Hydrodynamic response time of magnetorheological fluid in valve mode: an initial study

Michal Kubík[1, a *] and Karel Šebesta

[1] Brno University of Technology, Faculty of Mechanical Engineering, Brno, Czechia

[a] michal.kubik@vutbr.cz

Abstract. The transient behaviour of magnetorheological (MR) damper is a very important parameter affecting the performance of this technology in modern semi-actively controlled suspension systems. Currently, the transient behaviour of the MR damper is limited by dynamics of the MR fluid (MRF) itself. The significant part of MRF response time is a hydrodynamic response time which is connected with transient rheology and development of velocity profile in the slit gap. In this paper, the method for measuring the hydrodynamic response time of MRF operating in valve mode is presented. The hydrodynamic response time of MRF-132DG achieved value of $\tau_{90} = 0.78$ ms for H = 17.5 kA/m a value of $\tau_{90} = 0.65$ ms for H = 34 kA/m for given geometry of gap. The difference between model and experiment is lower in higher yield stresses of MRF.

1. Introduction

Magnetorheological (MR) fluid is a smart material that exhibits a reversible and fast transition from a liquid state to a solid-state (increase of yield stress) under an external magnetic field. This phenomenon is usually called a magnetorheological effect. MR fluid is a two-phase fluid consisting of micron-sized highly magnetizable particles, usually carbonyl iron particles, in a non-magnetizable carrier fluid, such as mineral or silicone oil. When the MR fluid is energized by the magnetic field, the ferromagnetic particles are magnetized and form chain-like structures in the direction of the magnetic field. The fluid then exhibits a significant increase in yield stress. These properties allow the use of MR fluid in electro-mechanical systems such as dampers. Magnetorheological (MR) dampers are currently used in automotive, railway, aviation, etc. The transient (dynamic) behavior of the MR damper is a fundamental property affecting the performance of this technology in modern semi-actively controlled suspension systems. Two sources of the time delay between the control signal and damping force are as follow: (i) dynamics of MR damper hardware and (ii) the magnetorheological fluid dynamics.

2. Dynamics of MR damper hardware

The response time of MR damper hardware was listed in several publications [1,2] and the main sources of the delay were identified as (i) eddy currents in coil core, (ii) inductance of MR damper coil, or (iii) compressibility of the hydraulic system of MR damper. When the magnetic field changes rapidly in the magnetic circuit of the damper, eddy currents are generated, which produce a magnetic field in the opposite direction than the initializing magnetic field [3]. Eddy currents can be eliminated by either a

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material (SMC, ferrite, etc.) or shape approach. The shaped approach is based on the use of a magnetic circuit with thin sheets or with suitably located grooves. This issue is currently being under development. The relatively slow increase and decrease of electric current on control voltage signal due to the inductance of the coil can be solved by the current controller with the over-voltage method. The compressibility of the magnetorheological fluid also affects the transient behaviour of the MR damper [4]. The issue of MR damper hardware dynamics is relatively intensively described. Currently published MR dampers achieve response time (1.2 ms) comparable with a response time of MR fluid itself [5].

3. Dynamics of MR fluid itself

The transient (dynamic) behavior of MR fluid was described just in a few papers. The best-known paper in connection with the MR fluid response time is the paper of Goncalves et al. [6]. This team published a measurement of MR fluid response time on a slit-flow rheometer. The author introduces the fluid dwell time. This is the time that ferromagnetic particles of MR fluid spend in the presence of a magnetic field. The author considered that if the dwell time is short enough, the ferromagnetic particles in the MR fluid will not be sufficient to create chains and the yield stress of the MR fluid will not be created. This can be connected with MR fluid particle chain dynamics. The yield stress decrease was observed in Goncalves experiments. However, the papers of Sherman [7] or Goldasz et. al. [8] show that this pressure drop decrease is due to transient rheology connected with the development of velocity profile. This statement is based on CFD simulations. It is assumed that the yield stress of MR fluid flow will decrease/increase much faster than energy dissipation (pressure drop) due to flow transient. This phenomenon is often referred to as the hydrodynamic fluid response time. Sherman [7] published a model for the hydrodynamic response of MR fluids. This model is based on an analytical solution of the start-up flow of Bingham plastic fluid between parallel plates [9]. The Sherman [7] construct fit of data Darpa et al. [9] (dimensionless response time T_r) as follows:

