Review of PhD Thesis

"MAGNETORHEOLOGICAL DAMPER FOR SPACE APPLICATION"

Author: Ing. Michal Kubik

Supervisor: Doc. Ing. Ivan Mazurek, CSc.

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Reason for review: Appointment letter by doc. Ing. Jaroslav Katolicky, Ph.D., Dean of Faculty of Mechanical Engineering, Brno University of Technology dated on 15/01/2018

Reviewer: dr hab. inż. Janusz Gołdasz, Associate Professor at Faculty of Electrical and Computer Engineering, Cracow University of Technology, Kraków, Poland

Review Date: 23 January, 2018

1. Thesis Objectives

The main objective of the research work stated in Chapter 4 is the development of a prototype MR (magnetorheological) damper (demonstrator) with a short response time for a space application. Another goal is the development of a methodology to aid the design process of fast MR actuators. Secondary objectives are related to the development of models of the damper: magnetic (steady-state, transient), hydraulic incl. experimental verification. Also, the author formulated three hypotheses to be verified during the course of the research study:

- The ferrite material for the magnetic circuit of the MR damper will allow for designing an MR damper with a response time of approximately 4 ms.
- The dynamic force range of the MR damper cannot be achieved more than 4 because the ferrite material has a low level of magnetic saturation.
- 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.

The essence of the research problem stated by Mr M. Kubik is 1) the development of methodology for the design of fact-acting MR (magnetorheological) actuators for semi-active vibration isolation systems with a focus on space applications of this technology and 2) the design of a fast MR actuator suitable for a space application.

In my opinion, the research problem is important and timely expecially in the context of potential industrial applications. The formulated engineering and research problems concern constrained optimization problems, i.e. designing an actuator that meets specific performance requirements in terms of both response time and dynamic range (force span).

The research can be considered as original and valid.

2. Analysis of the Thesis Contents

The PhD thesis of Mr Kubik is a study on the development of an MR damper design that can be optimized in terms of both response time and turn-up ratio (dynamic range).

The author's findings were documented on 112 pages including: summary, 9 chapters including Literature (94 references), list of figures, 2 attachments (MR damper geometry, summary of measurements of a low carbon steel magnetisation curve). **Chapter 1** is an introduction. In the chapter the author highlights the requirements for semi-active vibration isolation systems in terms of response time in particular from the point of view of space applications. Some fundamental knowledge on the development of MR fluids and its applications in civil engineerings, passenger vehicles is outlined as well. The author concludes the chapter with an explanation of his motivation for improving on previous attempts to develop a fast MR damper (response time below 4 ms and adequate dynamic range). **Chapter 2** presents a state-of-the-art summary of vibration isolation systems.

