ISSN 1392 - 1207. MECHANIKA. 2013 Volume 19(2): 210-214

Control of training facility loading by MRF damper

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crossref http://dx.doi.org/10.5755/j01.mech.19.2.4156

1. Introduction

Sports and rehabilitation in present society are hardly imaginable without exploitation of technical means. There are well-known mechanical exercise machines in the market and vibration, aerial and electrical training machines are increasingly gaining popularity [1, 2].

The units of load formation of exercise machines are getting more and more sophisticated. Now they are usually controllable and have feedback between the movement of input link and generated load. They may be used to form the loads of inertial resistance, as well as resistance of other types: elastic or viscous, hydrodynamic, maintaining them at constant level during the entire exercise or following the chosen law of exchange [3, 4].

Recently smart materials have been started to be used widely for the technology of various kind. In order to form the exercise machines load force, the devices of controlled resistance with electric/magneto rheological fluids are also perspective. Their viscous resistance force characteristics depend on the applied electric / magnetic field strength. The magnitude of such resistance may be regulated according to the training program or the person's condition using the sensors, which react to the heart's rhythm, intensity of perspiration and other physiological parameters, and the human organism may be loaded optimally [5, 6].

The work presents the attempt to use smart material damper in the inertial resistance type exercise machine. Hydraulic cylinder of the damper is filled with magnetorheological fluid (MRF), which running characteristic is controlled by changing the fluid viscosity through the application of variable magnetic field strength.

2. MRF damper

MRF damper used [Fig. 1] is a linear hydraulic cylinder type shock absorber, filled with a magnetorheological fluid MRF-140 CG (LORD corporation, USA) [7]. The device has been designed and developed at Kaunas University of Technology, Faculty of Mechanical Engineering and Mechatronics, Department of Mechatronics. The working diameter of the cylinder is 13 mm and the piston stroke is 44 mm.

The cylinder piston *6* mounted on the rod moves inside of the inner tube *2*. It makes the fluid *8* flow from the one chamber to another through two narrow (cross-section area 2 mm^2) channels between the inner *2* and outer *1* tube. Such design ensures the damper the ability to change effectively MRF viscosity during operation. The magnetic coil *7* contains 700 windings of 0.33 mm thickness copper wire, which resistance is 12.4 Ω and inductivity 1.0 mH.

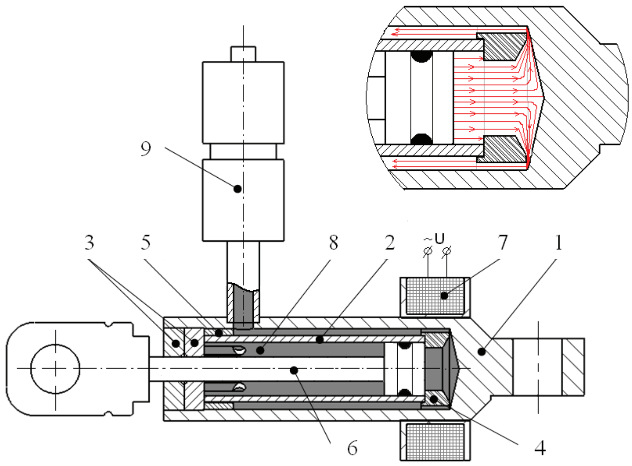

Fig. 1 MRF linear damper: *1* – damper frame-outer tube; *2* – inner tube; *3* – cover of damper frame; *4* – hub with two channels; *5* – centering hub; *6* – piston with a rod; *7* – magnetic field induction coil; *8* – RF; *9* – expansion reservoir

The dependencies of damper resistance force versus displacement, velocity and strength of the magnetic field are presented in Fig. 2 and are based on the results of the experimental research given in [8].