$$T_r = 0.235/(1+0.2B_i)$$

where B_i is Bingham number. For a Newtonian fluid, the dimensionless response time can be calculated as follows:

$$T_r = \tau_r \eta / \rho h^2$$

where τ_r response time, η is plastic viscosity, ρ is the density of the fluid, h is gap size. It is important to note that this is the time τ_r to reach 90% of the final steady-state velocity.

The main aim of this paper is to present a method for measuring the hydrodynamic response time of MR fluid operating in valve mode and preliminary results. The measured data will be compared with the model published by Sherman [7].

4. Materials and methods

4.1. Measurement method idea

This method is based on the measurement of pressure drop of the MR valve caused by an external magnetic field acting on the MR fluid Δp_τ depending on dwell time t_{dwell}. This method significantly extend the paper of Goncalves et al. [6]. The challenge is to separate the effect of viscosity on pressure drop from measured data and it change with temperature. Therefore, the measurement procedure consists of two blocks. The first measurement block is with zero magnetic fields (H = 0 kA/m) and Newtonian behavior of the magnetorheological fluid is considered in area I to III, see Figure. 1. The pressure drop Δp_{off} (H = 0 kA/m) for the first section (I) can be described as follows:

$$p_I - p_{III} = \Delta p_{off} = \Delta p_\eta + \Delta p_\chi$$

where Δp_η is the viscous pressure drop and Δp_χ is the pressure drop of entrance and exit losses to the gap. In the second section II of measurement, the test MR valve (gap) is divided into two areas: (I-II) without a magnetic field and (II-III) with a magnetic field, see Figure. 1. It is assumed that the velocity profile on interface (II) is fully developed (Newtonian).

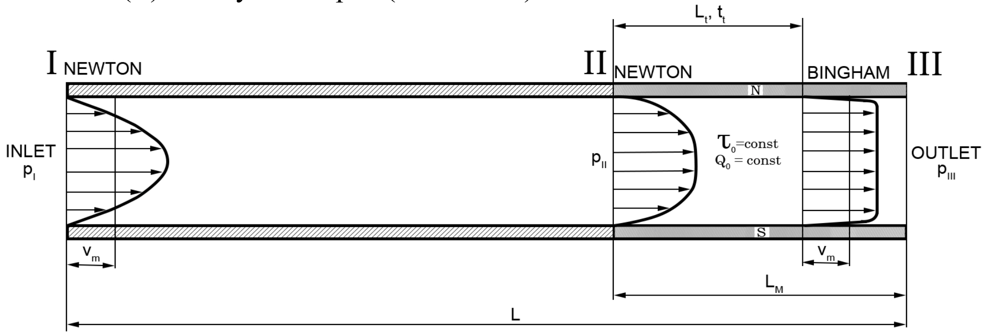

Figure. 1 MR fluid flow in slit gap

The second measurement of the pressure loss Δp_{on} is already in the presence of a magnetic field ($H \neq 0$ kA/m) at a given length (L_M). The pressure drop Δp_{on} is then:

$$p_I - p_{III} = \Delta p_{on} = \Delta p_\eta + \Delta p_\chi + \Delta p_\tau = \Delta p_{off} + \Delta p_\tau$$

where Δp_τ is pressure drop due to yield stress of MR fluid on the length L_M. From the measured pressure drops Δp_{off} and Δp_{on}, the pressure drop caused by the MR fluid yield stress Δp_τ is determined as follows:

$$\Delta p_\tau = \Delta p_{on} - \Delta p_{off}$$

These two sections must be measured as quickly as possible to keep the temperature difference as small as possible. However, there is always some change in temperature, which is reflected in the change in viscosity and is compensated in data post processing. Next, the dwell time t_{dwell} was defined. This is the time that the MR fluid spends in the presence of a magnetic field. The dwell time t_{dwell} was calculated by the mean flow velocity in the gap v_m and the length L_M as follows:

