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MAGNETORHEOLOGICAL SUSPENSION DAMPER FOR SPACE APPLICATION

MAGNETOREOLOGICKÝ TLUMIČ ODPRUŽENÍ PRO KOSMONAUTIKU

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1 INTRODUCTION

In recent years, an average 87 launches of launch vehicles were carried out. The communication or the researcher satellites were launched most often. Vibration and shock loads during the shipment may cause destruction of optics, electronics, and other sensitive equipment of the satellites. To compensate for the hard dynamic environment, satellites must be designed to high dynamic level [1], which rapidly increases the cost and weight of satellite components. An interesting method is to reduce dynamic loads using a vibration isolation system which is between the launch vehicle propulsion and the payload. From the point of view efficiency isolation, weight or cost, the semi-active control vibration isolation system appears a suitable option. The decrease of the dynamic load to the frequencies up 25 Hz is important for most design of satellites. It is necessary to have a damper that can quickly change its damping force (response time of the damper) for effective semi-active control. Specifically, for frequency 25 Hz, the response time 4 ms is needed. Until recently, the design of this type of damper was unknown. In 2013, Strecker at al. published the design of the magnetorheological (MR) damper with response time 1.5 ms. The MR damper works with magnetorheological fluid.

The MR fluid is composed of microscale ferro-magnetic particles, non-magnetic carrier oil, and additives [2]. In the presence of magnetic field, the MR fluid changes the rheological properties, especially apparent viscosity: from low value (fluid) to high value (pseudo-solid). The first mention of MR fluid comes from Rabinow and Winslow [3] in the 1940s. However, new generations of MR fluids and MR devices were intensely developed in the 1990s. At the turn of the 20th and 21st centuries, a wide range of application of MR fluids appeared in a variety of technical devices. The most successful application of MR fluid was a magnetorheological (MR) damper. The issue of decreasing the response time (time delay) of damping force of MR damper was intensively examined at the beginning of the 21st century. It was found that inductance of the coil, response time of MR fluid, and eddy currents generated in the magnetic circuit influence the response time of MR damper [4]. Strecker at al. [4] from Brno University of Technology published their finding that the response time of damping force of MR damper can by reduced by a suitable choice of the magnetic circuit material and by a suitable current controller.

The MR damper with short response time opens up new possibilities of using the MR damper for progressive vibration isolation systems, such as the vibration isolation system of the launch vehicle. However, the published design of MR damper by Strecker at al. is not suitable for space application. The design process of MR damper with short response time suffers from a number of limitations. The design of demonstrator of semi-active control of the magnetorheological damper for space application is main aim of present thesis.
2 STATE OF THE ART

2.1 VIBRATION ISOLATION SYSTEMS

Mechanical vibrations are generated due to the imbalance of rotating and reciprocating components, impact forces, pressure loadings at surfaces due to the winds or acoustic noises, etc. [5]. These vibrations are undesirable in most devices; therefore, a vibration isolation system is used for their elimination. These systems are usually composed of the springs that accumulate energy, and the dampers that dissipate the energy from system [6]. Vibration isolation systems are located between the source of vibration and the isolated devices. The target parameter, which is used to quantify the performance of the vibration isolation system, is the transmissibility.

In the passive vibration isolation system, damping is given from the “factory” and cannot be changed during the lifetime of vibration isolation system [7]. The material (silentblock) or viscous damping (hydraulic damper) can be used. A level of damping can be changed in adaptive vibration isolation system; this change of damping level is relatively slow (tens of seconds). The adaptive systems are commonly used in bogies of rail vehicle [8, 9] or in car suspensions [10]. The semi-active control of vibration isolation system is a real-time control of damping element by a control algorithm, which switches a damping level at the appropriate time. An important parameter of the damper for semi-active control is the time needed for the rise or drop of damping force on the control signal (the response time of damper) [11]. Small reduction of the response time (e.g. from 2 ms to 1 ms) has a significant impact on transmissibility. Therefore, the damper with short response time and Skyhook control algorithm seems to be the best vibration isolation system based on the damping principle.

