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REVIEW

of PhD dissertation of Mr. Joyraj Chakraborty, Master of Science in Engineering, entitled „Development of industrial monitoring systems with sensor integration, data fusion and information management".

Podstawa:

The review has been prepared for the requirement of Chairman of the Mechanical Engineering Discipline Council of the Silesian University of Technology, Prof. Ewa Majchrzak – official letter no RD(IME) -15/006/2019/20 from the 2nd of December 2019.

1. General and formal characteristics of dissertation

In the dissertation, the author raised an important problem of the civil infrastructure necessity of monitoring. As leading example of the dissertation, candidate focused his research on the art of engineering construction design, which undoubtedly are bridges. These structures are major construction for many connection routes which accelerate travel time through some geographical and land obstacles. Since these constructions are made of mixture of concrete and steel reinforcements, several and critical failure modes may occur in such elements during manufacturing. Moreover these constructions are subjected to complex loading spectra not only due to the traffic but also weather conditions such as heavy wind and wind gusts as well as temperature gradients. That implicate they severe possibility of damage nucleation and propagation in operation phase. Last but not least is aging problem, which may lead to decrease of the durability properties due to the concrete aging, steel reinforcement corrosion as well as steel to concrete interface damaging. These issues especially in the face of recent publicly announced information about catastrophic collapse of e.g. Morandi Bridge Collapse (Italy, August 2018 - 43 fatalities) or Pont de Mirepoix (France, November 2019, 2 fatalities and 5 injured) are raise a question about possibility of implementation of solutions which may act as early detection and monitoring systems. Such systems may monitor these construction constantly. Moreover in connection with data analytics they may inform about possible dangerous situation as e.g. structure overload or damage progression in critical location. On the basis of fact, that majority of bridges which are maintained in EU are now 40 + years of service - critical infrastructure monitoring necessity became an important issue.

The motivation for this dissertation is the fact that such structures are in economical importance of local authorities as well as are critical for safety of long term operations. Since there are

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several types of bridges constructions and loading spectra as well as critical hot spot locations such systems must have tailored solution to each type of the structure. That enforce taking into account sensors type and quantity selection as well as proper data collecting and evaluation. Presented thesis takes into account all major aspects of mature diagnostic approach to such systems design, implementation and data analytics.

The author's work include a number of interdisciplinary research about structure health monitoring. These include selection of the diagnostic method and physics understanding as well experiment design and run. Finally it take into account data processing with assistance of advanced algorithms of data fusion for decision making process.

Presented work consist of 150 pages and beside introduction, list of abbreviations, list of figures, summary in Polish and English includes as well:

- **Chapter two** where the author presents briefly bridges types and substructure information . Chapter also briefs about typical problems in concrete structures and steel reinforcements. This chapter includes also information about classification of the failure modes in bridges structure Classification is based on load condition, aging issues, environmental effects and material properties. That chapter also brings introduction to explanation of monitoring necessity due to hidden failure mode detection necessity - since that is not possible with naked eye. Author also presents overview of techniques used to non destructive damage detection failure modes which may occur in concrete reinforced structures. An essence of that discussion is the necessity of the use of more advanced methods than visual for internal damage characterization – especially **as in situ sensing** technologies. Author makes short summary of pros and cons of each individual method and presents introduction information about embedded system for data collection and analysis.
- **Chapter three** identifies research problem and presents goal and thesis of the dissertation. That is development of the methodology for the evaluation of the structural integrity of large scale structures based on embedded data collecting and advanced data analytics.
- **Chapter four** where the author presents introduction to the fundamental physics of the ultrasonic wave propagation and ultrasonic non disruptive based structure integrity evaluation. Chapter describes ultrasonic wave propagation in isotropic media based on Navier's equations and introduces all formal descriptions of wave phenomena's as reflection and scattering. Author also introduces Rayleigh waves as part of further research evaluation for the surface wave propagation. Moreover, evaluation of the wave propagation in the solid media under the complex load conditions due to the acoustoelastic effect as well as due to the temperature gradients has been presented. All these fundamentals are important to understand how to evaluate collected data.
- **Chapter five** presents an approach to signal processing. Author briefly describes signal characteristics such as RMS, correlation metrics, short time Fourier transform and wavelets which further will be used for damage detection. Author as it has been stated is being especially focused on the crack detection in reinforced concrete structures.
- **Chapter six** presents the results of the conducted tests. Chapter compose of three experiment subsections. In the introduction to the chapter, methodology for the experiment preparation has been presented. Chapter has got banausic character since it describes possible usage of such systems in real environment. Author delivers information about system configuration based on ultrasonic data acquisition system and processing

environment which is designed in Lab View. Author also provide with some poor discussion about necessity of proper frequency sampling due to large data sets collecting.

