

REVIEWER REPORT on PhD Dissertation Thesis

Author: **Ing. Marek Ciklamini**

Title of Thesis: **Hybrid Modeling of Mechanical Digital Twin by Finite Element Method and Graph Neural Networks**

1. ACHIEVING THE OBJECTIVES OF THE DISSERTATION THESIS

The aims of investigation are clearly defined in the chapter 2.2 by four objectives to fulfill the central hypothesis of this dissertation thesis whether Graph Neural Networks (GNN) can be applied as an effective Digital Twin (DT) modelling technique to store and evaluate information from the physical description of a mechanical system.

These objectives have been achieved by Physical Modelling (PM), focusing on cooperating with Data Driven (DD) modelling, and finalizing by GNN modelling as the key element of the presented research. Designed experiments on the training of a regressor and its validation approved the accuracy and generality of the hybrid model as a whole mechano-digital framework.

2. ANALYSIS OF CURRENT STATE OF THE ART

Current state of the art is presented in the Chapter 1. At the beginning there is described status quo of DT concept and its challenges. Next, principles of the Hybrid Modelling (HM) encompassing PM and DD modelling are described. Combining PM and DD techniques is expected to provide advantages with both methods. Finally, GNNs are presented as a new type of milestone in the field of neural networks and, therefore, in the DD technique.

3. THEORETICAL CONTRIBUTIONS OF THE DISSERTATION THESIS

The main theoretical contribution of the dissertation thesis is confirmation of the formulated hypothesis “Is it possible to use graph neural networks to extract calculated knowledge of finite element model?”. Finite element structures and consecutively in the dissertation thesis suggested process of graph extraction could be one possible imaginary bridge which is connecting the basics of graph theory continuing to the field of graph neural networks.

4. PRACTICAL CONTRIBUTIONS OF THE DISSERTATION THESIS

Possible practical applications are outlined in the Chapter 7.1. A DT based on a GNN can be applied in the control loops of systems to optimize their performance and enhance their functionality, as for example in model-based control, but also in real-time optimization, fault detection and diagnosis, and predictive maintenance.

5. SOLUTION METHODS USED, THEIR APPLICATION AND KNOWLEDGE LEVEL

A systematic approach based on integrating physical modelling principles with digital techniques to develop a comprehensive representation of the mechanical system was used to solve the hybrid modelling research problem. The methodology involves leveraging principles from Poisson and Hook's laws to establish a foundation for DT construction. The result of Finite Element Method (FEM) has been replaced by DT based on regressor of GNN after successfully validation. It was proved by experiments, that an architecture of the GNN is taking the expected ability to learn from models established by mesh-based information governed by physical laws. The obtained knowledge during research has been presented in 6 publications (all as the first author, 2 of them in review). There are also 2 patents applications and 1 published patents.

6. FORMAL COMMENTS ON THE DISSERTATION THESIS

The dissertation thesis is divided into 7 chapters (including Conclusion) plus Introduction and 4 Appendixes (including Bibliography) in the total number of pages 142. The formal level of the dissertation thesis is good, the dissertation thesis is well legible without significant formal shortcomings.

Comments:

- a) List of Symbols: A lot of symbols used in the thesis are missing in this list.
- b) Page 20, last paragraph of the Chapter 1.5: "DT" vs "DD".
- c) Page 25, penultimate paragraph: unfinished last sentence.
- d) Page 41, 42: Eqs. (3.17) and (3.19) are the same.
- e) Page 54: „SAGE“ vs „Sage“ vs „sage“.
- f) Page 54, last sentence: " W_j " vs " T_j ".
- g) Page 59, first sentence: "DTn"?
- h) Page 82, first paragraph: reference "[?]".

7. QUESTIONS AND REMARKS

- a) Chapter 4 is too short, would be better to include it into another Chapter.
- b) Page 85: It would be fine to explain in more details Table 5.2.
- c) Page 125: What is difference between "DTFMG" and "DTHMFG"?
- d) You use the term Digital Twin in the thesis. What about Digital Shadow?

8. CONCLUSION

Hybrid modelling encompassing physical-based and data-driven modelling supported by novel graph neural network methods is a perspective approach to study of mechanical systems. From this point of view, the reviewed thesis titled „Hybrid Modeling of Mechanical Digital Twin by Finite Element Method and Graph Neural Networks" is an important contribution to the further development of science and technology in the research field of interest.

The author Ing. Marek Ciklamini has proven the ability to scientifically work and creatively solve complex research problems, so I **recommend** to defend his dissertation thesis.

In Prešov, May 2, 2024

prof. Ing. Ján Pitel', PhD.
Reviewer