fundamentals of Warsaw University of Technology; it has a signature A-SiMR-MR-LD-203 (Fig. 1).



**Fig. 1.** A-SiMR-MR-LD-203 prototype of an MR shock absorber

The main objective of this paper is formulation of mathematical dependences describing connections between temperature and dissipative properties of the MR damper.

\* Institute of Machines Design Fundamentals, Warsaw University of Technology, Warsaw, Poland; jba@simr.pw.edu.pl

\*\* Institute of Vehicles, Warsaw University of Technology, Warsaw, Poland; w.grzesikiewicz@simr.pw.edu.pl

\*\*\* Laboratoire de Mathematiques et de Physique pour les Systèmes, University of Perpignan, Perpignan, France

\*\*\*\* Department of Mathematics and Statistics, Oakland University, Rochester, USA

The foregoing task has been realized in few stages, where the most important are:

- designing and building of the damper's prototype; signature – A-SiMR-MR-LD-203;
- experimental research which aim in determining characteristics of energy dissipation and including the influence of temperature;
- developing a suitable rheological model of the damper and its mathematical description;
- wide-ranging analysis of energy dissipation in the MR damper, taking into consideration the impact of temperature.

### 3. PROTOTYPE DESCRIPTION, LABORATORY STANDS, EXPERIMENTAL RESEARCH AND RESULTS

Entering into construction of the A-SiMR MR-LD-203 prototype, an assumption has been made that the construction has to provide an easy mounting on the laboratory stands and, what is more important, an easy assembling and disassembling of each constituent element, also a simple access to the internal elements of a damper. Also a proper decision related to the working rule of a MR device has been made.

These, seemingly small demanding have also determined dimensions of designed damper. They always have to provide a possibility of effortless mounting in the formerly predicted space on the laboratory stand. Existing limitations were mainly connected with construction of handles, mounted at the tip of a cylinder and piston. Size of the external diameter of a cylinder is limited by the possibility of performing the hollowing piston rod. An obvious for these types of devices is a fundamental requirement related to the axial loading necessity.

First of decisions, which was related to the working rule of a damper was decision of separation of a gas chamber and the rest of a damper, filled with a MR fluid. Among commonly applied solutions, decision has been made of splitting the existing inside the damper media by the free-floating piston (Fig. 2). Although such a solution is causing a little bit of disturbances, which was experimentally verified, it is convenient in a case of multiple mounting and dismounting of dampers. Finally, the correctness of chosen method of both chambers separation has been confirmed.

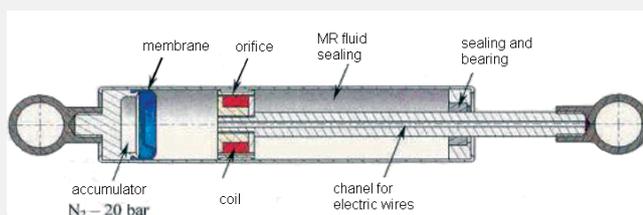


Fig. 2. Scheme of a A-SiMR-MR-LD-203 prototype

For a minimization of a magnetic field disturbances, generated by an assembly of the main piston, and for the decreasing of a weight of a device, the free-floating piston has

been made by a non-magnetic material (Teflon). As a sealing, a cylindrical seal has been applied. It was placed in a specially performed groove, in the middle of the piston's length. Gas supply for created in such a way chamber is possible thanks to the special valve, mounted on a damper's case.

The damper which fulfill all of the previously mentioned demanding has been tested on a special stand, which provides possibilities of three different kinds of research programs: two with a kinematical and one with force (impact) excitations. In the Figure 3 as well a picture as the scheme of the laboratory stand have been depicted.