- Finally chapter goes to test execution description and test results evaluation on the following elements:
    - **Laboratory specimen**. Based on destructive test done in laboratory it was possible to not only induced failure mode to the structure but to propagate them in controlled environment. It was possible with assistance of the displacement and force sensors to control strain distribution. Also results were compared with stress /strain model for four point bending. Ultrasonic sensors as well as DIC techniques were used to control crack nucleation and development.
    - **Full scale experiment.** Data were collected during large scale structure test. Test was named as BLEIB which was part of INFRASTAR project in Germany. Large scale element with length 25m has been tested with quasi static load in determined positions of the test block. Data from test were recorded with the use of network of distributed ultrasonic transducers. Such test enabled data correlation from distributed pairs of transducers which were acting as pitch–catch sensors along with load and time series.
    - **Real bridge experiment.** Experienced gained at the test execution in previous subchapters has been transmitted to the real structure. One of the important features of such structure is constant loading (due to the traffic, weather and environmental factors) which may interfere with failure mode signal. Chapter presents experiment execution, with data derived from known load source, based on strain gauges and ultrasonic systems.

Finally in that chapter author presents results which show correlation with introduced changes to the structure due to the damage propagation and external loading. That lead to main point of that thesis which is undoubtedly decision making system for inference about damage detection and damage monitoring.

- **Chapter seven** presents the strategy and results for fusion of data which comes from experiment. Author uses classification space based on probability of detection and false call ratio. Based on the known in literature Receive Operation Characteristic and using elaborated signal indicators, author provide with methods benchmark. Finally it helps to determine optimal technique for structure monitoring which is ultrasonic. Similar activity has been done for the determination of the fusion methodology which was to benchmark obtained fusion index with signal features. Main reason for such activity is the fact, that decision making system may be biased due to the different sensors type as well as sensors distribution in the object under the test. Signal based fusion proposed in the thesis was used to combine signals from different sources with different degree and category of information in order to obtain comprehensive data. In my opinion that chapter finally proved thesis stated in that work. Developed methodology is new and as it has been proved it is capable to detect and monitor damages in the concrete structure.

- **Chapter eight –** briefly summarize work which has been done and formulate recommendations for the future activities.

- **Finally** thesis ends up with list of cited literature.

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

The author presents the purpose and scope of his dissertation in chapter three. The main goal of the dissertation presented by the PhD student is: **development of the methodology for the evaluation of the structural integrity of large scale structures based on embedded data collecting and advanced data analytics.**

The scope of work presented by the PhD student includes development a method of monitoring of large scale objects with the use of sensors (ultrasonic and strain gauges). Based on delivered at work analysis of structural integrity problems of large structures, author identified and proposed solution which nowadays have been more and more used in civil engineering infrastructure monitoring. One of major challenges in modern diagnostic is to transfer technology from relatively low technology readiness level to field applications (***laboratory to application transition***). PhD student understood that challenge, therefore presented thesis has got strong applicable value. Author have prepared batch of tests to validate theory and provided validation of applicability of designed solution on real object. The PhD student undertakes in the work extensive data analysis based on the fusion of data for the purpose of the reliability increasing of designed system. That part of the work is original in his concept and approach to analyze data from distributed locations of sensor's of different type. For the purpose of the structure understanding author also prepared models of stress distribution and verified them with the use of DIC technique.

The presented in work research concerned in selected ultrasonic technology for failure mode (mainly crack) tracking and detection is a good methodology for its further development and the obtained results are encouraging.

In the coming decades, an increasing use of concrete structures in large scale civil engineering applications should be expected. On the other hand major of large scale concrete structures and such as bridges used in Europe are aging. That situation implicate importance of use embedded monitoring of such structures. On this basis, I **believe that taking up the proposed topic is deliberate and useful,** and the work done. Due to its wide scope including structure integrity problem understanding, experiment, data modelling and extensive data analytics, presented work is **interdisciplinary and banausic.**

3. Dissertation evaluation

The research methodology proposed by the author of the work contains elements of the research process.

There is a preparatory process in the form of:

- structure dynamic and work conditions understanding;
- selection of proper diagnostics approach to such structures with an attempt of physics understanding;
- signal processing methodology preparation.

The consecutive step in a developed research methodology is an experiment preparation, experiment delivery as well as a process of collected data analyzing from the results obtained on the basis of the tests carried out. Finally data integration model due to the benchmark of the best inferring criteria has been selected for application it in the system.

In my opinion, the thesis meets the requirements related to making an original contribution to the cognitive field of the scientific discipline which the PhD student deals with. In addition, I would like to underline that the work is **interdisciplinary** in nature combining the methods and tools of a modern approach to research work, including simulation, experiment and data analytics. The work presented for evaluation is of a **practical** nature and the conclusions resulting therefrom can be used to further development the methodology of the modern embedded diagnostics, especially for the large scale infrastructure engineering.

