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Esa Kostamo, Jari Kostamo, Jyrki Kajaste, Petri Kuosmanen, Matti Pietola

# Magnetorheological Technology in High Frequency Applications

## Abstract

Magnetorheological (MR) fluid belongs to the group of smart materials whose rheological properties can be varied rapidly by application of a magnetic field. The response time of magnetorheological technology is generally considered fast but there is large variation between estimated response times of MR devices in different studies. Typically the response times of MR actuation systems have been reported to be few milliseconds. However, a recent study has been shown the MR fluid responds to external magnetic field in less than 0.5ms which makes the fluid interesting possibility in high frequency applications. The aim of this research work is to evaluate applicability of the MR valve for high dynamic applications. The current status of the research related to high frequency magnetorheological systems will be reviewed and the main performance criteria affecting the dynamical response will be pointed out. Theoretical result will also be validated with an experimental device and the performance of the experimental system will be discussed via measured responses.

## Introduction

Magnetorheological fluids were invented by Jacob Rabinow at the US National Bureau of Standards in 1948. At the time the technology was not ready for the breakthrough but ever since some industrial issues were solved, both the technical and the commercial benefits for various magnetorheological applications have become very promising. During past years magnetorheological (MR) technology has been applied widely in different industrial areas. Due to the nature of the technology it is very well suited for semi active dampers and semi active vibration control. (1) (2)

The functional principle of magnetorheological fluid is based on micron sized ferromagnetic particles mixed into a base fluid. In consequence of the external magnetic field the ferromagnetic particles align parallel to the magnetic field lines and the shear stress of the fluid is increased and the volume flow is resisted or restricted. (3) The principle of magnetorheological effect is demonstrated in figure 1. Magnetorheological fluid can change from free flowing fluid into a semi solid material within a millisecond. This state transition of MR fluids can be used to implement various types of controllable dampers valves, brakes or squeeze film devices (2). The advantage of the magnetorheological devices is that no moving parts are needed for the valve function. This feature enables some novel designs compared to traditional hydraulics and makes the structure of the devices simpler. By directly controlling the shear strength of the fluid magnetorheological technology also provides simple and rapid response interface between electronic and mechanical systems.

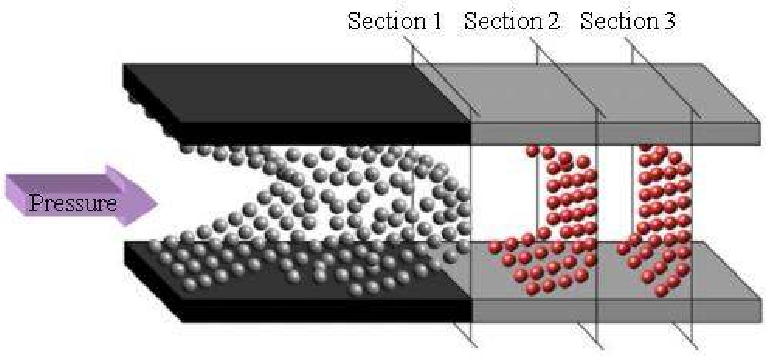



**Figure 1, MR valve flow response to a magnetic field** (4)

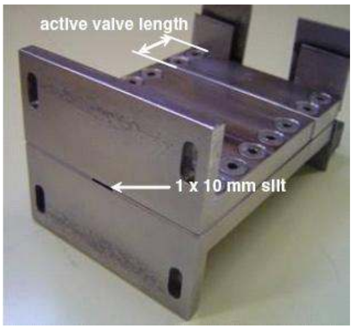
In this paper the state of the art of the response time measurements of magnetorheological fluids is reviewed and the applicability of this technology in high frequency applications will be discussed. Some of the latest magnetorheological actuator applications are also reviewed. The design considerations for high frequency valves will be outlined and the multidisciplinary nature of MR devices is taken into consideration. The paper will be concluded by evaluating the performance of experimental magnetorheological valve designed for high dynamic applications.

