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REVIEW

of PhD dissertation of **Joyraja CHAKRABORTY** entitled

Development of industrial monitoring systems with sensor integration, data fusion and information management

1. Base of elaboration

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 dated on 2nd of December 2019).

Reviewed dissertation was written under the supervision of prof. Andrzej KATUNIN and prof. Marek SALAMAK.

2. General assessment of the dissertation

PhD thesis is written in English on 152 pages, including one-page summaries in Polish and English, and a list of drawings. The work consists of eight chapters, a list of used abbreviations, and a list of literature covering 206 items. The thesis is experimental and theoretical in nature and concerns interdisciplinary issues related to civil engineering (in particular bridge testing), material physics, measurement signal analysis and measurement data collection. The subject of the dissertation is very important from a scientific and practical point of view, as it concerns issues of monitoring the technical condition of structures, mainly bridges, using modern measuring techniques. For this reason, I think the choice of topic is appropriate and in line with current trends in civil engineering, especially bridges. In conclusion, I consider the doctoral student's approach to this subject to be the most appropriate.

3. Detailed assessment of the dissertation

The reviewed PhD dissertation has an experimental and theoretical character. Chapters 6 and 7 are key to the dissertation due to the aims of the work and the thesis formulated in the introduction.

The first part of the work (chapter 1: Introduction) concerns the motivation of the PhD student to take up the subject and visibility of the Structural Health Monitoring (SHM). In my opinion, this chapter should be a part of the next chapter.

In Chapter 2, the author presents an introduction to Non-Destructive Techniques (NDT) which can be used for civil engineering. Subchapters 2.1-2.3 regarding civil structures, bridges, reinforced concrete and damages of concrete structures, from my point of view as a civil engineer, are superfluous in the PhD dissertation. However, considering the fact that the PhD student is not a civil engineer and the work was mainly prepared at the Faculty of Mechanical Engineering, this is not a serious shortcoming. Then, in this chapter, the author describes known NDT techniques. In chapter 3, the PhD student identified a scientific problem, defined the aims of the work and formulated a thesis. Chapter 4 provides the basics of ultrasonic techniques for testing structures, including the propagation of ultrasonic waves in various materials, as well as the problem of wave reflection and dispersion. Ultrasonic transducers have also been characterized. Next chapter 5 describes methods for early damage detection.

The main part of the dissertation is the experimental verification of the sensitivity of the used sensors (chapter 6). In addition, this chapter describes the details of the design of the new data acquisition system and the limitations of this system. The next section presents the reinforced concrete reference structure and the course of destructive testing in the laboratory. Next, the reference real concrete structure built on the testing field in Germany was characterized. The course of the study and data collection were described. An analysis and discussion of the research results were carried out. At the end of this chapter, experimental research was presented on a real road bridge located on the Klodnica River in Gliwice. The bridge is a continuous beam structure made of prestressed concrete, and the tests were carried out on the 36 m ending span.

In chapter 7, the author presents the results of different levels of data fusion based on the experiment presented in chapter 6. In addition, it describes the fusion of signal levels. Chapter 8 formulates the final conclusions from the doctoral dissertation, and the PhD student demonstrated the basic thesis set out at the beginning, about the possibility of using the developed methodology to monitor large civil structures. Importantly, the author also indicated the directions of further research in the subject of the dissertation - which testifies to the PhD student's research maturity.

4. Critical and discussion comments

Below I present critical and discussion comments to particular chapters of the dissertation.

4.1.Substantive remarks

General remark about the work layout: There is too much fragmentation of the chapters. For example, Chapters 1, 2 and 3 should form one large chapter.

Chapter 2:

1. As I mentioned earlier, subchapters 2.1-2.3 from my (civil engineer) point of view deal with obvious issues and should not be described as extensively. Nevertheless, I am aware that the PhD student is not a civil engineer, and the work itself was carried out with the participation of two supervisors representing two different disciplines of mechanical and civil engineering.
2. Point 2.4.1: It would be better to distinguish in NDT techniques that require contact with the tested object and non-contact. They are currently mixed, and the "philosophy" of their use is different.
3. Point 2.4.1: The effectiveness of NDT methods using electromagnetic, acoustic or ultrasonic waves are strongly dependent on the properties of the material (its magnetic permeability, electrical conductivity and dielectric permittivity). It all affects the speed of the above-mentioned waves in the material (e.g. concrete) and, as a result, the accuracy (or even correctness) of the results obtained. Please refer to these issues.
4. Point 2.4.1: At this point should also be mentioned the GPR (ground penetrating radar) technique, laser scanning, GPS or LiDAR technology. Recently also rotation sensors are used for SHM, which is a relatively cheap technology. In addition, research works are being created based, e.g., on measurements with smartphones that have such built-in rotational sensors. Please comment on the above-mentioned methods and their possibilities to use to monitor building structures.
5. Point 2.5 (Conclusion): Please take into account that from a construction point of view, cracking concrete or even scratching concrete (to some extent) is normal process. Which e.g. in mechanical engineering is unacceptable. So, the question arises: how to develop (design) a system that will not alert, e.g. about ordinary concrete shrinkage cracks, but will already alert the owner about e.g. exceeding the permissible deflections?