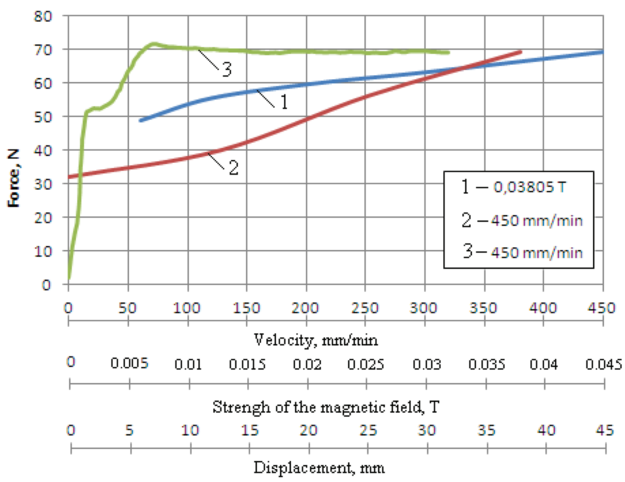

Fig. 2 MRF damper force dependencies on velocity displacement of piston, and strength of magnetic field

Curve *1* shows the dependency of the resisting force generated by MRF damper on the speed of piston motion at strength of the magnetic field equal to 0.03805 T.

Curve *2* shows the dependency of the resisting force generated by MRF damper on the strength of the magnetic field at the speed of the piston motion equal to 450 mm/min.

Curve *3* shows the dependency of the resisting force generated by MRF damper on the displacement of piston at 450 mm/min. speed of piston motion and strength of magnetic field equal to 0.03805 T [8].

3. Damping of MRF damper

One of the most significant problems in developing controllable device having necessary resisting force characteristic is to establish the dependencies of its damping force on the structural parameters of the device and magnetic field strength.

As the magnetic field is applied, the damping force F developed by MRF can be calculated by [9]:

$$F = \frac{12\eta L\pi r^2}{\pi R h^3} v + \left(\frac{K_0 L \tau_B \pi r^2}{h} + f \right) sgn(v), \quad (1)$$

where: v is the speed of piston, m/s; f is the friction coefficient for the piston and cylinder contact; $K_0 = 0.8-1.0$ is a coefficient; L is the piston height, m; τ_B is the yield stress developed in response to an applied magnetic field, MPa; η is the viscosity of MRF, Pa s; h is the thickness of the annular MRF volume between the piston and outer cylinder, m. The value of h can be given by:

$$h = R - r, \quad (2)$$

where: R is the outer cylinder radius, m; r is the piston radius, m.

If it is assumed that the value of f is very small, Eqs. (1) and (2) can be mathematically manipulated to yield:

$$F = 2\pi L \tau_B r^2 + \frac{2\pi\eta L r^3 v}{h}. \quad (3)$$

Eq. (3) shows that the damping developed in the cylindrical MRF damper can be divided into a magnetic field dependent induced yield stress component F_B, MPa and a viscous component F_η, Pa s [10].

The minimum volume of active fluid can be established as [11]:

$$V = Lwg = \left[\frac{12}{f_E^2} \right] \frac{\eta}{\tau^2} \left[\frac{\Delta P_{mr}}{\Delta P_r} \right] Q \Delta P_{mr}, \quad (4)$$

where: η is the dynamic viscosity, Pa s; Q is the flow rate, m^3/s and L, m; w, m; g, m are the geometric length, width and gap size of the flow channel; τ is the yield stress, MPa developed in response to the applied magnetic field; f_E is an empirical factor and is determined experimentally.

This minimum volume of the fluid is required to achieve a desired MRF effect at given flow rate Q, m^3/s with the specified pressure drop [12].

4. Theoretical premises for loading force control using MRF damper

When magnetic field is not acting the MRF damper the dynamics of the loading unit following the scheme which is given in Fig. 3, is described by the equation:

$$m\ddot{x} + h(\dot{x} - \dot{s}) + k(x - s) = 0, \quad (5)$$

where $s = s(t)$ is the law of motion of the handle of the training device and t is time.

The experimental data show that $s(t)$ can be described quite adequately by the polynomial:

$$s(t) = a_4 t^4 + a_3 t^3 + a_2 t^2 + a_1 t + a_0. \quad (6)$$

The solution of Eq. (5) is:

$$x = A_0 + \sum_{n=1}^{\infty} \left(A_n \cos(n\omega t) + B_n \sin(n\omega t) \right), \quad (7)$$

where

$$A_n = \frac{1}{\omega_0^2} \frac{\left(1 - n^2\eta^2\right)\bar{a}_n - n\frac{\Theta}{\pi}\eta\bar{b}_n}{\left(1 - n^2\eta^2\right)^2 \bar{a}_n + n^2\left(\frac{\Theta}{\pi}\right)^2 \eta^2}; \quad (8)$$

$$B_n = \frac{1}{\omega_0^2} \frac{\left(1 - n^2\eta^2\right)\bar{b}_n + n\frac{\Theta}{\pi}\eta\bar{a}_n}{\left(1 - n^2\eta^2\right)^2 \bar{a}_n + n^2\left(\frac{\Theta}{\pi}\right)^2 \eta^2}; \quad (9)$$

$$A_0 = \frac{\bar{a}_0}{m\omega_0^2}; \ \omega_0^2 = \frac{k}{m}; \ \eta = \frac{\omega}{\omega_0}; \ \Theta = \frac{2\pi\varepsilon}{\omega_0}; \ \varepsilon = \frac{h}{2m};$$

