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# Transient Magnetic Model of Magnetorheological Damper and Its Experimental Verification

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**Abstract.** The present paper deals with the transient magnetic model of the magnetorheological (MR) damper and its experimental verification. The response time of MR damper affects the quality of semi-active control of this damper. The lower the response time, the higher the system efficiency. The most important part of the response time of the MR damper is the response time of magnetic field of the MR damper which can be determined by transient magnetic model. The transient magnetic model was created by the software Ansys Electromagnetics 17.1 as 2D axisymmetric and verified by measurement of magnetic field in the gap of MR damper piston. The maximum difference between the model and the experiment was 28 %. The response time depends on the electric current in the coil of MR damper. The transient magnetic model was used for determination of influence of MR fluid type, material of cover and material of magnetic circuit on the response time of magnetic field of MR damper. The type of MR fluid has a significant influence on the response time. The lower the mass concentration of ferromagnetic particles, the lower the response time of magnetic field. A material selection of magnetic circuit is always a trade-off between the response time and the maximum magnetic flux density (dynamic force range) in the gap of the MR damper. According to the verified transient magnetic model, it is possible to find a suitable material of magnetic circuit for specific application (response time).

## 1 Introduction

Magnetorheological fluid (MRF) is a suspension of micro-scale, non-colloidal ferromagnetic particles in a non-magnetic carrier fluids and additives. The MR fluid exhibits a rapid change of rheological behaviour under the influence of external magnetic field. Ferromagnetic particles in MR fluid form chain-like structures in the direction of magnetic field with a rapid increase in yield stress [1]. The value of yield stress is strongly dependent on the level of applied magnetic field. The increase of yield stress in the MR fluid located in the external magnetic field is a basic feature of MR technology and is usually called a magnetorheological effect.

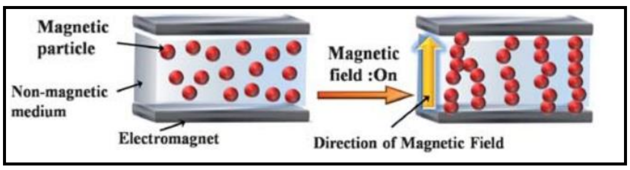


**Figure 1.** Magnetorheological effect [2].

An interest in MR fluid derives from its ability to provide a simple interface between the electronic and mechanical system. A magnetorheological (MR) damper is a device which profits from the unique properties of MR fluid.

This damper uses strong and rapid changes in yield stress of MR fluid in the direction of magnetic field which leads to an increase in damping force [3]. The MR damper is composed of piston, seal piston rod, floating piston, and MR fluid. The piston consists of magnetic circuit and electromagnetic coil. There is a gap in the magnetic circuit which is flooded with the MR fluid (through the annular orifice in piston). The piston divides the MR fluid volume between the compression chamber and the rebound chamber. The gap in the piston allows for the MR fluid to flow between the chambers during the piston motion. The value of yield stress (hydraulic resistance) can be controlled by the electric current in the coil during the passage of MR fluid through the gap. This causes a rapid increase in damping force. The MR damper is mechanically simpler than the traditional design of the hydraulic damper because it does not contain mechanical moving parts. For this reason, the MR damper is noise-free [4]. MR dampers are commonly used for adaptive control. MR dampers with semi-active control have been mentioned in scientific papers in the last years. The most significant factors of quality semi-active control of MR damper are as follows: response time of MR damper and dynamic force range of MR damper; the latter is well described in [3], [1]. The magnetic flux density in the gap of MR damper has a significant influence on the dynamic force range (yield stress of MR fluid).

