Bartosz MINOROWICZ[1], Frederik STEFANSKI[2]

Poznan University of Technology (1)(2)

Proposal of a new group of magnetorheological dampers

***Abstract**. The article presents a construction and testing of a new family of magnetorheological dampers. The work began with testing currently used solutions, which exist inter alia in vibratory machines for example in washing machines. Basis on this job required damping parameters were obtained and then these parameters were used as input data in new devices designing process. A distinguishing feature of newly designed dampers is considerably reduction of volume of smart liquid in comparison to existing solutions described in the literature.*

***Streszczenie.** W artykule przedstawiono budowę i badania nowej rodziny tłumików magnetoreologicznych. Prace rozpoczęto od przeprowadzenia badań obecnie wykorzystywanych konstrukcji tłumików wiskotycznych, które stosowane są między innymi w maszynach wibracyjnych na przykład w pralkach automatycznych. W wyniku przeprowadzonych badań ustalono wymagane parametry tłumienia i użyto ich, jako danych wejściowych w procesie projektowania nowego urządzenia. Charakterystyczną cechą nowo zaprojektowanych tłumików jest znacznie zmniejszenie objętości stosowanych cieczy inteligentnych w stosunku do istniejących rozwiązań, opisanych w literaturze.*
*(**Propozycja nowej grupy tłumików magnetoreologicznych**)*

Keywords: MR damper, magnetorheological fluid, viscous damper, damping force.
Słowa kluczowe: tłumik MR, ciecz magnetoreologiczna, tłumik wiskotyczny, siła tłumienia.

doi:10.12915/pe.2014.07.59

Introduction

Magnetorheological fluids are colloidal non-Newtonian mixture of ferromagnetic particles (usually made of iron, their size varies from 3 up to 10 micrometres), and oil (mineral or synthetic), or water as a carrier. What is more, additives are used to prevent a gravitational settling of the particles. This liquid reaches a very interesting properties at time of appearance of an external magnetic field, this field causes that randomly distributed molecules change orientation into regular chains. This results in a direct way on the rheological properties (for example viscosity), and yield stress in the range unattainable for other materials in time of milliseconds. Magnitude of yield stress depends on an intensity of the applied magnetic field, usually generated by coil. At the time of magnetic field application, the randomly distributed particles tend to distribute along the magnetic lines causing the growth of the chains which constitutes a barrier to fluid flow. MR fluid can be used in one of four operating modes: valve, shear, squeeze and pinch mode (Fig. 1.) [1, 2, 3]