2.2 VIBRATION ISOLATION SYSTEM FOR SPACE APPLICATION

Satellites are very important products used for many purposes, such as communications, navigation, or weather forecasts. The shipment of satellite is more complicated than that of all other products [1]. Vibration and shock loads during the shipment may cause destruction of optics, electronics, and other sensitive equipment. To compensate for the hard dynamic environment, payloads must be designed to high dynamic level [1], which rapidly increases the cost and weight of payload components. An interesting alternative is to reduce dynamic loads using a vibration isolation system which is between the launch vehicle propulsion and the payload [12]. Nowadays, the payload is connected to the launch vehicle by passive cone adapter made of composite or similar materials [13] (Fig. 1).
Fig. 1 Launch vehicle composite cone adapter [12]

This version is reliable and relatively cheap. However, for some types of payload, the elimination of vibration by composite cone of launch vehicle is insufficient. The company Honeywell developed the passive vibration isolation system ELVIS (Evolved Launch Vibration Isolation System) based on patented hydraulic D-Struts [14, 15], see Fig. 2.

Fig. 2 Vibration isolation system ELVIS (left); D-strut (middle), three parameter isolation system (right)[15, 29]

The D-Strut is composed of metal bellows, flanges, and damping annulus (Fig. 2. middle). The primary and the secondary bellows are connected via the fluid path of damping annulus where hydraulic oil flows while primary bellows are compressed. The D-Strut was developed with passive and active control, see Fig. 3. A future research step will be to use a semi-active control damper in D-Strut system. An interesting candidate is the use of magnetorheological technology.
2.3 MAGNETORHEOLOGICAL DAMPER

Magnetorheological (MR) fluid is a suspension of micro-scale, non-colloidal ferromagnetic particles in a non-conductive carrier fluid and additives [16]. The MR fluid exhibits a rapid change of rheological behaviour under an external magnetic field. Ferromagnetic particles in MR fluid form chain-like structures in the direction of magnetic field which rapidly increases yield stress of MR fluid. A magnetorheological (MR) damper or valve is a device which uses a strong and rapid change of yield stress of MR fluid in the direction of magnetic field. The MR damper is composed of piston, bearing and seal, floating piston or diaphragm (with accumulator), and MR fluid [17] (Fig. 4). The piston consists of magnetic circuit and electromagnetic coil. There is a gap in the magnetic circuit which is flooded with MR fluid (an annular orifice in the piston usually called the active zone). During the flow of MR fluid in the active zone, it is possible to control the value of yield stress (hydraulic resistance) by electric current in the coil. This causes a rapid increase in damping force.
An important parameter influencing the efficiency of MR damper in the adaptive or semi-active control is a **dynamic force range**. This is defined as a ratio between the damping force in On-state $F_{ON}(v, H)$ (resisting force) and the damping force in Off-state $F_{OFF}(v)$ (uncontrollable force). The higher the value of dynamic force range, the higher the quality of semi-active control [18, 19]. The **response time** of MR damper is the time needed for the rise to 63.3 % (in some publication 95 % ) of steady state damping force on the control current [11]. The lower is the value of response time, the higher is the quality of semi-active control that can be achieved [20]. Usually, the response time of MR damper was between 20 ms and 300 ms.

**2.4 METHODOLOGY DESIGN OF SEMI-ACTIVE CONTROL MR DAMPER**

The main goal of this chapter is to describe the design methods of the semi-active control MR damper. The dynamic force range and the response time of MR damper influence the efficiency of semi-active control. The following chapters are divided as follows: mechanical, magnetic, magnetorheological, and hydraulic sections. The influence of each section on the dynamic force range and the response time is discussed.

**2.4.1 Mechanical section**

A method of how to separate (to seal) the MR fluid from the environment is the fundamental part of mechanical section. **Rubber blade seal, bellows** and **magnetic seal** are presented. Coulomb friction losses of rubber blade seal significantly decrease the dynamic force range. The rubber blade seal has always leakage. An important advantage of bellows is no leakage of the hydraulic fluid and no friction losses. However, a disadvantage of the bellows is a relatively low stiffness which creates an inflation due to internal pressure. Other disadvantages are a high price and a relatively small stroke. The MR damper works with magnetic fluid which can be used for sealing. Kordonski et al. [21] and Matuszewski et al. [22] dealt with the design of magnetorheological shaft seal. A disadvantage of this concept is a considerable loss of moment due to the "tearing" of the particle chains during rotation.

**2.4.2 Magnetic section**

The magnetic design of MR damper affects the response time and the dynamic force range of the MR damper. The magnetic models (magnetostatic and
transient) and methods of elimination of eddy currents in magnetic circuit are present in this section.

The magnetostatic model is important for the dimensional design of magnetic circuit of MR damper due to maximization of magnetic flux in the active zone. This model is also important for the coil design.