**Response time of MR damper**

The response time of MR damper is defined as the time necessary for transition from the initial state to 63.3 % (in some publications 95 % [7]) of the final state [1] represented by a steady-state damping force. The response times of published designs of MR dampers are in the range of 20-100 ms [1],[3], [4]. From the existing literature, it can be assumed that the response time of MR damper has three sources [5], [6]: inductance of MR damper coil (response time of exciting current), response time of MR fluid, eddy currents in the coil core (response time of magnetic field in the active zone). The response time of MR fluid was estimated in the range of 0.45-0.6 ms by Goncalves [7]. Yang [1] published his findings that the use of a suitable current controller can significantly reduce the response time of exciting current. Strecker [5] stated that the response time of exciting current can be reduced to 1 ms. Eddy currents in the magnetic circuit create a time lag between the course of electric current and the course of MR damping force [8]. These currents produce a magnetic flux which flows in the opposite direction to the magnetic flux in the magnetic circuit. A selection of the suitable material or the geometry of magnetic circuit of MR damper can eliminate eddy currents (a short response time of magnetic field in the gap). One of the methods how to select the suitable material and the geometry of MR damper is to use a magnetic simulation. According to the available information, only Naoyuki [9] and Strecker [5] dealt with the magnetic modelling of eddy currents in the magnetic circuit of magnetoreological devices. However, in their contribution, this issue was solved only marginally.

The main goal of this paper is to create a transient magnetic model which allows to determine the response time of magnetic field in the active zone of MR damper, and its experimental verification. The influence of type of MRF, material of cover and material of magnetic circuit on the response time will be determined by a verified model.

## 2 Materials and method

### 2.1 Geometry of MR damper

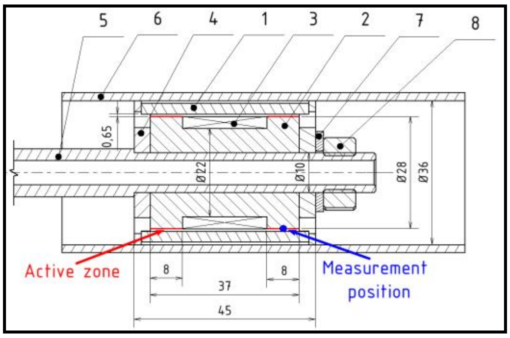


**Figure 2.** Geometry of MR damper used for verification.

The geometry of the MR damper was used to compare the proposed transient magnetic model and the experiment, according to fig. 2.

The MR damper is composed of outer cylinder (1), coil core (2), coil (3), covers (4), piston rod (5), hydraulic cylinder (6), washer 10 (7), and nut M10 (8). The coil (3) was wound on the coil core (2) with 120 turns of cooper wire (diameter 0.5 mm). The coil core (2) and the outer cylinder were made of steel 11SMn30 (fig. 3, red color). The B-H curve of this material was experimentally determined. The covers (4) were made of aluminum alloy. The piston rod (5) and the hydraulic cylinder (6) were made of steel 34CrMo4 (fig. 3, yellow color). The power line of coil passes through the hollow piston rod which is sealed.

### 2.2 Transient magnetic model

A transient magnetic model was created in software Ansys Electromagnetics 17.1. A simplified geometry of MR damper in this transient model was created (fig.3) as 2D axisymmetric.

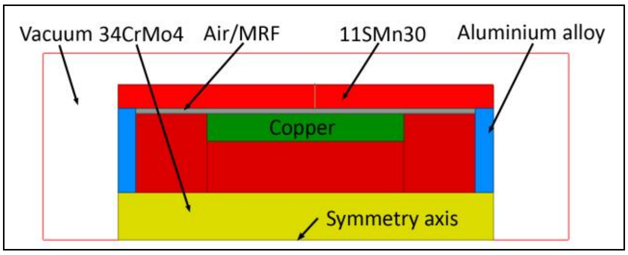


**Figure 3.** Simplified geometry of MR damper; 11SMn30 (red), MR fluid or air (grey), aluminium alloy (blue), copper (green), 34CrMo4 (yellow) and vacuum (white).

A boundary condition balloon was set on the outside part of the vacuum region. The excitation on the coil was a magnetomotive force I*120 A.turns. The external electric circuit was connected to the coil winding. The electric circuit is composed of resistor (resistance of winding coil) and current source. A rise time of the current source was set at 0.2 ms. This value was determined experimentally as an average value using the current clamp and the current controller. The important value for transient magnetic model is electric conductivity (resistivity) of magnetic circuit material. In our case, the electric conductivity of material 11SMn30 was set at 5.75 MS/m according to the datasheet. The eddy current effect in terms of the magnetic transient solution was applied to the entire geometry. 3584 elements were used for discretization of geometry. The time step of 0.1 ms and nonlinear residual at 0.0001 were used for the analysis.