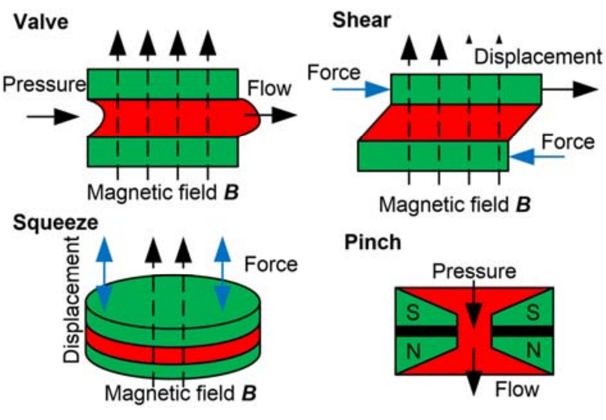

Fig.1. Magnetorheological fluid operating modes

Thanks to properties described above magnetorheological fluids are classified for a group of smart materials whose use significantly improves parameters of designed devices, this group includes rotary and linear dampers, clutches and brakes. This resulted in industrial applications of this type of equipment ranging from transport machinery through to the biomechanical structures for example artificial legs [4, 5, 6]. Authors decided to introduce a different design of MR damper than those which can be easily found in literature descriptions, where often ready-made Lord MR dampers are used [7, 8, 9, 10, 11]. At Institute of Mechanical Technology (Poznan University of Technology), many MR based devices were designed and manufactured, last of them is shock absorber [12], and earlier heavy duty MR damper for hydraulic servo positioning systems [13]. Another devices were designed at Warsaw University of Technology [14], this publication consists description of R-MR SiMR 132 DG damper design, Authors proposed and verify tool for fast parameters selection. Also another shock absorber A-SiMR-MR-LD-203 can be mention [15]. Classically (in valve operating mode), both chambers are separated by a piston, and there is a possibility of liquid flow between the chambers (flow/valve operating mode). While current passes through the coil(s), it changes viscosity of MR fluid in an orifice area that disrupts fluid flow and generates damping force adequate to an electric input signal. Such structure of MR damper needs narrow dimensions tolerances, fluid supplement, has an accumulator filled with compressed nitrogen (pressure 10 – 20 bar) [16, 17]. In this paper authors proposed solution envisages use of a fabric soaked with MR fluid which will be disposed between the piston and an internal wall of the cylinder, this solution is similar to dampers RD1097-01 made by Lord Company, but in this case a soaked polyurethane sponge was used. These dampers work in shear operating mode. The advantages of newly designed dampers include a significant reduction in amount of used MR fluid (down to 3 cm^3 [18, 19, 20]), which should definitely reduce weight and costs of such a device and almost complete elimination of problems with sealing and leakage of fluid. It is an ideal solution for low costs applications for example household goods industry [4, 17, 19 20]. The disadvantages of such a construction of damper should include a much smaller damping force than the other dampers (similar dimensions damper obtained values of the order of kN [21]). Use of smart fluid allows precise selection of attenuation parameters depending on the current needs and it is possible to make closed loop control system, which is successfully used in case of dampers for use in seismically active regions (Japan, California), an additional advantage in quick response to a given signal [22, 23]. Another practical application of shear mode dampers is vibration reduction in long steel cables. Experiments performed with 30 meter cable at Cracow University of Technology and AGH University of Science and Technology confirmed possibility of this application [8, 10, 24]. These kind of dampers were also used in manipulator design [25]. Another key note is low power consumption, in papers [11, 26], design of energy harvester was proposed as a power source for damper's coils.

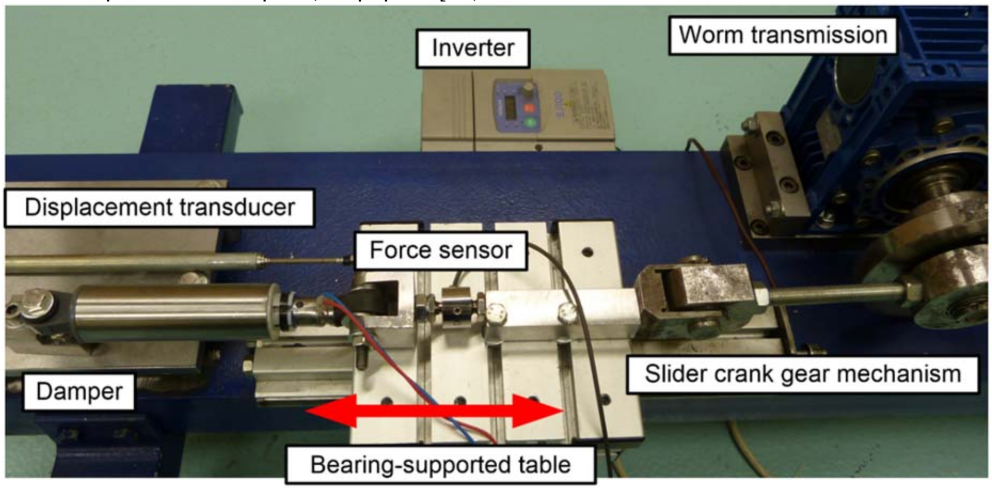

Fig.2. Laboratory stand for viscous and magnetorheological dampers testing

Viscous damper examinations

The main aim of designing work was to propose construction of semi-active damper, which in its operating parameters will not be worse than the same magnitudes distinguished for the viscous damper. For this purpose, work started from viscous dampers tests, that kind of dampers are commonly used in a construction of domestic washing machines. The study used specially designed test stand where it is possible to determine the basic characteristics of the dampers: force vs. speed, force vs. displacement (Fig. 2.). Test stand allows examination of classical viscous dampers and new design with MR fluid. The drive system provides AC motor whose speed is controlled by inverter. Transmission is carried out by worm gear connected to the slider crank gear mechanism, connection between those two components is provided by eccentric disk which makes it enable to adjust of the working stroke of a table which is roller bearing supported. Tested damper was connected with double-acting force transducer (HBM U9B with operating range ±5 kN), by special made forks, and that structure was bolted to the table. The result of the first study, characteristics force vs. speed is shown in Fig. 3. It is worth to notice that this viscous damper was disassembled from washing machine distinguished by parameters: maximum rotational speed 1400, maximum mass deposited on two dampers, during wash cycle (drum, drum housing, motor, concrete blocks, laundry, water et cetera), can be up to 50-55 kg