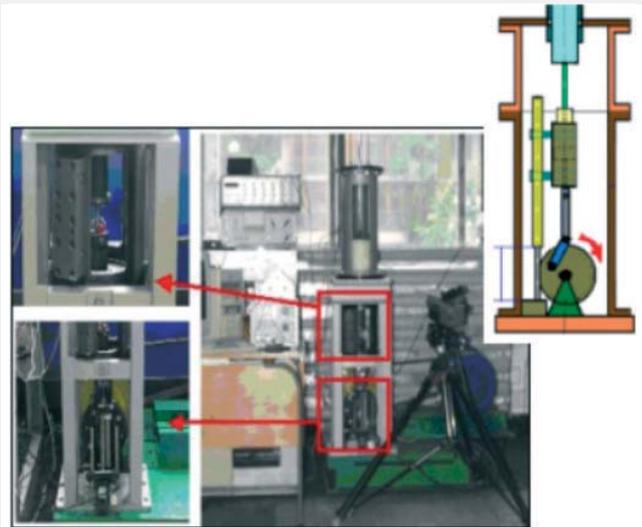


Fig. 3. Laboratory stand; picture and a scheme

Similar to other magneto-rheological devices, also in MR dampers, two different kinds of heat sources exist. The first one is current flow resistance through a coil. The second is a change of friction forces work, which occurs during the flow of liquid, through the specially shaped gaps, drilled in a head corp. Assuming the constant values of other parameters, increasing of temperature causes decreasing of the fluid's viscosity, which, in consequences, causes decreasing of a dissipative properties of a MR damper.

## 4. DISCUSSION OF EXPERIMENTAL RESULTS

### 4.1. Remarks on determining characteristics of energy dissipation and absorption in MR damper

Basing on existing bibliography and own experience related to absorption and dissipation of energy in MR dampers and other devices, where the working base is manotorheological fluid, it is easy to conclude, that the most suitable and interesting think for description of these physical processes are characteristics revealing the dependency between the force, acting on the piston, and the piston's displacement. Such characteristics are prepared for different values of electric current supplying the coil and at various velocities of the piston rod. Characteristics should be prepared in such a way to

emphasize the most important feature of MR fluid devices which is the possibility of controlling of damping properties. Controlling processes in this case is continuous and depend on the value of the magnetic field, generated by the electric current flowing in the solenoid.

Thanks to the specific properties of the main working factor of a MR damper (magnetorheological fluid), more important parameter, than in classical solutions, for the evaluation of the MR devices efficiency, is temperature. More precisely, we have take into consideration the influence of a fluid's heating phenomenon on damping properties of discussed device.

In case of force excitations of a movement, especially when the impact phenomenon is taken into account, the thermal aspect, because of the short-term acting, could be neglected. However, it doesn't mean that in the laboratory research, they shouldn't be taken into account.

Similarly to other structural solutions, most frequently, applied in magnetorheological devices, also in MR dampers two different heat sources exist. The first one is the resistance of the current flow through the coil's windings. The second is the change of the friction forces work, which exist during a fluid's movement throughout the specially drilled in a head gaps. For previously selected constant values of other parameters, increasing of temperature causes decreasing of viscous properties of a fluid. This, in consequences, causes decreasing of the dissipative properties of a MR damper.

#### 4.2. Experimental results of the A-SiMR-MR-203 prototype

In the Figure 4, a diagram presenting dependence between experimentally determined force, acting on the piston, in a time, displacement and velocity function, has been depicted. Cases for a current intensity form 0 A to 1.5 A and the gap size equal 0.5 mm, have been illustrated. Besides various values of a force, acting on the piston, also fluid's internal temperature has been illustrated. Presented results have been acquired for the constant value of the engine speed, forcing an angular motion of the circular cam ( $n = 100$ ).

Curves depicted in the Figure 5 present the variation of the force value on the piston in displacement function and temperature changing caused by increasing of the internal temperature of the MR fluid.

Illustrations depicted in the Figure 6a present characteristics of absorption and dispersion of the energy in MR damper, it is variations of the force, acting on the piston, in a function of displacement and temperature. In the Figure 6b hysteresis loops has been illustrated (force values in a velocity and temperature function).

Also an interesting seems to be a distribution of temperature on a damper's casing and a temperature run as a function of time in chosen points of a device. Such a diagrams have been depicted in the Figure 7.