$\bar{a}_0, \bar{a}_n$ and $\bar{b}_n$

are the coefficients obtained by expanding polynomial (6) into Fourier series.

If the properties of MRF are following Bingham model, the dynamics of the system when magnetic field is applied is described by the equation:

$$m\ddot{x} + h(\dot{x} - \dot{s}) + k(x - s) = -F(H) - G, \quad (10)$$

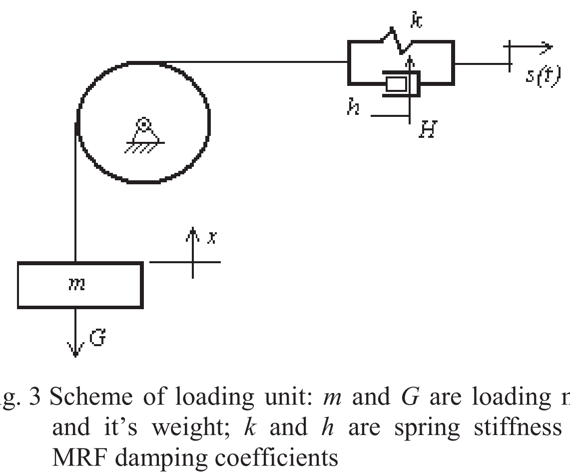

Fig. 3 Scheme of loading unit: m and G are loading mass and it's weight; k and h are spring stiffness and MRF damping coefficients

where $F(H)$ is the component of the resisting force depending on magnetic field intensity $H(t)$.

It allows us to control the loading force on the handle by controlling magnetic field intensity versus time.

5. Experimental and measurement equipment

The computer model of weight stack machine equipped with a MR damper (Fig. 4) was designed by the means of 3D CAD software SolidWorks.

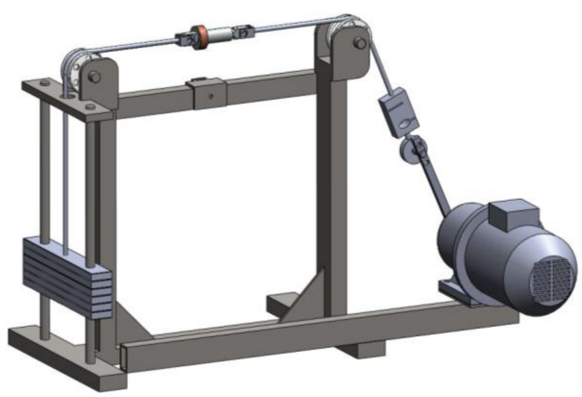

Fig. 4 Computer model of test bench

For the experimental research of the loading force, generated by such machine at different regimes of movement, the experimental test bench has been made meeting the principle of operation of inertia load exercise machine according to the computer model. Stack of five steel plates, each weighing 1.3 kg, used for the loading. To check mathematical model described in section 2 the exciter is designed consisting of electric motor (power of 0.55 kW, rotation speed 60 min^{-1}) with gearbox and crank mechanism, giving the harmonically varying kinematic excitation on the input ("handle") of the test bench (the duration of loading cycle and magnitude of kinematic excitation are set similar to the values obtained when performing exercises of pulling the handle by hand). The stack of plates is attached to the exciter via the flexible cable guided by two pulleys. In the middle of the pulleys the cable is interrupted and the MRF damper and the spring joined in parallel are embedded.