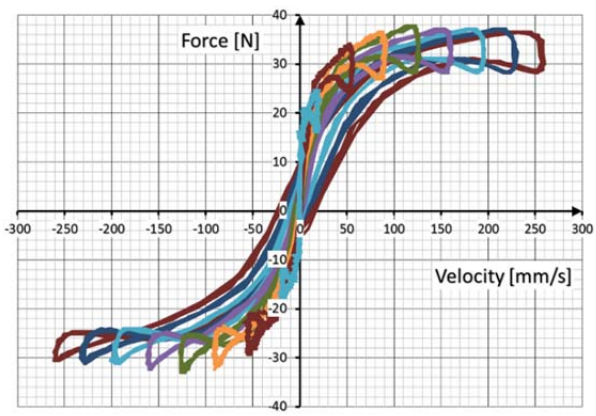

Fig.3. Viscous damper examinations, force vs. velocity

Magnetorheological dampers calculations

Input data for the MR damper design was the geometry, stroke and damping force generated by the viscosity damper. According to this, preliminary cross section of the magnetic circuit was set. The following step was to calculate the minimal number of coil turns which will meet the force requirements, for the smallest value of current. A low current magnitude has many advantages. First of all it will prevent form high energy consumption and overheating, which could cause fire. Moreover it will allow to increase the damping force in a secure range of current.

Designed MR dampers work in the shear operating mode and therefore the origin of the force will mainly come from the shear stress created during the fluid shearing.

Based on the expected force, the shear stress that must occur in the MR fluid was defined [27] by using equation (2).

(1) $$F = F_\eta + F_\tau = \frac{\eta S A}{g} + \tau_y A$$

(2) $$\tau_y = \frac{F}{A} - \frac{\eta S}{g}$$

where *F* is expected force, field dependent yield stress τ_y, *g* is the fluid gap, η is the fluid viscosity, *S* is the relative pole velocity and *A* is the shear area.

On base of received τ_y value the magnetic field strength H_f could be determined using the MRF-132DG MR Fluid characteristics [28]. Next according to the operating point in MR fluid the value of flux density B_f was defined. By using the principle of continuity of magnetic flux, the flux density B_s for the steel magnetic circuit was calculated (3).

(3) $$\Phi_{FLUID} = \frac{B_f}{A_f} = \frac{B_s}{A_s} = \Phi_{STEEL},$$

where B_f is flux density in the MR fluid, B_s is flux density in the coil core, A_f is effective pole area of the MR fluid and A_s is the minimal cross-section of the coil core.

By using the B-H graph for steel (Fig.4.), H_s was specified. On the base of Kirchhoff's law for magnetic circuits the number of turns of the coil was calculated [29] (4).

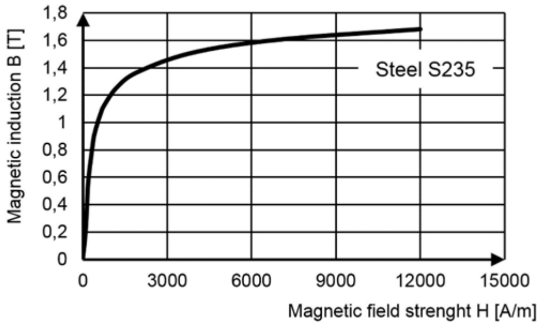

Fig.4. B-H curve for steel S235

(4) $$N = \frac{H_f g + H_S L}{I}$$

where H_f is magnetic field strength in the MR fluid, H_s is magnetic field strength in the coil core, L is the length of steel path and I is applied current.

Obtained from the theoretical calculation value of number of turns is 160, assuming that the force is equal to 40N, and the current is approximate 0,5A.

On the base of above relationship a simple mathematical model of the MR damper was prepared. The Matlab-Simulink model allows to show the dependency of the input current to the output damping force. The model and obtained on this basis current-force characteristics were shown in Fig. 5., 6., 7.