### 2.3 Measurement of response time of magnetic field in the gap of MR damper

The magnetometer Bell 5180 and the ultrathin Hall probe were used for experimental verification of transient magnetic model. Magnetic flux density was measured in the middle of the active zone of the MR damper free off MR fluid.

The relative permeability of Hall probe ($\mu_r = 1$) is significantly lower than that of MR fluid ($\mu_r$ = 3-10) which causes the magnetic flux to flow around the Hall probe (fig. 4). This will result in inaccurate measurement. For this reason, the experiment is carried out in the regime with the air in the active zone of MR damper ($\mu_r$ = 1). It is assumed that the change of material in the active zone does not affect the accuracy of the transient magnetic model.

The coil of MR damper was powered by laboratory source Manson SDP 2603 (fig. 5). The current controller was made by Strecker [5] and controlled by the Arduino system, which was switched between the maximum and zero current in the coil and, vice-versa, with the frequency of 2 Hz.

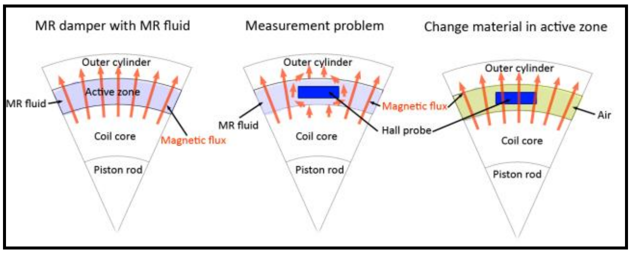


**Figure 4.** The flow of magnetic flux around the Hall probe.

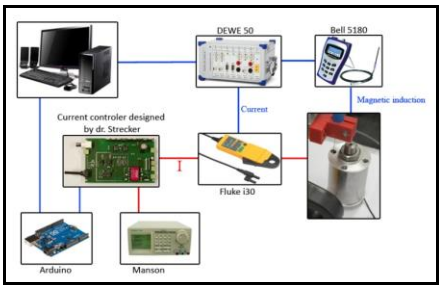


**Figure 5.** Measurement circuit.

The magnetic flux density in the middle of gap of MR damper was measured with the magnetometer Bell 5180 and the ultrathin Hall probe (fig. 2, fig. 6). The current clamp Fluke i30 was used to measure the electric current. Data from the magnetometer and the current clamp were acquired using Dewe 50 in the sampling frequency of 200 kHz; both channels were synchronized. The measured data were evaluated in software DeweSoft.

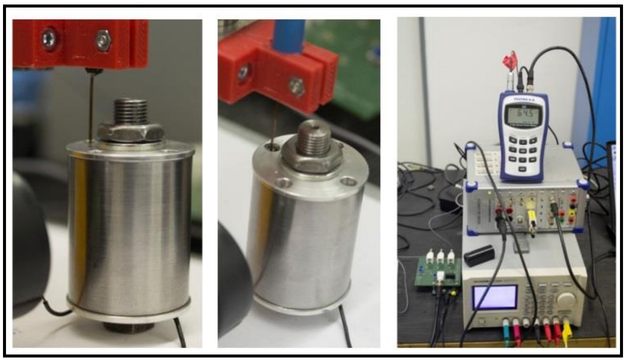

**Figure 6.** Ultrathin hall probe (left, in the middle) in active zone; power supply, Dewe 50, magnetometer and Arduino (right).

The following six cycles (current - switch on) were measured during each experiment (fig. 7). The rise and drop of magnetic flux density in the active zone were measured. The coil of MR damper was supplied with 0.3 A, 0.6 A, 1 A and 1.6 A. The measured data of magnetic flux density have been offset due to the residual magnetism in the magnetic circuit. For verification, the offset was neglecting. The response time of magnetic field of MR damper was determined as 63.3 % of steady-state value of magnetic flux density.

