ANALYSIS OF VISCOPLASTIC PROPERTIES OF A MAGNETORHEOLOGICAL FLUID IN A DAMPER

Jerzy BAJKOWSKI*, **Paweł SKALSKI****

*Institute of Machine Design Fundamentals, Warsaw University of Technology, ul. Narbutta 84, 00-524 Warszawa, Poland
**Institute of Aviation, Al. Krakowska 110/114, 02-256 Warszawa, Poland

jba@simr.pw.edu.pl, pawel.skalski@ilot.edu.pl

Abstract: The aim of presented paper is a mathematical description and an analysis of viscoplastic properties of a magnetorehological fluid in operational conditions of a damper's work. The authors consider the possibility of use the viscoplastic law, typically for metals, to describe the behaviour of device with a magnethorheological fluid.

Key words: Magnetorheological Fluid, Bodner-Partom Model, Numerical Simulations

1. INTRODUCTION

Magnetorheological fluids, beside ferromagnetic and electrorheological fluids, belong to the non-Newtonian rheostable fluids, which are characterized by a yield point (Haake, 1998). Magnetic, ferromagnetic and electrorheological fluids are colloidal suspension of microscopic solids in the liquid carrier, and their main characteristic is rapid grouping of particles into a dense grid under the influence of an external stimulus (Carlson & Weiss, 1994).

Magnetorheological fluids (MRF) are very useful in solving damping problems which are one of main engineering dilemmas of construction and exploitation of machines and devices. Magnetorheological fluids change their rheological properties under the influence of a magnetic field. These properties of MR fluids couldn't be fully used until the age of the computer steering equipment.

MRF are used e.g. in: dampers, shock absorbers, clutches and brakes (Goncalves, 2005; Lee et al., 1999). MR dampers and MR shock absorbers are applied e.g. in damping control, in operation of buildings and bridges (Dyke et al., 1996), as well as in damping of high-tension wires (Wu, 2006). Actually, MR fluids are used, in large scale production in the car industry and military industry (Poynor, 2001).

In the development and production area of MR fluids, LORD Company is a dominating figure on the global market, producing fluids and devices, it contributes to their development. Despite plenty of works being currently led at universities and research centres, still the need of a better and more extensive knowledge of particular properties of these liquids is noticed, their behaviour in exploitative conditions, as well as learning all possibilities to control their rheological properties.

The authors of presented paper took the attempt to describe the MR fluid's behaviour, by using constitutive equations which are generally applied for metals. Before taking such a decision one should think and answer following question: whether and why, and which constitutive equations, proper for metals, can be used in the mathematical description of MR fluid's properties and behaviour?

Responding to the question, we should note that in certain operational conditions an MR fluid changes its density, becoming semi-solid, or even solid. It is one of an MR fluid's most significant features.

Therefore, it was decided to undertake an analysis of magnetorheological fluid's viscoplastic properties in operational conditions of a damper's work, to be able to apply the Bodner-Partom law, for description of properties and behaviour of MR fluids.

2. RESEARCH OBJECT

The range of experiments was limited to the T-MR SiMR 132 DG damper prototype (Fig. 1) with a MRF 132 DG from the LORD company. In the presented damper prototype, a gas spring was neglected in its construction. The research program was carried out in the test stand with kinematic excitation (Bajkowski, 2005) at the Faculty of Automobile and Construction Machinery Engineering at the Warsaw University of Technology.

Tab. 1. Fundamental properties of MRF 132 DG fluid (www.lord.com)

Properties	**MRF 132 DG**
Viscosity, temperature 40 [°C]	0.092±0.015 [Pa·s]
Density	2.98÷3.18 [g/cm^3]
Solids content by weight	80.98%
Operating temperature	-40÷130 [°C]
Flash point	>150 [°C]
Appearance	Dark grey

Fig. 1. View of the T-MR SiMR 132 DG damper prototype

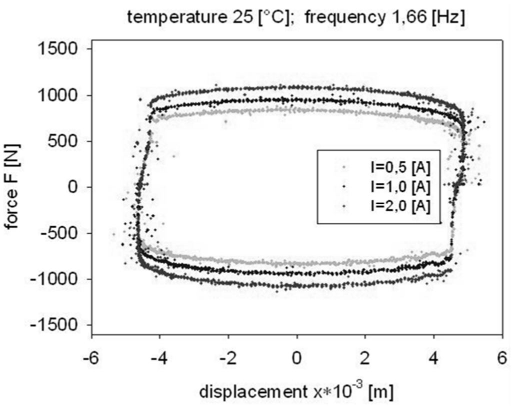
In presented work, MR fluid is the research object, which is a work base in the smart dampers. Selected to the analysis, MRF 132 DG, its based on hydrocarbon. Major properties of MRF 132 DG fluid are shown in Tab. 1, while detailed information are available on the producer's website – www.lord.com.

