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STATIC AND TRANSIENT BEHAVIOUR OF MAGNETORHEOLOGICAL FLUID AND DEVICES

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STATIC AND TRANSIENT BEHAVIOUR OF MAGNETORHEOLOGICAL FLUID AND DEVICES

STATICKÉ A PŘECHODOVÉ CHOVÁNÍ MAGNETOREOLOGICKÉ KAPALINY A ZAŘÍZENÍ

OUTLINE OF HABILITATION THESIS
BRANCH DESIGN AND PROCESS ENGINEERING

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ABOUT THE AUTHOR

Dr Michal Kubík was born on May 2, 1989, in Přerov, Czech Republic. He received his bachelor's degree in the branch of Mechanical Engineering at the Faculty of Mechanical Engineering (FME), Brno University of Technology (BUT), in 2011. He received his master in the Institute of Machine and Industrial Design (IMID) at FME BUT in 2013. His diploma thesis was entitled *Design of Testing Bench for Determination of the Operating Parameters of the Magnetorheological Shaft Sealing*. He then continued with doctoral study at the IMID and focused on the research area of magnetorheological technology. In 2018, he defended his PhD thesis entitled *Magnetorheological Suspension Damper for Space Application*. Dr Kubík received a prize of BUT Rector for excellent results in doctoral studies.

Since 2018, Dr Kubík has been working as a full-time assistant professor at IMID FME BUT. Dr Kubík gives lectures and seminars on Machine Design – Machine Elements, Machine Design – Mechanical Drives, Measurement and Experiment, and Mechanical Design Project. The last two are in master's study. He was also the supervisor of eight bachelor's and five diploma theses.

Concerning research activities, he has been involved in the research area of magnetorheological fluid technology and its application. Dr Kubík was the principal investigator in two fundamental research projects financed by the Czech Science Foundation (GAČR). He has also participated in several applied research projects supported by the Ministry of Industry and Trade (*Developement of Magnetorheological Damping System for Railway Vehicles*), the Technology Agency of the Czech Republic (*Semi-active damping system for a single floor electric unit*), etc. Until now, he has published *20 papers* in journals with an impact factor and received *235 citations*, while his current h-index is 8 (according to WOS on February 2, 2023). Furthermore, he is the author of one Czech and European patent. The patent deals with the problem of structured magnetic circuits made of 3D metal printing.

Dr Kubík spent six months at Cracow University of Technology (CUT), Poland, where he dealt with the problem of the hysteresis behavior of a magnetorheological damper. This internship resulted in long-term cooperation with CUT and a joint research project. In 2022, he spent three months at Dresden University of Technology, Germany. Dr Kubík is also interested in deepening cooperation with foreign institutions while he helped to establish cooperation with universities s from Germany, Poland, South Korea, and Malaysia. The international cooperation resulted in the publication of six papers and the submission of two research project proposals.

1 INTRODUCTION

Transporting people or cargo is an integral part of today's society. We live in an age when technologies and transport are evolving significantly. Ongoing development in transportation aims to increase safety, speed, reduce operating or production costs, environmental impact, or noise emissions. However, the most important is traffic safety. The number of seriously injured and dead persons in road accidents has been declining for a long time[1]. The main reason is that transportation safety is constantly increasing due to developments in electronics, driving assistants, intelligent transport communications, and also the materials themselves.

The so-called Smart Materials are increasingly used in transportation. Smart material is a material that one or more properties can be significantly changed by external stimuli, such as mechanical stress, temperature, light, electric or magnetic field, etc. These materials are used in smart sensors (vehicle condition monitoring, monitoring of concrete structures, roadways, and bridges for internal flaws racks, corrosion, and movement), smart glass windows (reflectivity of infrared light could be changed automatically to maintain internal temperatures), smart coatings (improved reflectivity), actuators (smart suspensions systems), etc.

One of the commonly used smart material in transport is the so-called magnetorheological (MR) fluid. It is a magnetically sensitive fluid which can change its apparent viscosity by applying an external magnetic field. Approximately 80 years ago, Jacob Rabinow [2] discovered the MR fluid at the US National Bureau of Standards. However, significant research started roughly 35 years ago. Since then, MR fluid has undergone tremendous development. This fluid has been used in dampers, clutches, brakes, or engine mounts. However, the most important application is an electronically controlled suspension damper in automotive. MR dampers with semi-active control have been used since 1998 for damping seats in heavy-duty vehicles to improve rider comfort and safety [3]. MR dampers have also been used commercially since 2002 in the vehicle suspension system (GM's Cadillac Seville STS)[3]. This technology is currently used by companies Ford, Ferrari, Audi, Chevrolet, Lamborgini, Range Rover, Porsche, etc. This system improves driving handling, comfort, and safety (reduction of braking distance)[4]. In 2007, more than 100 000 MR devices were used in the automotive industry [3]. The first application of this technology also appears in railways. The research team at the Brno University of Technology tested yaw MR damper on a real track [5], see Figure 1.

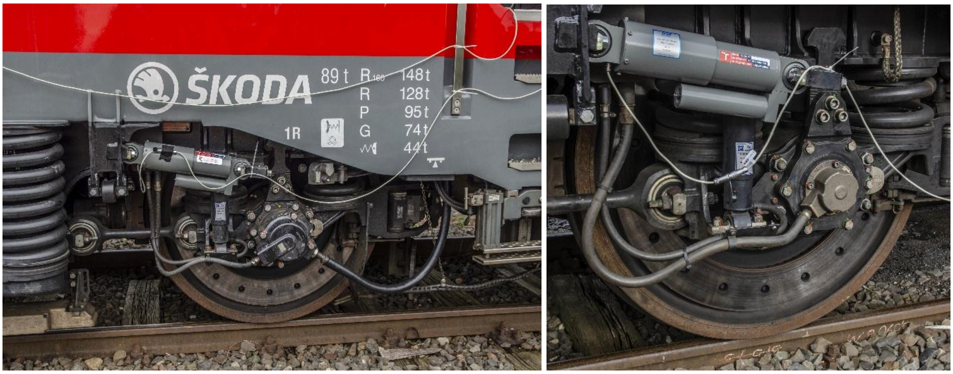


Figure 1: Mounted MR damper on railway vehicle during testing on real track [5]

As mentioned, this technology is currently widely used in automotive. However, intensive fundamental research is still underway in the area of MR fluid itself and the development of new and progressive MR devices. This intensive research can be documented by more than 400 scientific publications in the WOS database in 2021. The recent trend is the use of MR dampers with fast semi-active control, where the transient behaviour of the MR damper is very important (short response time). This can be documented by the two most cited papers in this research area in 2021, which focus on semi-active control. The papers show that fast semi-active control significantly improves the behaviour of the vehicle, especially in terms of safety. Currently, the development of new generations of MR fluids that have better rheological, tribological, transient behaviour, or sedimentation stability is performed.

The main aim of the thesis is to provide an insight into the current state of the art in the static and transient behaviour of magnetorheological fluids and devices to demonstrate the author's contribution to this research field. Chapter 2 deals with the rheological, tribological, and transient behaviour of the magnetorheological fluid itself. Chapter 3 focused on the magnetorheological devices and their transient behaviour. It should be noted that the presented state of the art in magnetorheological technology is not complete and provide just basic insight into this research field. At the end of each chapter, the research gap is listed to clearly show the author's contribution and the novelty of each presented study. In total, the thesis is built on 7 journal papers. Focusing on the papers with IF, five documents were published in journals in the first quartile (Q1), one paper in the second quartile (Q2), and one paper in the third quartile (Q3).

2 MAGNETORHEOLOGICAL FLUID

The word "smart" has become one of the keywords connected with modern scientific and technological progress. In everyday life, we encounter "smart" phones, appliances, and materials. Smart material is a material that one or more properties can be significantly changed by external stimuli, such as mechanical stress, temperature, light, electric or magnetic field, etc. One of those materials is magnetorheological (MR) fluid which is a magnetic field responsive material. MR fluid exhibits a reversible and very fast transition from a liquid to a nearly solid state under the application of external magnetic fields.