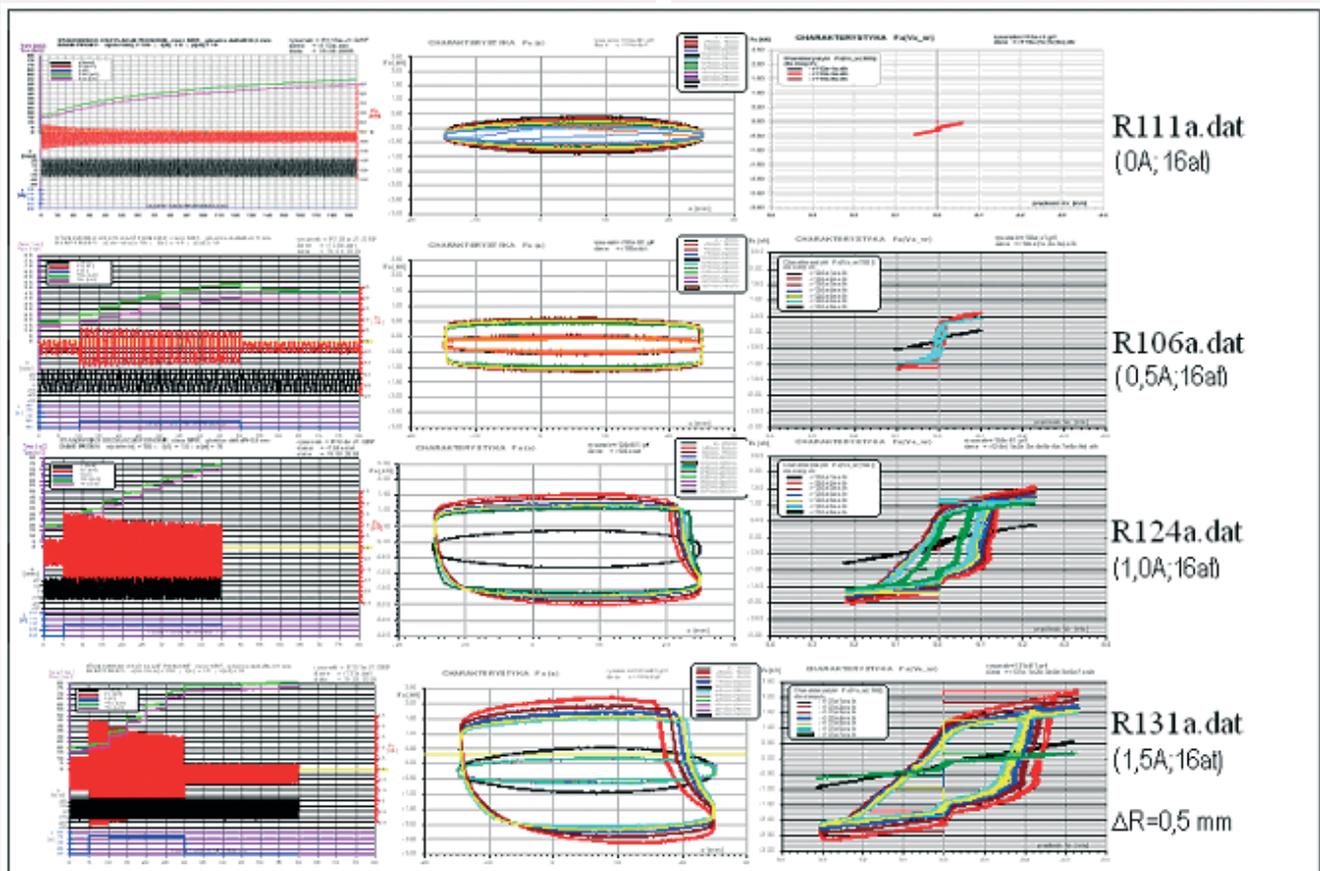
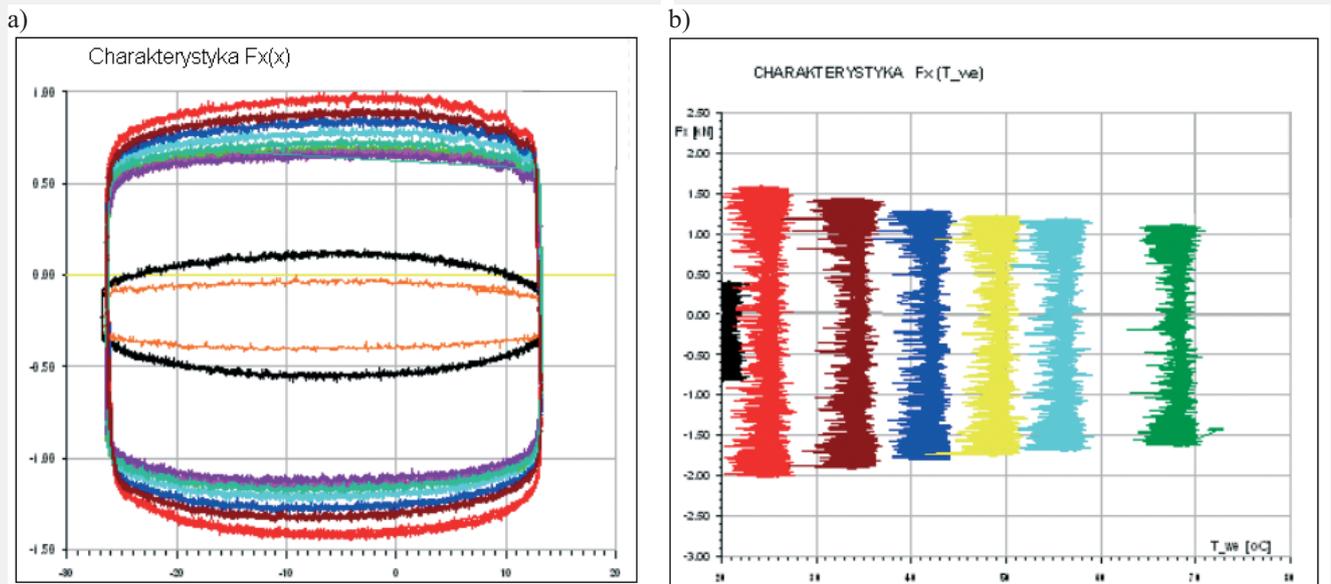