The authors separates them into 3 categories: passsive, adaptive and semi-active vibration isolation systems. One important omission is the lack of active systems for vibration isolation. In particular the author provides a background information on the sky-hook algorithm and briefly compares the performance of a (sky-hook controlled) semi-active system against a passive systems in terms of transfer ratio (acceleration transmissibility). The author then proceeds to highlighting vibration isolation systems for space application in section 2.2. with a focus on the patented so-called D-Strut system. Brief description of the active D-Strut system is given there, too. The following sections provide a background information on MR fluids and its properties, fundamental operating modes and specifically on flow-mode MR dampers. At this point the author starts describing the configuration of a typical single tube gas-charged MR damper and its key design features, and provides definitions of the response time and the dynamic range, respectively. A discussion on key factors influencing the overall response time of an MR system is included too. The chapter is concluded with a high-level overview of methods for designing MR dampers with an emphasis on the reduction of eddy currents in the magnetic circuit of the dampers and increasing the dynamic range. Then, **Chapter 3** contains an analysis and conclusion of the state-of-the-art review. In the chapter again the author discusses the needs for developing a semi-active vibration isolation system and explains his reasons for using MR fluid based systems. The author's motivation was an adequate response time and dynamic range. The author refers to Chapter 2 for the discussion on the factors influencing the two performance metrics. In **Chapter 4** the author formulates the key objectives and hypothesis of the doctorate research, and that is the design of an MR damper prototype with short response time for space applications. Other key questions of the author are related to the development of a method for the response time decrease, development of magnetostatic and transient models incl. their verification, development of the hydraulic bypass gap model incl. experimental verification and the verification of published hydraulic models. The author states three hypothesis related to the possibility of designing an MR damper with a ferrite core with a response time of 4 ms (Hypothesis 1) and achieving a high dynamic range (above 4) (Hypothesis 2). The third hypothesis concerns the possibility of structural modifications of the magnetic circuit in order to increase the effective resistivity (reduce eddy currents in the magnetic structure). The hypotheses and the thesis objectives were researched for by the author and the results published in several co-authored impact factor journals and in indexed conference proceedings. The material and the discussion are further demonstrated in **Chapter 5** which contains the methodology for the development of MR dampers with a short response time and a high dynamic range. In sections from 5.1.1 to 5.1.3. the author presents the results of magnetostatic and transient analyses. The output of this modeling stage is verified through experiments. One important addition to the thesis is section 5.1.3 in which means for reducing the eddy currents are analysed. section 5.2. includes a high-level description of the hydraulic analysis with a comparison of modeling data against the experiment. The thesis contents is further complemented by the material contained in **Chapter 6**. Apart from Chapter 8 (which is a compilation of the published papers by the author) this is the most important part of the thesis. The material that is contained in the chapter includes the required performance specification (performance target) for the MR damper/strut application followed by the description of the MR demonstrator and the MR valve (also highlighted in the co-authored paper entitled "Design and testing of mangetorheological valve with fast response time and great dynamic range") with the explanation of test rig setup, testing conditions and experimental results incl. response time measurements, dynamic range estimate, acceleration transmissibility. In the chapter modeling data were compared against the experimental results. The author presents two MR valve geometries: one with a ferrite core (tested and modeled), and one with a high resistivity core made of Vacoflux 18 HR material (modeled). Finally, in **Chapter 7** the author presents a conclusion of his research and discusses main developments, namely, the development of an MR damper with a specific dynamic range and response time, structural modifications of the magnetic circuit of the damper for the purpose of eddy current reduction, steady-state and transient models of the valve incl. experimental verification, presentation of hydraulic models of the damper also incl. experimental verification. **Chapter 8** is simply a list of published papers and a patent that were co-authored by Mr Kubik. The list includes 4 journal papers with a high IF (IF – Impact Factor) (min. 1.83), 6 indexed papers in conference proceedings, 4 conference papers and 1 patent. **Chapter 9** is a list of references. The remaining material includes the list of figures and 2 attachments (appendices) incl. a fairly detailed description of an MR monotube damper (based on the automotive damper design by Delphi/BWI) and a description of measurements of B-H (magnetisation) curves of some of the materials used in the damper design process. The thesis is further complemented with the following journal papers/patent as atachments: 1) "Design and testing of magnetorheological valve with fast force response time and great dynamic force range", 2) "Struktura jádra obsahujícího pruty z feromagnetického materiálu a způsob jejího vytvoření", 3) "Hydraulic resistance of magnetorheological damper viscous bypass gap", 4) "Transient magnetic model of magnetorheological damper and its experimental verification".

3. Evaluation

With reference to the simulations and experimental results shown in Chapters 5, 6, 8 the main hypotheses that were stated at the beginning of the thesis were confirmed/verified. The structure of the thesis makes it difficult to follow, however, the sequence of research actions and the significance of the obtained solution can be understood from the presented material. To summarize, Mr Kubik presented a rather brief yet fundamental state-of-the-art review, correctly identified key factors influencing the dynamics of MR structures, carried out complex simulations of the magnetic circuit subjected to steady-state/transient inputs. In addition to that, he verified the results of the modeling stage through laboratory tests, designed or aided in the development of the test rig.

