INSTITUTE OF MACHINE AND INDUSTRIAL DESIGN

FME

Faculty of Mechanical Engineering
Brno University of Technology

## Review of Doctoral Thesis

| 1. PhD candidate |
|---|
| Ing. Ondřej Macháček / Ondrej.Machacek@vutbr.cz |
| **2. Name of PhD programme** |
| Design and Process Engineering |
| **3. Title of PhD thesis** |
| **Magnetorheological Strut for Vibration Isolation System of Space Launcher** |

| 4. Principal supervisor |
|---|
| doc. Ing. Ivan Mazůrek, CSc. / mazurek@fme.vutbr.cz |
| **5. Co-supervisor** |
| Ing. Jakub Roupec, Ph.D. / roupec.j@fme.vutbr.cz |

| 6. Reviewer |
|---|
| dr hab. inż. Janusz Gołdasz, prof. PK / jgoldasz@pk.edu.pl |
| Faculty of EE and CS, Cracow University of Technology |

| 7. Overview of the scope of PhD thesis[1] |
|---|
| **Very good** |
| The contents of the thesis concerns the subject of semi-active MR (magnetorheological) struts for use in vibration isolation systems of launch vehicles. The revealed work has a clear application context targeting the above mentioned application field. The candidate presents a sound methodology that can be used for engineering of MR devices (based on the vibration isolation system's performance criteria) in that particular applications field comprising analytical or numerical/finite-element calculations in the field of solid body dynamics hydraulics, magnetics. Several aspects of the candidate's work, e.g. the optimization work of the MR valve's magnetic circuit, can be extended to or directly implemented in other application areas of MR actuators, too. |

| 8. Significance of the topic and clarity of problem statement |
|---|
| **Very good** |
| The research problem is defined by the candidate in section 4. It is to design a semi-active strut which combines spring and damping functions for use in vibration isolation systems (VIS) of launch vehicles. In addition to that, the candidate highlights several secondary goals for his research programme, incl. development of the multi-body dynamics model of the vibration isolation system and that of a single strut, |

[1] Overview of the scope of PhD thesis is a short description of objectives of PhD thesis's research and summary of main findings and scientific achievements.

performing a multi-physics (mechanical, hydraulic, etc.) analysis for sizing the strut, MR strut design for a launch vehicle, experimental testing and verification of the strut concept in the lab. The problem statement is supported by outlining a set of performance/operating requirements of an exemplary VIS system and packaging constraints. In general, the candidate plans to develop a methodology for designing MR struts for use in launch vehicles. The proposed design scheme is revealed by the candidate in Figure 46. In the essence, the candidate proposes to develop a set of tools/models to aid the design process of such MR struts according to a set of engineering/performance as well as packaging constraints through system analysis followed by a component design stage. The proposed approach is sound and follows engineering best practices as used by the industry.

**9. Knowledge of existing literature**

**Good**

The literature review is rather brief although adequate. In the review chapter (2) the candidate provides a brief review of the vibration isolation systems (VIS) for space applications, analyses common strut configurations that are implemented in such systems with a focus on D-struts, hybrid (voice-coil operated) struts and ELVIS (evolved launch vibration isolation system) struts, provides a critical overview of metal bellows for use in the struts, and then proceeds to discussing the MR (magnetorheological) damper technology incl. common MR damper design & key factors influencing their response time (and highlights the area of interest for the designed MR strut with respect to the actuator's response time). An important omission is the overview of key design factors influencing the dynamic range of MR actuators. Specifically, in section 2.5.4 the candidate discusses a rare study of an MR damper for use in space applications. Finally, in section 2.6 the candidate provides a detailed technical assessment of the ELVIS strut incl. estimating the strut's geometry and engineering calculations of the strut's stiffness.

**10. Choice of methods and technical soundness**

**Very good**

The proposed design process for the MR strut is highlighted in detail in Figure 46 of the candidate's thesis. The strut's packaging was based on the exemplary vibration isolation system (VIS) dimensions and requirements. The candidate developed multi-body models of the VIS system and the strut, respectively, in order to determine operating conditions of the strut through simulations as well as its performance criteria (related to dynamic range, response time). That was managed by the candidate through parametric studies using the above mentioned models. The multi-body study is then followed by an experimental work with an MR demonstrator device. The candidate determines the MR valve's force-velocity characteristics, its dynamic range and response time incl. bellows stiffness from real measurements, and then uses the obtained data as inputs in the multi-body simulations of the strut's work. The simulations were verified experimentally on an experimental test rig. The experimental work was performed with an MR strut device different than the version of the strut considered final by the candidate. The performance of the final concept was verified through simulations incl. finite-element (FE) analysis of the metal bellows stiffness and optimization of the magnetic circuit of MR (solenoid) valve developed via the so-called shape approach. The effect of temperature was omitted/neglected in the research work.