## High frequency applications for MR technology

The response time of magnetorheological technology is generally considered fast. The magnetorheological effect is based on the alignment of the magnetic particles in the magnetic field and this is demonstrated in figure (1). This organization of the particles will increase the shear stress of the fluid and resist or totally restrict the fluid flow. In the absence of a magnetic field the fluid exhibits Newtonian-like behavior, where particle orientation is random and the velocity profile is parabolic. In section 1 the fluid is exposed to the magnetic filed and the transition from free flowing fluid to Bingham plastic behavior begins. When the fluid reaches section 2 the particles have begun to align along magnetic field. At this stage the shear stress of the fluid is not yet fully developed but the volume flow is already resisted and the velocity profile has become blunt. In section 3 the shear stress of the fluid has reached its full potential and the pressure difference over the valve depends of the design factors of the valve. (3)

### Response time of magnetorheological fluid

The short response time of MR fluid makes measuring of the response time of the MR effect itself a chalenging task. In some publications the response time of the MR devices has been reported but the response time is given for the total system only. Response time of the fluid has been documented only in few papers in the literature. Goncalves et al. have been studying the response time of the MR fluid perhaps most successfully and reported the state of the art response time of the technology. In this study the issue was first confronted by defining the fluid dwell time. Dwell time is defined as the amount of time the fluid spends in the presence of the magnetic field. The dwell time as a term is easy to understand when the figure 1 is considered again. In such a case which fluid is stationary or flowing slowly in the active region of the valve the particles in the fluid have enough time to form chain structures between north and south poles of the electromagnet in the MR valve and the fluid will develop its full potential. On the other hand as the velocity of the fluid flow is increased the dwell time decreases and the fluid may not have time to activate completely. A slit-flow rheometer was combined with a hydraulic actuator to perform the measurements and the experimental setup is shown in figure 2a. The dwell time of the fluid in the active part of the rheometer was alternated between 6,4 ms and 0,18 ms.



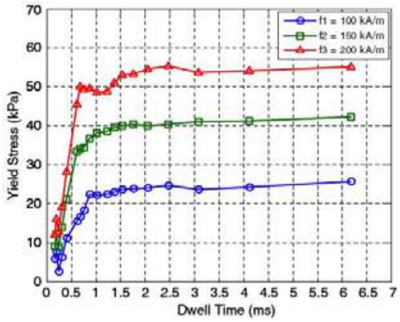




**Figure 2a) Slit-flow rheometer**

**2b) Yield stress as a function of dwell time** (3)

The resulting experimental yield stress data as a function of dwell time is shown in figure 2b. The measurements were repeated for magnetic field strengths of 100 kA/m, 150 kA/m and 200 kA/m and the response time of the fluid was 0,24 ms, 0,20 and 0,19 ms respectively. The results also indicated that the response time of the fluid decreased as magnetic field strength increased. (4)

### High frequency actuators

Based on the research result reviewed in the previous chapter it should be possible to develop highly dynamical magnetorheological actuators or valves. However there are only few studies demonstrating MR devices with response times in the scale of few milliseconds. This is probably mainly caused by the fact that the design process of a MR valve is a multidisciplinary task combining the design of control electronics, the design of power electronics, the magnetic design, the hydraulic design and the design of the MR fluid. Failure in any of these areas will limit the performance of the valve on a poor level even thought other areas would operate well. For example: It can be easily understood that if the response time of the current control circuit of the coils is more than 10 milliseconds, it is not possible to measure faster response from hydraulic circuit. On the other hand if the hydraulic circuit is designed poorly and the natural frequency of the hydraulic circuit is well below the maximum bandwidth of the current control circuit, the hydraulic circuit will not respond rapidly to the pressure changes created by the magnetic field in the fluid gaps. When the response of the magnetic circuit and the dynamics of the MR fluid are combined with these factors it makes it considerably more difficult to decide which part of the valve works well and which part is the bottle neck.
Many papers have been published evaluating the performance of magnetorheological

dampers, valves and MR brakes. Most of the studies seem to have examined magnetorheological dampers because it is perhaps the most attractive application of this technology. This is due to the fact that the construction of a linear MR fluid damper is very simple and similar to conventional viscous fluid damper. The damping oil is just replaced with MR fluid and active fluid is led from one side of the moving piston to another through annular flow channels in which the MR fluid can be activated by magnetic field. MR fluid dampers are typically characterized by large damping force and low power consumption. In figure 3 a typical MR damper construction is presented and the functional parts are pointed out. See e.g. (5-9)