The thesis contents has a substantial cognitive value, and it may provide guidelines in the area of design of semi-active vibration isolation systems featuring fast-acting MR actuators. Another interesting aspect of the research is the problem of reducing the eddy currents in MR structures through structural modifications resulting in higher effective resistivity of the core material.

Also, note the researcher's skills in conducting a complex R&D experiment, adequate use of commercial software tools for numerical calculations (CFD, magnetics) and the analysis of the obtained results.

The obtained results were published in top engineering journals, e.g. Smart Materials and Structures, a confirmation of quality of the research work.

4. Comments & questions

Detailed questions

- **page.3**. The word "lighter" should be explained with respect to the damper design, i.e. how or would the developed methods aid in the development of lighter structures of MR dampers?
- **p. 7**. The work of dr Strecker et al. is not the only one that addresses the issue of response time in terms of aerospace applications - see e.g. Mikułowski's PhD thesis "Adaptive impact absorbers based on magnetorheological fluids". Please, comment.
- **p. 9**. The CDC damper by ZF Sachs is a semi-active damper.
- **p. 9**. Note that adaptive vibration systems can be either semi-active or fully active (Citroen, Mercedes ABC). Most classifications of vibration isolation systems consider three categories: passive, semi-active, active.
- **p. 14**. Provide the reference for the data in Table 1.
- **p. 14**. The gradient pinch mode could/should be mentioned as one of the operating modes of MR fluids.
- **p. 15**. The sentence "...by electric current in the coil" is not correct. The fluid reacts to the magnetic field and not the current.
- **p. 16**. Typical response time metrics are: 1) the time needed for the flux/force needed to achieve 63% of the steady-state level, 2) the time needed for the flux/force needed to achieve 90% (or 95%) of the steady-state level. In my opinion the importance of the 63% metrics is not that important. The 90% or 95% time seems a better measure of the MR valve's dynamics as it accounts for both the coil dynamics as well as that of the eddy currents. The 63% response time better characterizes the primary response of the actuator whereas the 90 or 95% one the secondary one due to the eddy currents.
- **p. 17**. Provide the reference for the 20 ms response time of MR dampers.
- **p. 22**. The expression for the electromotive force U usually includes the "-" (minus) sign.
- **p. 23**. Laminations can be used for building complicated geometries – see. e.g. the laminated valve design in "Insight into magnetorheological shock absorbers" by Gołdasz and Sapiński.
- **p. 24**. Increasing the gap height may actually increase the dynamic force range. One good example is the MR valve design with multiple parallel flow paths which has a similar maximum force output as the single gap hardware but a low minimum force. Its effective dynamic range outperforms any other designs.

