płk dr hab. inż. Krzysztof Dragan, prof. ITWL

Instytut Techniczny Wojsk Lotniczych

ul. Ks. Bolesława 6

01-494 Warszawa

Warsaw, 10.09.2024

Recenzja spełnia wymogi formalne
Przewodniczący Rady Dyscypliny
Inżynieria lądowa, geodezja i transport

REVIEW

of PhD dissertation of MSc.Eng., Nguyen Cong Duc, entitled „Bridge health monitoring using automated FE model updating, signal processing, and machine learning".

Legal basis:

The review has been prepared for the requirement of Chairman of the Civil Engineering, Geodesy and Transport Discipline Council of the Silesian University of Technology, Prof. Marcin Staniek – official letter no RDILGT.512.2024 from the 5th of July 2024.

1. General and formal characteristics of dissertation

The provided for the review dissertation brings the research focus on the Structural Health Monitoring (SHM) of the large scale constructions, i.e. bridges which are master pieces of civil engineering design. Such constructions are subjected to the long term influence of the cyclic loading, including static and fatigue force impact as well as aging problems connected with external condition influence (such as weather) and materials specificity used in the construction. Having in mind also different operation conditions – such as railways track, car tracks as well as geographical locations, several factors influence design and operation need to be taken into the consideration. The presented work is an attempt to address the methodology for the quantification and estimation of the types of factors influencing the operation of the bridge taking into account the necessity of the structural integrity monitoring. The implementation however of the SHM methodology to such structure require the profound knowledge of the structure dynamics, the structural integrity problems which may influence on such dynamics as well as the appropriate approach for quantification of such structural implications. Such activity may be possible based on the data collection from structural sensors located on the structure of the monitored bridge. The dissertation includes the proper questions addressing the fundamental structural problems needs to be answered on the introduction chapter. Author highlights also in the dissertation the approach towards IOT4+ and smart industry direction, based on the pathway to implication of the smart SHM digital twins. The use of such models including structural geometry, feeding the system with data streams of integrated sensors together with smart processing and modelling, may bring the possibility of continuous structural integrity evaluation and prognostics towards the long term operation. The presented dissertation highlights also the possible application of SHM

POLITECHNIKA ŚLĄSKA
Rada Dyscypliny Inżynieria Lądowa, Geodezja i Transport
wpłynęło dnia 23.09.2024
nr 187 zał. —

Wpłynęło dnia 19.09.2024 r.

strategy on the evaluation of the structural performance of the bridges in Republic of Poland and Vietnam. The dissertation provides with estimation of the market specificity and size for railroad and road infrastructure together with the bridge presence in the above mentioned countries. That justification is the driving motivation for the research application. The proposed research include the description of the methodology used in the SHM for bridge structures as well as for the approach for signal acquisition and data evaluation. Based on the presented methodology author provides with research on signal processing combined with modeling approach for selected structures. The presented work combines experimental mechanics, civil engineering dynamics, signal processing and use of modern approach for statistical data analysis with data classification models known as Machine Learning.

Presented to the evaluation dissertation compose of 164 pages which includes acknowledgements, summary, list of figures, list of tables, list of nomenclature and abbreviation, seven chapters of the work presenting the discussion and results and bibliography with 184 citations. Additionally, presented dissertation includes attachments with:

- ANN and ANFIS listing models in Matlab;
- Wavelets assisted CNN models in Matlab;
- FE models in Python/Matlab
- Publications list in the PhD thesis subject.

The presented work includes the following content of the work:

- **Chapter one** where the PhD candidate very briefly presents an approach for the SHM systems used for several applications in the industry. Author justify the motivation for the development of the efficient SHM system for bridge monitoring based on the structured questions. Finally, the chapter provides with general description of the planned work and highlights three main concerns to be considered at work which are:
  - Automatization of the calibration of FE models to validate material and stiffness parameters;
  - Use of regression models for prediction of the structure dynamics based on load history;
  - Development of the classification models based on convolutional networks architecture for the vibration based data transformed with the assistance of the wavelet transformation.
- **Chapter two** where the author presents very briefly the current status of the technologies as well as studies related to SHM of the investigated object in the thesis. Interesting discussion goes in the following part of the chapter where the transportation infrastructures for Republic of Poland and Vietnam has been presented. Author highlights the brief statistics of the railroad and road system as well as refers to already installed the SHM system on the bridges. The consecutive part of the chapter leads to brief overview of the techniques and methods of signal processing and machine learning for the data collected from SHM systems. Based on the well-structured review analysis, author presents a proposal for data management system referenced as smart SHM digital twin. That is an interesting hyperbole to Yin Yang of ancient Chinese principle, which can be implemented to use in term of physical and virtual asset of the digital data and model assisted information. Chapter ends with very short concluding remarks.
- **Chapter three** presents review of the hardware solutions used for data collection and signal processing methods description used for further study within the presented work. At the chapter introduction author shortly presents the instruments and devices which are used for structural