**11. Quality, originality and significance of the results**

**Very good**

With reference to the reviewed material (thesis, co-authored papers) I estimate the quality of the presented work as substantial. Although the contents concerns mainly the subject of semi-active MR struts for use in space launch vehicles the obtained results can be immediately translated into other areas

(related to the development of fast MR actuators in particular). The candidate presents a procedure/methodology that can be used or followed for designing the semi-active struts meeting particular performance criteria. In my opinion the presented work can be effectively used in the development process of the actuators to speed up the engineering work. As such, it should be considered as substantial and highly appraised. In particular, the actuator's optimization work presented in section 5.4.3 (MR valve design) can be immediately implemented in all application areas of MR actuators.

**12. Quality of attached papers**

**Very good**

The list of attached publications and patents includes 7 co-authored papers in WoS journals (section 7.1), 1 co-authored paper index in a Scopus-indexed journal (see section 7.2) and 13 conference papers in WoS/Scopus indexed proceedings. It should be appreciated that several of these papers were published in highly renowned international journals such as Smart Materials and Structures or Journal of Intelligent Material Systems and Structures and were subject to a rigorous peer review. Mr Machacek is also a co-author of a European patent related to the concept of 3D-printing of ferromagnetic cores for use in fast solenoid actuators such as MR (magnetorheological) valves. The papers span the years from 2015 to 2018 and are generally closely related to the main topic of the PhD thesis. The range of published topics varies from, e.g. fast MR (magnetorheological) dampers characterized by a short response time and a high turn-up ratio (dynamic range), material testing and characterization to the development of design techniques for MR dampers and related vibration isolators.

**13. Overall assessment, strengths and weaknesses (based upon the above evaluation categories 8–12)**

**Very good**

In my opinion the thesis presents the results of independent and creative research work. It demonstrates the candidate's ability to conduct independent research. The candidate has correctly defined the operating requirements for the designed strut, provided an adequate literature review, and then conducted numerous numerical simulations using, e.g. commercially available tools for solving multi-body dynamics problems, performed large-displacement finite-element analyses of the metal bellows, carried out several steady-state and transient magnetics analyses related to the development of the ultra-fast damper. For example, the analyses in chapter 5 provide an in-depth evidence of learning computing skills in several rather distant fields (flow/hydraulic analysis using analytical models, FE structural analysis, magnetic circuit analysis via FE). In addition to that, it seems the candidate is capable of planning complex experiments with an MR demonstrator (as revealed, for example, in section 5.3) and providing a critical assessment of the test results and their interpretation. As way of criticism, the candidate does not provide an explanation for omitting the effect of, e.g. temperature of the performance of the MR strut and the dynamic range in particular. Specifically, the viscosity of MR fluids exhibits a strong dependence on temperature which has an immediate impact on the dynamic range of MR actuators. This effect was omitted in the analysis. To summarize, the material has a clear application context in a unique field. I encourage the author to carry out further research in that aspect.

**14. Other comments**

EDITORIAL COMMENTS: The contents of the thesis is more than adequately typeset, however I have several general comments: 1. English is understandable but needs improvement, 2. Quality of several figures, e.g. Figure 50, 64, could be improved, and they are not up to scale considering the information they contain, 3. Units are not consistent throughout the text (e.g. cm, mm, m/s), 4. Numbers are often typeset using an italic style font. 5, There is no nomenclature, i.e. list of symbols, 6. Due to the complexity