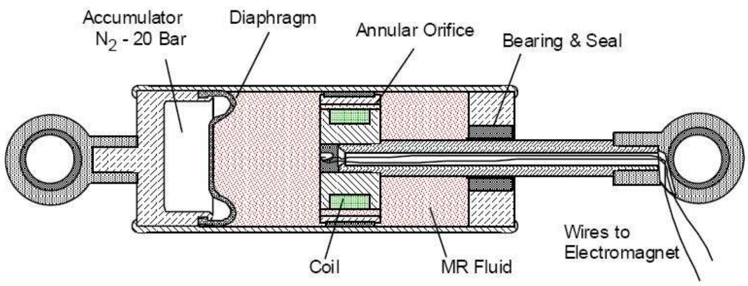
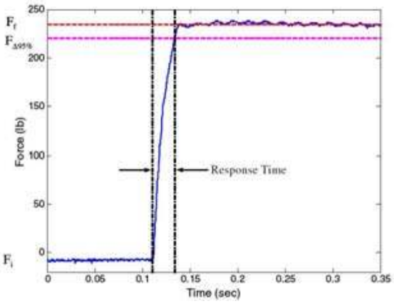



**Figure 3, Draft of MR-damper** (2)

In reviewing the literature a detailed description of the response time of magnetorheological dampers is seldom given. However, the current state of the art in the field of damper dynamics is documented by (5). The damper employed in this study was commercially available RD-1005-3 used in Lord Corporation's Motion Master® Ride Management system. The excitation of the damper was realized by using a material testing system (MTS) ranging the constant velocity from 0,1 to 4 in/s. The response time of the damper was measured by applying a step control to the coil current during the constant piston velocity and measuring the change in the damping force. A demonstration of approach for finding damper response time is shown in figure 4a and response time as a function of coil current is presented in figure 4b for two input velocities. In this study the response time of the magnetorheological damper was reported to be an average of 20 ms beyond the velocity of 1 in/s. However, in this study the response time of the damper was defined from the increasing point of the damping force up to 95% of the maximum force. In the literature it has been well documented that magnetorheological fluid has a certain response time measured from the applying the magnetic field before the shear stress of the fluid begins to increase. (4) If the response time of the damper would have been defined from the control signal to the damping force response could the response time be even a little bit more moderate.



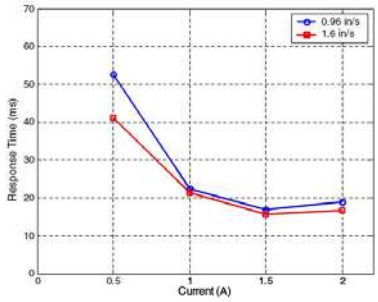
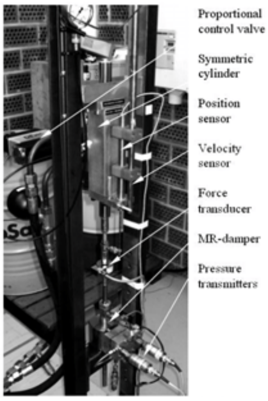




**Figure 4a) Response time definition      4b) Response time as a function of current**(5)

The response time of the magnetorheological damper has also been studied by Kajaste et al. (10). In their study an experimental MR damper was constructed by combining a symmetric hydraulic cylinder with a highly dynamic magnetorheological valve. The damper was attached to a servo hydraulic system and the damping force and the pressure differences over the MR valve were measured. The test setup is shown in figure 5a. The dynamic response of the damper was measured by the same kind of procedure as in the study by Galvin et al. Figure 5b shows how the experimental MR damper reacts to the step input in coil current.