3. RESULTS OF EXPERIMENTAL RESEARCH

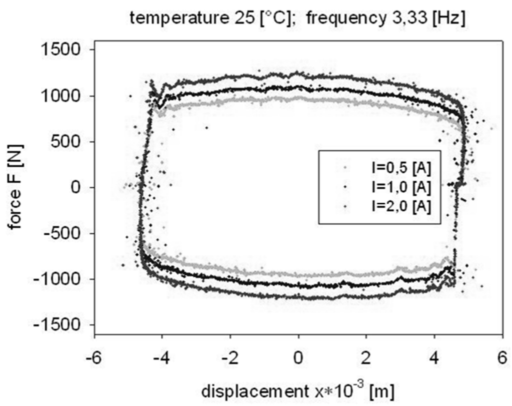
During the implementation of studies, using sensors of: displacement, force, temperature and speed, following physical parameters were recorded:

- the force acting on the piston rod of the test device;
- the movement of a piston housing;
- the temperature of the outer casing of device;
- the rotational speed of the movement.

a)



b)



c)

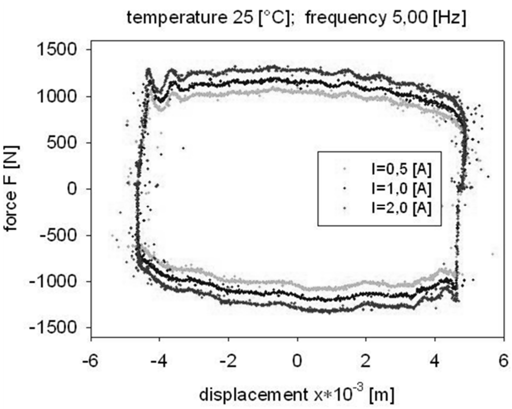


Fig. 2. Impact of the current intensity on the damping force in function of a displacement of the piston, for three oscillation frequencies: (a) 1.66; (b) 3.33; (c) 5.00 Hz

As intended, and pursued in the research program, the impact of changes of oscillation frequency of rod's kinematic excitation, current intensity in the coil winding head mounted in the test sample; effects of changing temperature of the test subject and the gap's height, by which the fluid flows through, were all considered when determining the characteristics of work of examined devices. The final result of research is estimated by the courses of damping force of tested device in function of displacement its piston's rod. All efforts were made to register and record the results as accurate and precise as possible, and the obtained results are burdened with possibly smallest errors.

Constant input signal in such prepared research programme, was a harmonic function $x(t) = A\sin(\omega t)$ for the displacement of the damper's piston, where the amplitude was $A = 10$ mm and rotation speed of circular cam $\omega =$ 100; 200; 300 (400) rpm; response to this signal was a function $F(t)$. Time of recording a single experiment was set to $t = 5$ s, and the sampling frequency to 400 Hz. Investigations were conducted for three values of the piston oscillation frequency: $f =$ 1.66; 3.33; 5.00 Hz, and three current values: $l =$ 0.5; 1.0; 2.0 A. The gap's height was $h =$ 7x10-4 m.

The important issue is to determine the impact of frequency oscillation of a piston in the damper and shock absorbers, on characteristics of tested devices. Changing the velocity of a piston movement, changes the speed of fluid flow through the gap in a head, it turns into the value of the damping force. Oscillation frequencies of the piston were selected by evaluating the capabilities of the test stand and the damper prototype.

Oscillation frequencies of the piston were selected by evaluating the capabilities of the test stand and installed object for tests. Three values of oscillation frequencies of the piston, converted to the corresponding values of shear rate of the liquid in the gap, is the minimum value in the identification of parameters of viscoplastic constitutive equations.