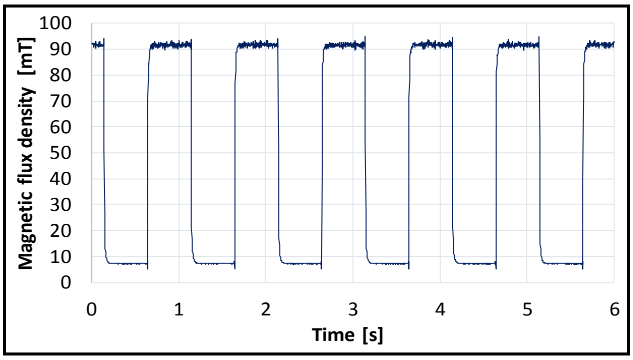


**Figure 7.** The course of magnetic flux density at 1A according to control.

## 3 Results

### 3.1 Experimental verification of model

Fig. 8 shows a comparison of magnetic flux density courses between the transient magnetic model (blue) and the experiment (red) for the rise and drop of the supplied current 1 A (green).

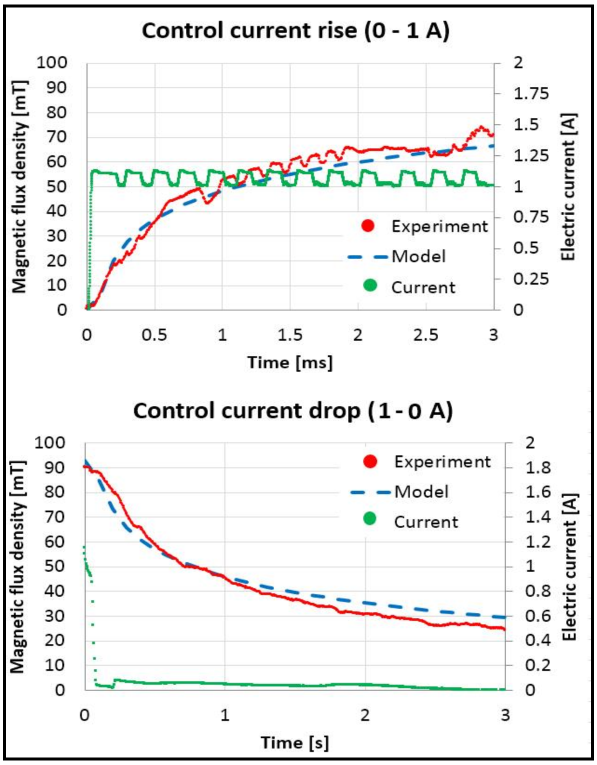


**Figure 8.** Rise of magnetic flux density; drop of magnetic flux density.

The response time of magnetic field in the gap was determined from the measured data and the transient magnetic model for different currents on the coil (fig. 9).

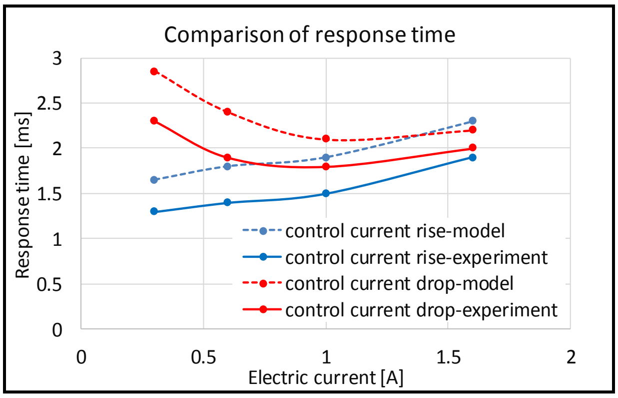


**Figure 9.** The response time of magnetic field from the model and the experiment for different currents.

A maximum difference between the model and experiment is 28 %. However, the slope of measured data and that of the experiment is similar. The difference between the model and the experiment can be justified by inaccurate specification of electrical conductivity, which was used according to the material product list. Interestingly, the response time of magnetic field is not constant but dependent on the electric current. This dependency on the response time of magnetic field is probably caused by non-linear B-H curve of material of magnetic circuit.