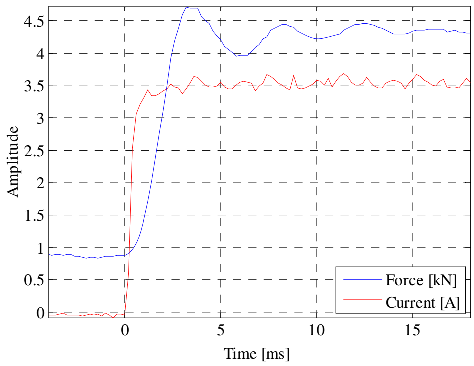




**Figure 5a) Test setup for MR damper      5b) Dynamic force response of the damper** (10)

The results reported in this study prove that notably faster response time of the MR damper is attainable and technology is applicable for high frequency semi-active damping applications. Response time reported in this study can be estimated to be over 10 times faster than the measured by (11) and the damping force level three times higher. (5)

A lot of effort has also been invested in studying the magnetorheological brakes and clutches. The working principles of MR brake and clutch are almost identical and the

magnetorheological effect can be utilized to increase in counteracting torque. The advantage of the MR brake is likewise in the case of MR damper the ability to execute the function of the device without any moving mechanical valve parts. However, the results documented in literature have been reporting typically the design considerations of the device, magnetic design of the actuator and static properties of the brake. (12) Dynamic performance of the MR brakes and clutches has not been studied so much.
In one paper found in the literature the response time of the MR brake is evaluated and some considerations to improve the response time are proposed. The influence of the modifications is validated by experimental measurements. In this study by Takesue et al. (13) two approaches are proposed for improving the response time of the MR brake: one reduces the eddy current by changing the material and the other reduces the counter-magnetic flux. The layout of the MR brake is shown in figure 6a. In eddy current's point of view the approach of changing materials was focused on magnetically inactive parts. The material of the connection part in the analyzed region and the coin bobbin was changed to cast nylon and bakelite, respectively. This state of modification was called advanced actuator 1. In addition to changing the materials, the shape of the actuator was changed in order to increase the magnetic reluctance and reduce the counter flux. MR actuator with modified geometry was called advanced actuator 2. After modifications the response of the magnetic circuit and the response of the torque of the brake were measured and the torque response measurements are presented in figure 6b.

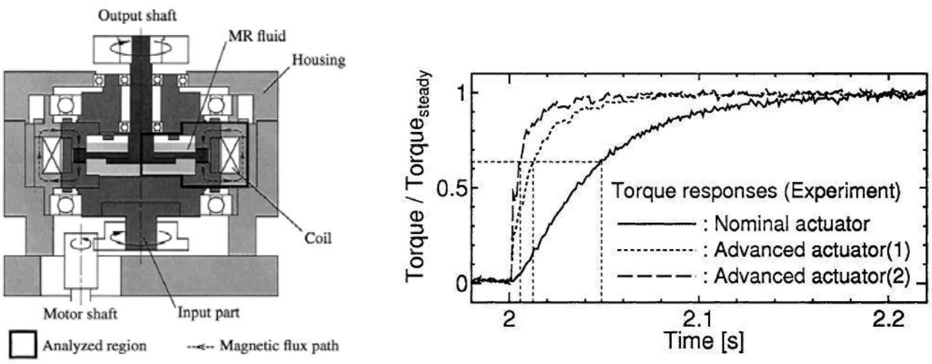



**Figure 6a) Layout of the MR brake** **6b) Torque measurements** (13)

The documented results shown in figure 6b prove that in this study the response time of the MR break could be reduced to 5 ms which is reported to be one-ninth of the original response time. It is also notable that the increase of the dynamic performance did not compromise the maximum torque.

## Design considerations of a high dynamic MR valve

In this chapter the starting points for the design process are discussed. It was pointed out in the previous chapters that the design process of an MR valve is a multidisciplinary task. The factors related to the performance of the valve are listed here and some of them are discussed in more detail. It is, however, well beyond the scope of this paper to describe the entire design process of an optimal high frequency valve. Factors affecting the performance of a magnetorheological valve are:

- Properties of the MR fluid
- Design of flow channels and the hydraulic circuit.
- Mechanical design and stiffness of the structure
- Magnetic circuit: the coil, geometry and materials
- Power electronics
- Control electronics

Each of these can be divided into subcategories if they are examined more closely. In addition the demands for the performance of the MR vary in different applications. Usually it is more expensive and more difficult to design the performance of the valve on any of these areas to be very good. The required performance criteria should be kept in mind from the beginning of the design process and the valve should not be designed to better than needed on any aspect.