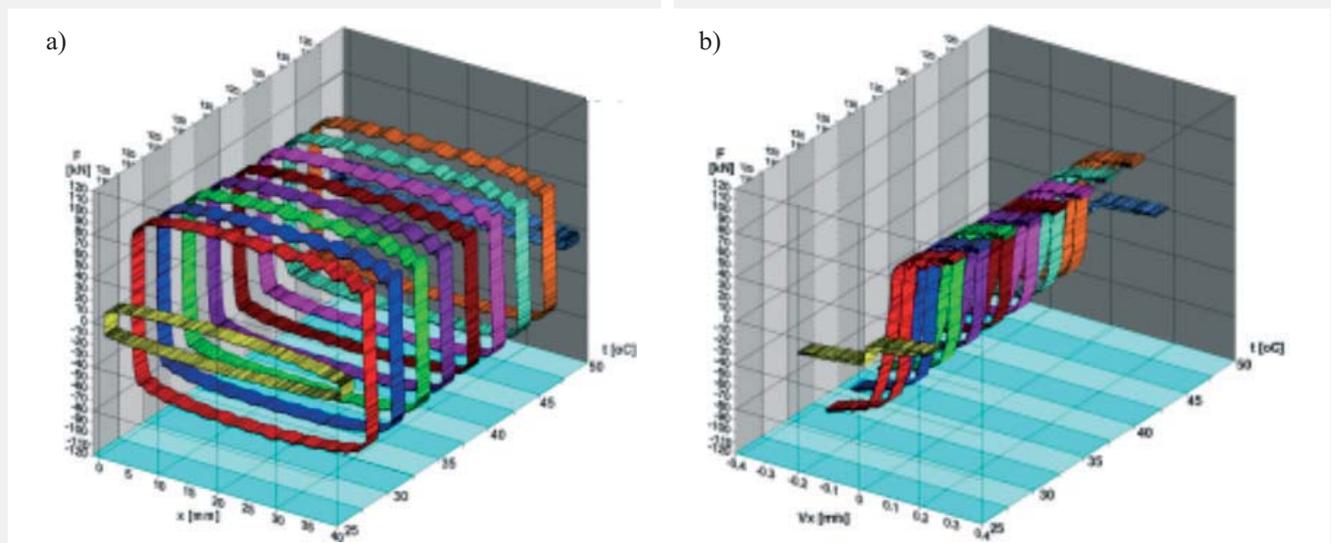