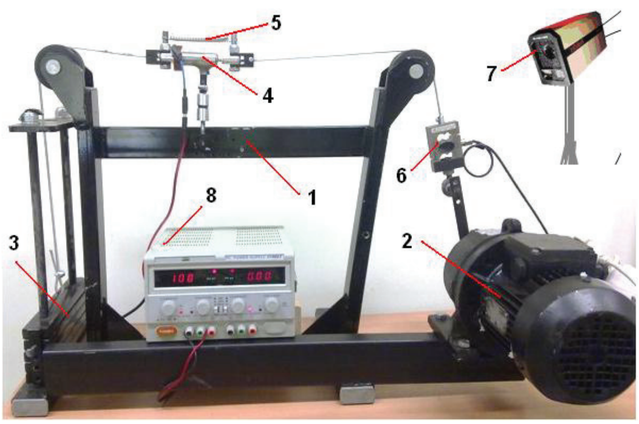

Fig. 5 Test bench: *1* – frame, *2* – exciter electric motor with gearbox, *3* – weight stack, *4* – MRF damper, *5* – spring, *6* – force gauge, *7* – video cameras of motion capture system, *8* – power supply device HY3002-2

To define the main kinematical and force parameters the measuring equipment was implemented into the test bench (Fig. 5). Thus the input force ("on handle" or near the force generator) has been measured by tensometric force gauge, attached to the portable computerised multichannel measuring chain Spider Mobil (HBM, Germany), and synchronically the kinematic parameters of movement of the loading plates, exciter and the stabilizer roller have been measured by means of 3D motion Capture system Qualisys (Qualisys, Sweden).

The force gauge S9 (HBM, Germany) was used for the force measurements: nominal force F_{nom} – 500 N, accuracy class – 0.05, sensitivity C_{nom} – 2 mV/V, relative tensile/compression sensitivity difference $dzd < \pm 0.1\%$, nominal shift $S_{nom} < 0.4$ mm.

The 3D video MoCap system Qualisys (6 digital infrared cameras Pro-Reflex) was used for capturing motion parameters (translations, velocities and accelerations) of characteristic points of the test bench where the 15 mm diameter reflective markers were affixed. The maximal measurement frequency of the system 500 Hz (100 Hz frequency was used), measurement range: 0.2 – 70 m, horizontal field-of-view: 10° to 45°, effective resolution – 20000 × 15000 subpixels, exposure time –100 – 400 μs.

The strength of the magnetic field was controlled by changing the electric current strength I in the magnetic coil by means of the power supply device HY3002-2 (8). The resisting force generated by the damper was investigated at the absence of magnetic field and at three levels of strength (0.013, 0.025 and 0.038 T).

6. Results of experimental tests

The measurements were done using the gross weight of 2.6 kg. The movement was repeated for 10-13 cycles at the velocity of exciter equal to 4.71 rad/s.

The resistance force curves received by changing the strength of magnetic field strength are shown in Fig. 6.

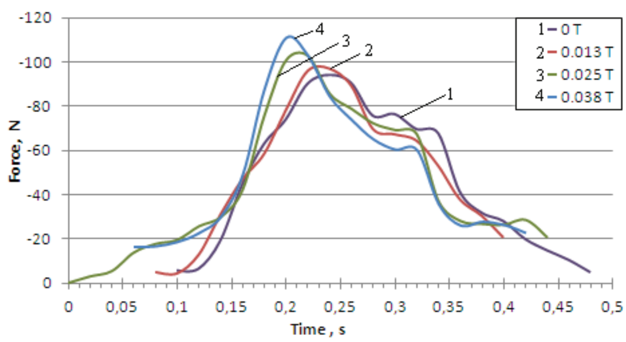

Fig. 6 Dependencies of resisting force at different strength of magnetic field: *1* – 0 T, *2* – 0.013 T, *3* – 0.025 T, *4* – 0.038 T

In order to ascertain the possibility to control the load formed by the loading unit using prompt impulses the influence of the impulse of magnetic field on the load's alteration was registered.

The resistance force curves presented in Fig. 7 show how the load is changing in time while the MRF damper is working without magnetic field and when the MRF damper is provided with the 0.038 T pulse of magnetic field that lasts for approximately 0.05 s.

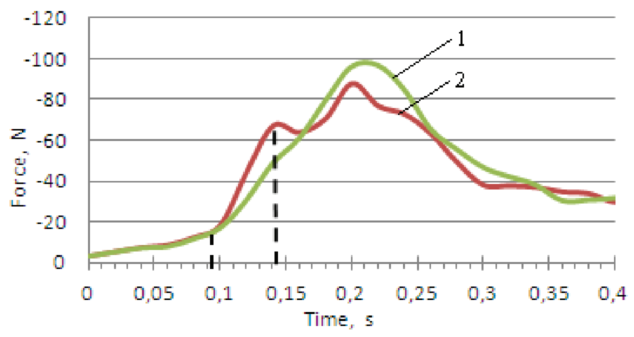

Fig. 7 Dependencies of resisting force when MRF damper is working without magnetic field (*1*) and with impulse of magnetic field (*2*)

Fig. 8 shows the system's reaction to the instantaneous pulse of magnetic field of 0.05 s duration and 0.038 T strength, depending on the impulse's position in the cycle of workload's alternation.