MR fluid is a suspension of fine, non-colloidal, low-coercivity, high-magnetisable particles in a carrier fluid [6]. Particles are usually made of carbonyl iron [7], iron/cobalt alloy, iron oxides (Fe_2O_3, Fe_3O_4), nickel, cobalt, silicon steel, and their alloys. These materials usually exhibit magnetic saturation up to 2.1 T ($\mu_0 M_s = 2.1$ T). The most used is carbonyl iron powder (CIP) which is obtained by the thermal decomposition method [8]. However, the CIP manufacturing process is very expansive compared to other methods of producing iron particles. This is the most expensive item of the total price of MR fluid (1 kg of CI powder = app. 300 USD). The vast majority of commercially available MR fluids are CIP-based. The solid phase by the volume is in the range of 20 % to 48 %. In the automotive industry, the typical particle content by volume is 26 % [6]. The particle size is in the range of 1 to 100 μm, preferably in the range of 1 to 10 μm. The ferromagnetic particles have a spherical shape due to durability and tribological properties. Occasionally, flakes [9] or plates shape [10] of particles appear.

The continuous phase of MR fluids are typically silicon oil, mineral oils, synthetic hydrocarbon oils (PAO), water, glycols, or ferrofluids. The carrier fluid should be chemically compatible with particles, exhibit low thermal expansion, excellent lubricity, low viscosity in the high-temperature range, and be economical. The preferred carrier fluid is polyalfaolefin (PAO). This oil exhibits a great operating temperature range, lubrication properties, and chemical stability. The typical dynamic viscosity of carrier fluid is between 0.01 to 0.1 Pa.s at ambient temperature. The commercial MR fluid manufacturers use a hydrocarbon-based carrier fluid (Lord corporation or FemFluid corporation).

The MR fluid exhibits a rapid change of apparent viscosity in several orders of magnitude under the application of an external magnetic field [8]. 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, see Figure 2. The fluid then exhibits a significant increase of the yield stress in tens of kPa.

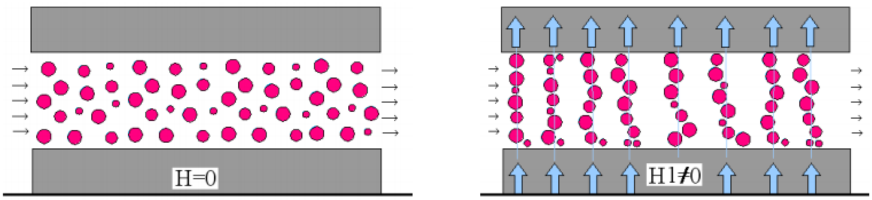


Figure 2: Magnetorheological effect; left: without the magnetic field, right: with the application of magnetic field (blue arrow)[11]

In the next parts of the thesis, the current state of the art in the field of rheological, tribological properties, and transient behaviour of MR fluid is described. The chapter on the rheology of MR fluid is important because it provides basic information, which is essential for the section on transient behaviour. These next chapters aim to meet the reader with basic information about the selected research area with regard to defining the author's contribution to this research area. However, sedimentation stability [12, 13], fluid durability [14], etc., are also important areas but in the thesis are not discussed.

2.1 Rheology of magnetorheological fluid

The rheological behaviour of MR fluid is affected by several factors such as particle concentration, particle size, particle shape, particle distribution, properties of carrier fluid, temperature, magnetic field, or additives. The rheological behaviour of MR fluid can be divided into off-state and on-state (energized) behaviour. In an on-state regime, the magnetic field is applied.

In the off-state, MR fluid appears similar to liquid paints and exhibits a comparable value of apparent viscosity (0.1 – 1 Pa.s^{-1}, at low shear rates). The off-state behaviour depends on particle volume concentration, particle size, additives, and carrier fluid properties. In general, viscosity increases with particle concentration. In 1940, the equation (Einstein equation) describing the viscosity of a suspension of solid spheres η_{MRF} as a function of the viscosity of the carrier liquid $\eta_{0,}$ and the volume concentration of the particles ϕ_v was published [15], see below.

$$\eta_{MRF} = \eta_0(1 + 2.5\emptyset_v) \tag{1}$$

The other more advanced models were also published as the Batchelor equation [16], Krieger-Dougherty equation [16], Mooney [17], etc. MR fluid in off-state exhibits Non-Newtonian behaviour because it usually has a small yield stress in units or tens of Pascals. However, for MR device modeling, the Newtonian behaviour of MR fluid is usually assumed [18].

The rheology of MR fluid in on-state is characterized by pre-yield and post-yield regimes. In the pre-yield regime, the MR fluid usually exhibits viscoelastic behaviour. The complex modulus G is a magnetic field and particle concentration-dependent. The shear stress τ in the fluid can be described by the equation below:

$$\tau = G\gamma, \qquad \tau < \tau_0(H) \text{ and } \gamma^{\cdot} = 0 \tag{2}$$

where γ is shear strain, $\gamma^{\cdot}$ is shear strain rate and $\tau_0(H)$ is dynamic yield stress. The shear strain is usually in the order of 10^{-3}. However, several models have been presented to characterize the pre-yield behavior of MR fluids. These models are composed of elastic springs and viscous dashpot elements.

The post-yield regime of MR fluids has been experimentally determined and described by models in a number of publications. Thus behavior is often represented as a Bingham plastic having variable yield stress [19] by the equation:

$$\tau = \tau_o(H) + \eta\dot{\gamma}, \qquad \tau > \tau_0(H) \tag{3}$$

Where η is dynamic fluid viscosity. However, the Bingham model is insufficient to characterize the MR fluid at high shear rates [6]. In both models, the most relevant rheological property of an MR fluid is the dynamic yield stress $\tau_0(H)$. It should be noted that this value is usually determined by the fitting method. The paper of de Vicente et al. [8] or Seo et al. [20] pointed out that yield stresses are three types: the elastic limit, the static τ_{sy}, and the dynamic τ_{dy}. The static (or frictional) yield stress is the minimum stress which creates the fluid to flow. The dynamic yield stress corresponds to the stress needed to continuously break the particle chains, which reform in the presence of the magnetic forces. The dynamic yield stress of MR fluid depends on particle size, particle volume fraction, particle material, particle distribution, type of carrier fluid, magnetic field, additives, etc. However, the dynamic yield stress is insensitive to operating temperature.

2.2 Tribology of magnetorheological fluid

The tribological properties of MR fluid can be strongly moderated by their composition. The special group of MR fluid is a so-called Magnetorheological polishing fluid [21], where a significant part of the fluid consists of abrasive particles such as alumina, silicon carbide, or diamond particles. This fluid is used as a magnetic field-assisted finishing method (Magnetorheological Polishing method). This method is used for manufacturing the lowest surface roughness values for optics of the highest quality. However, in the other applications of MR fluids is a fundamental improvement in the tribological properties as a decrease of friction coefficient and wear.