of the material each chapter should end with a concluding section summarizing the important results (a suggestion). 7. Math font should be the same as the regular font. GENERAL COMMENTS: 1. Provide reasons for omitting the temperature in the design process, 2. Discuss disadvantages of the 3-parametric system with respect to response time/force authority, 3. Question: were any other technologies considered for the vibration isolation system project, e.g. piezo actuators? 4. The response time analysis of existing MR dampers is limited to R&D units only w/o commercially available actuators. Has the author examined the performance of automotive commercial MR dampers, for instance, using similar excitation inputs and control techniques as in the thesis? 5. The multi-body analysis, e.g. as in section 5.2.1, has been performed assuming linear/equivalent damping rather than nonlinear damping, 6. The method of determining the static force-velocity characteristics is fine for low and medium excitation frequencies only. At high frequency excitations due to the resulting phase shift between the force and the velocity the method described in p. 59 (see Figure 69) would provide inaccurate results. 7. A more accurate estimate of the mass effect frequency could be possibly obtained through an elasto-acoustic approach in which the motion of an elastic structure is examined when in contact with a compressible fluid (assuming irrelevant viscous effects). Has this been considered by the author? 8. Were other control algorithms (than sky-hook) considered for the application?

| **15. Conclusion** |
|---|
| PhD thesis is an independent scientific work that presents a novel solution to a significant problem in the research area and demonstrates the candidate's ability to conduct independent research. |
| **YES** |

| **16. Date and signature** | |
|---|---|
| **27/11/2018** | |

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12-618-26-07, 12-628-26-08

Please note

A. *Evaluate categories 7 to 13 using the following scale: unacceptable, acceptable, satisfactory, good, very good, excellent. The qualification of 'excellent' should only be given for a PhD Thesis in the top 3% of the research in your field of expertise.*
B. *E-mail the completed form to:* Klara.Javorcekova@vut.cz

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| 6. Reviewer |
|---|
| Dr. Dmitry Borin / Dmitry.Borin@tu-dresden.de |
| Institut für Mechatronischen Maschinenbau, Technische Universität Dresden |

| 7. Overview of the scope of PhD thesis[1] |
|---|
| **Good** |
| The main objective of the thesis is to design and evaluate a single strut element for a semi-active vibration isolation mechanism of the space launcher according to given technical requirements. It is proposed to use a magnetorheological damper as a strut for the evolved launch vibration isolation system developed previously by Honeywell. The system and the single strut are simulated with multi-body models to justify benefits of the semi-active control, determine parameters and dimensions of the strut as well as to evaluate their influence on the vibration isolation efficiency. The proposed magnetorheological strut is based on the bellows unit and a corresponding FEM model of the bellows is analysed and verified with measurements. An experimental prototype of the magnetorheological strut was manufactured and experimentally tested, providing important information for further design of the final strut. Such optimized strut with a reduced weight and enhanced estimated performances for the vibration isolation system of the space launcher is proposed as a final result of the thesis. |

| 8. Significance of the topic and clarity of problem statement |
|---|
| **Good** |

[1] Overview of the scope of PhD thesis is a short description of objectives of PhD thesis's research and summary of main findings and scientific achievements.

Performance requirements of the space applications becoming more challenging. On the one hand, magnetorheological technologies have not found wide applicability for spacecraft so far. It is related to the fact, that more conventional devices are still preferred for space mission critical systems. However, future spacecraft obviously require new approaches, which should enable to provide parameters not reachable with traditional technologies. Thus, the task to develop new devices based on smart technologies is of high significance. The author exemplifies critical issues of vibration isolation systems known for space applications as well as some new existing technologies with their advantages and disadvantages in order to cover the problem statement. Intermediate conclusions, which are outlined to clarify the problem in details are basically provided, but could be given for all sub-chapters for a better justification.

**9. Knowledge of existing literature**

**Satisfactory**

This is an obvious problem to make a review on spacecraft technologies due to the limited number of available public studies. Nevertheless, vibration isolation systems and related technologies can be basically addressed and the author tried to accomplish this task. The author provides related citations on systems used for the space applications and discusses state of the art. However, devices different to voice coil and MR dampers, which are known to be used for the vibration isolation systems, are ignored. Novel approaches to MR-based dampers are as well not discussed. Citations on own works are given in the context of the introduction of the MR fluid, though these studies are not fundamental and not belong to the review papers. Furthermore, it appears that the candidate has occupied himself with magnteorheology relatively uncircumstantial, because the topic is considered rather too sketchy and with inaccuracies. The author may provide citations on more fundamental works in the field of magnetorheology and must made necessary corrections in the corresponding chapter (chapter 2.5). Parameters of existing magnetorheological dampers and a designation of the area of interest are illustrated in Fig .45. This figure is of importance in the context of the above evaluated problem statement. In my opinion, additional comments, specifying all given in the diagram examples, are required, preferably, before the conclusion section. Citations must be provided using the same style as for the thesis text (Fig. 45).