Fig. 2 shows the impact of the current intensity, flowing in a solenoid, on the damping force, with oscillation values: (a) 1.66; (b) 3.33; (c) 5.00 Hz. Used on the test stand measuring equipment have been chosen so that, to minimize the error of the method of measurement.

4. ANALYSIS OF MR FLUID

The results of the cyclic experimental tests of the damper and the shock absorber, became a base for an analysis of viscoplastic properties of a magnetorheological fluid under influence of a magnetic field, in operational conditions of a damper's work. The authors of this paper decided to examine yield point in MR fluid, when the fluid flows through the working gap in the head of the damper.

Analysis of these parameters of MR fluid, will be subjected to the influence of shear parameter of fluid flowing through the gap, as well as changes in the value of current flowing in a solenoid and changes of the temperature of the liquid.

Fig. 3a shows an example of graph illustrating the change in force value acting on the piston rod of the tested damper in function of the displacement of the rod. The curve shown in Fig. 3a was a base to obtain the graph in Fig. 3b.

The curve in Fig. 3b was created by cutting a portion of the curve from Fig. 3a, where the force begins to rise. Next, to make analysis easier, cut curve was shifted to position zero of displacement.

The authors estimated the impact of dry friction's work on the total value of force operating on the rod. Empty damper (without MR liquid) resisted 9 N, which is max. 2% of the total value of a resistance force on the piston rod. This variable has been intentionally omitted, due to its very small value. Because of such small influence of friction force, when the damper is not filled with MR fluid and because of the lack of a gas spring, the authors, on that basis, appealed directly to the MR fluid in its operational conditions, so that measurement could be maximally real.

a)

b)

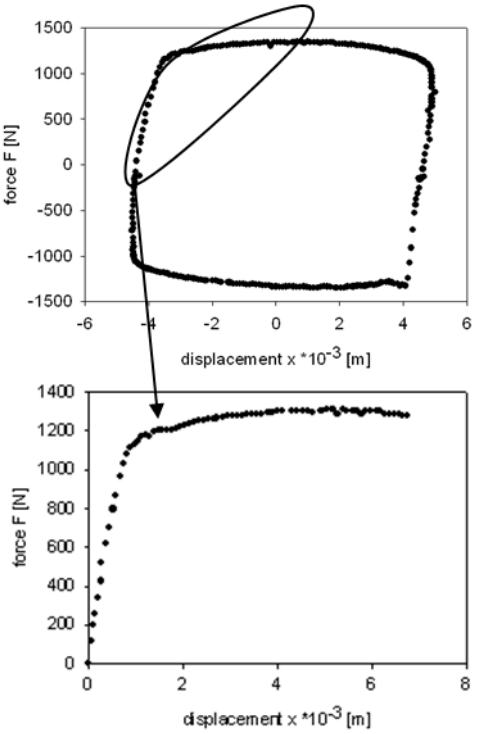


Fig. 3. Characteristic of a work force acting on the piston rod in function of a displacement(a); characteristic of the selected part of Fig. 3a (b)

Such prepared curve in Fig. 3b, allowed to prepare data for analysis on MR fluid, and it enabled the calculation of fluid shear stress τ, fluid shear strain γ, plastic shear strain γ^I, which have been designated in accordance with equations (1), (2), (3) described below:

$$\tau = \frac{F}{A}, \tau = \frac{\Delta x}{h} \tag{1}$$

$$\gamma^I = \gamma - \frac{\tau}{G} \tag{2}$$

$$r = r_1 + \frac{2}{3}(r_2 - r_1), A = 2\pi r l \tag{3}$$

where indicated: A – field shear surface of fluid in the gap, h – the value of the gap's height, Δx – increase of displacement, G – unit value of Kirchoff's modulus, r_1 – the value of the internal radius of the gap, r_2 – the value of the outer gap's radius, r – the radius value calculated from equation (3), l – the length of the piston's head.

In Fig. 4a the working gap of damper's head was indicated, and in Fig. 4b radiuses r_1, r_2 determining the height of the gap, and *l* the length of the head.