$$t_{dwell} = v_m / L_M$$

It is necessary to note that the length L_M is not connected with magnetic pole geometry but has to be calculated by magnetic model. In our case L_M achieved a value of 8.8 mm. It is assumed that the MR fluid needs a certain time t_t or length L_t to transform the Newtonian velocity profile to a velocity profile with a plug (Bingham plastic) to exhibits dissipation energy due to MR fluid yield stress. This time t_t or length L_t is probably the result of MR fluid deceleration/ acceleration in the gap. In the case of $L_t >> L_M$ and at given mean velocity in the gap v_m, the velocity profile was not developed from Newtonian to Bingham, and dissipation energy due to MR yield stress is not observed $\Delta p_\tau = 0$ although the yield stress is not zero ($H \neq 0$ kA/m). Otherwise ($L_t << L_M$) the velocity profile was developed very quickly and there is no significant effect of MR fluid deceleration/acceleration.

4.2. Experimental device

The functional layout of the apparatus is shown in Figure. 2. The experimental device (slit-flow rheometer) is energized by the Inova hydraulic dynamometer which imposes the motion of the floating piston (d_p = 32 mm). The motion of the floating piston forces the test MR fluid through the slit gap of the rheometer (MR valve). The slit gap geometry (gap size t_g = 0.6 mm, width w_g = 32 mm and length L = 50 mm) is made of two grind blocks (position 4 a 5 in Figure. 3). Each block consists of a part made of non-magnetic stainless steel (position 5.1) and a part made of pure iron (5.2). Therefore, the magnetic flux can flow just through part 5.2.

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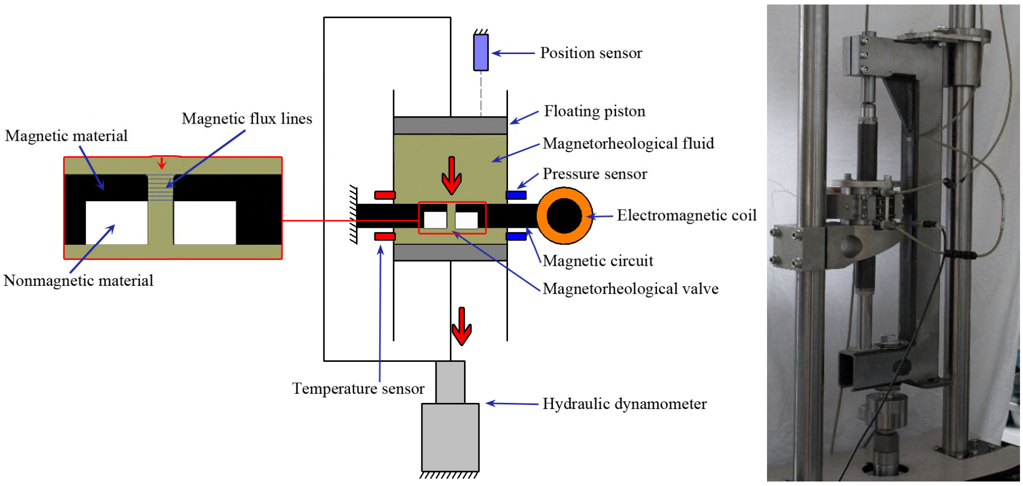

Figure. 2 Functional layout of the rheometer, rheometer during tests on a hydraulic dynamometer

The magnetic circuit is composed of the electromagnetic coil (1), pole pieces (2), and non-magnetic washer (3). The magnetic pole pieces are manufactured from pure iron. The electromagnetic coil is wound with 160 turns of copper wire with a diameter of 0.5 mm. The important dimensions are shown in Figure. 3.