Chapter 3:

1. Cracking concrete is its normal process, e.g. related to concrete shrinkage. Therefore, it is not necessary to alert about the detection of damage in the initial stage, but a very good solution would be to save the detected micro-damages and send a signal to the manager when a certain limit is exceeded. Please comment, how the doctoral student intends to solve it?

2. Point 3.1: The PhD student mentions concrete damage, i.e. very small (10^{-6}). When can the damage be considered significant and when not yet?

3. Please briefly summarize the literature review on the main subject of the dissertation and show your contribution against this background.

Chapter 4:

1. Point 4.2.2: Is the attenuation of wave propagation included in equations (4.2) - (4.3)?

2. Page 43: The velocity of waves in the material is a very important indicator on which the test results (their correctness) depend. How to determine the real wave speed in a given material?

Chapter 5:

1. Point 5.1.3: The cross correlation function is very useful, e.g. to determine to what extent a vehicle passing the left side of the bridge affects the right part of the bridge (transverse load distribution). Can it be used e.g. to determine the effect of local damage (cracks) on the overall load capacity of the bridge?

2. Page 61: Is there a fundamental difference between CWT and WT?

Chapter 6:

1. Point 6.2.1: The tests were performed on only one beam. In general, it is good to study elements on at least 3 specimens, then better statistical conclusions can be drawn, especially for heterogeneous materials.

2. Page 67: Please provide the Nyquist criterion and how does it affect signal analysis? Are there any restrictions on it?

3. Page 73: Strain sensors measure unit strains, not displacements. In addition, please show the location of other sensors on the beam.

4. Please provide more details of beam modelling using FEM.

5. Please comment on obtained FEM and experiment results.

6. Have dynamic beam tests been carried out? They are crucial for bridge structures.

7. Point 6.4: It would be better to show cross-sections of the tested beam with dimensions. Was it a reinforced or prestressed concrete beam?

8. Figure 6.29 is essential, so it should be clearer, e.g. show static load dimensions, load locations, etc.

9. Please provide shaker data. What dynamic excitation was applied to the beam and in what places?

10. Point 6.4.5: A better explanation is required regarding the conduct of the tests: whether after each series of static loads, the load was removed from the beam and waiting outside (for example 1 min), or experimenter after reading of beam deformation (in each stage) waited some time (without removing the load)? Were permanent deformations measured? Have dynamic beam tests been carried out in a damaged (cracked) condition? The results could be very interesting.
11. Figure 6.32: The markings in the drawing are different than in the text. In addition, why the curve marked Pa has a negative factor?
12. Figure 6.38: Why the lack of symmetry in the obtained strains?

Chapter 7:

1. The main question in the case of reinforced concrete structures, when should you alert the manager that something is going wrong?
2. Please explain what affected the false alarm rate?
3. It would be interesting to test the proposed method on an old bridge that has a reduced load-carrying capacity. Perhaps the PhD student has already done such tests?

4.2. Editorial and editorial comments

Chapter 4:

1. What does "u" mean in formulas (4.5) and (4.6)?
2. A PhD student once uses the phrase "speed of wave" and other times "velocity of wave". It is better to use one term per wave speed.

Chapter 5:

1. Equation (5.3): No explanation for PA.
2. Point 4.1: No explanation for AR.
3. Equation (5.6): No explanation for *i, n.*
4. Equation (5.9): What indexes mean?
5. Equation (5.10): What do mean γ and t?
6. Page 53: Please explain to NMSE. I think it means "normalized mean square error". None in the list of abbreviations.

Chapter 6:

1. Symbols in the text other than in Figure 6.36. E.g. the Gekon 4911, 4200, 4202, 4370 sensors cannot be seen in the Figure.

Chapter 7:

1. Equation (7.2): What does mean W1?
2. Equation (7.4) and (7.5): some symbols are not explained.

5. Recapitulation

The PhD student solved the research task himself, analysed the available literature, formulated the scope, purpose and thesis, and then consistently aimed to prove it. The aims of the work set out in the introduction have been achieved. The proposed system for monitoring of civil structures, in particular bridges, is a new approach to the study of this type of structures. The developed system has been tested and validated on a selected structural element on a natural scale and on a real bridge structure. The critical and discussion remarks mentioned above do not in any way diminish the scientific and practical value of work. I believe that there is a good chance that the obtained research results will be published in major world journals.

To recap, in my opinion, the reviewed PhD dissertation prepared by Joyraja CHAKRABORTY entitled *„Development of industrial monitoring systems with sensor integration, data fusion and information management"*, meets all the requirements of the relevant acts (Ustawa o stopniach naukowych i tytule naukowym oraz o stopniach i tytule w zakresie sztuki z dnia 14 marca 2003 roku (Dz.U. z 2017 r. pozycja 1789 z późniejszymi zmianami).

Therefore, I am applying to the Discipline Board of Mechanical Engineering of the Silesian University of Technology for admission PhD student Joyraj CHAKRABORTY for public defence of the reviewed PhD dissertation.