Design of Semi-active Magnetorheological Valve with Non-magnetic Bypass

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Abstract — **The paper presents a methodology of design of a semi-active magnetorheological (MR) valve. The methodology was composed of the non-Newtonian fluid flow analysis and FEM analysis of a magnetic circuit. Based on the present methodology a MR valve was designed. The MR valve achieves damping force 1600 N at a velocity of 0.15 m/s. The time response was determined to 6 ms.**

Keywords — Magnetorheological valve, MR valve, MR fluid.

I. Introduction

Modern mechatronic systems often enable to control the damping elements. A semi-active damper is often known as a fail-safe system because in case of a power failure, it can operate as a passive system. The functionality of the semi-active damping element can be provided by a damper with the MR valve.

The MR valves or dampers are devices which can control the amount of dissipated energy depending on the current in the coil. The MR valve is usually built from a coil, which creates a magnetic field, magnetic circuit and MR fluid. The MR fluid is a colloidal suspension formed by micron-sized magnetic particles (most often powdered iron) and carrying fluid [2]. Upon application of an external magnetic field, the MR fluids are able to change their behaviour from a fluid state to a semi-solid or plastic state (fig. 1), and vice-versa, in a couple of milliseconds. The time which is needed for the change of the state is shorter than 1 ms according to research of Goncalves et al. [7].

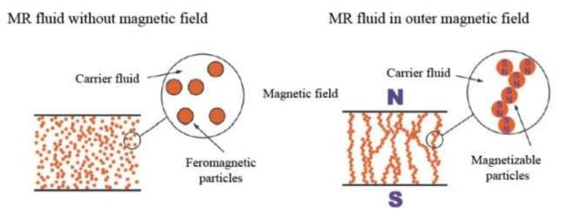

Fig. 1. MR effect [6].

This phenomenon is known as the MR effect (Fig. 1). Such field-dependent behaviour is often represented as a Bingham plastic having a variable yield stress [5]. Thus, it is possible to modify the characteristics of the damper. Many authors were involved in designing of the MR dampers [2], [3] or [4]. These dampers (valves) can be found in some seats in automobiles [3], in the control of seismic vibrations in buildings [2] or in guns [4]. The MR valve is influenced greatly by its design and material.

The main goal of this paper is to propose methodology for a semi-active MR valve design. Based on this methodology, the physical MR valve has been designed.

II. Materials and Methods

A. Hydraulic Model

MR fluids in the presence of a magnetic field exhibit Non-Newtonian behaviour [5]. This behaviour is often represented as a Bingham plastic with a variable yield stress [5]. Carlson and Yang published in their research [2] that: “Bingham model is very effective, especially in the damper design phase”. However, this model does not include all the rheological characteristics of a MR fluid, such as shear thinning [2]. In the absence of a magnetic field the Newtonian behaviour was expected from the MR fluid [5]. The shear stress in the Bingham model is given by equation [5]:

$$\tau = \tau_y(H) + \eta\dot{\gamma}, \quad |\tau| \geq |\tau_y|,$$
$$\dot{\gamma} = 0, \quad |\tau| \leq |\tau_y|, \tag{1}$$

where H is the magnetic flux intensity (A/m), $\dot{\gamma}$ is the shear rate (1/s), η is the apparent viscosity in off-state (H = 0 A/m) (Pa.s), τ is the shear stress in the MR fluid (Pa) and τ_y is the yield stress of the MR fluid (Pa).

The MR fluid in commercial valves is usually flowing across an annular gap [2], [5] or [9]. In the design phase, it is more advantageous to use a simplified model. A parallel plate model would sufficiently approximate the annular gap. The error that occurs due to this simplification is less than 0.5 % for the ratio valve geometry h/R <0.2 [2]. The mean velocity of the flowing MR fluid in the presence of a magnetic field is given by equation (2). This equation includes the plug effect of the MR fluid [1]. The validity of this relation is limited by a laminar flow.

$$v_s = \frac{-\Delta p h^2}{12\eta l}\left(1 - 3\frac{y_0(H)}{h} + 4\left(\frac{y_0(H)}{h}\right)^3\right) \tag{2}$$

A mean velocity of the flow is described by the pressure difference Δp (Pa), length of the gap l (m), dimension of the gap h (m) and dimension of the plug $y_0(H)$ (m). The dimension of the plug is determined by the yield stress and pressure difference [6]. Therefore, a plug dimension is particularly dependent on the magnetic field.