The surfaces of MR devices (MR dampers, clutches, brakes, etc.) are in contact with the MR fluid, and it works with relative motion. The wear of MR devices is much faster than hydraulic oil devices because of the abrasive nature of the iron particles. The particle material, hardness, size, shape, carrier fluid, magnetic field, and additives significantly affect the tribological properties. The additives in the form of anti-wear agents such as zinc dialkyl dithiophosphate (ZDDP) and anti-friction agents such as molybdenum-dithiocarbamate (Mo-DTC) or organomolybdenums (MOLY) are used [22]. Those additives are also generally used for hydraulic oils. The nano-sized particles are also used when friction and wear need to be reduced. The low concentration of colloidally stable nanoparticles (app.1 wt %) is sufficient to improve tribological properties (reducing wear and friction). If the concentration of nanoparticles exceeds a limit, the effect is insignificant. However, the exact composition of commercially available MR fluids is the know-how of the manufacturers. Hu et al. [23] experimentally determined that in the presence of a magnetic field, the friction coefficient is four times higher than without a magnetic field. Similar results were published by Zhang et al. [24]. However, the increase in friction coefficient was not so significant because of the low level of magnetic field (app. 10 times lower than Hu et al. [23]). Particles higher than 100 μm usually increase friction and accelerate wear. Gahr et al. [25] describe the effect of particle diameter on wear rate. The wear rate is linearly dependent on particle size. The higher the particle size is, the higher the wear rate is. It is necessary to note that this research was not performed with CI particles. Wang et al. [26] tested the effect of particle size on frictional coefficient and wear on o-ring flooded MR fluid. The higher the particle size is, the higher the frictional coefficient and wear are, see Figure 3. The friction coefficient slightly increases with increased particle concentration at low particle concertation (roughly 20 g/L)[27]. Walker et al. [28] studied the effect of particle shape of white iron slurry on wear. The wear rate decrease exponentially with increasing circularity factor CF (perfect circle CF = 1). However, these experiments were performed on high-size particles (roughly 300 μm) made of a different material than CI. Several authors measured the friction coefficient for commercially available MR fluids and also for homemade MR fluids. Wong et al. [27] measured COF using configuration block-on-ring, where the block is in contact with the cylindrical ring surface. The contact was lubricated by Lord MRF-132DG. The measured COF was in the range of 0.085 to 0.096. Shahrivar et al. [29] compared the friction coefficient of MR fluid and FF fluid as a function of sliding speed. Zhang et al. [30] measured COF for different particle volume content in commercial MR fluid from Lord Corp. The COF was almost identical (ca 0.35) for 22, 32, and 40 vol.% of CI particles. Jolly et al. [31] measured the coefficients of friction for MR fluid lubricated iron-on-iron and nylon-on-iron conformal interfaces. The COF was almost identical for both contact pairs. Jolly et al. [31] compared the four types of MR fluid from Lord corporation with dry friction (0.18), and the measured COF was in the range of 0.04 to 0.07 for all samples.

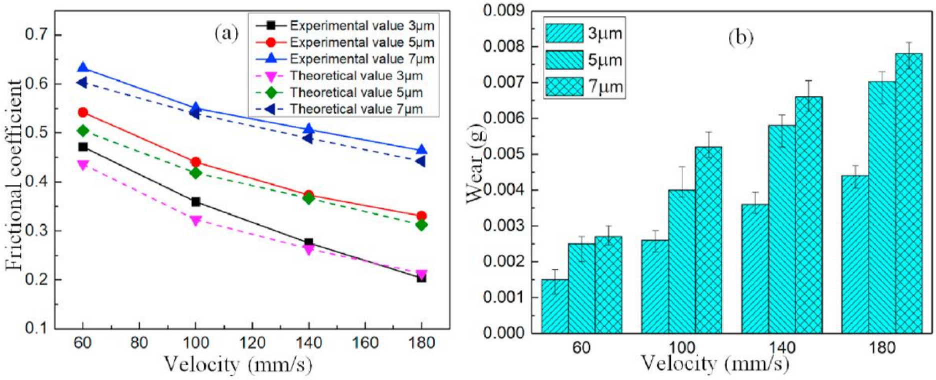


Figure 3: The effect of particle size on friction coefficient and wear for O-ring seal flooded in MR fluid [26]

2.3 Transient response of magnetorheological fluid

The MR fluid exhibits a time delay between the course of the magnetic field and dissipation energy (shear stress, force, torque, etc.). This time delay is associated with several factors such as particle microstructure development, deformation of particle chains (clusters) or hydrodynamic phenomena during the flow, which are differently important depending on loading mode and shear rates. The simplest dynamic system, which can serve as an approximation of the dynamic behaviour of MR fluid, is a first-order system. The response of such a system to a step control signal (magnetic field) is shown in Figure 4. The response is expressed by the time constant τ_{63} (primary response time), which determines the time when 63.2 % of the maximal controlled value is achieved. Despite this, several papers also use the response time (rise time) τ_{90} as the time when 90 % of the maximal controlled value is achieved [32–34]. The criterion of 90 % is frequently used for the description of the dynamic behaviour in industrial applications.

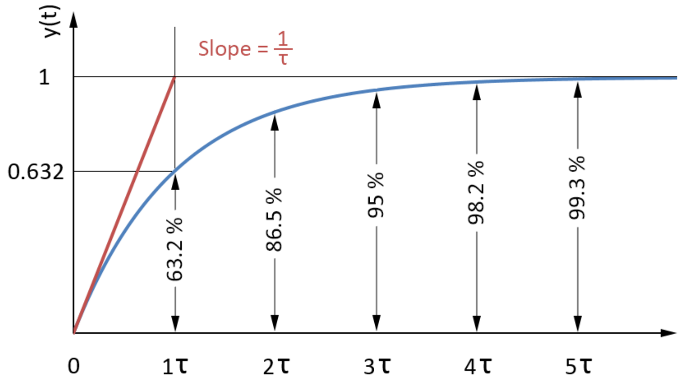


Figure 4: First-order system

The information for evaluation of the response time of MR fluid is always connected with the monitored phenomenon (physics) or the method of its measurement. It can be monitored shear stress, pressure drop, or magnetic permeability of MR fluid. The MR fluid response time is composed of other partial time responses, which are differently important depending on the operating conditions and the method of MR fluid loading. The response time of MR fluid can be divided into (i) *particle structure development response time*, (ii) *rheological response time*, and (iii) *hydrodynamic response time*. It is necessary to note that this division is not stable and was introduced by the author of the thesis.

The particle structure development response time is related to the *chaining of particle*s (particle microstructure development) in the direction of the magnetic field *without flow conditions* of MR fluid. Jolly et al. [35] proposed a method by which particle chaining time can be deduced from the transient change in the relative magnetic permeability of the MR fluid. Two-time responses were observed. The first attributes the connection with the transfer of particles into diverse chains (pair formation). The second (an order of magnitude slower) connection with the migration of these initial chains into longer and stronger structures. The response time was between 5 and 10 ms. The response time increases with increasing carrier fluid viscosity and decreases with increasing magnetic flux density. A similar measurement method was also published by Horváth et al. [36].

The rheological response time is connected with the *development of shear stresses* in MR fluid *during deformation/ flow* (shear rate) on step change of magnetic field. This response time also includes the response time of particle structure development (previous section). The mechanism in shear mode is relatively simple. The deformation of the particle chains (clusters) creates an increase in shear stress τ due to restoring force. The rheological response time is the time needed to increase 63.2 % or 90 % of the final value of MR fluid shear stress. Sherman [34] noted that the MR fluids have no response time but instead a response shear γ_r. The information or papers in this research field is rare. Sherman et al. [34] created a chain model of MR fluid. This model is based on one million particles. One result of this paper is shear stress time history on step change of magnetic field, see Figure 5 left. The rheological response time τ_{r90} was determined as roughly 0.4 ms. The MR fluid has a volume particle fraction of 25 % and was under the shear rate of 500 s^{-1}. Koyanagi et al. [37] developed a method for the measurement response time of electrorheological (ER) fluid. ER fluids exhibit similar rheological behaviour as MR fluids. This team [37] experimentally determined the response time as 0.95 ms. Laun and Gabriel [38] determined the response time of MR fluid of

2.8 ms at a shear rate of 100 s^{-1} and magnetic flux density of 2.08 T. Sherman [34] also evaluated from the chain model results that the shear response of MR fluid is dependent on Mason number and also particle concentration. In the current state of the art can be found more papers dealing with the response time of MR fluid [39, 40]. In these cases, the authors measured the time constant of measuring devices instead of the time constant of MR fluid. A similar statement was made by Sherman [34].