The transient magnetic model is fundamental for determination of the response time of magnetic field in the active zone for the step rise of control current. Nevertheless, this model is not commonly used for the design process of MR damper. According to the available literature, the transient magnetic model was published only by Takesue [23] and Zheng [24]. The methodology of this model is not clear.

A selection of material with high magnetic saturation (Fe-Co, pure iron) increases the dynamic force range. However, these materials have a low electric resistivity, which negatively influences the response time. A selection of material for magnetic circuit is always trade-off between the dynamic force range and the response time of MR damper. The lamination method of magnetic circuit significantly increases the electric resistance in the direction of eddy currents flow. However, for the geometry of magnetic circuit of MR damper, this method is difficult to use. However, the alfa-omega is to find the material or geometry of magnetic circuit which provides a high dynamic range and short response time of MR damper.

2.4.3 Magnetorheological section

The in-use-thickening of MR fluid affects the dynamic force range of the MR damper because it causes an increase on Off-state forces. Carlson [25] published his finding that if the MR fluid in the MR damper is subjected to high stress and a high shear rate over a long time period in MR damper, the off-state force increases.

2.4.4 Hydraulic section

A hydraulic section contains three areas of interest referring to the F-v dependency which has an influence on the dynamic force range. The off-state, pre-yield, and post-yield regime are described below. In each regime, the hydraulic model is present.

The important part of pre-yield regime is a bypass gap, which is parallelly connected to the active zone of MR damper. The bypass gap causes a decline in F-v dependency at low piston velocity as was described in [26, 27]. The
analytical hydraulic model of bypass gap was published in [26] but the model presented in this publication is strongly simplified and inaccurate. For this reason, the CFD model of bypass gap represents a more precise way. A numerical model of bypass gap and its experimental verification are important.

The hydraulic models of post-yield regime are described in publications [16, 17, 28]. However, the important input into this model is the yield stress of MR fluid which must be obtained from the datasheet of MR fluid and the magnetostatic model. Unfortunately, in the whole range of publications, this step is omitted. The experimental verification of Yang hydraulic model of post-yield regime connected with magnetostatic model will be performed.
3 SUMMARY AND CONCLUSION OF STATE OF THE ART

The most commonly used vibration isolation system for space applications is a composite cone [35]. This is an economic and reliable variant of vibration isolation system. However, the elimination of vibrations and shocks by composite cone is insufficient for many types of payload by composite cone. For this reason, more progressive vibration isolation systems are still under development. The company Honeywell developed a vibration isolation system based on Steward platform (ELVIS) [29, 30]. A patented passive D-Strut, which has a springing and damping function, [31] was used in this system. The main disadvantage of ELVIS vibration isolation system is a weight higher than that of composite cone. For this reason, the methods to increase the efficiency of vibration isolation system are still under development to justify the higher weight. From the point of views of efficiency and weight of vibration isolation system, the semi-active control seems to be the most appropriate. However, the efficiency of semi-active control is influenced by the response time of damping element [31] and the dynamic force range [14, 90]. According to the information from European Space Agency, those are important parameters for design:

- the response time of damping element shall be 4 ms or lower,
- the hermetic separation of operating fluids from the rest of the launch vehicle.

The magnetorheological damper with ferrite magnetic circuit with bellows seems to a be good candidate for semi-active control damping element for space application. However, some methods, from chapter 2.4, impact the response time and the dynamic force range of MR damper are unknown:

- the method or material for the design of MR damper with short time response without the use of ferrite material (method elimination of eddy currents in magnetic circuit),
- experimental verification of magnetostatic model,
- transient magnetic model and its experimental verification,
- CFD model of bypass gap and its experimental verification,
- experimental verification of post-yield and off-state Yang hydraulic model.
4 AIM OF THE THESIS

The present dissertation thesis was closely connected with the project for European Space Agency: “Semi-active damping system FLPP3”. This project was solved in co-operation with the company Honeywell. The semi-actively control MR damper of strut appears to be an effective version to decrease the transmissibility of vibration isolation platform for space application. The design of demonstrator of this type of MR damper is the main aim of presented thesis.

In 2013, the only option of how to design the MR damper with the response time of 4 ms was to use the ferrite material for magnetic circuit which has a lot of limitation. An important sub-goal of the present thesis was to find the method or material for the design of MR damper with short time response without the use of ferrite material. Another important sub-goal was to add new methods for the design of MR damper with short response time, e.g. the model of bypass gap or magnetic models.