**10. Choice of methods and technical soundness**

**Good**

The author uses appropriate methods of investigations. Simulation, analytic considerations and experimental approaches are sound technically. Results obtained by the FEM in the context of the bellows are verified with measurements. The model chosen for the analytical calculations of the hydraulic part is adopted from the well known studies and is applicable. The author also uses commercial software for magnetic simulation. The final design of the strut was unfortunately not evaluated experimentally and corresponding judgement regarding its real performances is not possible. Such essential parameter as time response is estimated for the optimized magnetic circuit and not for the whole strut, therefore, a transfer of the obtained value to the strut in general seems questionable and requires verifications.

**11. Quality, originality and significance of the results**

**Good**

The results of simulations, analytical analysis and experimental measurements have allowed proposing an optimized design of the magnetorheological strut, which can be used for the space launcher and, therefore, these results are of significance. The author proposed and analysed an original construction for the grooved magnetic circuit, which is novel in the context of the magnetorheological valve. Due to this approach, performances of the strut can be significantly enhanced. If the final design of the

magnetorheological strut would have been realized and evaluated experimentally, then the significance of the results would be much higher. Moreover, it would have been interesting to see a direct comparison of the performances of the whole struts with various designs, e.g. of the experimentally obtained for the studied prototype and estimated for the finally proposed variant.

**12. Quality of attached papers**

**Satisfactory**

The candidate has co-authored numerous conference contributions and some papers in per-reviewed scientific journals with impact factor. This indicates a wide presentation of the study as well as its scientific assessment due to pre-reviewing process of the published articles. However, I would have preferred to see more than one journal publication (which is given as under review) authored by Mr. Machacek as a principal (first) author. It is difficult to judge about his personal contribution to attached co-authored papers.

**13. Overall assessment, strengths and weaknesses (based upon the above evaluation categories 8–12)**

**Good**

The author has addressed a challenging and interesting engineering issue regarding implementation of the novel smart technologies into the space application. It has required solving of the versatile scientific tasks.To the weaknesses of the thesis belong the lack of the intermediate conclusions to outline achieved results and logically move to further task. This would have significantly increased a quality of the work. Some statements are given in the text, without to be confirmed or explained in details. Additionally, in my opinion, one of the main disadvantages of the study is the missing evaluation of the finally proposed strut as a whole unit. Furthermore, outlook, which actually should summarize the thesis are missing.

**14. Other comments**

There are minor typos in the text, figures and tables. Some abbreviations are used inconsequently. Not all positions in certain technical drawings are mentioned/explained in the text. I believe, that corresponding corrections will improve the thesis after thoroughly proofreading. The author should include an Appendix with additional data on used in the experimental evaluation of the prototype magnetorheological fluids, physical parameters of the materials used in the prototype and proposed to use in the optimized design. Accuracy of the printing design of the figures is as well not always perfect and graphical representation of the plots in a unified style may as well increase a presentation quality.

**15. Conclusion**

PhD thesis is an independent scientific work that presents a novel solution to a significant problem in the research area and demonstrates the candidate's ability to conduct independent research.

YES

**16. Date and signature**

**22/11/2018**

Please note

A. *Evaluate categories 7 to 13 using the following scale: unacceptable, acceptable, satisfactory, good, very good, excellent. The qualification of 'excellent' should only be given for a PhD Thesis in the top 3% of the research in your field of expertise.*
B. *E-mail the completed form to: Klara.Javorcekova@vut.cz*

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# Principal supervisor's final report on the PhD study

| 1. PhD candidate |
|---|
| Ing. Ondřej Macháček / Ondrej.Machacek@vutbr.cz |
| **2. Name of PhD programme** |
| Design and Process Engineering |
| **3. Title of PhD thesis** |
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| **5. Co-supervisor** |
| Ing. Jakub Roupec, Ph.D. / roupec.j@fme.vutbr.cz |

| 6. Stays at other institutions (min. 7 days) |
|---|
| UNIVERSITE DE NICE SOPHIA-ANTIPOLIS / France **/ 01/10/2016 / 30/11/2016** |

| 7. Teaching activities |
|---|
| CAD / 234 |
| 4KC / 208<br>ZKP / 182<br>QEM / 78 |