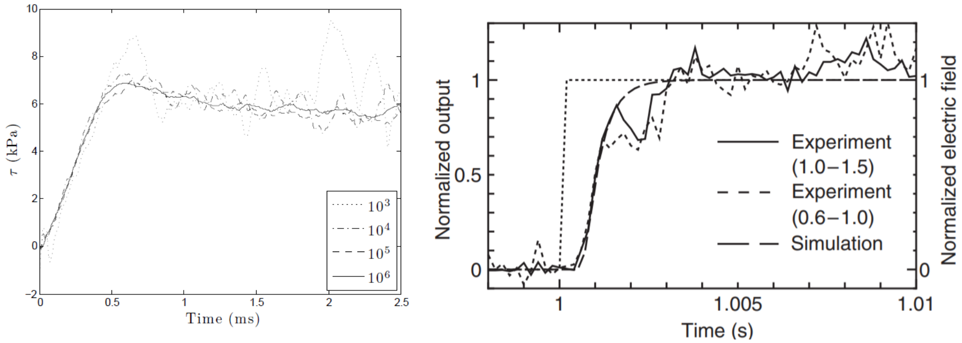


Figure 5: The time dependency of shear stress on step change of control signal from Sherman model (left) [34] and Koyanagi experiments (right) [37]

The research studies of Sherman [34] or Goldasz et al. [6] show that pressure drop across the flow channel created by MR fluid yield stress decreases with the increasing gap velocity. This statement is based on CFD (computational fluid dynamics) simulations. This phenomenon is related to transient rheology connected with the *development of velocity profile in the gap* and is often referred to as the hydrodynamic fluid response time, see Figure 6. This response time is connected with high shear rates and valve mode. Goncalves [41] experimentally determined that the hydrodynamic response time (63.2 %) is 0.73 ms for magnetic field 100 kA/m and 0.53 ms for magnetic field 200 kA/m. The MRF-132LD was used in this study. Gavin et al. [42], in the study on ER dampers, modelled the transition from a fully developed Bingham profile to a Newtonian flow. The yield stress of ER fluid was assumed to drop to zero quicker than the dissipation energy due to the development of the velocity profile. The characteristic time scale is connected with an MR fluid density, the geometry of the gap, and the fluid's viscosity

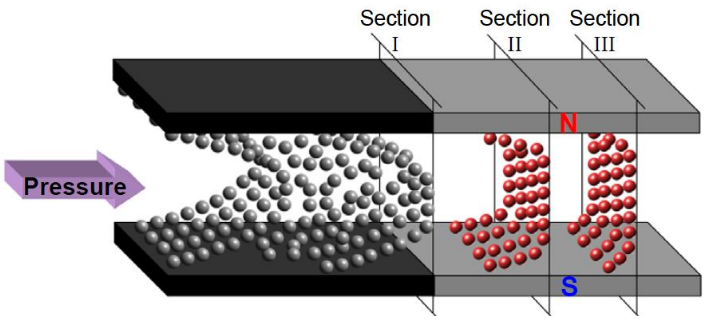


Figure 6: Velocity profile development of MR fluid under magnetic field [41]

2.4 Knowledge gaps

In the current state of the art in the field of (i) tribological properties and (ii) transient response of MR fluid can be found several knowledge gaps.

(i) Transient response: hydrodynamic response time

Studies on the transient behaviour of MR fluid at shear rates encountered in MR dampers are relatively rare, especially with experimental data. The Goncalves [41] stated that the hydrodynamic response time decreases as the magnetic field increases. However, the trends are unknown. *The temperature effect (viscosity) on this behaviour was not studied*. Therefore, our study deals with this knowledge gap.

(ii) Transient response: rheological response time

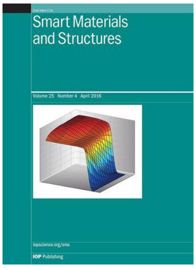
In general, the information about the transient response of MR fluid is limited. This issue is becoming more critical due to the development of MR devices with excellent transient behaviour, where the limiting part is the MR fluid itself. The rheological response time of MR or ER fluid was experimentally determined in two studies [37], [38]. Both studies presented response times for one experimental condition and one selected MR fluid. *The effect of shear rate or MR fluid composition on rheological response time is unknown.* Therefore, our study deals with this knowledge gap.

(iii) Tribological properties

Many papers deal with the measurement of the friction coefficient of MR fluids [22, 24, 26]. However, most of these studies were limited to a narrow range of loads or speeds (low range of Hersey numbers). Only Shahrivar et al. [29] measured friction coefficient in the higher range of sliding speeds. Therefore, the i*nformation on the course of the friction coefficient in a wide range of Hersey numbers (Stribeck curve) is limited.* The effect of particle concentration on each lubrication regime is also limited. Therefore, our study deals with this knowledge gap.

2.5 Author's contribution to the field

Based on the above references, the information about the tribological properties and transient behaviour of MR fluid is still limited. Therefore, the author of the thesis published three papers focused on those research fields. The *first study* **(i)** deals with determining the hydrodynamic response time of MR fluid. The new experimental approach and unique rheometer design were published. The effect of the magnetic field, viscosity (temperature), and gap size were determined. The *second study* **(ii)** contains the measurement of transient response (rheological response time) of MR fluid on the rapid change of magnetic field in shear mode. The effect of carrier fluid viscosity, fluid magnetization, or the shear rate was determined and discussed. The *third study* **(iii)** deals with measuring friction coefficient in the high range of Hersey number. The effects of particle concentration and temperature were presented. All the papers were published in peer-reviewed WOS journals with IF. The list of the included papers is as follows:



KUBÍK, M, K ŠEBESTA, Z STRECKER, F JENIŠ, J GOLDASZ and I MAZŮREK. Hydrodynamic response time of magnetorheological fluid in valve mode: model and experimental verification. *Smart Materials and Structures*. **2021**, 30(12)

Author's contribution (BUT)	= 60 %
Journal impact factor (IF_{2020})	= 3.585
JIF Quartile	= Q1
Citations (WOS)	= 1 (excl. self-citations)

KUBÍK, M, J VÁLEK, J ŽÁČEK, F JENIŠ, D BORIN, Z STRECKER, I MAZŮREK. Transient Response of Magnetorheological Fluid on Rapid Change of Magnetic Field in Shear Mode. *Scientific reports*, **2022**, accepted

Author's contribution (BUT)	= 70 %
Journal impact factor (IF_{2020})	= 4.38
JIF Quartile	= Q1
Citations (WOS)	= 0

ROUPEC, J, F JENIŠ, Z STRECKER, M KUBÍK and O MACHÁČEK. Stribeck Curve of Magnetorheological Fluid within Pin-on-Disc Configuration: An Experimental Investigation. *Materials*. **2020**, 13(20)
(Author thesis: corresponding author)

Author's contribution	= 20 %
Journal impact factor (IF_{2020})	= 3.623
JIF Quartile	= Q2
Citations (WOS)	= 3 (excl. self-citations)

3. MAGNETORHEOLOGICAL FLUID DEVICES

Smart material systems or smart structures are systems that learn and adapt their behaviour in response to the external stimulation, which is provided by the environment in which it operates [43]. Those systems work on a feedback mechanism. From a technological point of view, the feedback system's function can be subdivided into (i) sensor, (ii) control, and (iii) actuator subsystems [44], see Figure 7. The main aim of the sensor system is to collect the required raw data needed for appropriate sensing and monitoring of the structure. The role of this control system is to manage and control the whole system by analyzing the data from sensors, reaching the appropriate conclusion, and determining the actions required. The main purpose of the actuators subsystem is to take action by triggering the controlling device.

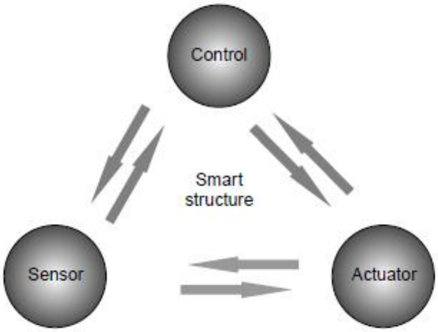


Figure 7: Feedback mechanism of the smart material system [44]

In the following chapters, the magnetorheological actuator subsystem as a part of the smart material system is described in more detail. State of the art is focused on static (quasi-static) and transient behaviour of this actuator/subsystem concerning the highlighted the author's contribution to this research field. This text does not contain the issue of control and sensor. However, it should be noted that these two subsystems also fundamentally affect the performance of the whole system

3.1 Magnetorheological devices

Magnetorheological devices take advantage of the unique properties of MR fluid. MR devices have been developed in various sizes, configurations, and load requirements to accommodate specific application needs. MR fluid-based devices are mainly based on four operational modes of MR fluid, including flow mode, shear mode, squeeze mode, and pinch mode, which provide different benefits in various practical applications. Several devices utilize more than one operating mode and are mix-mode devices. A significant development (analysis of publications from 2021) in the field of MR devices is in engineering and medical application. The predominant applications are in dampers, clutches/brakes, or seals. However, the dominant development is in the field of dampers. In the following section, state of the art in MR dampers and seals are described in more detail.