4.1 THE AIM OF THE THESIS

The main aim of the submitted dissertation thesis is to design and tests a demonstrator of magnetorheological damper with short response time for space application. A design of MR valve is fundamental for the design of the MR damper. The sub-aims of the thesis refer to the methods necessary to add for the design of semi-active control MR damper with short response time.

The sub-aims of the thesis are as follows:

- a method to decrease the response time of MR damper,
- magnetostatic, transient magnetic models and their experimental verification,
- a model of bypass gap and its experimental verification,
- experimental verification of published hydraulic models.

4.2 SCIENTIFIC QUESTION AND HYPOTHESES

Scientific question 1:
It is possible to design a semi-actively controlled magnetorheological damper for space application, which has a response time of about 4 ms and a dynamic force range more than 4?
Hypotheses 1: The ferrite material for the magnetic circuit of the MR damper will allow designing an MR damper with a response time of approximately 4 ms.

Hypotheses 2: The dynamic force range of the MR damper cannot be achieved more than 4 because the ferrite material has low level of magnetic saturation.

**Scientific question 2:**

*It is possible to design a magnetic circuit of MR damper from material with high magnetic saturation and low electric resistivity which achieved a short response time?*

Hypotheses 3: The decrease of creation of eddy currents, which has significant effect on the response time, is possible by suitable structural modification which rapidly increases the electric resistivity in the flow path of eddy currents.

4.3 THESIS LAYOUT

The main goal of the present dissertation thesis was published in the impact journal *Smart Materials and Structures* (IF 2.909). The design and experiments related to the developed MR damper with short time response were published in the paper (I.).

The methods to decrease the response time of MR damper were searched for. The main limitation parameter of response time are the eddy currents in the magnetic circuit of MR damper. The research was focused on the elimination of eddy currents in the magnetic circuit. In this area, a considerable progress has been achieved by using a suitable shaped groove (structural modification) in the magnetic circuit of MR damper. This method allows for development of magnetic circuit of MR damper with a high dynamic force range and a low response time. The efficiency of this method can be increased by 3D metal printing (SLM). This method was patented (II.).

The transient magnetic model of MR damper and its experimental verification were published at the International Conference in Kuala Lumpur (III.). The paper passed the review process. This model is important for the design of MR damper for the specific response time.

The CFD model of bypass gap of MR damper and its experimental verification were published at the International conference in Svratka, Czech Republic. The paper passed the review process (IV.).
Impact journal Smart Material and Structures (IF = 2.909)


Application of the Czech patent


Article in conference proceedings – (after review, Scopus)


Article in conference proceedings - WOS

5 NEW METHODS FOR THE DESIGN OF SEMI-ACTIVE CONTROL MR DAMPER

In this chapter, new methods for the design of the semi-active control MR damper with short response time and high dynamic range are presented. The next sections are divided into the same sections as the methods in the state of the art section.

5.1 MAGNETIC SECTION

5.1.1 Magnetostatic model of the MR damper and its experimental verification

The magnetostatic model allows to determine the magnetic flux density in the active zone of the MR damper, which is a fundamental input into the post-yield hydraulic model and into the transient magnetic model.

**Material and methods**

The geometry of the magnetic circuit of the MR damper was simplified in the magnetostatic model as 2D axisymmetric and the software Ansys Electronics 17.1 was used. Low carbon steel 11SMn30 was set as the material for the magnetic circuit. The B-H curve of this material was experimentally determined. The magnetic flux density in the active zone was measured with the ultrathin Hall probe and the magnetometer F.W. Bell 5180 (Fig. 5). The measurement circuit see in Fig. 5.

![Fig. 5 Measurement circuit (left); position of Hall sensor](image)

**Results and discussion**

The maximum difference between the model and the experiment was under 1 % (Fig. 6). However, the accuracy of the magnetostatic model is strongly dependent on the accuracy of measurement of B-H curve. The magnetic circuit
of the MR damper was composed of the same material as the testing sample for measurements of B-H curve (the same chemical composition). The magnetostatic model was experimentally verified on the air in the active zone.