data collection from bridges located in Poland and Vietnam. These are deflection measurements, strain and displacement measurements and vibration monitoring. The proposed system may monitor the steel elements and the reinforced concrete structures. More and more solutions use Wi-Fi data transmission. The following part of the work presents an introduction to signal analysis based on the wavelets transforms - the definition of the CWT, Morse and Morlet transforms has been presented. Author provides with the explanation of the approach for optimization of the neural network architecture for the selection of the best solution for the performance of the classifiers. Author presents approach for the methodology based on vibration data estimation features and such as signal RMS (Root Mean Square). The chapter presents description of the methodology for the network optimization for the training application of the data set from steel span hangers expressed by the RMS. Based on the deep learning approach the activation functions as well as the network topology can be optimized, with the assistance of the implemented Matlab code. Author presents also ANFIS architecture as well as briefly characterize the classification method – random forest for calculated signal indices such as RMS. Also in the chapter, the general discussion regarding the use of CNN has been presented together with final description of the metrics used for accuracy and precision evaluation for machine learning regression and classification models fit and training. Finally concluding remarks highlights the features and evaluation metrics selected for classification study.

- **Chapter four** where the author presents approach for the vibration based SHM for the bridges. The main focus of that chapter is to provide description of the methodology for combined ANN and ANFIS model and its optimization for the final metrics evaluating the model credibility based on the reduction input data with the use of the real data from presented object of study. As the object of study, the chapter presents the Dębica railway steel arch bridge. The main focus for the monitoring goes to steel hangers and welding joints of the hangers with I shaped beam as well as with arch rib. Author presents the construction geometry as well as structural constraints of the bridge substructure. That part compose well introduction to formulation of the process of data acquisition description as well as the FE model implementation. Further part explains in details the type of the sensors used in the vibration and structural monitoring and such as accelerometers, with the exact location of the sensors. Based on the collected data the discussion towards input reduction based on the correlation of the processed RMS of signals is being visualized as the correlation matrix. Based on the random forest, the gradient of the data homogeneity is possible to determine and the group separation is being provided for the importance of the structural elements input in the collected dynamics. Author highlights the most important groups for further study, based on obtained node purity analysis. Such analysis is provided as use case study for two bridge parts – deck bridge span 1 and span 2. The use cases present approach for data reduction model based on the vector and scalar data approach for data analysis. Further part of the work focuses on the analysis of the ANN an ANFIS SHM models for span 1 and span 2. The author presents strategies of the neural network optimization base the on the hidden layers reduction depending on number of valuable inputs. As the results the set of the regression graphs presenting the predicted and actual data sets for optimized model has been presented. The chapter includes a large number of regression plots for each case, visualizing correlation values as well as fit line plots. However, such details could be presented in more compact form for more easily comparison of obtained regression

coefficients. Finally, remarks conclude the data analysis for the training and analysis as well as obtained performance results.

- **Chapter five** presents an approach to data analysis from Dębica railway bridge based on the CNN classification models with the used of wavelet methodology described in chapter 3. That chapter is the main core of the work as brings the methodology for condition evaluation of the construction based on historically collected data. The presented methodology refers to FE modelling of the dynamics of the structure and estimation of the model uncertainty based on real collected data. Author define the metrics for model update and based on collected data presents estimated deviation. Based on the load models estimation and collected data the distribution of the tension force is being presented. Comparison of the baseline model with updated data may lead to inference about the structure degradation due to the divergence in initial state of data and obtained sparse data. For the purpose of the classification possibility the use of wavelets transformation is being presented. It is well adopted concept of the transformation of data to 2D array of image like. Then digital representation of such values is analyzed with the use of convolutional network. The main feature is identification of the state of the structure differentiation (healthy or damaged) as the orbit of the group of data is the key indicator. The author provides with saturation of data for confusion analysis of obtained results. The analysis is being provided for the around 31460 images (224x224 pixels) divided for two categories – healthy and overload cases. Finally, author provides with concluding remarks where the final score has been evaluated and referenced to constraints connected with data categorization as well as influence of the data quality and model accuracy.
- **Chapter six** presents the results of the FE model update. In the chapter, the approach for automated update of the FE model has been presented. Such activity is connected with error minimization for the collected data and the model, which increase the model precision for the prediction. The load configuration has been presented for explanation of the consecutive steps for model implementation. As a use case the implementation of the model for two structures of the bridges located in Vietnam has been presented. The first scenario goes to RC bridge structure. The first scenario uses static and dynamic load testing and correlation with displacements data from LVDT system as well as accelerometers. The collected data are presented and the model results based on the load configuration has been presented. Based on the presented procedure with the use of GA algorithm the final error estimation has been delivered for the model. The second study presents the similar load scenario which was applied however to the bridge with steel concrete structure. As in the first test case scenario, the model was developed and finally verified also for the determination of natural frequencies decomposition. Finally, the model update with the use of PSO and GA approach was determined in reference to initial data. The presented chapter brings the methodology for the calibration of the model with the any truck load configuration and based on collected data and developed code. Moreover, the presented methodology can be used as declared for different types of bridges and flexibility of the model calibration can be transferred between different types of load limits.
- **Chapter seven** presents the conclusions and recommendations for future work. Author briefly sum up the obtained results based on collected data. The main conclusion is the successful model verification for presented cases and intention of implementation of AI based vibration sensors. Author also presents the future work intentions, where the declaration of the use of