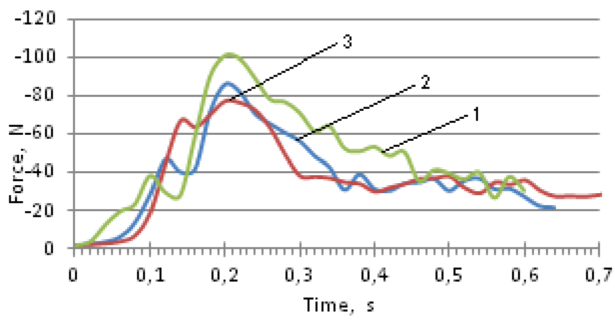

Fig. 8 Dependencies of resisting force on the same instantaneous impulse of magnetic field provided at different places of loading cycle: *1* - impulse time at 0.1 s, *2* - impulse time at 0.12 s, *3* - impulse time at 0.14 s

To summarize the measurement results it was stated that the resistance force of MRF damper affects directly the exercise machine resistance force. When the magnetic field strength is increasing, the exercise machine load is increasing faster and bigger maximal values are achieved. In this specific case the steady value of the resisting force increases from 94.54 to 110.97 N (16.43 N increment) when increasing the strength of magnetic field from 0 to 0.038 T (Fig. 6).

When the damper provides pulse of magnetic field, the exercise machine resistance force suddenly increases, whereas the buffer acts as an absorber when the signal disappears and the force is reduced suddenly.

7. Conclusions

In order to make the exercises more effective and provide the possibilities to adjust them to the individual peculiarities, modern exercise machines are developed through the application of loading mechanisms controlled during the exercise cycle.

The experimental test bench including magnetorheological fluid damper was designed to investigate the possibilities to use such devices for the loading control in the inertial resistance type exercise machines.

The investigation has shown that alteration of the fluid viscosity may have visible impact on the load exchange and its stabilization during the exercise cycle.

The possibility to control the exercise machine loading during the cycle was determined by applying the prompt pulses of magnetic field for the damper. The obtained results have shown that such control is possible.

The investigations carried out have been mainly of qualitative character and need the following investigations directed to define the achievable range of controllable loading for practical applications.

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TRENIRUOKLIO APKROVOS VALDYMAS MRS SLOPINTUVU

R e z i u m ė

Moksliniu ir techniniu požiūriu labai svarbu kurti ir tobulinti sporto įrangą taip, kad ji įgalintų treniruotis ir testuoti individualiai pagal vartotojo poreikius, leistų kontroliuoti bei valdyti treniruotės procesą. Straipsnyje aprašomas vienas iš galimų būdų jėgos treniruoklio inercinėms apkrovoms stabilizuoti ir valdyti naudojant MRS slopintuvą. Metodui patikrinti sukonstruotas tyrimų stendas, leidžiantis išmatuoti pasipriešinimo jėgą bei įvairių sistemos dalių (svarmenų, slopintuvo, elektros variklio) judesių kinematinius ir dinaminius parametrus. Pirminiai eksperimentinių tyrimų rezultatai patvirtino, kad toks slopintuvas yra efektyvus.

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TRAINING FACILITY LOADING CONTROL BY MRF DAMPER

S u m m a r y

From the scientific and technical point of view it is very important to develop training equipment which would allow us to exercise and perform tests individually according to the needs of each user and control, and manage the entire training process. The paper analyses the possibilities to stabilize the inertial load in the simulator of the weight stack machine and control it by means of the MRF damper. The test bench was designed allowing measurement of the resistance forces and kinematic parameters of various parts of the system (weights, stabiliser, handle). The preliminary results of experimental investigations proved the effectiveness of the developed MRF damper.

Keywords: magnetorheological fluid, mechatronics, subpixels, tensometric, computerise.

Received January 10, 2012
Accepted March 25, 2013