To determine the shear rate, it was necessary to know the value of a shear strain in a function of time. The value of a shear strain was calculated from the formula (1), and time t was recorded during the experiment. When carrying out the process to determine the shear rate, a graph was prepared (Fig. 5), illustrating the growth of a shear strain in a function of time. The value of a strain rate was determined based on the slope of the line passing through a section of the curve on which shear stress reached maximum value. Straight line whose slope corresponds to the value of a shear rate was marked in Fig. 5.

a)

b)

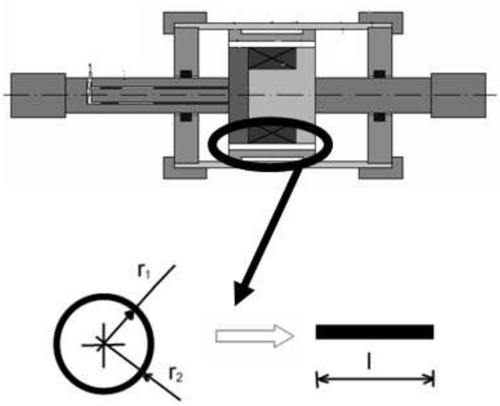


Fig. 4. Scheme of the damper with selected working gap (a); „view" of the working gap (b)

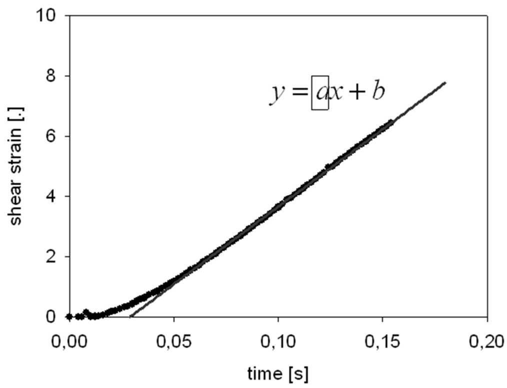


Fig. 5. Determination of a shear rate value

This way was used to estimate the value of shear rate for each rate of the frequencies of rod's oscillation. For a gap's value of h=7x10^{-4} [m], the value of the piston oscillation frequency were 1.66; 3.33; 5.00 Hz, values of shear rate are, respectively 73; 144; 217 [1/s].

In order to estimate the value of a conventional yield point of a magnetorheological fluid under magnetic field, working in the test device, it was necessary to draw a chart (Fig. 6), which presents the course of shear stress in function of strain. The values of shear stress were calculated from equations (1). The yield point, in this case, is designated by the intersection of two lines, one approximately reproducing the elastic part of shear stress in a function of non-dilatational strain and the order, illustrates roughly, the change of plastic values.

Another parameter, which describes the properties of an MR fluid in the magnetic field is a Kirchoff's modulus, also called the shear modulus. In carrying out the process of designating the Kirchoff's modulus, a chart was made (Fig. 7), illustrating the change in a reproducing approximately the elastic part of the curve to the abscissa, on which non-dilatational strain values were marked, expresses the value of the Kirchoff's modulus.

Eliminating the elastic deformation from the total value of non-dilatational strain, the course representing the viscoplastic properties of an MR fluid in operational conditions of the damper's work was obtained.

Extremely important thing is the value of the yield point, beyond which, as shown in Fig. 8, in the next phase of a plastic deformation, viscoplastic course of the MR fluid is determined.