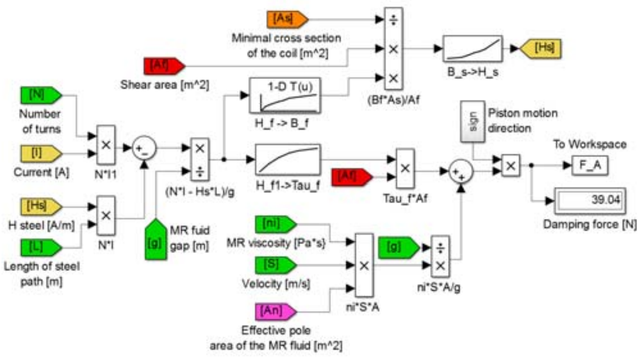

Fig.5. Model in Matlab-Simulink environment

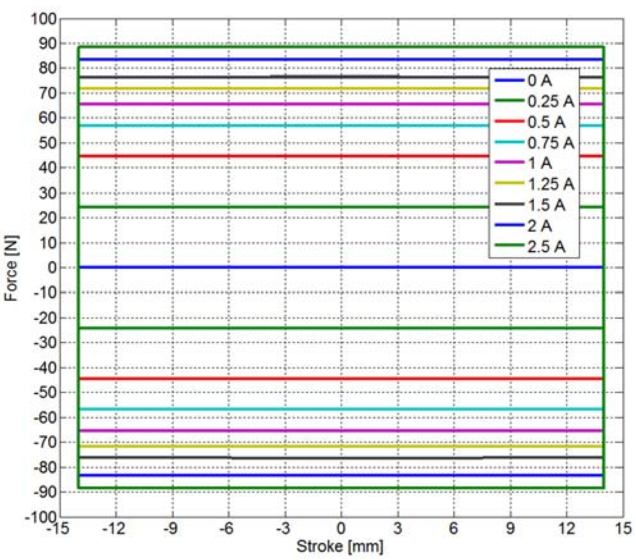

Fig.6. Single coil MR damper examinations, force vs. stroke

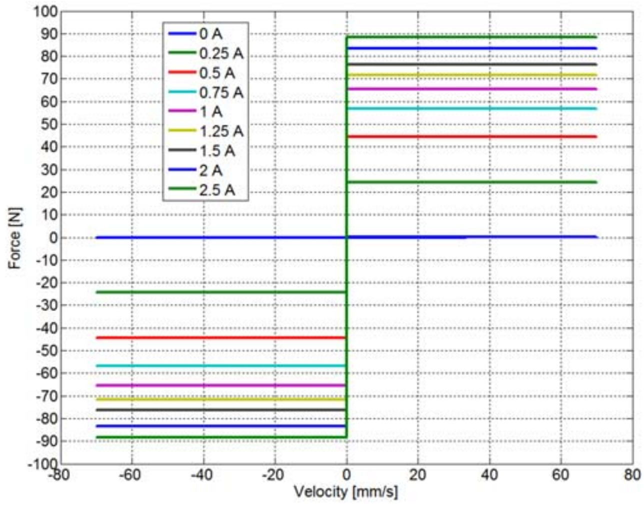

Fig.7. Single coil MR damper examinations, force vs. stroke

Design concept of magnetorheological dampers

As a result of the construction work two semi active dampers were made. The first has a piston with single coil, while the other is equipped with two coils (in this case coils are connected in series). Each coil has 160 turns and it is made of copper. The main aim of single coil damper is to replicate damping parameters of tested viscous damper, while for the double coil damper goal was to achieve maximum damping in specific dimensions and stroke in case of further applications in vibratory machines. Both structures are very similar, consisting of a piston with wound coils. This subcomponent is bolted (by ISO 7379 shoulder screw), with rod adapted from the viscous damper. The whole assembly is placed in a steel cylinder with a precisely machined inner surface to minimize fabric wear. Whole magnetic circuit is made of ferromagnetic steel. Radial clearance between piston and cylinder equals 1 mm, it is a free space for fibre soaked with MR fluid, which is located on the circumference of piston. Soaking process was carried by syringe with MR fluid. That method makes possible to measure volume of used fluid, 1 cm^3 for single coil and 1,5 cm^3 for double coil damper. In addition, holes were drilled in the piston rod, to hide wires which powered coils. Whole space in rod was filled with silicone based material to minimize risk of wires damage or short circuit effect. Assembling process is shown in Fig.8.