The *MR dampers* are energy-dissipating devices. Those dampers are filled with MR fluid which is controlled by a magnetic field, usually using an electromagnetic coil. The MR fluid changes apparent viscosity in the gap, which affects the hydraulic gap resistance. This allows continuously controlled damping by varying the power of the electromagnetic coil. The apparent viscosity increase as an electromagnet power increase. The main advantages of MR dampers are mechanical simplicity, low power demands, high dynamic force range, noiseless work, and great transient behaviour. The MR valve does not contain the mechanical moving part (shim valve, etc.), which is also a significant advantage. The MR damper design can be categorized according to three aspects: (i) hydraulic housing, (ii) piston structure, and (iii) operating mode.

As regards of operating modes of MR dampers are divided into four categories: (a) flow mode dampers, (b) shear mode dampers, (c) squeeze mode dampers, and (d) pinch mode dampers, see Figure 8. Pinch mode dampers are quite new, and just several papers exist. The squeeze mode dampers are suitable for damping of small amplitude in dimensions of several millimetres and achieve high damping force compared to the flow of shear mode dampers. Many different squeeze damper designs or approaches for modeling have been published. MR rotary dampers mainly work in shear mode. These dampers are structurally very similar to clutches or brakes. Linear dampers operating in this mode can also be found in the papers. However, in general, these dampers achieve significantly lower damping forces than dampers operating in flow mode at the same dimensions. The advantage is that they do not need a high-pressure expansion chamber. However, the most common is the design of the MR damper working in flow mode.

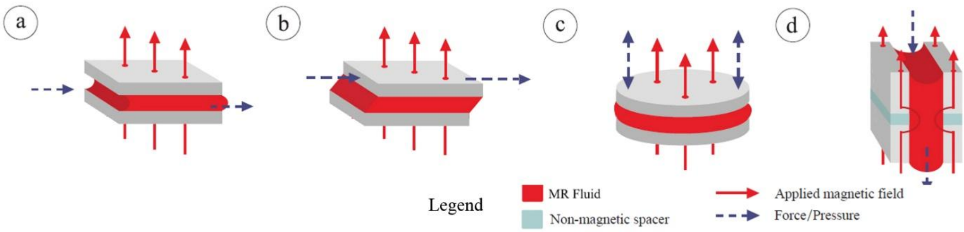


Figure 8: Operating mode of MR fluid [45]

The hydraulic housing of the damper is a mono-tube or twin-tube device. Mono-tube dampers are the most commonly used devices that utilize the MR fluid, see Figure 9. The main advantage is mechanical simplicity. In most cases, it is a gas-charged MR damper (accumulator), where high pressure is necessary. High pressure is necessary for cavitation-free operation. The damper contains a piston, MR fluid, bearing and sealing of piston rod, and hydraulic cylinder, see Figure 9. The possible modification can be an MR damper in a twin-rod configuration, where high gas pressure is not necessary (just a small compensation volume to account for fluid expansion with temperature).

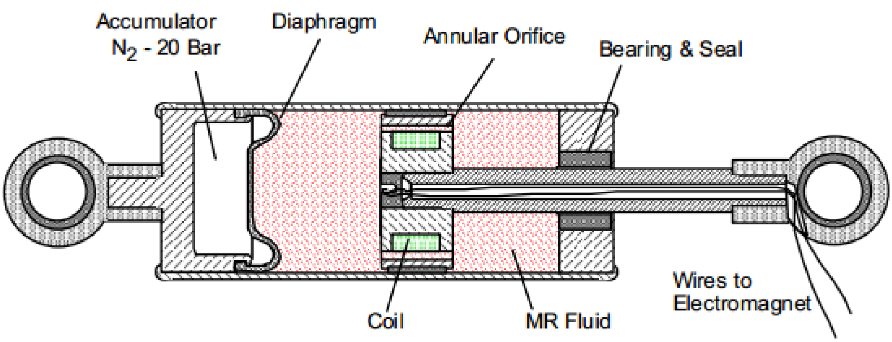


Figure 9: Mono-tube magnetorheological damper [18]

The double-tube configuration is typical for hydraulic oil dampers. Compared to mono-tube configuration, double-tube configuration features concentric hydraulic cylinders. Usually, the inner cylinder contains a piston valve and foot valve. The damper work with low gas pressure. The publications or patents of magnetorheological double-tube damper designs are rare. These designs usually work with two MR valves, or it is necessary to use a minimum one foot/ check valve.

The MR damper piston (control valve) is composed of an electromagnetic coil or coils (2), a magnetic circuit (1), and one or more annular gaps (3), see Figure 10. The control valve modified the damping forces of the damper. The MR control valve can be categorized in terms of the number of arrangements of the flow path, coil arrangement, etc. [46]. The most common categorization is according to the number of coils as single-coil and multi-coil structure (Figure 10).

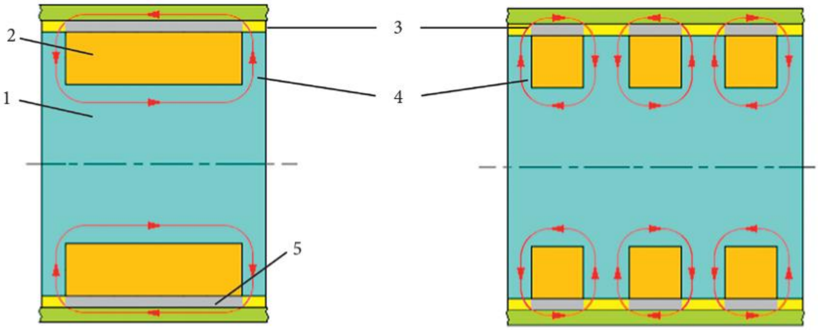
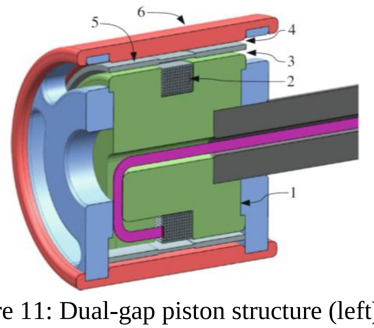


Figure 10: Single-coil structure (left); three-coil structure (right): 1, magnetic circuit; 2, electromagnetic coil; 3, annular gap; 4, magnetic flux lines; 5, non-magnetic section [46]

The single-coil structure is commonly used due to its simplicity. However, the two- or three-coil structure is becoming more common due to the improvement of dynamic force range and transient behaviour (response time) [46]. Another possible grouping is according to the arrangement of path flow. The number of parallel flow (one or multi parallel flow), geometry (tapered), or a change in the flow direction (meandering flow path valve) can be found in papers. In the current state of the art, it can be quite often found a dual-gap variant (two parallel flows) that significantly improves the dynamic force range or MR valve with a meandering flow path which allows for designing an MR damper with a small-sized valve.



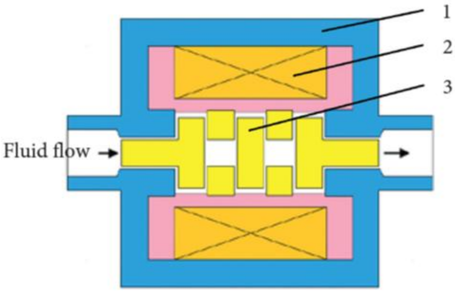


Figure 11: Dual-gap piston structure (left)[6]: 1, core coil; 2, electromagnetic coil; 3, gap 1; 4, gap 2;5, non-magnetic spacer; 6, sleeve; meandering valve (right) [46]:1, magnetic circuit; 2, electromagnetic coil; 3, meandering path

A significant problem of the MR damper is its poor fail-safe behavior. In the case of power supply is interrupted, the damper will stay at the minimum damping level. This limits the use of MR dampers in aerospace or railway. A suitable solution is to use a permanent magnet in the MR damper magnetic circuit. The permanent magnet creates a magnetic flux in the magnetic circuit, which ensures damping during a power supply failure (fail-safe state). The damping level with no electric current and with a permanent magnet usually achieved one-third of the maximum damping force. Several different designs of MR dampers with permanent magnets were published.