Fig. 4. Dependence between experimentally determined force, acting on the piston, in a time, displacement and velocity function



**Fig. 5.** Changing of force values, acting on the piston of the A-SiMR-MR-203 damper with simultaneous illustration of temperature variation: a) in a displacement function; b) for selected sections of damper’s temperature



**Fig. 6.** Changing of force values, acting on the piston of the A-SiMR-MR-203 damper: a) in a displacement and temperature function; b) in a velocity and temperature function for the current intensity 2 A

It is worth mentioning, that for a discussed damper’s prototype, a stabilization of temperature is attained on the level about 76°C, what isn’t a high value for such a type of device. The highest value of temperature is observed after working for about 11 min.

**4.3. Analysis of experimental research of MR damper**

Examples of acquired experimental results of A-SiMR-MR-LD-203 prototype, have been depicted in the Figures 4–7. Illustrated curves show the force variation, acting on the damper’s piston, working temperature and displacement in time function (Fig. 4 – left column). Characteristics depicted in this figure reflect all of the most interesting fragments of charts, which are illustrations of full experimental data runs. Taking into consideration data obtained in a numerical form,

two independent diagrams have been prepared: force vs. displacement (Fig. 4 – middle column) and force vs. velocity (Fig. 4 – right column). On the basis of presented diagrams, there is a possibility of determination the influence of energy absorption and distribution on the temperature increasing. Particular temperature distribution on the damper’s prototype casing have been depicted in the Figure 7.

**4.4. Analysis of the force variation, acting on the piston**

Recorded in the initial form experimental data, obtained for the damper’s prototype and depicted in The Figure 4 (left column), illustrate force runs in time and velocity functions for the case when the fluid’s gap 0.5 mm. Current intensity in the solenoid’s winding was 0 A, 0.5 A, 1.0 A and 1.5 A, respectively.