Table 1. Dampers comparison

Parameter	RD-1097-01 [24]	Single coil	Double coil
Max. length	253 mm	224 mm	224 mm
Min. length	195 mm	184 mm	194 mm
Body diam.	32 mm	36 mm	36 mm
Weight	0,48 kg	0,58 kg	0,66 kg
Stroke	±25 mm	±14 mm	±14 mm
Coil res. (25ºC)	20Ω	2,0 Ω	3,9 Ω
Coil inductance	No data	4,65 mH	4,45 mH
Coil wire diameter	No data	0,4 mm	0,4 mm
Magnetic core	No data	Steel S235	Steel S235
Amount of MR fluid	3* cm^3	1 cm^3	1,5 cm^3
Max. force	100 N 51 mm/s 1A	90 N 80 mm/s 2,5A	125 N 80 mm/s 2,5A
Min. force	9 N 200 mm/s 0A	7 N 80 mm/s 0A	10 N 80 mm/s 0A

* based on [18, 19]

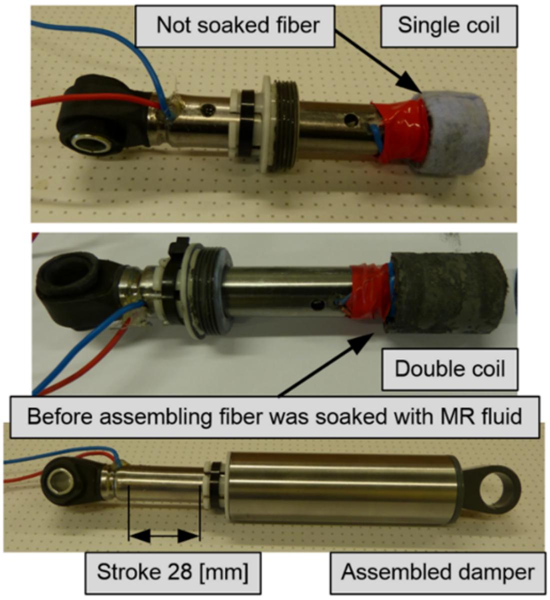

Fig.8. Design and assembling of single and double coil magnetorheological dampers

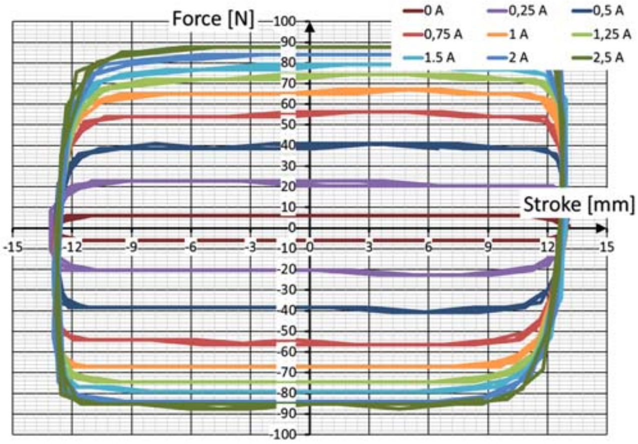

Fig.9. Single coil MR damper examinations, force vs. stroke

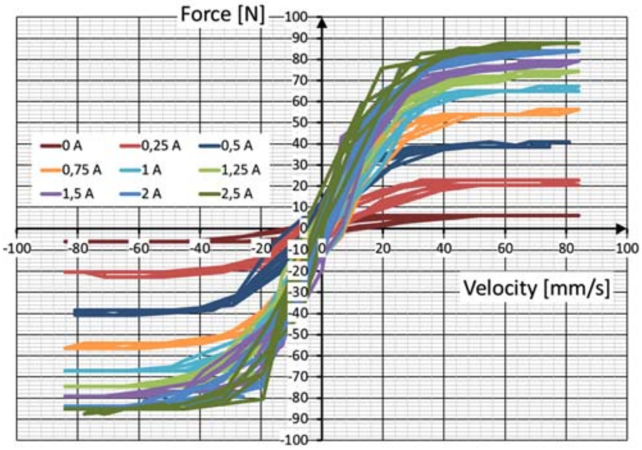

Fig.10. Single coil MR damper examinations, force vs. velocity

Magnetorheological dampers testing

The investigations of single and double coils damper were done on the same test stand as for the viscous damper. The test consisted damping force measurement for a sinusoidal change of piston displacement. Further the test was repeated for different current settings applied to the coil. The current was changed in the range from 0 A to 2,5 A for both dampers. The current settings were controlled by a stabilized laboratory DC adapter EA PSI 8032-10T of accuracy lesser than 0,2%.