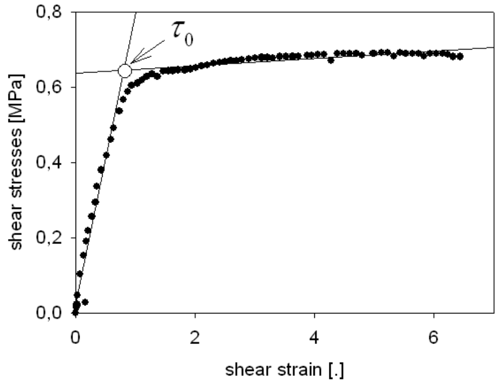


Fig. 6. Evaluation of a yield point τ_0 of an MR fluid

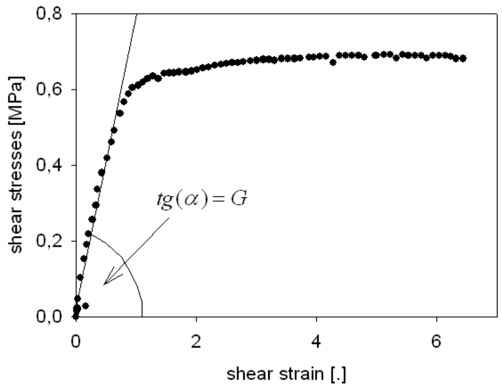


Fig. 7. Evaluation of a Kirchoff's modulus

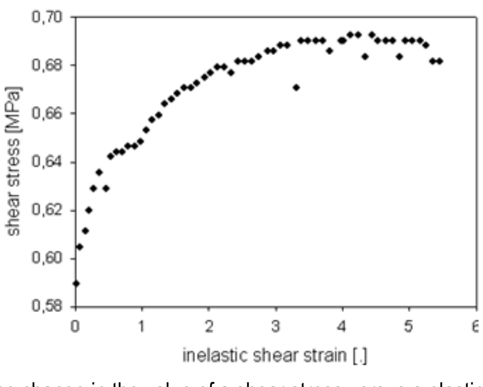


Fig. 8. The change in the value of a shear stress versus a plastic shear strain

Explained above, methodology of presentation of shear stress, non-dilatational strain, its plastic part, estimation of the yield point and the Kirchoff's modulus, obtained results of the fluid MRF 132 DG. The results are summarized in Tab. 2.

The Kirchoff's modulus was 0.95 MPa and was constant for different shear rate and the current value of the variable in the analyzed area.

Tab. 2. Yield point of fluid MR 132 DG

current intensity [A]		0.5	1.0	2.0
yield point [MPa]		τ_0		
shear rate [[1/s]]	102	0.29	0.32	0.37
	202	0.33	0.36	0.41
	304	0.35	0.39	0.45

Fig. 9 illustrates the changes of yield point, obtained for three values of current intensity 0,5; 1,0; 2,0 A and three values of shear rate 73; 144; 217 [1/s]. The increase of shear rate and the increase of current intensity causes the increase of the yield point.

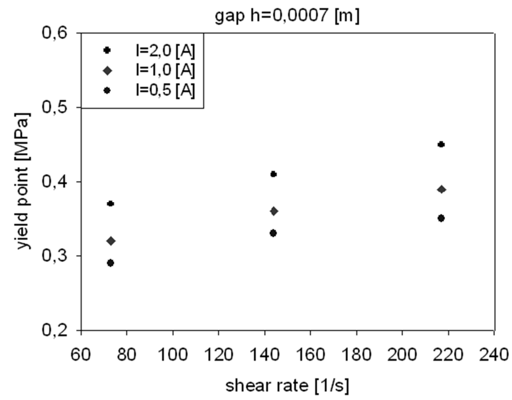


Fig. 9. Impact of shear rate and a current intensity on the yield point, for the gap h=7x10[-4] m

5. BODNER-PARTOM LAW

The Bodner-Partom law is a typical law for metals. Equations of this model allow to describe a viscoplastic behaviour of analysed material. The constitutive formulation of Bodner-Partom can be expressed in the following form (Skalski, 2010):

$$\dot{\varepsilon}'^{ij} = \frac{3}{2}\dot{p}\frac{\sigma'^{ij}}{J(\sigma'^{rs})} \tag{4}$$

where $\dot{p}$ – the accumulated inelastic strain rate, $\dot{\varepsilon}'^{ij}$ – the deviatoric plastic strain rate tensor, σ'^{ij} – the deviatoric stress tensor, and $J(\sigma'^{rs})$ – the invariant of the plastic strain rate tensor.

The constitutive equation of the Bodner-Partom law was written in the form (Skalski, 2010):

$$\dot{\gamma}^{I} = 2D_0\exp[-\frac{1}{2}(\frac{R_0}{\sqrt{3}\tau})^{2n}\frac{n+1}{n}]\mathrm{sgn}(\tau) \tag{5}$$

where $\dot{\gamma}^{I}$ – plastic strain rate, τ – shear stress, n, R_0, D_0 – model parameters.

A large number of parameters describing the constitutive equations, makes considerable problems with their identification.