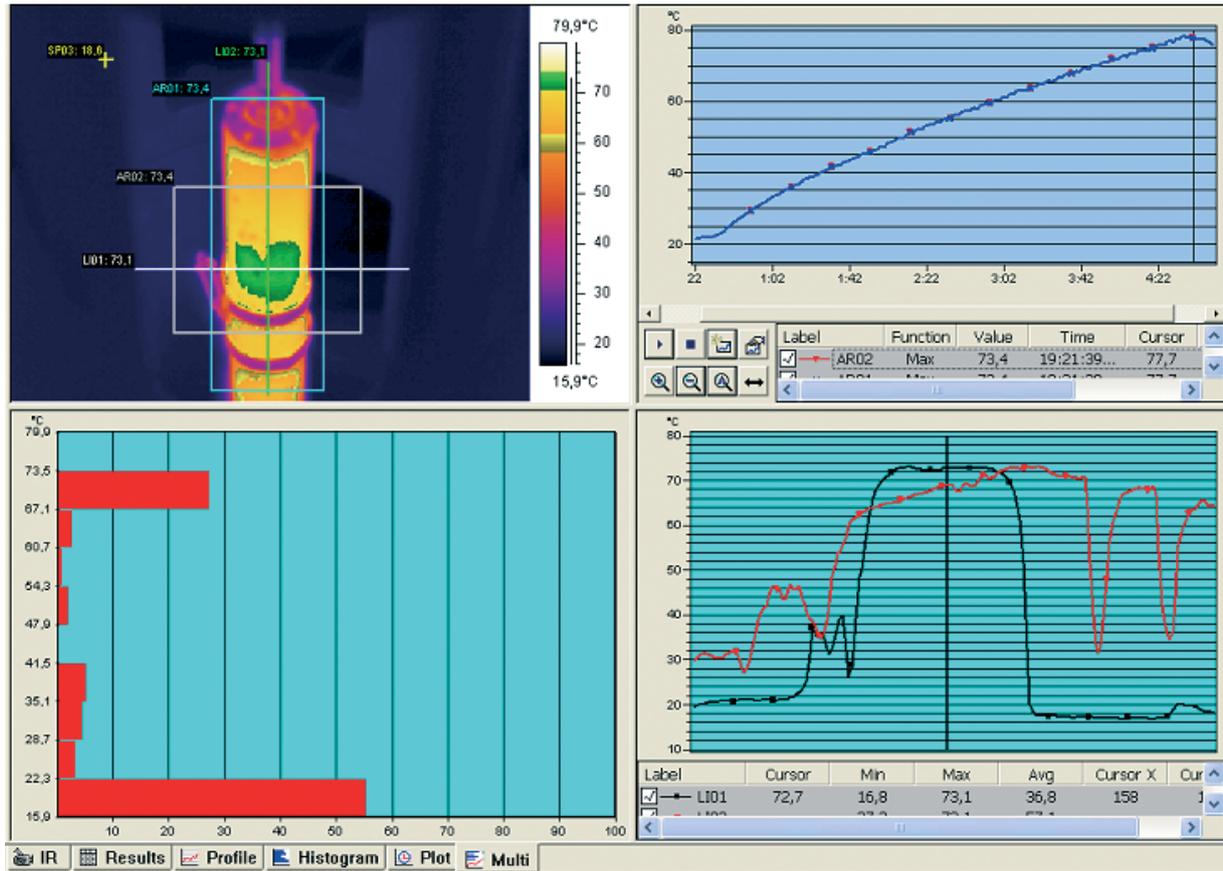


Fig. 7. Temperature distribution on the A-SiMR-MR-LD-203 prototype's casing and temperature run in selected points of the casing, recorded by thermal camera

On the basis of experimental data (first column in the Fig. 4), damping characteristics of the MR damper have been prepared. They reveal dissipative possibilities of the tested device. Force runs in velocity function have been depicted in the third column (Fig. 4).

Scrupulous analysis of the previously mentioned charts show that the force necessary to displace a piston, without the magnetic field ( $I = 0$  A), is dependent on the movement direction. Observed values are from  $-85$  daN to  $40$  daN (Fig. 4 – first row). When generated intensity current equals  $I = 1.5$  A, than analogous forces vary from  $-262$  daN to  $+222$  daN (Fig. 4 – row IV). For average values of the current intensity ( $I = 0.5$  A), the range of forces acting on the piston vary from  $-115$  daN to  $+60$  daN (Fig. 4 – row II). For the  $I = 1.0$  A case, force values are  $-200$  daN to  $+158$  daN respectively (Fig. 4 – row III).

#### 4.5. Determining of “gas spring” stiffness

For the actually discussed case (A-SiMR-MR-LD-203 MR damper prototype), the difficulty of selecting a suitable stiffness of a gas spring was a typical constructional problem. In the designed system, there is a possibility of internal pressure controlling thanks to the special valve, mounted in the damper's casing. This parameter was selected in such a way to provide a piston return to the initial position after unloading.

Taking into consideration such an assumption, after appropriate calculations and experimental research, the gas spring stiffness was established as  $k = 246$  N/m.

#### 4.6. Analysis of temperature influence on typical characteristics of damper, for various values of the current intensity

It is obvious that temperature variations are phenomenon strictly connected with dampers working. However, in contrary with classical technological solutions of dampers where the heat source is only friction forces, for the case of MR dampers, we have to deal also with additional heat source. It is the flow resistance of a current through a coil. It is the reason why determining the influence of temperature on a shape and character of obtained results, especially energy damping and dispersing characteristics is very important task.

From the technical point of view, precise measurement of these parameter for such a type of devices is rather difficult. The measurement process sometimes even made difficult conducting experimental courses.

Curves depicted in the Figure 4, besides reflecting the influence of a current intensity on energy absorption and dispersion characteristics, also reveal the magnitude of temperature parameter.

In currently analyzed devices, increasing of MR fluid temperature is strictly related to both parameters, the value of electric current and working parameters of device (piston's velocity, piston stroke etc.).

Taking into considerations detailed analysis of charts depicted in the Figure 4, once could notice, that in the first column, besides force and displacement variations, also temperature run in time function have been illustrated. The middle column of the Figure 4 and the right one illustrate the shape variations of characteristics related to work of device. All of characteristics variations are illustrated using suitable colors.