### Hydraulic design

The requirements for the hydraulic power controlled by the valve and the properties of the MR fluid define the possible geometries for the fluid gaps. In MR valve applications the geometry of the flow channel is mainly defined by the desired maximum pressure difference created by the valve and the maximum volume flow in the off state. Yet the geometry for a single fluid gap is not uniquely defined based on the power requirements but the geometry can be chosen from a set of different possibilities.

The behavior of a magnetorheological valve is very different from a traditional hydraulic valve because of the nature of the MR phenomenon. If MR valve is compared with traditional hydraulic components it is more like a rapidly controllable pressure relief valve rather than a traditional servo or a proportional valve. This is caused by the fact that the behavior of the magnetorheological fluid differs significantly from Newtonian fluids.

The magnetic field induced yield stress in the fluid is often represented as a Bingham plastic having magnetic field dependent yield strength. For stresses $\tau$ above the field dependent yield stress $\tau_0$, the flow is governed by Bingham's equation. In the Bingham model the total shear stress is given by

$$\tau = \tau_0(H)\operatorname{sgn}\left(\dot{\gamma}\right) + \eta\dot{\gamma} \quad |\tau| > |\tau_0| \tag{1}$$

$$\dot{\gamma} = 0 \quad |\tau| < |\tau_0|, \tag{2}$$

where $\tau_0$ is the yield stress caused by the magnetic field; $\dot{\gamma}$ is the shear rate and $\eta$ is the field-independent viscosity. (14)

When MR fluids are used in a valve application and the Bingham plastic model of the behaviour is adopted the pressure difference over the valve can be estimated with a following equation.

$$\Delta P = \frac{12\eta Q l}{d^3 w} + 2{,}5\frac{l\tau_0}{d}, \tag{3}$$

where $l$ is the length of the flow channel, $w$ is the width of the fluid channel $Q$ is the volumetric flow rate and d is the height of the fluid gap. (15) It can be seen from equation (3) that the pressure difference is a sum of two terms. The first term describes the pressure difference caused by the viscous flow of the fluid and the second term is the pressure difference caused by the field dependent yield stress. If the pressure difference caused by the second term is not exceeded, there will be no flow through the valve.

**Magnetic design**

A magnetic circuit is needed to increase the yield stress of the MR fluid. When the geometry of the fluid gap is known the magnetic circuit must be designed so that the desired operation point of the fluid can be achieved. Usually more than 250kA/m magnetic field strengths are required to achieve the full performance of the MR fluid. This requirement is not exceptional in the magnetic devices but can not be achieved without proper design. (16) Typically equation (4) can be used to approximate the most important parameters of the magnetic circuit of magnetorheological valve. (17)

$$NI = H_{Fe}l_{Fe} + H_{MR}d, \tag{4}$$

where $N$ is the number of ampere turns, $I$ is the electric current of the coil, $H_{Fe}$ is the magnetic field in the iron core, $l_{fe}$ is the length of the magnetic path in the iron core and $H_{MR}$ is the magnetic field in MR fluid. When the operation point is decided and the height of the fluid gap is known the ampere turns needed in the coil can be determined. After this the geometry of the magnetic cores can be designed and selection of the magnetic

core material can be done based on the required magnetic flux density in the magnetic circuit.
Finite element programs can be used to model the magnetic circuit more precisely. FEM modeling of the magnetorheological valve has been presented e.g. in (18) Numerical methods are especially useful when more complex magnetic circuit geometries are designed.
If MR fluid device is going to be used in application requiring fast dynamical response more attention should be given to the selection of the proper core material. The selection of the material will have an effect on the eddy currents in the magnetic core and the response time of the magnetic circuit can be reduced if the core is chosen so that eddy currents are reduced. There are many different commercial magnetic materials available for high frequency applications. However getting specially made magnetic cores is expensive and difficult in general.

## Construction of the MR valve

The experimental valve presented in this paper is a square shaped magnetorheological valve and it is specially designed for high dynamic applications. The MR valve consists of the aluminum body, laminated iron cores and coils and it has two separately controlled edges. The magnetic circuit of the valve is designed so that the magnetic field can be switched on and off rapidly. Figure (7) shows the MR valve without side cover plates.