![Graph](image)

**Fig. 6** Comparison of the magnetostatic model and the experiment (left), the detail of a comparison of the magnetostatic model and the experiment (right)

### 5.1.2 Transient magnetic model and its experimental verification

**Materials and methods**

The transient magnetic model allows determination of the response time of the magnetic field (the most important part of the response time of the MR damper). The model was created in the software Ansys Electronics 17.1. The geometry was simplified as 2D axisymmetric. A description of the model and experiment was published in the paper entitled “**Transient magnetic model of magnetorheological damper and its experimental verification**” (International Conference in Kuala Lumpur) [32].

**Results and discussion**

The verification of the transient magnetic model was possible only with air in the active zone where the maximum difference between the model and the experiment was 28 % (Fig. 7, left) with air in the active zone. This difference is probably caused by inaccurately specified electrical conductivity given in the datasheet of the material manufacturer. The response time was dependent on the electric current.
The experimentally verified transient magnetic model was used for determining the influence of the magnetic circuit material or the type of MR fluid on the response time of the magnetic field in the active zone. A more detailed description can be found in [32]. The 2D transient model can be simply extended to a 3D model.

5.1.3 Elimination of eddy currents in the magnetic circuit

From the point of view of high dynamic force range and short response time, a suitable material for the magnetic circuit should have a high magnetic saturation and a low electric conductivity. Unfortunately, the material with a low electric conductivity usually has a low magnetic saturation. **A selection of the material for the magnetic circuit is a trade-off between the magnetic saturation and the electric conductivity.**

Therefore, the question has arisen: “Could the electric resistivity in the direction of eddy currents be increased by structural modification of any part of the magnetic circuit?” In this case, the material with a high magnetic saturation could be used; the response time would be reduced by the geometric adjustment. The higher the length in the direction of flow path of eddy currents, the higher the electric resistance in this direction. The increase in the length of the eddy currents “path” is possible via appropriate grooves in the magnetic circuit, see Fig. 8. This method is demonstrated on the MR damper geometry, specifically on the yellow marked part.
Fig. 8 Direction of the magnetic flux (left), influence of the grooves on the path of the eddy currents (middle, right)

Materials and methods

Based on the verified magnetic transient analysis (3D analysis), a suitable geometry of the grooves of the MR damper was determined. A more detailed analysis of influence of grooves was dealt with Strmiska in diploma thesis [33]. The grooves were manufactured by electro erosive wire machining of the magnetic circuit parts. Forty-eight 0.3 mm wide grooves were manufactured (Fig. 9). The magnetic circuit was made from the low carbon steel 11SMn30.

Fig. 9 Manufactured grooves on the geometry of the MR damper

For the comparison of influence of the grooves on the response time, two identical magnetic circuits were manufactured from the same material. The first magnetic circuit was with the grooves while the other was without the grooves. Magnetic flux density was measured in the active zone with air with the ultrathin Hall probe and the magnetometer F.W. Bell 5180. The coil was energized by power supply Manson SDP 2603 and current controller (our design). Measurements of the response time of the magnetic circuit were based
on the methodology in [34]. The response time of the magnetic circuit without grooves was measured using a rise in the control current.

**Results and discussion**

The measured response time of the magnetic field in the active zone was 1.69 ms (air). The course of the magnetic flux density over time is shown in Fig 10. The response time of the magnetic circuit with the grooves was measured with a rise in the control current. The measured response time of magnetic field in the active zone was 0.36 ms (air), see Fig. 10.

![Fig. 10 The response time on the air of the magnetic circuit with grooves](image)

According to the obtained results, the response time of the magnetic circuit of the MR damper can be significantly reduced by suitable grooves on the magnetic circuit, according the results. The response time of the magnetic field in the active zone dropped 4.6 times using a grooving structure. The maximum magnetic flux density remained the same. The response time of MR damper with the grooved magnetic circuit and the MR fluid in the active zone was solved by the transient magnetic model at 1.7 ms.

It can be concluded that a grooving method is feasible. However, where is the limit for decrease in the response time and dimensions of the grooves? The thickness of grooves (number of grooves in the part) has a limit because of manufacturing technology. The author of this thesis proposed a different method of how to decrease the eddy currents, i.e. to manufacture a magnetic circuit with ferromagnetic rods oriented in the direction of the magnetic flux by SLM (Selective Laser Melting) – method of 3D print. The rods are interconnected only by some small connecting bridges.
Fig. 11 An example of the design of the magnetic circuit according to the patent manufactured by the 3D metal printing [35]

This method was patented under the title: “The magnetic circuit containing rods of ferromagnetic material and the method of its manufacture” [35].