Precise determining the influence of temperature on acquired experimentally results of damping characteristics, basing on the Figure 4, reveals that in case when the current supply is turned off, so the magnitude of the magnetic field is negligible and temperature increasing is caused only by the friction forces, the difference between maximal and minimal values of acting forces, measured in the initial part of the measuring cycle and at the end, was about 17 daN (Fig. 4 – middle column, 1st row).

For the case when the current supply is turned on, and the current intensity is 0.5 A, the analogical difference in forces values equals 35 daN (Fig. 4 – middle column, 2nd row).

Similar differences for higher current loading cases, it is for  $I = 1$  A and 1.5 A are respectively: 79 daN (Fig. 4 – middle column, 3rd row) and 86 daN (Fig. 4 – middle column, 4th row).

It is worth mentioning, that resulted from temperature increasing, previously mentioned values of forces acting on the piston, characterize characteristics of energy damping and absorption only in very narrow scale.

Basing only on the force values differences, the temperature influence problem has been more precisely illustrated in the Figures 5 and 6.

Characteristics depicted in the Figure 5a uniquely confirm dependences of working time on the acquired results. In the Figure 5b a similar results, for successive temperature intervals have been depicted.

It turns out, that temperature increment by about 50°C results in decreasing of loading force, acting on the piston by about 1 kN.

Charts depicted in the Figure 6, illustrate in a multifarious way force values dependence in a displacement, temperature (Fig. 6a) and displacement velocity functions (Fig. 6b) respectively.

As a conclusion of considerations related to the influence of temperature on working conditions of MR device (A-SiMR-MR-LD-203), charts depicted in the Figure 7 have been performed. They illustrate in very transparent way temperature distribution in chosen points of damper's casing. Such a distribution is very inhomogeneous. It also reveals how many problems have to be solved to achieve the situation when the thermal loading is homogenous across the whole casing of the MR damper. Stabilized working temperature for a considered prototype is about 70–75°C is being achieved approximately after 11 minutes.

## 5. PROPOSITION OF THE RHEOLOGICAL MODEL OF THE MR DAMPER

### 5.1. Model description, motion equations, thermal balance

Having a lot of experimental data related to discussed damper's prototype, authors have proposed a new rheological model, although a long list of existing is published in a world literature. Such an innovatory MR model more precisely describes phenomenon observed in considered device. Proposed mathematical description takes into consideration Coulomb friction forces as a multivalent function.

Detailed analysis of experimental results, also previous works of authors [1–7], were the base to formulation of the MR damper's rheological structure which has been depicted in the Figure 8.

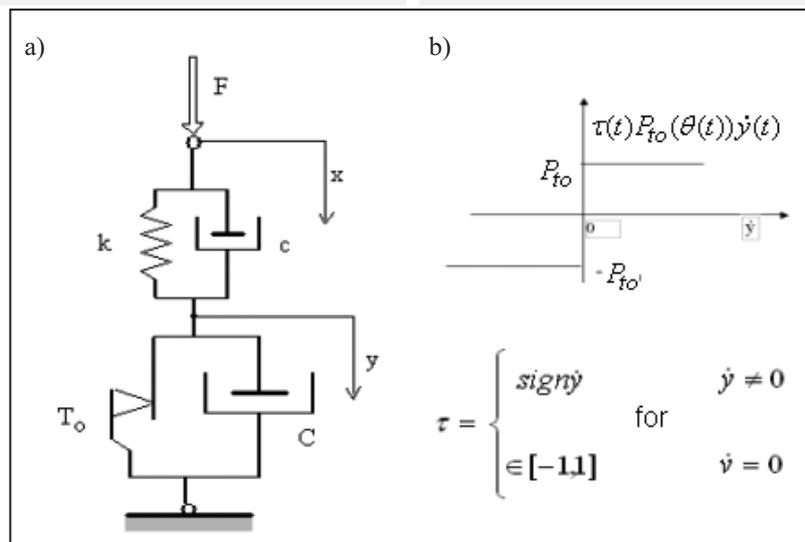


Fig. 8. Proposed scheme of a rheological structure of the MR damper: a) rheological model of A-SiMR-MR-LD-203 prototype; b) dry friction force characteristic and its description

In the previously proposed model, elastic properties of the damper have been reflected by the spring, having stiffness coefficient  $k$ . Damping properties are represented by two viscose dampers having damping coefficients  $c$  and  $C$ . Friction phenomenon are characterized by friction forces model  $T_0$ . Models displacement could be caused by different kinds of excitations.