Test results for single coil damper are shown below. First chart shows curves of damping force vs. velocity (Fig.9.), second one shows curves of damping force vs. displacement (Fig.10.).

Test results for double coil damper are shown below. First charts shows curves of damping force vs. velocity (Fig.11.), second one shows curves of damping force vs. displacement (Fig.12.).

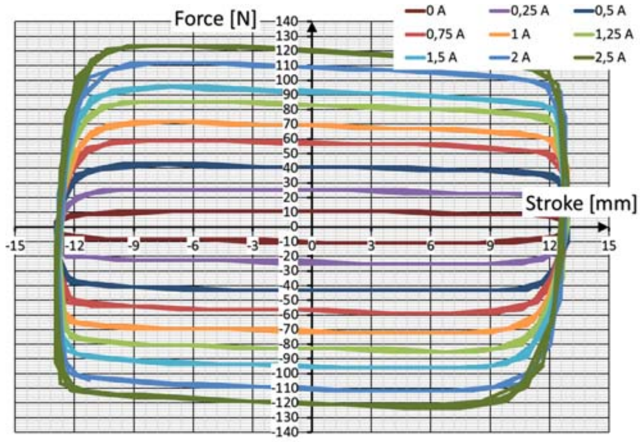

Fig.11. Double coil MR damper examinations, force vs. stroke

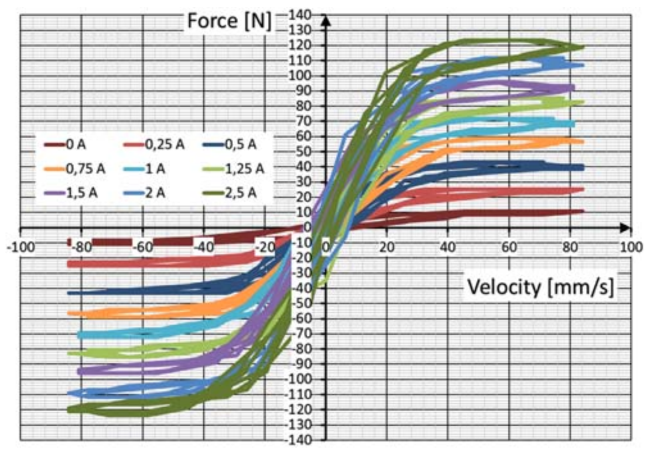

Fig.12. Double coil MR damper examinations, force vs. velocity

Conclusions

Design process was successful, new dampers satisfy all preliminary assumptions. Single coil damper is distinguished by low power consumption (0,4W), for required damping force (~40N), which is obtained for current 0,5A, but on this damper higher damping force also can be set. Increase of current (up to 2,5A), causes increase of damping force up to 90N, and stops when magnetic circuit is fully saturated. Without changing stroke and external dimensions double coil damper was proposed, in this case damping force rises by 30% to 120N.

Application of small amount of MR fluid, adjustable damping force of the MR damper, and low power consumption, are the greatest advantages of the design, comparing to viscous and classical MR dampers. Real time damping force control allow to design a close loop control system. It will make possible to precise set the damping force regard to current needs. Centre of concern of following research of the dampers will be durability and performance during long time work, and at different temperatures.

Fibre needs less MR fluid than polyurethane foam (double coil damper 1,5 cm^3 vs. damper [18, 19, 20], 3 cm^3).

REFERENCES

[1] Spaggiari A., Properties and applications of Magnetorheological fluids, *Fracture and Structural Integrity*, 23 (2012), 57-61

[2] Kciuk M., Turczyn R., Properties and application of magnetorheological fluids, *Journal of Achievements in Materials and Manufacturing Technology*, 18 (2006), nr 1-2, 127-130

[3] Baranwal D., Deshmukh T. S., MR-Fluid Technology and Its Application – A Review, *International Journal of Emerging Technology and Advanced Engineering*, 2 (2012), nr 12, 563-569

[4] Spelta C., Previdi F., Savaresi M.S., Fraternale G., Gaudiano N., Control of magnetorheological dampers for vibration reduction in a wasching machine, *Mechatronics*, 19 (2009), 410-421

[5] Parlak Z., Engin T., Calli I., Optimal design of MR damper via finite element analyses of fluid dynamic and magnetic field, *Mechatronics*, 22 (2012), 890-903

[6] Li F., Xianzhuo L., The Modelling Research of Magnetorheological Damper in Advanced Intelligent Prosthesis, Control and Decision Conference, 2009. CCDC '09. Chinese, 781-784