physics informed ML has been considered. The consecutive step it will be also implementation of web based digital twin application for the data driven SHM.

- **Finally** thesis ends up with list of cited literature, list of codes, list of indexes and list of publications of the PhD candidate.

2. Assessment of the topic and purpose of the scope of dissertation

The main aim and main goals of the thesis are highlighted in chapter 1. The main goals of the dissertation are as follows:

- Automated FE model calibrations were proposed to update the stiffness and material properties of bridge structures using measured static strains and natural frequencies. Case studies consist of the highway bridges in Vietnam to demonstrate the applicability and effectiveness of the proposed FE model updating algorithms.
- Machine learning-assisted regression models were performed to predict the dynamic behavior of the railway bridge span under various train events. Data sets used in prediction models that were collected from the vibration-based SHM system of the Dębica railway steel arch bridge in Poland over a period of nine months from December 2019 to September 2020.
- GoogLeNet CNN classification models were developed to predict the hanger health conditions of the existing railway bridge using wavelet-based and orbit-shape signal images.

The presented thesis includes a holistic approach to a structural integrity monitoring of the civil engineering structure on the example of railway bridges. The described methodology composes of several components which could be integrated towards Industry 4.0 future requirements and such as digital twin. Having the structural information, about the operated infrastructure gives a possibility for individual object tracking, which enables condition based maintenance as well as the optimized cost of operation and possible interventions. The proposed work include empirical part connected with the data collection, structure dynamics for effectiveness of the data evaluation, material engineering for the understanding of the fatigue, modelling which includes the theoretical mechanics and use of data analysis and clustering with the use of Machine Learning approach. That approach is a modern scientific activity which combines the necessity of the knowledge and tools of science and engineering work in that thesis. That gives an impression that presented work is interdisciplinary, utilitarian and combines modern scientific approach for preparing and evaluating the very practical experiment. The scope of the thesis is very important from the point of view of the transportation and infrastructure point of view. The increased number of transportation operations, the aging problem of the structural components (which may drive to catastrophic failures), the use of new class materials, the increased changes in climate conditions (elevated temperatures, heavy storms) in the coming next decades will enforce the use an application of the structural integrity monitoring. The presented work holistically highlights the approach for the structure monitoring based on structural dynamics control. The development of the sensors, cost drop of the hardware utilization, the possibility of the wideband data transmission, creates opportunity for gathering of large sets and subsets of data. Such data should be not only collected but monitored for the data cleanliness, data correlation and finally for anomaly detection and modelling of the structure on the example of

presented models fed by the real data (on the example Physics Informed Neural Network). Taking all above in account I **believe that presented topic is deliberate and useful,** and the presented work is well done. Taking into account the broad approach for the presented problem including, structure analysis, mechanical modelling, signal processing, software development and the use of regression models ML assisted, with optimization algorithms the presented work is **interdisciplinary and utilitarian.**

3. Dissertation evaluation

The presented to the evaluation thesis, include the most current research trends involving the use of structural integrity monitoring, methods for automated classification of the condition of the railway bridges with the assistance of Machine Learning algorithms and FE modelling. The presented work gives an impression that candidate well understands the phenomenology of the described problem. However, the presented work suffers of the more detailed description of the current state of the art for the SHM for such constructions, including the FE modelling and ML assisted data processing. Such well-presented recognition would be better platform for further justification of the proposed method of final inference about structure condition. The presented work also includes large spectrum of presented data from the regression models, as well as optimization with comments embedded in the text which make reading of the work difficult. The better would be summation of the results with best results and direct comparison for. e.g. the best selected parameters for network optimization and including the obtained specific data in attachments.

The thesis includes all stages which can be listed as the modern approach for scientific and technical problem solve. There is a problem identification, there is a small discussion however with large number of bibliography on the scientific state of knowledge, there is technical recognition of the experiment approach, experiment planning and very well presented approach for data analysis. The work includes also well prepared software analysis with codes developed in MATLAB and Python for implementation of models and optimization algorithm, which means that author is well familiar with current art of the programming and algorithm design cookbook.