- **p. 25**. Actually, it is possible to measure the magnetic flux density in the active zone with MR fluid. That can be done through current & voltage measurements (coil voltage integration) or by using sensing coils. See e.g. the patent by Nehl and Gopalakrishnan "Direct flux controller for magnetorheological structures" or research on electric motors control algorithms.
- **p. 28**. Provide the reference for the statement on the 70 N friction force exhibited by MR dampers.
- **p. 28**. It should be stated that equations 2.8 – 2.10 are valid for low Re (Reynolds number) flow regimes only. At higher Re other effects should be accounted for (quadratic losses).
- **p. 29**. Were other technologies considered for the project, e.g. piezoelectric actuators?
- **p. 34**. Such statements as in the Hypothesis 2 (impossible to achieve better turn-up ratio than 4 with ferrite cores) are dangerous. It might be possible to design a valve with an improved dynamic range provided different criteria/packaging, et.c. What is the basis for this claim? Explain.
- **p. 40**. The dependency shown in Figure 39 and 40 should be commented on in more detail.
- **p. 45**. Provide the justification for designing MR valves with hydraulic bypasses. The primary reason for the presence of this feature in automotive actuators is passenger comfort. What is the reason for including that in your application?
- **p. 45**. The methodology for designing MR valves with slot bypasses or thru-the-core bypasses was outlined, e.g. in the book "Insight into hydraulic shock absorbers" by J. Gołdasz (myself) and B. Sapiński (2015).
- **p. 49**. The neighboring plots in Figure 54 have different units. The left plot is scaled in mm/s, whereas the right one in m/s.
- **p. 51**. Explain the discrepancy in Figure 57. The Yang model is effective only at low Re flow regimes.
- **p. 51**. Were other models considered in calculating the damper forces in Figure 57?
- **p. 54**. Explain the statement in section 6.3 regarding the ferrite N95. Also, SMCs (Soft Magnetic Composite) may be suitable candidates.
- **p. 58**. Explain the behaviour see in Figure 68 (green curve).
- In the SMS paper "Design and testing of magnetorheological valve with fast response force time and great dynamic force range" provide the reference for equation 5.
- Is the finite-element mesh used in the development of the transient magnetic model in the these (as well as the paper "Transient magnetic model of magnetorheological damper and its experimental verification") the same as used in the static model (see Figure 31) ? In general, in transient models the mesh distribution should be non-uniform due to the so-called skin effect.
- **p. 41**. Provide the reference for the statement in section 5.1.3 regarding the low conductivity materials with low magnetic saturation. The range of materials suitable for fast-acting solenoids includes e.g. silicon steel alloys, cobalt steel alloys (Vacoflux 18HR), etc.

Editorial comments

- English and grammar should be corrected.
- Quality of the plots should be improved, e.g. 22, 25, 27, 31, 36, 53, etc.
- Numbering of sections in Chapter 2 should be corrected

General questions

- What is the theoretical limit for the response time for your application given force limits, and e.g. packaging?
- What are the other limitations of the MR technology with respect to aerospace applications?
- Is the 63% response time adequate for characterizing the dynamics of magnetic structures?

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5. Publications

- 4 co-authored publications with high impact factor
- 6 co-authored conference papers that are indexed in Scopus or Web of Science databases.
- 4 co-authored conference papers
- 1 co-authored patent

6. Conclusions

In my opinion and with reference to the above mentioned results of the doctorate thesis by Mr Kubik the quality of the presented work (in the field of fast-acting MR actuators) can be considered as substantial. Again, in my opinion the specified goals were achieved. The research is valuable and thorough. The results can be translated into other application areas of MR actuators. Also, it should be appraised the researcher performed individually or as part of a research team complex investigations in the field of mechanics, flow simulations, magnetic simulations and data acquisition.

The list of references publications (directly related to the thesis scope) includes 14 co-authored publications and 1 co-authored patent of which the majority is related directly to the research topic of the thesis.

The presented material is rid of substantial errors. The shortcomings stated in section 4 of the review do not undermine the quality of the obtained data. The material is very well documented. On the editorial side, the thesis is correct although quality of some presented images or illustrations leaves something to be desired. Although the author is not an English native speaker, the thesis should be double-checked for grammar and minor mistakes.

To summarize, the material in the thesis has a clear application context aimed at the development of fast-acting MR actuators. Moreover, it can be extended to other application areas. I encourage the author to carry out further work in this research field.

In my opinion the reviewed thesis meets the requirements for obtaining doctorate (Ph.D.) degree. I recommend it for presentation with the aim of receiving the degree.

/Janusz Gołdasz/

Review of doctoral thesis

Title of thesis: Magnetorheological suspension damper for space application

Author of thesis: Ing. Michal Kubík

Supervisor: doc. Ing. Ivan Mazůrek, CSc.

Institute: Institute of Machine and Industrial Design, FME BUT

Reviewer: doc. Ing. Petr Porteš, Ph.D.