The damper with the MR valve is usually designed that the MR fluid can flow through two different types of gaps. The first one is a magnetic gap in which it is possible to change the yield stress of the MR fluid. The second one is a simple connection inlet and outlet of the MR valve through geometric constrictions. This type of the MR valve is often called bypass. These gaps can be connected in various ways to obtain the required Δp-v characteristics of the MR valve. The magnetic gap and the bypass are often connected in parallel where the bypass dimension affects the slope of the Δp-v characteristics. The magnetic gap and MR fluid properties have an effect on the breakpoint of the Δp-v curve (Fig. 2). A dynamic range of the MR valve is defined as a pressure drop in on-state divided by the pressure drop in off-state at a specific velocity.

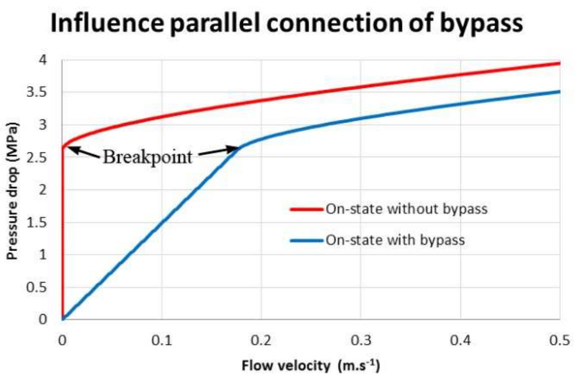

Fig. 2. Influence of bypass to Δp-v curve.

The dynamic range reaches its maximum point below the breakpoint. After that, it decreases nonlinearly. The dimension of the bypass changes the dynamic range and it also moves the breakpoint to a higher velocity on the Δp-v dependence.

B. Magnetic Model

The yield stress of the MR fluid is dependent on the magnetic field (Fig. 3). Thus, in the MR valve design phase, the magnetic model is important. Main design elements of the MR valve magnetic circuit are the dimension of magnetic gap, geometry of the magnetic circuit and number of turns of the coil [9]. The common dimensions of the magnetic gap in the MR valves are in the range of 0.25 mm to 2 mm [9], [2]. Magnetic circuits of the MR valves are usually made of low carbon steel [2], [3]. Low carbon steel has a high magnetic saturation limit and a high relative permeability. Both MR fluid and low carbon steel exhibit a non-linear magnetic behaviour. Non-linearity is described by the magnetization curve (Fig. 3). The analytical solution is complicated. Therefore, the numerical solution is more suitable. For the described MR valve magnetic simulations the finite-element program Ansys Maxwell was used. A magnetic model of the MR valve was solved as a 2D axisymmetric model with an adaptive mesh. An adaptive mesh with maximum error of 1 % was used. The purpose of the magnetostatic analysis was the design of the magnetic circuit geometry with respect to the uniform magnetic field saturation of the circuit components. The transient analysis was performed for determining time response of the magnetic field in the magnetic gap on an electric current step change.

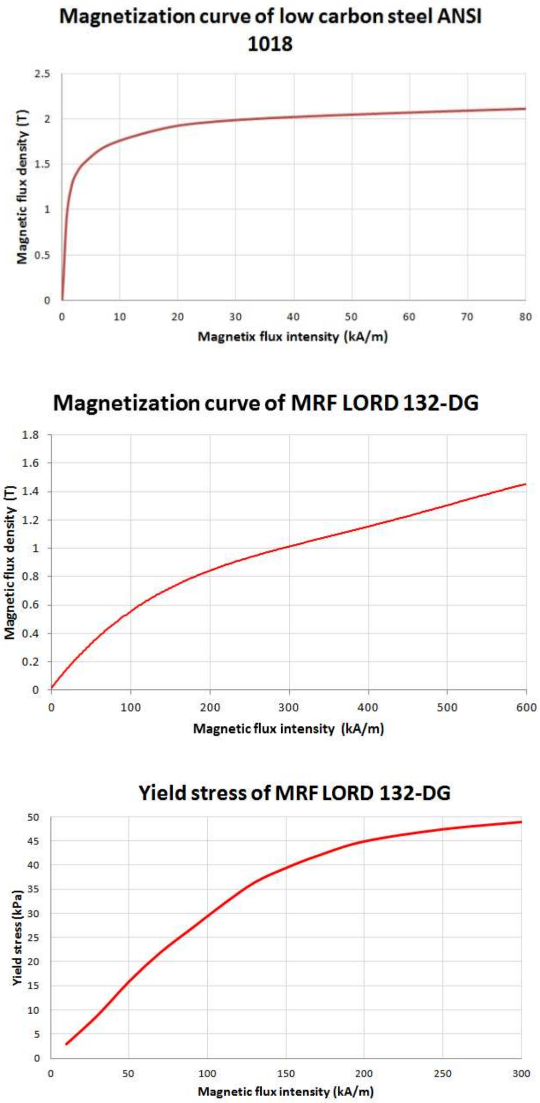

Fig. 3. Magnetization curve of low carbon steel and MR fluid.