5.2 HYDRAULIC SECTION

5.2.1 Bypass gap in the MR damper (pre-yield regime)

A parallel connection between the bypass gap and the active zone causes a decrease in the damping force at low piston velocity. A methodology for designing the bypass gap has not yet been published in the available literature. The analytical approach is very complicated and inaccurate.

Materials and methods

The CFD model of the bypass gap and its experimental verification on the developed test rig were published in the following paper:” Hydraulic resistance of magnetorheological damper viscous bypass gap” [36]. The CFD model was created in software Ansys CFX and the k-ε turbulent model was used. The experimental test rig was designed and manufactured for the testing of bypass gap (Fig. 12). The maximum difference between the experiment and the CFD model was 24 %.
Fig. 12 The experimental test rig [36]

Results and discussion
The maximum difference between the experiment and the CFD model was 24%. CFD model can be used for the design of the bypass gap in the magnetorheological damper; the achieved results were published at the conference listened in WOS.

5.2.2 Post-yield regime

Materials and methods
The Yang hydraulic model was experimentally verified on the geometry of MR damper with MRF-132DG. The most important parameter influencing the accuracy of hydraulic model of MR damper is the yield stress in the active zone. The value of yield stress for different currents in the coil is based on the MR fluid datasheet and the results of magnetic flux density obtained by the magnetostatic model. The tested MR damper with MRF-132DG was placed into the test rig with a hydraulic pulsatory. The load cell Interface 1730 ACK-50 kN was used for measurement of the damping force and the Messotron WLG150 sensor was used for stroke measurement.

Results and discussion
A comparison between the experiment and the model for currents of 0.2 A, 0.4 A, 0.5 A, 1 A and 1.5 A is shown in Fig. 13. The maximum difference between the hydraulic model and the experiment was 21%. For the design of MR damper, this accuracy of the model is sufficient.
5.2.3 Off-state regime

Materials and methods

The off-state regime of the MR damper was based on the hydraulic model by Yang. The most important parameter for the model is a dynamic viscosity of MR fluid at different temperatures. The temperature of the MR fluid in the hydraulic system was 30 °C. The dynamic viscosity for this temperature is 0.156 Pa.s, according to Kubik [37]. The presented measured data was obtained by method presented in previous section.

Results and discussion

The maximum difference between the model and the experiment is 24 % (Fig. 14). However, the accuracy is strongly dependent on the proper measurement of the MR fluid temperature. The accuracy of the model is also influenced by the developed of the velocity profile in the active zone or turbulent flow.
6 MAGNETOREHEOLOGICAL SUSPENSION DAMPER FOR SPACE APPLICATION

The Honeywell company addressed Brno University of Technology with the offer to participate in the development of the semi-actively control D-Strut for the space applications. The use of a semi-actively controlled MR damper was planned with the framework of the project for the European Space Agency (ESA). It was necessary to experimentally demonstrate that a semi-active control of MRD-Strut system would bring a significant reduction in transfer of vibration to payload. As early as in 2014, the development of the MRD-strut demonstrator (the project Semi-active Damping System FLPP3) started. The demonstrator of magnetorheological suspension damper (in the following section used abbreviation magnetorheological suspension damper strut) for space application was designed according to specific requirements (chapter 6.1). Tests of MR valve with short response time and the valve development were carried out by the author of this thesis (chapter 6.2) as its main goal; consequently, the results were published in the impact journal [34]. A vibration isolation test rig was developed for the tests of vibration isolation efficiency. The benefit of the MR semi-active damping control with the control algorithm was tested on the previously described test rig (chapter 6.3).

The MR valve design, described in chapter 6.2 was created earlier than the methods in the chapter 5 were specified. Therefore, these methods were not used for the design of the MR valve.

6.1 DEMONSTRATOR OF MRD-STRUT

The demonstrator of MRD-strut was based on the Honeywell D-Strut for the vibration isolation platform ELVIS. The resonant frequency of MRD-strut demonstrator was set to 10 Hz.

![Fig. 15 The demonstrator of the MRD-strut with the MR valve [35]](image)
This system uses bellows for the separation of the MR fluid from surroundings. The demonstrator of MRD-strut allowed for a simple change of the stiffness springs, assembling and disassembling, a simple connection of measuring sensors, etc. The weight of this demonstrator was not an important requirement. The demonstrator of MRD-strut was composed of coil springs, bellows unit, MR valve and connection fittings, see Fig. 15.