The *magnetic fluid seal* has been commonly used in industry since the 1970s. The conventional design of a seal with magnetic fluid contains a source of electromotive force, two ferromagnetic pole pieces, magnetic fluid, and a sealed shaft, see Figure 12. The magnetic fluid is usually used as Ferro fluid (FF).

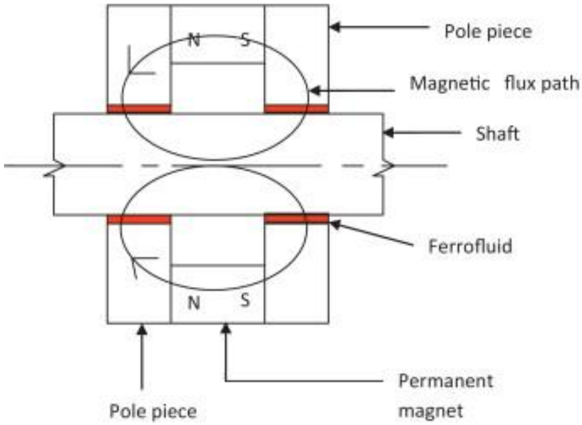


Figure 12: Conventional design of seal with magnetic fluid [47]

A FF is composed of nanoparticles and a carrier fluid. A FF seal (FFs) is characterized by a small friction torque and a high level of tightness. However, the disadvantage of FFs is the relatively low burst pressure. In recent years, several designs of magnetic fluid seal which uses MR fluid instead of FF appears. The main advantage of MR fluid is better magnetic properties (higher magnetization) than FF, which leads to an increase in bursts pressure. The typical static burst pressure of MR fluid seal is in the hundreds of kPa. Kordonski et al. [48] published a one-step magnetorheological fluid seal and experimentally determined burst pressure and friction torque. MRFs exhibit higher burst pressure and higher friction torque than FFs. Urreta et al. [49] confirm the measurement of Kordonski et al. [48].

3.2 Transient response of magnetorheological damper

Magnetorheological dampers are often used in semi-actively controlled suspension systems. It turns out that the transient response of the controlled damping element is crucial for the performance of these systems. Yoon et al. [50]identified that the shorter the response time (better transient response) of the MR damper is, the better the vibration control of the car wheel can be achieved. They demonstrated this effect on the full car suspension model (7 DOF). Oh et al. [51] also tested the effect of MR damper response time on the comfort and driving performance of the car. They stated by the model that the shorter the response time, the better driving performance and comfort. Similar conclusions were published by Strecker et al. [52] or Macháček et al. [53].

The simplest dynamic system (transient response), which can serve as an approximation of the dynamic behaviour of the MR damper, is a first-order system, see Figure 13. The response is expressed by the time constant τ_{63} (primary response time), which determines the time when 63.2 % of the maximal controlled value is achieved. However, the response time of the MR damper is also presented as 90 % or 95 % of the steady-state force at a given piston velocity.

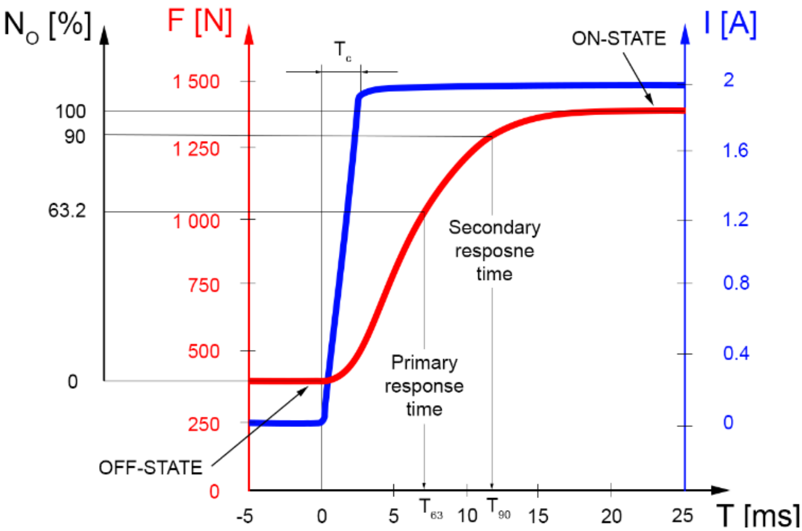


Figure 13: Response time definition

Koo et al. [54] measured the transient response of the LORD automotive MR damper. The response time of the MR damper was identified in the range of 15 – 55 ms. Guan et al. measured the response time of MR damper in the range of 160 - 240 ms. Zhang et al. measured MR damper response time in the range of 34.6 to 75.4 ms. The force rise was significantly faster than the force drop. They concluded that the higher the piston velocity, the higher the response time is. Takesue et al. published the design of the MR actuator (clutch) with a response time of 5 ms. This short response was achieved by a suitable design of a magnetic circuit based on transient magnetic simulation. Giorgetti et al. [55] developed an MR actuator (clutch) with a response time of 17 ms. The measured response time was not affected by excitation velocity. They stated that the measured time delay is a combination of power supply dynamics, magnetic circuit dynamics, fluid rheology effect, and fluid compressibility. Occhiuzzi et al. [56] tested MR damper with a response time of 10 ms. Goncalves et al. [57] measured the response time for rebound activation as 15.4 ms and rebound deactivation as 13.9 ms. It can be stated that many authors measured the response time of MR dampers and the response time differed significantly.

It can be identified *four main sources of the time lag* between damping force and control signal (response time) as (i) response time of MR fluid itself, (ii) inductance of MR damper electromagnetic coil, (iii) creation of eddy current in the magnetic circuit, and (iv) compressibility of fluid and hydraulic system. The response time of MR fluid will be discussed in detail in following chapters.

The *electromagnetic coil inductance* creates a time delay between voltage and electric current. From the electrical point of view, the MR damper can be simplified as inductance L connected in series with resistance R. The course of electric current $i(t)$ after switching on can be expressed by the equation:

$$i(t) = \frac{U}{R}\left(1 - e^{-\frac{Rt}{L}}\right) \tag{6}$$

Where U is voltage, R is the resistance of the coil, L is inductance, t is time. The time constant is the ratio of inductance L and resistance R. This response time is significant and ranges from units to hundreds of milliseconds depending on the size of the damper (electromagnetic coil). Yang et al. [58] presented a current controller which works with the over-voltage method. The controller keeps higher voltage inputs than corresponding to Ohms law until the desired current is achieved. Using this method, Yang et al. [58] reduced the response time of the MR damper from 300 ms to 60 ms. A similar method was published by Strecker et al. [59]. Goldasz et al. [6] presented lumped parameter model of the LR circuit, which was connected to the hydraulic domain and determined the transient response of electric current and damping force.

Mass and Guth [60] found out time lag between the course of electric current and the course of damping force. They explained this lag as a result of *eddy current* induced in the magnetic circuit. Similar conclusions were published by Guan et al. [61]. Guan et al. [61] stated that the reducing of the eddy current is the key to developed MR damper with a short response time. The main idea is the following. When the magnetic flux changes rapidly, an electromotive force is generated in the magnetic circuit according to Faraday's law (1):

$$\varepsilon = -N\frac{d\Phi}{dt} \tag{7}$$

Where ε is the electromotive force, t is time, N is the number of turns of the coil, Φ is the magnetic flux. From Ohm's law, the magnitude of eddy currents can be determined as follows:

$$\varepsilon = R_{circuit} . I_{eddy} \tag{8}$$

Where $R_{circuit}$ is the electrical resistance of magnetic circuit material in the direction of eddy currents flow and I_{eddy} is the magnitude of the eddy currents. By increasing $R_{circuit}$ is possible to reduce the magnitude of I_{eddy} with the same change in magnetic flux. Therefore, the problem of eddy currents can be solved by two approaches: (i) *by suitable material selection* and (ii) by *suitable shape*. The material selection for the magnetic circuit is a trade-off between the static and transient efficiency of the magnetic circuit. Materials like ferrites or soft material composites (SMC) generally have lower permeability or a lower magnetic saturation limit compared to pure iron. However, those materials have high electrical resistivity, thus preventing the creation of eddy currents. Other problems with these materials are their low mechanical strength, high cost, and poor machinability. The second approach to preventing eddy currents is the shape approach. This approach is commonly used at low-frequency transformers using isolated sheets. The MR control valve with an isolated sheet was also published [6]. The magnetic circuit of the piston is similar to the magnetic circuit of the electric motor. The electromagnetic coil is wound around the outside of the core, see Figure 14. This design exhibits a short response time.