As experimental results revealed, the factor which plays an important role in description of discussed phenomenon in MR devices and influences on the final shape of characteristics reflecting absorption and dispersion characteristics is variation of temperature. This phenomenon caused supplementation of the mathematical description by the thermal part. It is quite innovatory in accordance to actually published mathematical formulations related to discussed problems.

Taking into consideration these previously mentioned system's properties, in the mathematical description of discussed MR damper also thermal balance equations have been introduced. It fulfills the classical mechanical description of dampers features. Assuming signatures depicted in the Figure 8, also:

$$\begin{aligned} y(t) &- \text{piston's displacement,} \\ Q = Q(t) &- \text{temperature function,} \\ Q_0 = 0 &- \text{thermal initial condition,} \\ F(t) &- \text{external force,} \\ \tau(t)P_{t0}(Q(t)) &- \text{friction force,} \end{aligned}$$

force equation and thermal balance could be formulated as

$$\begin{cases} F(t) = C_R(\theta(t))\dot{y}(t) + \tau(t)P_{t0}(\theta(t)) \\ \tau = \begin{cases} \text{sgn}(\dot{y}) & \text{for } \dot{y} \neq 0 \\ [-1, 1] & \text{for } \dot{y} = 0 \end{cases} \\ C_p \dot{\theta}(t) = I^2 R + C_R(\theta(t))\dot{y}(t) + \tau(t)P_{t0}(\theta(t))\dot{y}(t) - \kappa\theta(t) \end{cases} \quad (1)$$

where:

$$\begin{aligned} C_p &- \text{fluid's specific heat,} \\ C_R(\theta(t))\dot{y}^2(t) &- \text{energy dissipation,} \\ \tau(t)P_{t0}(\theta(t))\dot{y}(t) &- \text{thermal energy (resulting from} \\ &\text{friction forces),} \\ \kappa &- \text{heat conductivity coefficient,} \\ \kappa\theta(t) &- \text{energy variation,} \\ I &- \text{current intensity generating the} \\ &\text{magnetic field,} \\ R &- \text{solenoid's electric resistance.} \end{aligned}$$

These formulation could be transformed to the more convenient form (2)

$$\dot{\theta}(t) = \begin{cases} \dot{y}(t) = F(t) - \tau(t)P_{t0}(\theta(t)) / C_p(\theta(t)) \\ \left\{ \frac{(I^2 R + F(t)^2)}{C_p(\theta(t))} - \frac{F(t)\tau(t)P_{t0}(\theta(t))}{C_R(\theta(t))} - \kappa\theta(t) \right\} \frac{1}{C_p} \end{cases} \quad (2)$$

$$\text{where } \tau = \begin{cases} \text{sgn}(\dot{y}) & \text{for } \dot{y} \neq 0. \\ [-1, 1] & \text{for } \dot{y} = 0. \end{cases}$$

Such a description enables multifarious simulation researches of MR devices movement, taking also in considerations the influence of temperature.

Actually discussed problem related to object's simulations has been presented in details in [1] and will not be discussed in this paper.

## 6. SUMMARY

In this paper experimental results of designed in Warsaw University of Technology MR damper's prototype A-SiMR-MR-LD-203 have been presented. The work especially is focused on determining of dependences between energy dispersion and absorption and temperature of a fluid or a device. Innovatory rheological model with differential equations of motion has been proposed. It takes into consideration a multi-values friction forces function for velocity  $v = 0$ . Also thermal balance equations have been defined. They are in force for the proposed rheological model of the MR damper.

This paper enlarges the educating range of discussed mechanical field, by introducing to the mathematical description, the influence of temperature, which is experimentally affirmed.

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