Identification methods of the Bodner-Partom model parameters are described well in (Chan et al., 1988). In this paper, the methodology and the identification of parameters of the B-P law, based on the scheme given in (Kłosowski and Woźnica, 2007). Parameters estimation was performed using the Marquardt-Levenberg algorithm (Marquardt, 1963) for the objective function, which was adopted as the difference of least squares.

Carried out analysis of yield point value changes of an MR fluid, working in a damper, forms the basis for the parameters identification of the Bodner-Partom model. The values obtained at different shear rates, allow to determine the main parameters of viscoplastic models.

For small values of inelastic deformation, the impact of the isotropic hardening is $\mathrm{R} = \mathrm{R}_0$, and kinematic hardening in negligible, and can be omitted. Formula (6) can be treated in a law as the Bonder-Partom contractual definition of a yield point and can be presented in the following form:

$$\tau_0 = \frac{R_0}{\sqrt{3}[\frac{2n}{n+1}\ln(\frac{2D_0}{\dot{\gamma}^I})]^{\frac{1}{2n}}} \qquad (6)$$

Fig. 10 shows the initial yield limit (yield point) values τ_0, corresponding to three values of a shear rate. Then, using the method of least squares and using the formula (6), plotted curve and the values of the parameters n and R_0. Parameter D_0 is chosen arbitrary (Kłosowski and Woźnica, 2007).

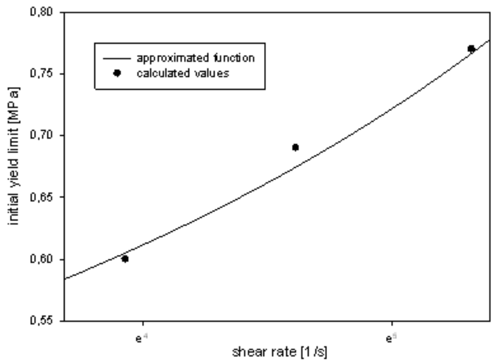


Fig. 10. Evaluation of n and R_0 parameters of the B-P model

At the current values: 0.5; 1.0; 2.0 A, parameters values obtained respectively: $n =$ 0.21; 0.23; 0,27 [.] and $\mathrm{R}_0 =$ 9.4; 9.4; 8.9 MPa. The value of the D_0 parameter was 1000000 [1/s], related to the shear rate 102; 202; 304 [1/s] (Kłosowski and Woźnica, 2007).

6. NUMERICAL SIMULATIONS AND CONCLUSIONS

Identified viscoplastic model was used to develop numerical simulations to verify the proposed mathematical model to describe the behaviour of MR fluid in the working gap of the head, with data from the experiment. The equation (5) was used to solve the numerical simulation. Obtained results are shown in Fig. 11 – 13.

A comparison between computer simulations of presented viscoplastic model and results of investigations, show that proposed viscoplastic model describes the behaviour of the damper with an MR fluid, very well.

The realized investigations allowed to estimate the yield point and then to evaluate the parameters of Bodner-Partom model. This is a big advantage of this type of identification which refers to the physical phenomena.

The study aimed to explore the possibilities of viscoplastic laws application, usually used to describe a metal behaviour in the decription of devices with a magnetorheological fluid.

Further work will be included in the mathematical model not only the influence of shear rate, and current intensity, but also an impact of a temperature and a gap's height.

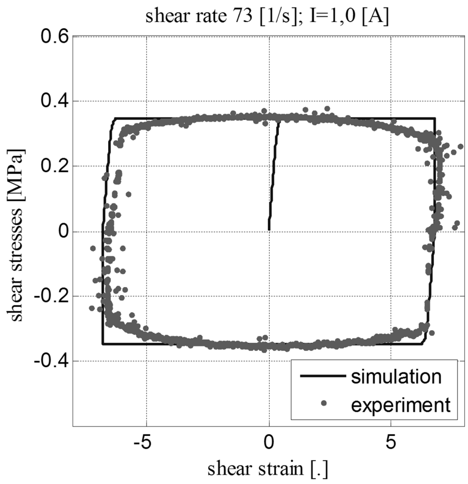


Fig. 11. Comparison of a numerical simulation of the Bodner-Partom law with results of research, when experiment's parameters are: current intensity 1.0 A; gap's height 7x10^{-4} m; shear rate 73 [1/s]