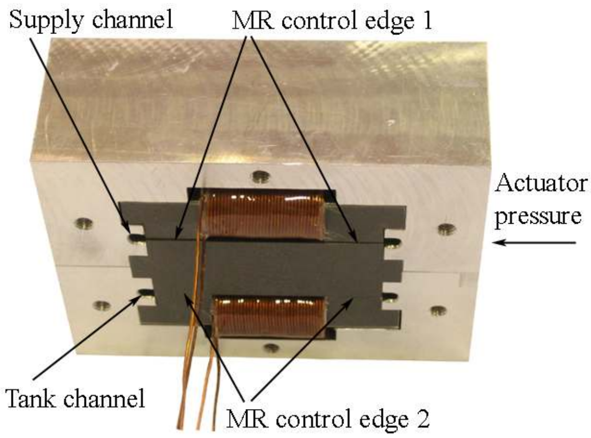



**Figure 7, MR valve without side covers**

When the valve is assembled, the pressure supply line will be attached to the cover plate. MR fluid flows through the cover plate to the supply channel which distributes the volume flow equally over the width of the MR control edge 1. Next the MR fluid changes

its direction and flows through the MR control edge 1.
After the first control edge the MR fluid flows to the actuator pressure measurement and continues to the supply of the second control edge. After the MR control edge 2 the MR fluid ends up to the tank channel from where it is lead through the cover plate to the tank line.
The dimensions for the MR valve are listed in table (1).

| Dimension | Value |
|---|---|
| Length of the fluid gap | 2*15mm |
| Width of the fluid gap | 36mm |
| Height of the fluid gap | 0.35mm |
| Length of the valve (outside) | 110mm |
| Height of the valve (outside) | 87mm |
| Width of the valve (outside) | 54mm |

**Table 1, Dimensions of the MR valve**

## Measurements of the prototype MR valve

The measured results of the experimental MR valve are presented in this chapter. The results include the measurements of the static pressure measurements with constant coil current and dynamic step response measurements.

### Static pressure measurements

The pressure difference over MR control edges was measured with different current values. During the measurements a constant, small fluid flow was forced through the valve. It was noticed that if there is not any flow before coil current is increased, MR fluid can form a 'plug' in the inlet of the valve. Therefore pressure will increase more than models predict and in addition the measurements will not be repeatable.
In figure (8) two repeated static pressure measurements are plotted in the same figure. It can be seen that the measurements are repeatable and the magnetorheological valve can create a pressure difference of over 7.5MPa with 4A coil current.

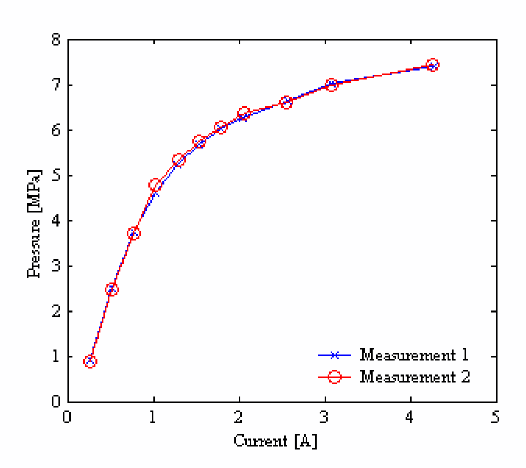



**Figure 8, Static pressure measurements**

**Dynamic pressure measurements**

When dynamic pressure measurements were done the maximum supply pressure level was set to 8.0MPa. The frequency of the square wave reference signal was 40Hz in order to measure how fast the MR valve was able to generate the maximum pressure difference. Figure (9) shows one period of the step response experiment.

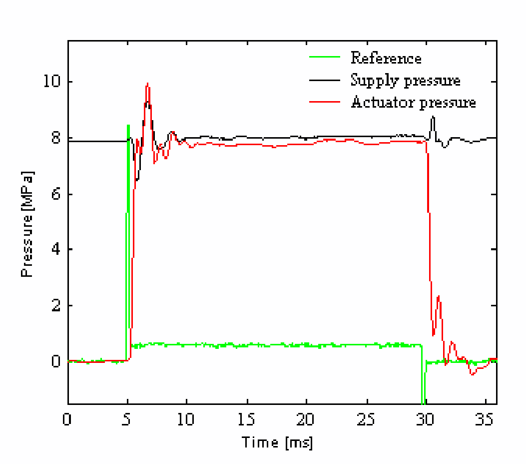



**Figure 9, Pressure step response**

It can be seen from figure (9), that the valve can be used to control the pressure in full 8.0Mpa pressure range. It can be also noted that there occurs some oscillation in the pressure difference in rise period and fall period. The cause of the pressure oscillations was not fully clarified but one likely explanation could be the pressure shock caused by the sudden pressure change.