III. Results

Based on the presented methodology, a hydraulic and magnetic model of the MR valve was created. The magnetic circuit was made from the low carbon steel ANSI 1018 (ČSN 11 523) (1, 4, 5, 8). The outer tube (4) was cut longitudinally and the cut surface was electrically insulated. This method reduces the time response of the MR valve due to the reduction of eddy-currents. In the other parts of the magnetic circuit, this method was unsuitable. Other components of the MR valve were designed from stainless steel (6, 7). Magnetic (D) and bypass (E) gaps are connected in parallel. The MR valve was designed by iterative process from these models.

The design of the MR valve has the magnetic gap dimension 0.6 mm and length 32 mm. The gap between magnetic gaps has dimension 1.6 mm and length 22 mm. The diameter of the core is 30 mm (1). The bypass gap has a diameter 1.5 mm and length 33 mm (3). The magnetic circuit is composed of three coils wound in a way that each adjacent coil has a different winding direction. Positions A and B show the direction of the magnetic field (winding direction).

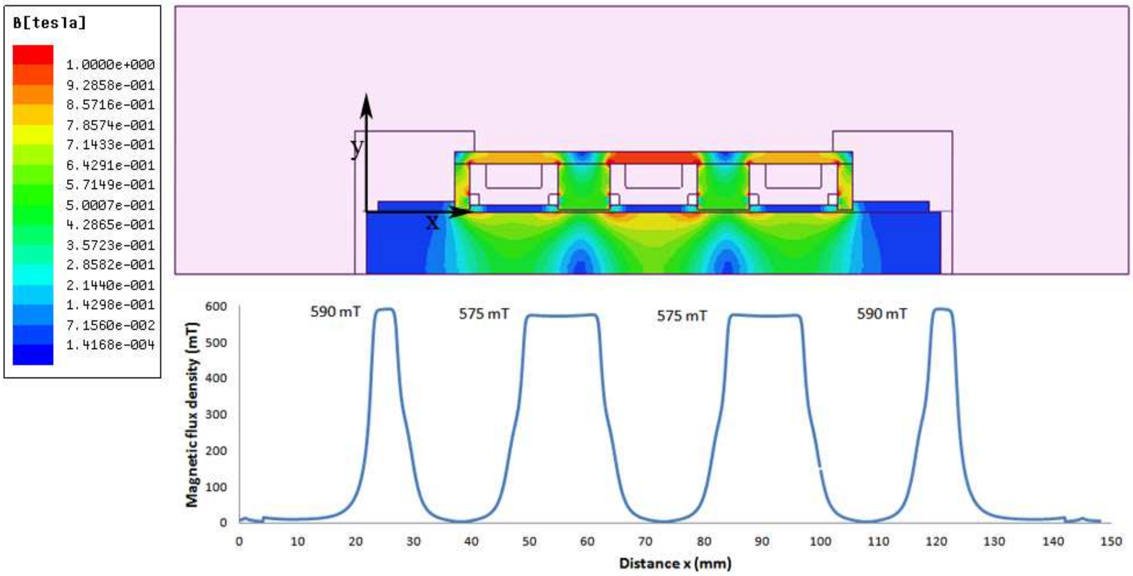

Fig. 4. Magnetostatic analysis of damper with MR valve.