| 8. List of main publications |
|---|
| KUBÍK, M.; MACHÁČEK, O.; STRECKER, Z.; ROUPEC, J.; MAZŮREK, I. Design and testing of magnetorheological valve with fast force response time and great dynamic force range. *Smart Materials and Structures*, 2017. 26(4), 47002. ISSN 0964-1726. IF = 2.963 |
| STRECKER, Zbyněk, Jakub ROUPEC, Ivan MAZŮREK, Ondřej MACHÁČEK a Michal KUBÍK, 2018. Influence of response time of magnetorheological valve in Skyhook controlled three-parameter damping system. *Advances in Mechanical Engineering*. 10(11). DOI: 10.1177/1687814018811193. ISSN 1687-8140. IF = 0.848 |
| STRECKER, Z.; MAZŮREK, I.; ROUPEC, J.; MACHÁČEK, O.; KUBÍK, M.; KLAPKA, M. Design of magnetorheological damper, with short time response. *Journal of Intelligent Material Systems and Structures*, 2015, vol. 26, no. 14, p. 1951-1958. ISSN: 1045- 389X. IF = 2.211 |
| MACHÁČEK, O.; KUBÍK, M.; STRECKER, Z.; ROUPEC, J.; MAZŮREK, I. Design of Frictionless |

Magnetorheological Damper with High Dynamic Force Range. *Advances in Mecahnical Engineering*. IF = 0.848 (under review)

ROUPEC, J.; BERKA, P.; MAZŮREK, I.; STRECKER, Z.; KUBÍK, M.; MACHÁČEK, O., ANDANI, M. Taheri. A novel method for measurement of MR fluid sedimentation and its experimental verification. *SMART MATERIALS & STRUCTURES*, 2017, roč. 26, č. 10, s. 1-13. ISSN: 0964-1726. IF = 2.963

KLAPKA, M.; MAZŮREK, I.; MACHÁČEK, O.; KUBÍK, M. Twilight of the EUSAMA diagnostic methodology. *MECCANICA*, 2016, roč. 52, č. 9, s. 2023-2034. ISSN: 0025-6455. IF = 2.211

KLAPKA, M.; MAZŮREK, I.; KUBÍK, M.; MACHÁČEK, O. Reinvention of the EUSAMA diagnostic methodology. *INTERNATIONAL JOURNAL OF VEHICLE DESIGN*, 2017, roč. 4, č. 74, s. 304-318. ISSN: 0143-3369. IF = 0.816

**9. Assessment of the supervision process**

Evaluate:

Ing. Macháček is an independent worker, there was no problem with the supervision. The dissertation thesis follows up on his master thesis, which deals also with the vibration isolation of launch vehicle payloads.

**10. Assessment of the candidate's ability to work independently**

Evaluate:

Ing. Macháček is fully capable of independent scientific work what he proved durink active participation in several grant projects: 1) Výzkum magnetoreologické kapaliny s vysokou sedimentační stabilitou - GC17-10660J / spoluřešitel 2) Výzkum chování magnetoreologické kapaliny ve slit-flow reometru za podmínek vysokých smykových spádů a neustáleného toku - GA17-26162S / spoluřešitel 3) Vibroizolační systém užitečného nákladu kosmických nosičů - FSI-S-14-2329 / spoluřešitel 4) Vývoj technologie výroby rychlých magnetoreologických ventilů - FSI-S-17-4428 / spoluřešitel 5) Vývoj nové objemové jednotky pro semi-aktivní magnetoreologický ventil - FEKT/FSI-J-16-3694 / řešitel 6) STABILIZACE SUSPENZÍ MAGNETOREOLOGICKÝCH KAPALIN PŘÍDAVKEM ADITIV - FCH/FSI-J-17-4534 / spoluřešitel

**11. Assessment of the contribution that the research makes to knowledge in the field**

Evaluate:

Ing. Macháček reveals a completely new design of strut for vibration isolation system of on orbit launch vehicle. He had to overcome a number of obstacles during designing proces. To solve this problems a new and original methods had to be used.

**12. Other comments**

**13. Conclusion**

| PhD thesis is an independent scientific work that presents a novel solution to a significant problem in the research area and demonstrates the candidate's ability to conduct independent research. |
|---|
| YES |

| **16. Date and signature** | |
|---|---|
| **07/12/2018** | |

Please note

A. *Evaluate categories 9 to 11 using the following scale: unacceptable, acceptable, satisfactory, good, very good, excellent.*
B. *In each category 9 to 11 explain reasons for evaluation using between 100–200 words.*
C. *E-mail the completed form to: Klara.Javorcekova@vut.cz*