The rising edge of the step response is investigated in more detail in figure (10). Some interesting points are marked in this figure and the coordinates of the corresponding points are given in table (2). The reference point of step response is plotted with square, the point where the pressure starts to rise is plotted with circle and the maximum operating pressure point is plotted with diamond.

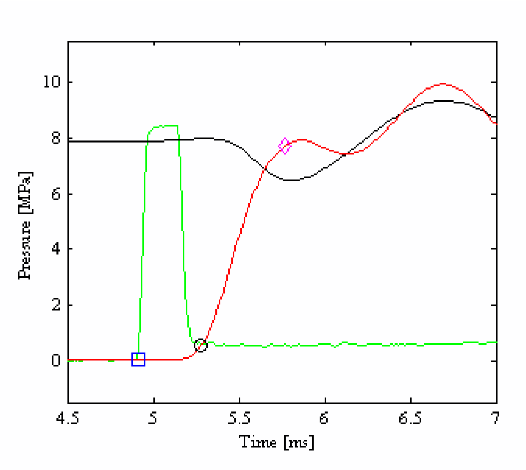



**Figure 7, The rise period of the step response**

| Symbol | Time [ms] | Pressure [Mpa] |
|---|---|---|
| □ Square | 4,91 | 0,041 |
| ○ Circle | 5,28 | 0,524 |
| ◊ Diamond | 5,77 | 7,719 |

**Table 2 Symbol coordinates from the figure (10)**

The delay time for the MR valve can be evaluated by measuring the time difference between square and circle symbols. The delay time was measured to be 0,37ms. Another interesting feature which can be evaluated from the figure (10) is the rate of the pressure change. The rise rate can be evaluated between circle and diamond or square and diamond whether the delay time is neglected or not. If the delay time of the valve is neglected, the pressure difference can be calculated to rise with the speed of 14.7MPa/ms. If the delay is taken into account, the pressure rises with the rate of 8.9MPa/ms. The full pressure difference was achieved in 0,86ms.

The black curve in the figure (10) represents the supply pressure. It can be seen that there is a gap in the supply pressure during the rise period of the actuator pressure. The drop of the supply pressure was tried to be compensated with a small high dynamic accumulator but it could not be completely be avoided.

The results of dynamic measurements are in accordance with the results published in (14). If the response time of the MR fluid is less than one millisecond the response of the valve should be in approximately same scale. The performance of the valve was not clearly optimal but it shows that rapid pressure differences can be created with MR technology.

## Conclusions

This paper presented a review of the state of the art of in MR fluid technology in high frequency applications. During past years magnetorheological technology has been applied widely in different industrial areas and there is plenty of MR applications documented in the literature. Even though there is only few studies about high frequency applications of MR technology.

This study presented some main design considerations which should be taken into account when applying MR fluids in high dynamic applications. In consequence of the multidisciplinary nature of magnetorheological technology all these factors together will establish an interaction chain which will define the dynamic range and the performance of the MR device. Generally a satisfactory solution will be found even if some compromises are made. However, if the objective of the MR device design is to strive for the best possible performance, it means that every sub factor of the interaction chain needs to be optimized.

Performance of an MR valve for highly dynamic applications was also experimentally investigated in this study. An experimental valve was built by the authors to demonstrate the fast response time of MR technology. It was shown that with a proper design a pressure difference of 7.7Mpa with response time of 0.86 milliseconds can be achieved. The maximum rate of pressure raise was 14,7MPa/ms. Controlling about 1kW of hydraulic power with response time of less than 1 millisecond offers some interesting possibilities in designing servo actuators based on MR technology. Future work is also planned in applying the MR valve for actuator applications and its applicability in e.g. active vibration damping applications will be investigated.

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