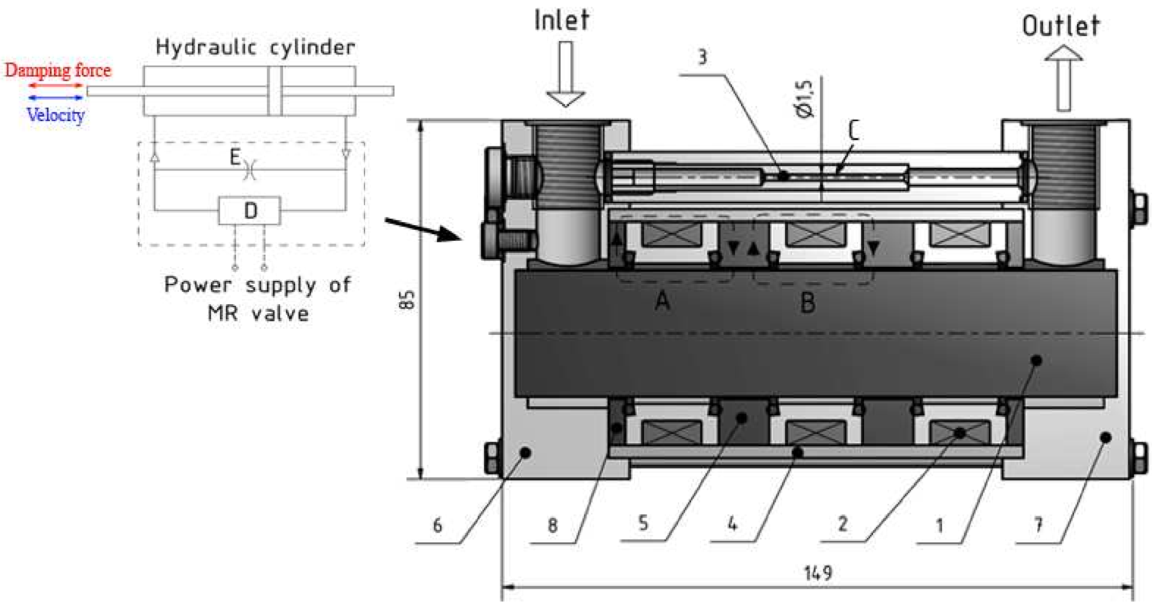

Fig. 5. Design of semi-active MR valve.

The magnetostatic solution was carried out in the Ansys Maxwell (fig. 4). A current 1 A in the coil creates a magnetic flux intensity in the magnetic gap (in the MR fluid LORD 132-DG) of 105 000 A/m (575 mT). This magnetic field creates in the MR fluid LORD 132-DG yield stress 30 kPa.

Using the transient magnetic solution in the Ansys Maxwell, the time response of the magnetic field in the valve was calculated. The results show that the time response of the magnetic field on a control signal step change is about 6 ms.

A hydraulic cylinder with a double-ended piston rod creates a flow of the MR fluid through the MR valve. The diameter of a hydraulic piston is 32 mm and piston rod is 18 mm (area 550 mm^2).

Based on the hydraulic model, the damping force-velocity curve of the MR valve system was determined. In the hydraulic model MR the fluid LORD 132-DG with apparent viscosity 0.112 Pa.s (40 °C) was used.

The model was simplified by the parallel plate geometry ($\frac{h}{r} = \frac{0,6}{15} \ll 2$).

The final force-velocity curve of the MR valve system is in Fig. 5. Dynamic range of the designed MR valve ($\tau_y = 30\ kPa$) is 13. Such range can be achieved up to the breaking point. However, in the model there are neglected passive losses in the hydraulic cylinder and hydraulic losses of fittings.

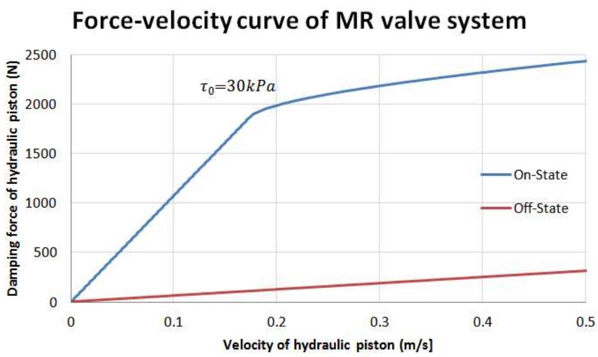

Fig. 6. Force-velocity curve of the designed MR valve system.

IV. Conclusion and Discussion

This paper deals with the methodology of designing a damper with the MR valve. The magnetic circuit of the valve was designed of low carbon steel. The time response of the designed MR valve was determined to 6ms. The hydraulic solution shows that the MR valve is appropriate to operate up to the breakpoint on the force-velocity curve resulting in a maximum dynamic range. The bypass gap has a major effect on the dynamic range.

The MR valve should have a minimum force of 1600 N in the on-state at a velocity of 0.15 m/s in the piston and this requirement was met. However, this applies to the temperature of 40 °C because at another temperature, the damping force will be different.

Future research in this area leads to the manufacture and tests on the designed MR valve. The proposed methods will be verified using the manufactured MR valve system.

Acknowledgment

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