6.2 MAGNETORHEOLOGICAL VALVE

Materials and methods
The MR valve design was composed of three coils (1), which were wound with opposite orientation, the ferrite magnetic circuit (2,3,5), outer tube (4), coil support (6), valve flange (8) and sealing (7, 9, 10), see Fig. 16. The magnetic circuit was made from Epcos ferrite N95 material as the ferrite material is the only material suitable for the MR valve design with short response time. The main disadvantage of this material was its poor machinability, low mechanical properties, and low level of magnetic saturation.

Results and discussion
The response time and force-velocity-current course were measured on the manufactured and assembled demonstrator of the MRD-strut with the MR valve. According to the experiment, the developed system with the MR valve achieves a maximum dynamic force range 8. The response time of developed system with the MR valve achieved the response time of approximately 4.1 ms for bellows velocity higher than 0.08 m/s (Fig. 17).

Fig. 16 The developed MR valve; ferrite N95 (green), S235JR+C (grey), MR fluid (yellow), Aluminum (red), Ercatel POM (blue), copper (orange) and NBR (black) [38]
6.3 Vibration isolation efficiency of developed system with MR valve

Materials and methods
The developed MRD-strut with the MR valve was placed to the vibration isolation rig, see in Fig. 18. The bellows unit was excited by the hydraulic pulsator with constant acceleration of 1 g in the range from 3 Hz to 50 Hz over 60 sec.

![Vibration isolation rig with demonstrator of MRD strut with MR valve](image)

Fig. 18 Vibration isolation rig with demonstrator of MRD strut with MR valve (left), description of demonstrator(right)

The acceleration of the hydraulic pulsator $a_2$ (base) and the weight $a_1$ (payload) were measured. Two mathematical channels were created by the FFT analysis of the base acceleration and FFT analysis of payload acceleration.
Results and discussion
An increase in the electric current caused a decrease in acceleration transmissibility at the resonant frequency and an increase in the acceleration transmissibility at the isolation frequency. The semi-active control algorithm LQR was used for the control of the damping force.

![Graph showing comparison of passive and semi-active variant of vibration isolation system](image)

**Fig. 19** Comparison of the passive and the semi-active variant of the vibration isolation system

A comparison of the passive variant (maximum and minimum damping) and the semi-active variant with the control algorithm LQR is illustrated in Fig. 19. The acceleration transmissibility from the semi-active control at the resonant frequency is similar to the acceleration transmissibility from maximum damping (1 A), while at the isolation frequency, it is similar to minimum damping (0 A).

6.4 Preliminary concept of the MR valve with application of new methods

A preliminary concept of the MR valve for space with application of new methods can be seen in Fig. 20. A magnetic circuit is made from Fe-Co alloy (Vacoflux 27 and Vacoflux 18 HR) and a grooving method for designing a magnetic circuit is used. The material Vacoflux achieves the yield strength about 250 MPa. The thickness of the grooves is 0.2 mm. The covers are made from Al alloy. The response time of magnetic field of this MR valve was estimated to 1.4 ms according to the transient magnetic model. The damping force of 1600 N at 0.1 m/s and dynamic force range 10 will be achieved in the MR valve according to the hydraulic model. The weight of this valve is 1.04 kg.
Fig. 20 A proposed concept of the MR valve for space with application of new methods; Vacoflux 27 (green), Vacoflux 18 HR (yellow), Al alloy (red) and steel (grey).
7 CONCLUSIONS

The present thesis deals with the development of the MR damper with short response time for space application. Vibration and shock loads during the shipment of launch vehicle may cause destruction of sensitive equipment of the satellites. Therefore, satellites must be designed to high dynamic level, which rapidly increases the cost and weight of satellites. Other method is used to the vibration isolation system which is between the launch vehicle propulsion and the payload. An interesting candidate for vibration isolation system for space application is a semi-active control vibration isolation system which contains a magnetorheological damper (valve) with short response time. The design process of MR damper with short response time suffers from a number of limitations. Some methods for design of MR damper with short response time doesn’t exists.

The main aim of the present thesis was to develop a demonstrator of the MR suspension damper with short response time for space application. The original design and results were published in scientific paper. The magnetic circuit of this damper was manufactured from the ferrite material which allows for short response time of the MR damper. The measurement of F-v-I and response time were performed on the manufactured demonstrator. A designed MR damper achieved the dynamic force range 8 (eight) and the response time of 4.1 ms according to the experiment.