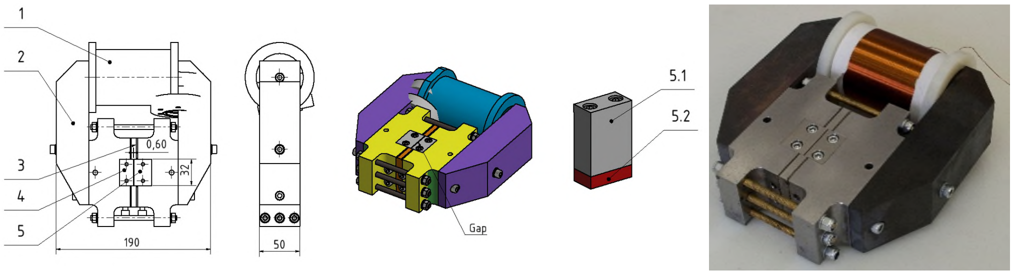

Figure. 3 Important dimension of magnetic circuit (left, middle), manufactured magnetic circuit (right)

4.3. Measurement methodology

The pressure drop across the slit gap is acquired with pressure sensors HBM P8AP. The MR fluid temperature was acquired by resistance temperature sensor PT100 which was located near the entrance to the slit gap. The motion of the floating piston was measured using the LVDT transducer/position sensor accommodated in a hydraulic dynamometer. These signals were recorded and conditioned with a sampling frequency of 1 kHz by analyzer Dewe-800. The measurement procedure was as follow: (i) 8 sinusoidal cycles at given frequency f were measured; (ii) pause of 10 sec to switch on the power supply current I; (iii) 8 sinusoidal cycles at given frequency f and given electric current I were measured; (iv) demagnetization of the magnetic circuit using a sinusoidal cycle with decreasing amplitude. The rise and fall of the frequency were always with a transition time of 2 s. Measurements were performed for different frequencies at a stroke amplitude of 48 mm. This corresponds to a maximum piston velocity of 0.48 m/s and a mean flow velocity in the slit gap of 22 m/s. The piston velocity v_m was determined by derivation of piston position. The data of pressure drop from the center of stroke (± 2 mm) were selected for the next evaluation. The measured data which achieved at least 99 % of maximum piston velocity was taken also for the next evaluation to eliminate transition to given frequency f. Selected points of pressure drop Δp_{off} and pressure drop Δp_{on} were averaged and presented in the chapter results. The results were normalized ψ due to the quantitative comparison. The normalized data ψ were then fitted by a least-squares method in Matlab software by the following function:

$$\psi(t_{dwell}) = \left[1 - c_1.e^{c_2.(t_{dwell} - c_4)}\right].tanh(c_3.(t_{dwell} - c_4))$$

where c_1, c_2, c_3, and c_4 are constants that were obtained by the fitting. From this equation, the primary (τ_{63}) and secondary (τ_{90}) hydrodynamic responses of the MR fluid were determined. MR fluid MRF-132DG from Lord Corporation was used for testing. The volume concentration of ferromagnetic particles in the tested sample was experimentally determined to be 32.6 % and the density to be 3106 kg/m^3.

5. Results and discussion

The graphs below (Figure. 4) show the dependences of the pressure drop Δp_{on} and Δp_{off} on the mean flow velocity in the slit gap v_m for an electric current of 0.4 A and 0.6 A applied to the electromagnetic coil.

It can be seen that with increasing gap velocity v_m, the differences in pressure drop decrease. This also corresponds to the data published by [10].

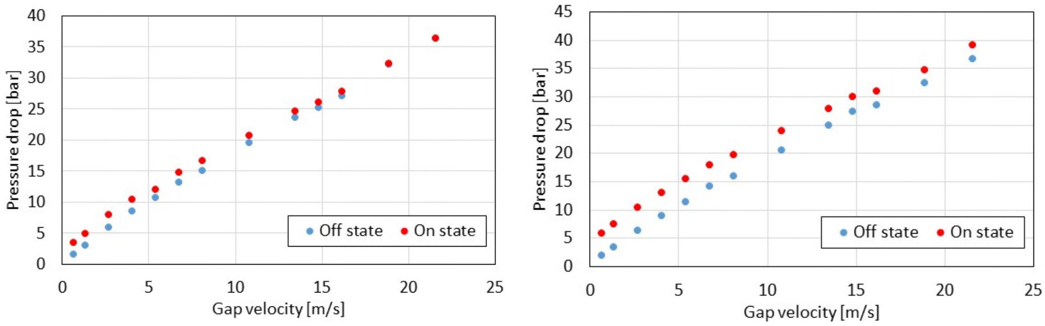

Figure. 4 Pressure drop Δp_{on} and Δp_{off} for electric current 0.4A (left), and electric current 0.6 A (right).