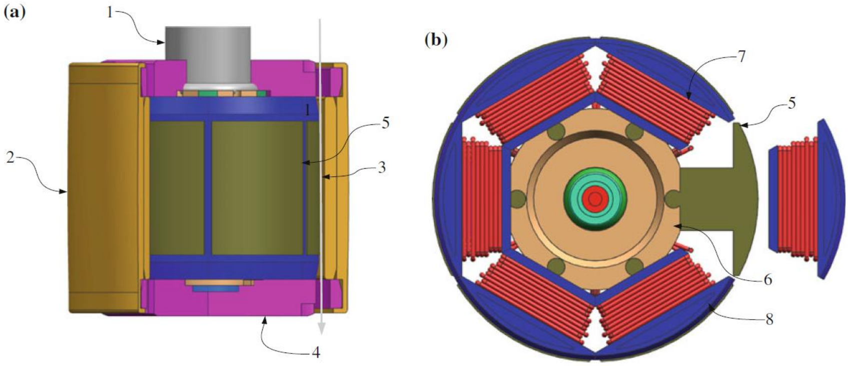


Figure 14: MR control valve with laminated magnetic circuit:1, rod; 2, sleeve; 3, annulus gap; 4, lids; 5, magnetic poles; 6,coil core; 7, electromagnetic coil; 8, casing [6]

Koo et al. [54] studied the effect of piston velocity on the response time. They determined that the response time decreases exponentially with increasing piston velocity. They conclude that the response time at low velocities is highly dependent on system compliance (stiffness). The compliance inputs to the system in different ways as fluid compressibility, accumulator compressibility, silent block, or load frame stiffness. The MR damper behaves as a spring in series with the damper, see Figure 15. The deformation of the MR actuator can be calculated as a ratio of force *F* and system stiffness *K* as follows:

$$X = F / K \tag{9}$$

Therefore, the response time *T* can be calculated very simply as follow:

$$T = X / v \tag{10}$$

Where *X* is deformation and *v* piston velocity. Clearly, *T* becomes large as v becomes small. Giorgetti et al. [55] stated that compressibility of MR fluid is very important to the transient response of MR damper.

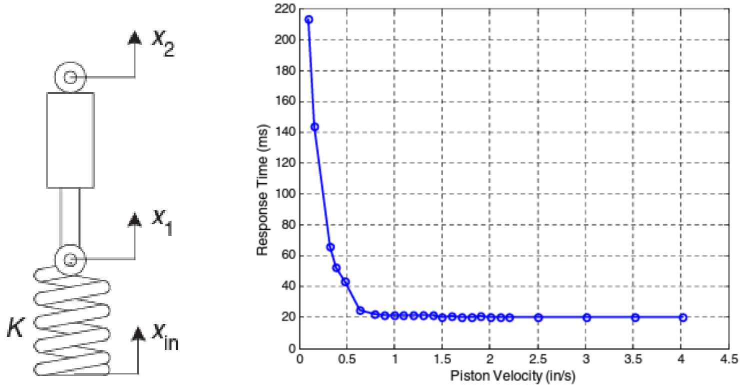


Figure 15: The effect of piston velocity on MR damper response time [54]

3.3 Knowledge gaps

In the current state of the art in the field of the transient response of MR dampers and MR fluid seals can be found several knowledge gaps.

(i) Transient response of MR damper: effect of permanent magnet

If the power supply of the MR damper electromagnetic coil is interrupted, the damper will stay at the minimum damping level. This is a significant problem for a wide range of MR damper applications (aerospace, rail, automotive, etc.). Many MR damper designs have been published that include a permanent magnet to ensure fail-safe behaviour. These papers were focused on adjusting suitable damping. However, th*e information about the permanent magnet effect on MR damper transient response is unknown*. Therefore, our study deals with this knowledge gap.

(ii) Transient response of MR damper: eddy current effect

The transient behavior of the MR damper is degraded by the formation of eddy currents in the magnetic circuit. Several approaches how to improving MR damper transient response were published. However, each approach has significant limitations. *The information on how to design of MR damper which meets with a short response time, great dynamic force range, good mechanical properties, and low weight is unknown*. In our paper, we decided to present this type of MR damper design.

(iii) Transient response of MR damper: fluid compressibility effect

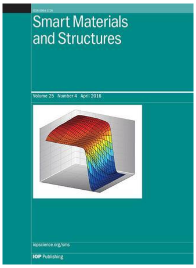
The transient response of the MR damper is probably also affected by the compressibility of the damper system and the MR fluid itself. *The effect of MR fluid compressibility and MR fluid volume is unknown.* It is relatively difficult to experimentally determine the effect of fluid compressibility on damper response time. Therefore, the multiphysics model, which includes magnetic, hydraulic a mechanical domains, will be necessary create to determine MR fluid compressibility effect. Therefore, our study deals with this knowledge gap.

(iv) MR fluid shaft seal

The main advantage of MR fluid seal is higher burst pressure than FF fluid seal. However, the friction torque of the MR fluid seal is significantly higher than FF fluid seal. *The design of the MR fluid seal, which combines the high burst pressure and low friction torque, is unknown*. This type of design was published in our paper.

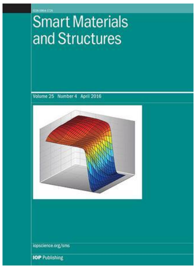
3.4 Author's contribution to the field

The author of the thesis published three papers focused on the research field of the transient response of MR damper and one paper on the research field of MR fluid seal. The *first study* **(i)** deals with the transient response of the MR damper with a permanent magnet in the magnetic circuit. The *second paper* **(ii)** is connected with the design of an MR damper with a short response time which is secured by a structured magnetic circuit made of 3D metal printing. The *third paper* **(iii)** in this section deals with the multiphysics model of the MR damper. One important result is the effect of fluid compressibility on transient response. One publication **(iv)** also deals with the design of magnetorheological fluid seals with low friction torque. The design is based on the pinch mode of MR fluid. All the papers were published in peer-reviewed WOS journals with IF. The list of the included papers is as follows:



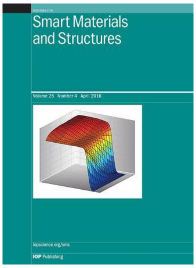
JENIŠ, F, M KUBÍK, O MACHÁČEK, K ŠEBESTA a Z STRECKER. Insight into the response time of fail-safe magnetorheological damper. *Smart Materials and Structures*. **2020**, 30(1)

Author's contribution = 45 %
Journal impact factor (IF_{2020}) = 3.585
JIF Quartile = Q1
Citations (WOS) = 0 w/o self cit.



STRECKER, Z, M KUBÍK, P VÍTEK, J ROUPEC, D PALOUŠEK and V ŠREIBR. Structured magnetic circuit for magnetorheological damper made by selective laser melting technology. *Smart Materials and Structures*. **2019**, 28(5)

Author's contribution = 25 %
Journal impact factor (IF_{2019}) = 3.613
JIF Quartile = Q1
Citations (WOS) = 5 w/o self cit.



KUBÍK, M, D PAVLÍČEK, O MACHÁČEK, Z STRECKER and J ROUPEC. A magnetorheological fluid shaft seal with low friction torque. *Smart Materials and Structures*. **2019**, 28(4)

Author's contribution = 50 %
Journal impact factor (IF_{2019}) = 3.613
JIF Quartile = Q1
Citations (WOS) = 17 w/o self cit.