[7] Sapiński B., Filuś J., Analysis of parametric models of MR linear damper, *Journal of Theoretical and Applied Mechanics*, 41 (2003), 215-238

[8] Maślanka M., Sapiński B., Snamina J., Experimental study of vibration control of a cable with an attached MR damper, *Journal of Theoretical and Applied Mechanics*, 45 (2007), 893-917

[9] Sapiński B., Rosół M., MR damper performance for shock isolation, *Journal of Theoretical and Applied Mechanics*, 45 (2007), 133-145

[10] Sapiński B., Magnetorheological dampers in vibration control of mechanical structures, *Mechanics*, 28 (2009), 18-25

[11] Sapiński B., Vibration power generator for a linear MR damper, *Smart Materials and Structures* 19 (2010), 105012

[12] Milecki A., Hauke M., Application of magnetorheological fluid in industrial shock absorbers, *Mechanical Systems and Signal Processing*, 28 (2012), 528-540

[13] Milecki A., Sędziak D., The use of magnetorheological dampers to reduce servo drive velocity jumps due to load changes, *Journal of Intelligent Material Systems and Structures*, 16 (2005), 501-510

[14] Bajkowski J. M., Design analysis and performance evaluation of the linear magnetorheological damper, *Acta Mechanica et Automatica*, 6 (2012), 5-9

[15] Bajkowski J., Bajkowski M., Grześkiewicz W., Sofonea M., Shillor M., Zalewski R., Analysis of the dependence between a temperature and working parameters of the MR damper, *Mechanics*, 26 (2007), 149-155

[16] Milecki A., *Investigation and control of magneto-rheological fluid dampers,* International Journal of Machine Tools & Manufacture 41 (2001), 379-391

[17] Xiaocong Zhu, Xingjian Jing, Li Cheng, Magnetorheological fluid dampers: A review on structure design and analysis, *Journal of Intelligent Material Systems and Structures*, 23 (2012), 839-873

[18] Carlson J.D., Jolly M.R., MR fluid, foam and elastomer devices, *Mechatronics*, 10 (2000), 555-569

[19] Carlson J.D., Low-Cost MR Fluid Sponge Devices, *Journal of Intelligent Material Systems and Structures,* 10 (1999), 589-594,

[20] Nguyen QH, Choi SB, Woo JK, Optimal design of magnetorheological fluid-based dampers for front-loaded washing machines, *Journal of Mechanical Engineering Science,* 228 (2014), 294-306

[21] Wang J., Meng G., Magnetorheological fluid devices: principles, characteristics and applications in mechanical engineering, *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, 215 (2001), nr 3, 165-174

[22] Dyke S. J., Spencer F. B. Jr, Sain M. K., Carlson J. D., Modelling and control of magnetorheological dampers for seismic response reduction, *Smart Materials and Structures*, 5 (1996), 565-575

[23] Liu D.Y., Lee J., Choi B.S., Choi H.J., Silica-coated carbonyl iron microsphere based magnetorheological fluid and its damping force characteristics, *Smart Materials and Structures*, 22 (2013), 1-7

[24] Sapiński B., Snamina J., Maślanka M., Rosół M., Facility for testing of magnetorheological damping systems for cable vibrations, *Mechanics,* 25 (2006),135-142

[25] Hoyle A., Arzanpour S., Shen Y., A novel magnetorheological damper based parallel planar manipulator design, *Smart Materials and Structures*, 19 (2010), 055028

[26] Sapiński B., Snamina J., Jastrzębski Ł., Staśkiewicz A., Laboratory stand for testing self-powered vibration reduction systems, *Journal of Theoretical and Applied Mechanics*, 49 (2011), 1169-1181

[27] Lord Corporation: *Design with MR Fluids*

[28] Lord Corporation: *Technical data MRF-132DG MR Fluid*

[29] Lord Corporation: *Magnetic circuit design*

***Authors**:*

M.Sc. Eng. Bartosz Minorowicz, Poznan University of Technology, Institute of Mechanical Technology, ul. Piotrowo 3, 60-695 Poznan, E-email: bartosz.minorowicz@doctorate.put.poznan.pl

M.Sc. Eng. Frederik Stefański, Poznan University of Technology, Institute of Mechanical Technology, ul. Piotrowo 3, 60-695 Poznan, E-email: frederik.stefanski@doctorate.put.poznan.pl