### 3.2 Transient model with MR fluid

The material in the active zone was changed in the verified transient magnetic model from the air to MRF. The B-H curve of MR fluid MRF-132DG, produced by Lord company, was set in the gap. The response time for different currents (0.1 A, 0.3 A, 0.6 A, 1 A, 1.6 A and 2 A) was determined by transient magnetic model (fig. 10).

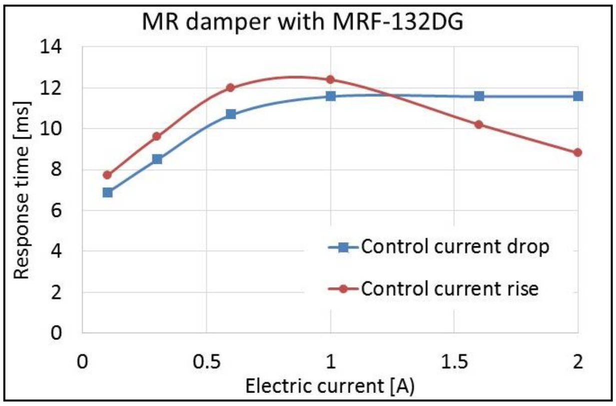


**Figure 10.** The response time of magnetic field in the active zone of MR damper with MRF-132DG for drop and rise of control current.

The response time of magnetic field of MR damper with MR fluid is also dependent on the electric current because of non-linear B-H curve of magnetic circuit material and MR fluid. The response time of control current rise from 0 A to 1A is increasing. After that, the response time is decreasing (fig. 10). The response time of control current drop from 0 A to 1A is increasing. After that, the response time is being stabilized (fig. 10).

The magnetic flux from the transient magnetic model at different times (0, 1, 5 and 20 ms), and the current of 1 A for control current drop was shown in fig. 11.

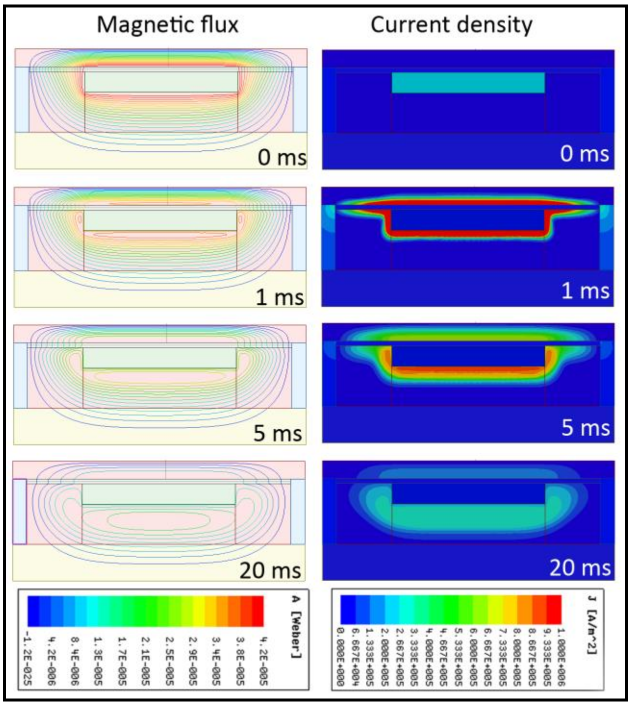


**Figure 11.** Current drop; magnetic flux (left), eddy current density (right).

The magnetic flux in the magnetic circuit caused by the induced eddy currents can be seen after a control current drop. The largest flow of eddy currents is near the coil surface.

### 3.3 Influence of MR fluid

The influence of MR fluid on the response time of magnetic field for three different MR fluids was tested. We chose the MR fluids produced by company Lord (MRF-122EG, MRF-132DG a MRF-140CG). The chosen MR fluids have different mass concentration MRF-122EG 72 %, MRF-132DG 80.98 % and MRF-140CG 85.44 %. The results are shown in tab 1.