New methods for design of MR damper with short response time were published as sub-aims of the thesis. First sub-aim of thesis was to find a method to decrease the response time of the MR damper. A grooving method of magnetic circuit (shape approach) of the MR damper and the magnetic circuit containing rods of the ferromagnetic material with bridges were presented as a new method allowing for decrease in the response time of the MR damper. The decrease in the response time of the MR damper to 1.7 ms occurred when steel or similar material were used (high magnetic saturation). This method was patented under the title: “The magnetic circuit containing rods of ferromagnetic material and the method of its manufacture”.

Second sub-aim was magnetostatic, transient magnetic models and their experimental verification. A magnetostatic model and its experimental verification on the geometry of the MR damper were presented in this work with a difference between the model and the experiment under 1 %. The output of this model is an important input into the post-yield hydraulic model. The transient magnetic model and its experimental verification were presented in this thesis with a difference between the model and the experiment 28 %. The transient magnetic model allows to design (material selection, geometry etc.) the MR damper for specific response time of magnetic field. The shape of B-H curve of the material magnetic circuit influences the dependency of the response
time of magnetic field on the electric current of the MR damper according to the transient magnetic model.

Third sub-aim was hydraulic models of the MR damper and their experimental verification. The CFD hydraulic model of the bypass gap (pre-yield regime) of the MR damper was presented. The experimental test rig was developed for testing the bypass gap. A different diameter and length of the bypass gap were tested and compared with the experiment. The maximum difference between the model and the experiment was 24\%. The Yang hydraulic model of the post-yield regime and the off-state was compared with the experiment on the geometry of the MR damper (attachment). The maximum difference between the model and the experiment was 21\% for the post-yield regime and 24 \% for the off-state, respectively.

The current thesis contains the original results extending the knowledge in the area of magnetorheological damper. The main contribution of the thesis can be summarized as follows:

- Experimental verification of the transient magnetic model of the magnetic circuit of the MR damper [32]. This model allows to design MR damper with specific response time of magnetic field.
- New method for the elimination of the eddy currents in the magnetic circuit of the MR damper [35]. This method allows to design MR damper with short response time and high dynamic force range.
- A unique design of the MR damper with short response time for space application was published [38].

Regarding the scientific questions, the obtained knowledge can be summarized in the following concluding remarks:

- Experiments conducted using ferrite material for magnetic circuit is possible to design MR damper with response time near 4 ms (hypothesis H1 was confirmed).
- Multi-coil configuration of MR damper allows for dynamic force range higher than 4 when the ferrite material is using (hypothesis H2 was falsified).
- The grooving method of magnetic circuit or magnetic circuit containing rods of ferromagnetic material allow to design magnetic circuit of MR damper from material with high magnetic saturation and low electric resistivity which achieved a short response time. Those methods increase path of eddy currents (hypothesis H3 was confirmed).

The presented methods allow for a design of the MR damper with response time of magnetic field under the response time of the MR fluid itself.
parameter for the response time of the MR damper is the MR fluid itself. Next research will be targeted at the development of MR fluid with a lower response time than that commercially available.
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AUTHOR’S PUBLICATIONS

Journals with impact factor


Conference proceedings in Scopus or WOS


Conference proceedings


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Teaching and scientific activities
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Participants in scientific project
- 2017 The development of manufacturing method of magnetorheological damper with short response time (FSI-S-17-4428)
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ABSTRACT

The present thesis deals with the development of the MR suspension damper for space application. Some important requirements for semi-active control damper for space application are a hermetic separation of operating fluids from the rest of the launch vehicle and short response time of damping element. Those requirements meet magnetorheological damper with bellows unit, according to state of the art. Magnetic circuit of the MR damper was made from ferrite material which allows to rapidly decrease the response time of the MR damper. Hermeticity was ensured using a bellows unit. Design of this type of damper exhibits a lot of design limitations. The developed MR damper with ferrite magnetic circuit achieved response time 4.1 ms and dynamic force range 8. During the design of the MR damper for space application, a new method for design of semi-actively control MR damper with short response time were searched. Specifically, the method for elimination of eddy currents in magnetic circuit of MR damper, magnetostatic and transient magnetic model, CFD model of bypass gap, hydraulic model of MR damper and their experimental verification. The presented methods allow for the design new MR damper for space application lighter, with short response time and with higher dynamic force range.
ABSTRAKT