The pressure drop Δp_τ was then calculated as a function of dwell time t_{dwell}, and the data were normalized, see Figure. 5. The measured data were fitting functions presented above.

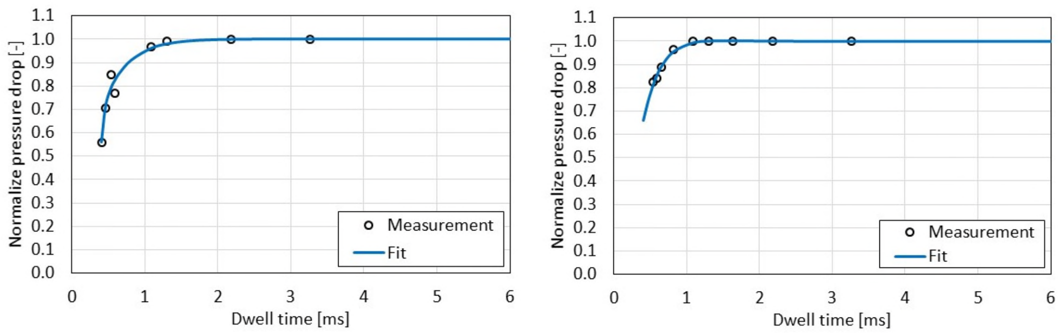

Figure. 5 Normalize pressure drop Δp_τ for electric current 0.4 A (left), and for electric current 0.6 A (right)

The table below (Table 1) shows the fitting coefficients c_1 to c_4, primary and secondary response time from the experiments for the two magnetic fields. The magnetic flux intensity *H* was estimated based on data from the MR fluid manufacturer and measured yield stress. The results of the experiment were compared with the model.

Table 1. Result of the experiments

I [A]	c_1 [-]	c_2 [-]	c_3 [-]	c_4 [-]	τ_{63} [ms]	τ_{90} [ms]	$\tau_{r\,m}$[ms]	Y. stress [kPa]	H [kA/m]
0.4	0.38	-2.98	0.332	14.75	0.43	0.78	1.15	5.9	17.5
0.6	-0.15	-2.31	0.09	2.28	0.4	0.65	0.9	12.8	34

For the MR fluid yield stress of 5.9 kPa (17.5 kA/m), the secondary response time was τ_{90} = 0.78 ms which is lower than predicted by model ($\tau_{r\ model}$ = 1.15 ms). In 5this case, the difference between model ad experiemnt is 34 %. At a higher value of yield stress (12.8 kPa), the difference between model and expeiemnt is slightly lower (28 %). Nevertheless, it can be stated that the measured data corresponding to the model. The differences can be explained by slightly different temperature for each measured point (each dwell time) and simplification of the model. In the following research, it is necessary to focus on determining the effect of the magnetic field, density, or temperature on measured hydrodynamic response time.

6. Conclusion

In this paper, the measurement method of the hydrodynamic response time of magnetorheological fluid was presented. The measured data of hydrodynamic response time of MRF-132DG for two levels of the magnetic field was compared with the model. The difference between model and experiment is lower in higher yield stresses of MRF. The measured hydrodynamic response time for yield stress of 12.8 kPa (H = 34 kA/m) was 28 % lower than predicted by the model and achieved a value of 0.65 ms. It can be stated that the model published Sherman correlate with our initial experiment for given geometry and MR fluid rheology. The model is simplified and therefore a difference of about 30% is acceptable.

Acknowledgments

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