The submitted doctoral thesis consists of 59 pages of the text (without contents and a list of literature), as well as three published scientific articles and one patent application, which are included in the annexes that form an integral part of the thesis. The literature contains 94 predominantly foreign titles.

The thesis is focused on the design of magnetorheological (MR) dampers. Vibration isolation continues to be a topical issue. MR dampers are relatively modern elements of these systems. Although they have been intensively developed approximately since 1990, this development is far from being complete, as is also shown in this thesis. The specific objective is to design a MR suspension damper for space applications. The thesis is linked to the project of the European Space Agency: "Semi-active damping system FLPP3", which was solved in cooperation with the company Honeywell. This also underlines the topicality of the issue.

Content of thesis

The author of the thesis presents in chapters (1-2) an overview of the current state of the art in the areas of:

- vibration isolation from passive to semi-active systems and systems for space applications,

- magnetorheological fluids and their modelling, and also the configurations of MR dampers,

- magnetic properties of dampers with a focus on eddy currents and magnetic field modelling.

The author closes these reviews with an analysis (Chapter 3), which results in demands on properties of MR dampers for the specific application. In particular, this is a requirement for a semi-active system based on MR dampers with a short time response (around 4 m/s) and an increased dynamic range of power. Furthermore, there is a requirement for a hermetic sealing of the liquid filling of the unit using bellows.

Based on these conclusions, the author formulates the main objective (Chapter 4): Design of a demonstrator of MR suspension damper with short time response focused on the specific space application. The author also sets out partial objectives, two research questions and three hypotheses aiming at overcoming the critical pitfalls, which would enable us to reach the main objective.

The last part of the thesis is devoted to the description of the dissertation project solution.

Chapter 5 is devoted to the methods used to design the valve of MR damper. It contains a brief description of the mathematical models, the results and the method of their verification.

Chapter 6 describes a design of a demonstrator of MR suspension damper for space applications. In addition to the demonstrator design, tests are described for verification of the achieved parameters, namely the time of response, the dynamic force range and the transmission characteristics of acceleration (amplitude characteristics). This chapter is completed with a new MR valve concept designed with full use of the methods developed and described in this thesis.

To conclude with, the author presents the results achieved in relation to the individual objectives and the submitted scientific questions and hypotheses.

Comments and related questions

- Inaccurately formulated objectives:

  "a model of bypass gap and its experimental verification" - which model?

  "experimental verification of published hydraulic models" - which models?

- Some figures with important content are small and / or of poor quality, e.g. figures 31, 33, 43, 44, 48, 49, etc.
- Figure 55 shows the friction pattern of MR damper. Can you explain this pattern and your choice of F_f = 51 N?
- How to achieve, using the demonstrator, an increase in the dynamic force range to the value 8 from the assumed value 4?
- Figure 72 illustrates a frequency transmission of demonstrator acceleration for one excitation frequency. Would the transmission look the same if the damper was excited by a signal composed of several frequencies?
- Chapter 6.5 refers to the concept of a MR valve designed using the developed methods. What improvement in parameters can you estimate?

Assessment

The introductory part is well-structured and, despite the relative brevity, it contains essential information and starting points for the entire thesis.

The choice of partial objectives (including questions and hypotheses) can be evaluated in a very positive way. In my opinion, the author has managed to capture the essence of the problems that prevent the parameters of MR dampers to be improved. Their fulfilment directly leads to the achievement of main objective. However, the formulation of the objectives should be more exact.

The chapters of thesis describing the solution contain all the important information. In my opinion, this part pays the price of the chosen form, which combines a brief statement of what has been done and the scientific articles listed in the annex. It is assumed that some of the information will be supplemented by the reader from the enclosed articles. It happens that if a reader wants to make a more comprehensive idea of the developed models, he/she has to put together the part of the description given in the overview of the current state of the art, the part mentioned in the text chapters dealing with the solution and the part mentioned in the article in the annex. This makes it difficult to navigate through the text. Thus, some relations presented in the thesis are neglected, e.g. what is the relation between the valve modelled in section 5.1.1 and the valve referred to in section 5.1.3, the valve and damper specified in section 5.2. and the demonstrator valve described in chapter 6.3.