KUBÍK, M. and J. GOLDASZ. Multiphysics Model of an MR Damper including Magnetic Hysteresis. *Shock and Vibration*. **2019**, 2019, 1-20

Author's contribution (BUT)	= 100 %
Journal impact factor (IF_{2019})	= 1.298
JIF Quartile	= Q3
Citations (WOS)	= 5 w/o self cit.

The author of the thesis is also significantly connected to applied research (projects) in this research field (Figure 16). The most important outputs of applied research are (i) the European Patent Office [62], where the main idea is based and a structured magnetic circuit made of 3D metal printing that improves magnetic circuit dynamics, and (ii) a functional sample of a magnetorheological yaw damper with a short response time for the locomotive of Škoda Transportation, see figure below.

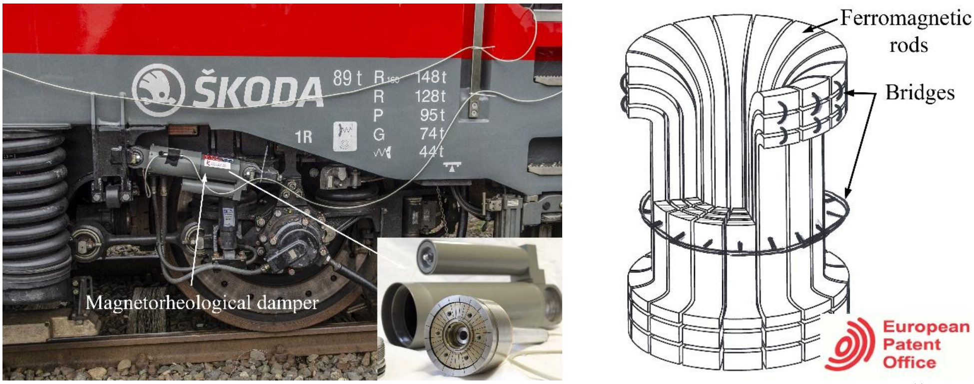


Figure 16**:** Developed MR damper with short response time mounted on locomotive Škoda Transportation during testing (left), the main idea of structured magnetic circuit patent (right)

4 CONCLUSIONS AND IMPLICATIONS FOR FURTHER RESEARCH

MR fluid development has been going on intensively for more than 35 years. Since then, MR fluid has undergone tremendous development. The MR fluid has been used in dampers, clutches, brakes, seals, or engine mounts. Currently, this technology is widely used in automotive. The most important application is in electronically controlled dampers. However, intensive fundamental research is still underway in the area of MR fluid itself and the development of new and progressive MR devices. The recent trend is the use of MR dampers with semi-active control, where the transient behaviour of the MR damper is very important (damper with short response time).

The habilitation thesis provides a short insight into MR fluid (chapter 2) and MR devices (chapter 3). Specifically, in chapter 2, the rheological, tribological, and transient response of MR fluid is discussed. The main goal of chapter 2 was to provide the current state of the art and highlight the main findings and some limitations of the previous studies. At the end of this chapter was presented the author's contribution to the field. The main findings of the author on the field of *MR fluid fundamental research* are:

(i) The author of the thesis developed a unique rheometer design and a method for measuring the rheological response time of MR fluid in shear load mode. It was determined the effect of shear strain rate, carrier fluid viscosity and magnetization on the rheological response time. The experimentally determined data were generalized in the form of Non-dimensional response time and Mason number. The master curve was obtained from the measurement, which allows calculating the rheological response time of MR fluid for any MR device operating in shear mode during the design phase.

(ii) The author determined the effect of the magnetic field, fluid viscosity and gap size on the hydrodynamic response time of MR fluid operating in valve mode and shear strain rates common in MR devices. The measured data were generalized in the form of Non-dimensional response time on Bingham number, and one master curve was evaluated. The hydrodynamic response time for different MR damper configurations and different MR fluids can be determined from the master curve during the design phase.

(iii) The author experimentally determined the MR fluid friction coefficient in a wide range of Hersey numbers (Stribeck curve) in a typical range of MR devices.

Chapter 3 deals with magnetorheological devices and their transient behaviour. Specifically, the current state of the art in the MR damper, MR fluid seal and MR damper transient response were presented. The main factors affecting the MR damper transient response were also presented. At the end of this chapter, it is presented the author's contribution to the field. The main findings in the research field (*fundamental and applied research*) of MR devices and their transient response are:

(iv) The design of an MR damper with a permanent magnet (fail-safe MR damper) was developed and tested. The important result was that the permanent magnet significantly affected the MR damper transient response. This behaviour can be modelled by transient magnetic simulation quite precisely.

(v) The unique approach for designing of MR damper with a short response time, great dynamic force range, good mechanical properties, and low weight was presented. This method is based on rods made of 3D metal printing manufacturing method. The author of the thesis also patented this method (EP 3373311 A1).

(vi) The author creates the multiphysics model of the MR damper. The effect of MR fluid compressibility is important, especially at low piston velocities. The response time course on piston velocity has an exponential character .

(vii) The unique design of the MR fluid shaft seal, which allows high burst pressure and low friction torque, was presented. The main idea of the seal is based on MR fluid pinch model loading mode.

It can be stated that the presented papers extend the current state of the art in the field of the transient response of MR fluid and MR devices. Understanding the transient behavior of MR fluids is essential for the development of a new generation of MR fluids with the shortest possible response time. Even a small change in response time can be significant. The presented methods of MR damper design allow optimizing the response time or weight with regard to the requirements of the given technical application. Those methods ensure the lowest MR damper response time of around 1.3 ms. This fast damper significantly increases the performance of semi-actively controlled suspension systems. In automotive, this damper with semiactive control can improve comfort, improve driving handling or even shorten braking distances and thus passengers safety. In total, the *thesis is composed of 7 papers* (5x Q1, 1x Q2 and 1x Q3). All papers were published in peer-reviewed journals with a high impact factor.

It can be stated that the research and development in the field of MR fluids and MR devices are definitely not over. I assume that the large future research areas are (i) the durability of MR devices (especially seals), (ii) the durability of MR fluids under long-term loading, (iii) the transient response of MR fluids, (iv) high-velocity regime of MR fluid, or (v) rheology of new load mode of MR fluid (pinch mode). In my opinion, all these areas are interesting for high-quality research/ publication. In 2012, Murphy [63] stated that in 15 years (considered the year 2027), half of the automotive dampers are expected to rely on MR fluid. Unfortunately, the reality now is different. The main limit of this technology is the price of MR fluid itself, which is given by the high price of iron particles. So, in my opinion, the biggest challenge in the field of magnetorheology is the development of a method for producing high-quality CI powders quickly and cheaply. In the case of cheaper MR fluid, this technology will be used in most applications where any damping is required.

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Static and transient behaviour of magnetorheological fluid and devices

ABSTRACT

Magnetorheological fluid is one of the smart materials that change its rheological behaviour in the presence of a magnetic field. This fluid has found application in electronically controlled dampers and is widely used in automotive with semi-active control. This thesis focuses on the issues of rheology, tribology, and transient behaviour of the MR fluid itself, as well as on MR devices and their transient behaviour. Each chapter provides an overview of the current state of the art, followed by a description of the author's contribution to this research area. A total of 7 papers were published in scientific journals with high impact factors

KEYWORDS: Magnetorheological fluid; rheology; tribology; transient response; response time; MR damper; eddy currents

Statické a dynamické chování magnetoreologické kapaliny a zařízení

ABSTRAKT

Magnetoreologická kapalina je jeden ze smart materiálů, který mění své reologické vlastnosti v přítomnosti magnetického pole. Tato kapalina našla uplatnění v elektronicky řiditelných tlumičích a je široce používána v automotive spolu se semiaktivním řízením. Tato práce se zaměřuje na problematiku reologie, tribologie a přechodového chování samotné MR kapaliny a také na MR zařízení a jejich přechodového chování. Jednotlivé kapitoly poskytují vhled do problematiky, následovaný popisem vlastního přínosu autora do dané oblasti. Celkem bylo publikováno 7 prací ve vědeckých časopisech s vysokým impaktním číslem.

KLÍČOVÁ SLOVA: Magnetoreologická kapaliny; reologie; tribologie; přechodové chování; časová odezva; MR tlumič; vířivé proudy