**Table 1.** The influence of MR fluid on the response time.

| Name | Magnetic flux density | Response time of rise 1A | Response time of drop 1A |
|---|---|---|---|
| 122EG | 286 mT | 8.7 ms | 9.8 ms |
| 132DG | 342 mT | 12.4 ms | 11.6 ms |
| 140CG | 387 mT | 14.5 ms | 13.8 ms |

The lower the mass concentration in the MR fluid, the lower the response time and the magnetic flux density.

### 3.4 Influence of material of cover

Fig. 11 shows eddy currents in covers, which creates opposite magnetic flux in the gap. The influence of cover material was tested for this purpose. The result is that, according to the transient magnetic model, the material of cover has no influence on the response time of magnetic field.

### 3.5 Influence of material magnetic circuit

Five different samples of material magnetic circuit were tested: pure iron (behanit), low carbon steel (11SMn30), magnetic stainless steel (AISI 416), the alloy Fe-Co (Hyperco 50A), and the ferrite Epcos N95. These materials were compared using the previously described transient magnetic model with MRF-132DG at the current of 1 A. The results obtained from the model were the response time and magnetic flux density in the gap (tab.2). A selection of magnetic circuit material for the MR damper is always a trade-off between minimizing the response time of magnetic field and maximizing the magnetic flux density in the gap.

**Table 2.** The influence of material magnetic circuit on the response time and magnetic flux density in the gap.

| Name | Electric conductivity [MS/m] | Magnetic flux density at 1A [mT] | Response time of drop at 1A [ms] |
|---|---|---|---|
| Pure iron | 8.3 | 410 | 18.5 |
| 11SMn30 | 5.75 | 342 | 11.6 |
| AISI 416 | 2.33 | 315 | 3.5 |
| Hyperco 50A | 2.45 | 466 | 5 |
| Feritte N95 | $0.16x10^{-6}$ | 112 | 0.2 |

## 4 Conclusion

The present paper deals with the transient magnetic model of magnetorheological (MR) damper and its experimental verification. This model was created by software Ansys Electromagnetics 17.1 as 2D axisymmetric. The verification of magnetic model was performed on the geometry of MR damper by comparing the simulated value of magnetic flux density and the value measured with the magnetometer Bell and the ultrathin Hall probe. A maximum difference between the model and the experiment was 28 %. The response time of magnetic field in the gap of MR damper with MRF 132-DG was around 12 ms, according to the transient magnetic simulation. The response time of drop and rise in the control current of MR damper has different courses, depending on the electric current. This effect is probably caused by a nonlinear B-H curve of magnetic circuit and MR fluid. The verified transient magnetic model allows to design and select the material for magnetic circuit of MR damper for a specific engineering application with respect to the response time and the dynamic force range.

The influence of type of MR fluid, material of cover and material of magnetic circuit on the response time of magnetic field was determined by verified transient magnetic model. A type of MR fluid has a significant influence on the response time of MR damper. The higher the mass concentration of ferromagnetic particles in MR fluid, the higher the time response of magnetic field of MR damper and the lower the magnetic flux density in the gap. The selection of material of cover has no influence on the response time. On the contrary, the analysis showed that the material of magnetic circuit significantly affects the response time and magnetic flux density in the gap. The ferrite material had the lowest response time of magnetic field for chosen materials. However, the magnetic flux density of this material in the active zone was almost three times lower than that of other materials. The ferrite material is suitable for the magnetic circuit of fast semi-active control of MR damper. Unfortunately, a dynamic force range is very low. The material of magnetic circuit Hyperco 50A is suitable for the adaptive regime of MR damper because of high dynamic force range. The selection of material of magnetic circuit of MR damper is always a trade-off between the response time and the dynamic force range.

Further research is focused on finding the method of how to reduce the response time while maintaining a similar dynamic force range. A promising method to use is a shape approach (grooving magnetic circuit).

## Acknowledgement

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