From the point of view of the achieved results, it can be stated that the set objectives have been met. Specifically, the main objective was achieved by developing and building up a demonstrator with experimentally verified response time of about 4.1 m/s and a maximum dynamic force range of 8. The results are published in a scientific article.

The partial objective of "building up a method to reduce the response time of MR damper" has been fulfilled by designing, with a 3D printer, the core made of specially shaped bundles of rods of ferromagnetic material interconnected by fixed bridges. The method has been patented.

The partial objective focused on magnetic models was accomplished by building up a magnetostatic and transient model. The first model was verified by experiment with a maximum model and experiment difference of 1 % and the second model with a maximum difference of 28 % with air in the active zone and a maximum difference of 25 % with MR fluid. The results were published in scientific articles.

The third partial objective "a model of bypass gap and its experimental verification" was accomplished by building up a CFD model of MR fluid flow in “the pre-yield“ mode by bypass channel and its verification for different lengths and diameters on a specially designed test device. The maximum difference between the model and the experiment was 24 %. The results were published in the scientific article.

The last partial objective of "experimental verification of published hydraulic models" was achieved by building up the Yang hydraulic models for "post-yield" and "off state" modes and their experimental verification. The maximum difference between the model and the experiment was 21 % for the first mode and 24 % for the second mode.

Answers to the research questions asked and verification of established hypotheses that contribute to the expansion of know-how in the area of MR dampers can also be assigned to the results.

The results of the present thesis were published in four articles in impacted journals and in ten articles published at scientific conferences, six of which were registered in the Scopus or WOS databases. One patent application has been filed. The investigator was a co-author of these articles and the patent.

Conclusion

In conclusion, it can be stated that the objectives of the submitted thesis have been met; they contribute to the development of the respective scientific field. In particular, it is necessary to emphasise the benefits for practice. The results of the thesis directly contribute to the increase in the parameters of MR dampers.

For the above-mentioned reasons, **I recommend** the submitted doctoral thesis

for defence and in case of successful defence

I recommend to award the academic title "philosophiae doctor" /PhD./.

Done in Brno, January 27, 2018

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January 10, 2018
Student affairs department
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Statement by Supervisor

Michal Kubík submitted the doctoral thesis entitled Magnetorheological Suspension Damper for Space Application.

During his work, it means during last 4 years, on dissertation thesis, he became a key member of our research team. The magnetic simulations of magnetorheological devices belong between his main responsibilities, especially magnetostatic and transient simulations in 2D with applied axis-symmetry and very difficult 3D simulation. Michal has also high level of knowledge about suitable materials for designing of ultra-fast magnetorheological valves. He is also author and executor of idea of shape approach for achieving of ultra-fast response time at MR dampers. He can combine various materials with grooves having the specific shape, location, or number of these shape. He can evaluate the contribution of these combinations by 3D transient simulation of magnetic circuit, which is really, difficult because of the thin grooves. The experimental verification of all models took a lot of time.

His dissertation thesis is focused on combination of many models (hydraulics, magnetics) ensuring design of the magnetorheological valve on the basis of requirements for given purpose. The most often basis on requirements on the damping forces and controlled frequencies. I am very satisfied that Michal finished his work. I think that the use of his methodology to designing of MR valves in practice is the best evaluation of his thesis. And based on his work, the ultra-fast MR damper for Hyundai company and adaptive yaw damper for railway were designed.

Michal is hardworking man, sometimes a little rash, but I think that all scientists are a little rash.

Sincerely,

Doc. Ing. Ivan Mazůrek, CSc.
Michal Kubík´s supervisor