The basic advantages of the dissertation in terms of the description of the problem presented, the choice of methods and scope of research, and approach to problem solution are as follows:

a) the subject of the dissertation and the wide range of experimental research presented in the work;
b) research methodology development based on: structure understanding, key diagnostics technology selection, building block approach to experiment delivery and finally benchmarking of the elaborated signal processing techniques;
c) correctly done literature analysis in the scope of applied solutions for the development of the embedded diagnostics systems and data processing with large data sets;
d) a wide spectrum of tests for validating the signal and elaborated signal features performance by the structure together with an attempt to correlate them;
e) since work is interdisciplinary - description and presentation of all advantages and disadvantages of the potential NDT techniques which may be used for structure diagnostics;
f) an innovative and interesting approach to data fusion to elevate indications from crack and load changes as a step towards decision making system development;
g) 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) not using the obtained data from experiment to develop more detailed conclusions, especially in the process of verification of the data from laboratory and large scale specimen tests. In my opinion especially at that stage proper verification of the used signal metrics will enable proper selection of the best players for further analysis;

b) lack of description of the elaborated signal metrics in the preliminary tests phase. As an example there are several values of the signal from pairs of sensor collected in the chapter 6.4.5. Most of the signal metrics are correlated but one of the is not (figure 6.33. and 6.34). There is missing more detailed discussion why situation like that occurred.

c) the author also does not provide explanation to some signal metrics as e.g. decorrelation coefficient, names of the pairs of the sensors (S and R) or NMSE which makes the reader wonder;

d) in the chapter 4 with description of fundamentals of wave propagation physics there are some errors in the equations description and such as:

- Equation 4.4 - lack of rotation tensor only symbolic description;
- Equation 4.11 - from the definition of the Lame constant first bracket in the denominator should be stated as (1+n);
- Equation 4.12 - Rayleigh waves are expressed as the ratio Rayleigh wave velocity to shear wave - not to compressional wave;

- Equation 5.8 does not reflect description of the equation 5.1;

- There are several mistakes in the definition of the equations of the wave motion in the structure along and perpendicular to stress direction (Equations 4.13 - 4.17) connected to the sign expressing wave polarization to the uniaxial load state.

e) some editing errors occurred in the dissertation (few of them are listed below) , e.g.:
- p. 42 - *sound wave* - *sound* refers to audible acoustic waves in range lower than used in thesis. Author used that phrase also in further chapters. Correct description is to use - elastic or acoustic waves.
- p. 58 - the author refers to equation 5.10 with describing AR model whereas it should be referred to equation 5.1. The same page bring reference to high order model as figure 5.5.a as it should be 5.5.b;
- p. 90 - in the figure 6.32 the author refers to the cross-section A. In accordance with scheme presented on the figure 6.29, pairs of sensors named as S02R06 refers to cross-section B. That implicates mistakes in description of the consecutive charts as e.g. figure 7.7.

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

- for the voting scheme described in the chapter 7.2.1 author use statistical metric named as PoD which is well defined in the NDT. PoD requires maximum likelihood regression to get the cumulative distribution function representing the chosen POD model. Could you provide with more detailed description of the data were used to estimate POD model for that study?

- on the figure 6.33. and 6.34 most of the signal metrics are correlated but one which is peak to peak amplitude is not correlated to following ones. Please explain in more detailed way the behavior of these metrics.

- in the recommendations for future work you explain that further steps will be connected with long term study which is obvious. Could you comment if there are any certification /qualification criteria for the system like that (hardware and software) to be implemented on real structures like bridges?

4. Final conclusion

PhD thesis presented by Mr Joyraj Chakraborty, its content and form, despite the disadvantages described, indicates his knowledge in the field of diagnostics and monitoring large scale constructions. The way the work is carried out indicates the PhD candidate is able to use modern research tools and prove his ability to conduct research and scientific experiment.

To sum up, I believe that the level of the work presented meets the requirements for doctoral dissertations within the meaning of relevant legal acts (**art. 13 pkt 7 ustawy z dnia 14 marca 2003 r. o stopniach i tytule naukowym oraz o stopniach i tytule w zakresie sztuki (Dz. U. z 2017 r., poz 1789) w związku z Art. 179, ust.1, Ustawy z dnia 3 lipca 2018 r., „Przepisy wprowadzające ustawę - Prawo o szkolnictwie wyższym" (Dz.U. z 2018 r., poz 1669).** In connection with above presented opinion, I apply for admission of PhD student Joyraj Chakraborty to publicly defend his dissertation.