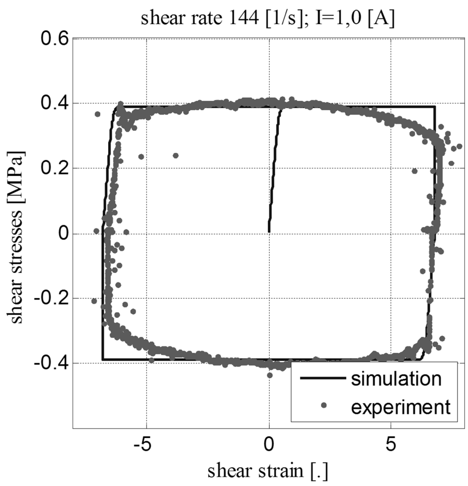


Fig. 12. Comparison of a numerical simulation of the Bodner-Partom law with results of research, when experiment's parameters are: current intensity 1.0 A; gap's height 7x10^{-4} m; shear rate:144 [1/s]

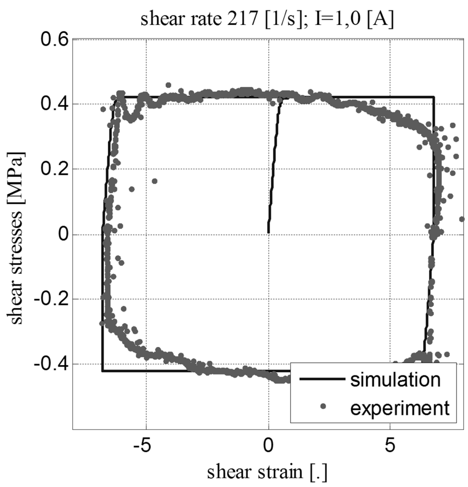


Fig. 13. Comparison of a numerical simulation of the Bodner-Partom l aw with results of research, when experiment's parameters are: current intensity 1.0 A; gap's height 7x10^{-4} m; shear rate 217 [1/s]

REFERENCES

1. **Bajkowski J.** (2005), Research and educational stands for the determination of selected characteristics of a magnetorheological damper or a shock absorber, *XXII Sympozium PKM*, Gdynia-Jurata, 47-56.
2. **Bodner S. R., Partom Y.** (1975), Constitutive equations for elastic-viscoplastic strain-hardening materials, *Journal of Applied Mechanics*, Vol. 42, 385-389.
3. **Carlson J. D., Weiss K. D.** (1994), A growing attraction to magnetic fluids, *Machine Design*, 61-66.
4. **Chan S. C., Bodner S. R., Lindholm U.S.** (1988), Phenomenological Modeling of Hardening and Thermal Recover in Metals, *J. Eng. Mater. & Tech.*, Vol. 11, 1-8.
5. **Dyke S. J., Spencer B. F., Sain M. K., Carlson J. D.** (1996), Modeling and control of magnetorheological dampers for seismic response reduction, *Smart Materials and Structures*, Vol. 5, No. 5, 565-575.
6. **Goncalves F. D.** (2005), Characterizing the behavior of magnetorheological fluids at high velocities and high shear rates, *PhD thesis*, Virginia Polytechnic, Blacksburg.
7. **Haake G. S.** (1998), Rheology. Fundamentals and applications, *Center of Scientific Publications PAN*, Poznań.
8. **Kłosowski P., Woźnica K.** (2007), Non-linear viscoplastic constitutive laws in some structural analysis, Publishing House of Gdansk University of Technology, Gdańsk.
9. **Lee U., Kim D., Jeon D.** (1999), Design analysis and experimental evaluation of an MR clutch, *Journal of Intelligent Materials and Structers,* Vol. 10, 701-707.
10. **Marquardt D. W.** (1963), An algorithm for least square of parameters, *Indust. Math.*, Vol. 11, 431-441.
11. **Poynor J. C.** (2001), Innovative designs for magneto-rheological dampers, *master thesis*, Virginia Polytechnic, Blacksburg.
12. **Skalski P.** (2010), Analysis of viscoplastic properties of a magnetorheological fluid in operational conditions of a dampers work, *PhD thesis*, Warszawa.
13. **Wu W.** (2006), Theoretical and experimental study on cable vibration reduction with tmd-mr damper, *PhD thesis*, Luisiana State University.