In my opinion, the thesis meets the requirements related to making an original contribution to the cognitive field of the scientific discipline in which the PhD student deals with. In addition, I would like to highlight that the work is **interdisciplinary and utilitarian** based on the usage of modern research methods and tools, including data analysis, modelling, experiment preparation and data analytics and optimization as well as use of coding. Undoubtedly the proposed work due to the presented use cases as well as analytical solutions is practical and the results of that work can be used in engineering practice. Such solution should be implemented in presented civil engineering sector.

The basic advantages of the dissertation in terms of the presented topic, characterized problems, approach for experiments as well as the used methods for the research are as follows:

a) the very actual and presented technological problem for structural integrity monitoring of the large scale constructions as bridges;
b) the approach for the solution of the problem, including the design of the experiment methodology preparation, large scale data analytics and model implementation;
c) the use of real data for model optimization and selection of the methods for data analytics of such data;

d) the use of clustering methodology for the parameters optimization for ANN based on the real data;
e) the preparation of the methodology of the model update and optimization based on genetic algorithm and swarm optimization;
f) the use of CNN for image based analysis with the use of CWT and orbit shape feature extraction;
g) verification of the presented approach for the real case scenario based on data collection from two bridges located in Vietnam;
h) well written work in English.

Due to the wide range of tests and analysis, the work is not free from defects to which I include:

a) lack of more detailed discussion of obtained results in few sections and such as:
   - ✓ the structure based selection of input based variables selection based on random forest analysis;
   - ✓ the more detailed explanation supported with the structure constraints of the criteria for case selection of strategies for ANN model optimization;
   - ✓ lack of discussion of the effectiveness of methodology of the different architecture of ANN and ANFIS optimization;
   - ✓ lack of discussion regarding the selection of the best parameters for vibration based analysis (RMS selection).
   - ✓ lack of more detailed discussion with exemplary data for orbit reconstruction for wavelets analysis.
b) lack of justification for the selection of the number of accelerometers per element as well as total number of accelerometers for gathering the data, on example the experiment presented on the page 35;
c) chapter 3 very briefly sounds with the evaluation of the used SoA solutions for the bridge monitoring. The better focused on the problem synthetic description of the advantages and disadvantages used solutions could bring better justification for the proposed scope of the work and presented motivations;
d) lack of addressing the precision and recall in definitions of metrics – page 26;
e) some errors addressing literature reference as an example p.33 – reference to [33] not [133];
f) some editing problems with data description clarity as the understanding of the data on the fig.5.6 – the distribution of the sparse data on the damage, unhealthy or overload state.
g) the visibility of data labels for the heat maps for optimization of number of neurons in fig. 4.11 – 4.335 is not well presented for analysis.

In addition, I expect the author of the dissertation to answer the following questions:

- Please explain the justification for selection of the RMS for vibration analysis. Why the other parameters such as skewness or kurtosis were not selected for data clustering?

- Please explain in more detailed way the criteria for case selection of strategies for ANN model optimization presented in the table 4.2 – page 42. How did you select the strategies for optimization?
- In the Fig. 5.6. the numerical values of the model of the tension force was presented with the box plot. Please explain the cause of the distribution of quantified values (box whiskers) as well as change in distribution range for all hangers in damaged state.
- Large data sets are vulnerable for data shift or data gaps. How do you deal with data shift of missing values? Is there a need for calibration of the vibration sensors due to the shift of the signal and how to monitor that (shift and data missing) for the continuum use of SHM system?
- The chapter 5.2.5 and 5.2.6. presents approach for qualification of the structure for healthy and damaged state. Please explain in more detailed way the training data set which was used as labelled ones.
- How the relatively slow processes – as the corrosion in steel reinforcements and aging of the concrete may influence the observed data. Is there a necessity of the retraining a model?
- How possibly the use of PINN's (Physics Informed Neural Network) could effect on the model precision and possibly bring benefits for more specific classification?

4. Final conclusion

PhD thesis presented by Mr Nguyen Cong Duc, its content and form, despite the disadvantages described above, indicates his knowledge in the field of diagnostics and monitoring large scale constructions. The way the work is presented, shows that PhD candidate is able to design, conduct and conclude properly the advanced scientific work with assistance of modern scientific and engineering tools. **Considering the assessment of the doctoral dissertation, I believe that it is an original solution to a scientific problem and demonstrates the general theoretical knowledge of the PhD student in the conduct scientific work. It also confirms the ability to conduct scientific work. It thus meets the requirements of the Act of July 20, 2018, Law on Higher Education and Science (Journal of Laws of 2018, item 1668, as amended)**. I request that it be accepted and allowed for public defense".

Recenzję podpisał
Krzysztof Dragan