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Review

Monograph by Kaleeswaran Balasubramaniam, M.Sc. Eng

Damage localization based on piezoelectric and fiber bragg grating Sensed guided waves

The doctoral thesis was reviewed at the request of the Scientific Council of the Institute of Fluid-Flow Machinery Robert Szewalski PAN, letter RN-421-1/23, with a copy of the dissertation attached.

1. Selection of the topic of the doctoral thesis

The subject of the doctoral dissertation concerns essential issues from the point of view of assessing the condition of construction materials and, in particular, the application of techniques enabling the detection and localization of damage. It covers areas related to guided wave excitation, signal acquisition methods, and signal processing techniques for Structural Health Monitoring. The topic of the work fits into many scientific activities undertaken by the research team of the Institute of Fluid-Flow Machinery.

Currently, assessing the safety status of a structure and monitoring it for damage is a critical issue. The increasing use of modern materials as responsible construction elements results in greater functional possibilities, is cheaper and more efficient. However, this requires the development of methods for assessing the condition of such elements both in the production process and during operation. For this reason, monitoring structures' condition is becoming a key scientific issue, enabling proper operation, ensuring safety, reducing costs, and even protecting the natural environment.

The specificity of the composite industry, and in particular its branch related to the production of responsible structural elements (e.g., airplanes, rockets, cars, trains), requires ensuring the appropriate quality of products and repeatability of the mechanical parameters of the structure. It translates directly into the durability of the elements and safety. For this reason, detecting and localizing damages in construction materials for this type of structure requires searching for new, better methods to ensure an appropriate level of safety through ongoing condition assessment.

In the scientific and research aspect, the presented problem is important and current, and its solution may have a significant impact not only on improving the quality of manufactured materials but also on significantly increasing the level of safety, which is extremely important in this type of application. The research topics presented in the dissertation require knowledge of many fields of science and technology, starting with purely engineering knowledge related to the structure and technology of producing engineering materials, strength of materials, signal processing, acquisition techniques, and statistics.

The presented work is an original scientific problem solution. It demonstrates the candidate's general theoretical knowledge in a given scientific discipline, mechanical engineering, and the ability to conduct scientific work independently. The damage detection and location system implementation was supported by research conducted in a strict scientific regime using appropriate methods to verify the adopted approach. Not all of the considerations presented in the work are new. Still, their proficient knowledge and the ability to adapt to new applications are necessary in terms of the effect of developing a complete methodology for assessing the condition of construction materials. For the above reasons, it should be considered that the topic of the work undertaken by the author is justified from a scientific point of view, and its effects are desirable both in cognitive and practical aspects.

2. Title, content, and layout of the dissertation

The proposed title of the dissertation, "Damage localization based on piezoelectric and fiber bragg grating Sensed guided waves" generally reflects the content contained in the thesis. There is no reference to the specific application for which the research process was carried out.

The entire dissertation was presented on 138 pages in English. The bibliography includes 128 items, most of which are works by Polish and foreign authors published after 2015. It proves the author's knowledge of the latest trends related to the issues of detection and location of damage in construction materials.

The content of the work is well supplemented with graphic material relating mainly to the research results and analyses performed by the author and the adopted methodology. All presented characteristics include the necessary markings of the reference system axes. The patterns are numbered appropriately and contain the required markings. The language used in the work is understandable, and the terminology used is correct and does not raise any objections.

Chapter 1 contains an introduction to related issues from SHM and Guided Waves. The chapter has been enriched with information about sensors used for signal acquisition and a short theoretical description of the propagation phenomenon of selected basic wave types.

Chapter 2 provides a detailed review of the knowledge of guided wave applications in SHM/NDT applications. Issues related to detecting and locating damage using guided waves, sensors, acquisition systems, and the influence of environmental conditions were discussed.

Chapter 3 describes the motivation and points out the weaknesses of the currently used methods. Inconveniences resulting from the impact of the near field on the damage (in the case of a small distance of the damage from the excitation), the problem resulting from many damages located close to each other, and the influence of mounting piezoelectric elements were indicated. A multi-step method based on the initial detection of damaged areas is described. The objectives of the work were presented, and the thesis was stated: "It is possible to develop a common multi-step SHM methodology for reliable and accurate damage identification for piezoelectric-based, fiber optical-based, and vibrometer-based sensing."

The **next chapter** describes the SEC (Sectional Elliptical) method and its use in the localization process based on the Time of Flight (ToF) parameter. Potential advantages of using the algorithm were indicated.

Chapter 5 deals with the experimental verification of the algorithm. Data from two types of samples, CFRP and ACS, were analyzed. The results showed that the identification error was less than 1%.

Chapter 6 describes in detail the multi-step methodology used. It includes a discussion on the selection of frequency and waveform, considerations of the numerical model, an analysis of the case of multiple faults, and a discussion of the results considering the simulation time.

Chapter 7 examines various sensor configurations. It includes numerical analyses and experimental verification. The bond length and its impact on the recorded wave propagation signals were analyzed.

Chapter 8 contains conclusions and proposals for subsequent stages of work on the method.

To sum up, the structure of the work is correct. The research methodology was presented in detail, and the results were commented on, presenting conclusions resulting from the discussion of the research results.

3. Substantive assessment of the dissertation

The work discusses essential issues related to the detection and localization of damage and monitoring the condition of structures. The author uses a scientific approach aimed at solving the research problem. It should be assumed that the thesis of the work has been formulated correctly and the entire research process aims to prove the thesis. By completing the individual stages, the doctoral student demonstrated knowledge of issues from many fields, such as signal processing, measurement techniques, mechanics (wave phenomena), modeling, and materials science. The research tasks defined at the beginning of the work are carried out following the adopted scenario. They are based on available methods to apply new solutions proposed by the PhD student. Most tasks are carried out taking into account the modeling phase and verification of results, although in some cases, in my opinion, the order of individual stages should be different. In the case of modeling tasks, the description of the work performed is quite general. The adopted damage model is quite simple, which, compared to existing works on modeling damage in construction materials, leaves some disappointment. When assessing the content of the work, it should be stated that some of the issues related to the scientific part of the work are known and used in various fields of science and technology. The value of the work is their skillful combination, which ultimately leads to the development of an original concept of a system for assessing the condition of structures by identifying damage. It required the author to integrate various techniques and draw correct conclusions based on the obtained results. In my opinion, this task was performed correctly. A significant drawback of the study is the lack of consideration of the method's sensitivity. It is extremely important because the algorithm assumes several stages of identification. The method will, therefore, only work as well as its weakest link. The "Critical remarks" section includes the question regarding this issue.

In my opinion, the most significant achievements of this work include:

- Development of an original concept of the damage detection and location procedure applicable to various sensors and materials.
- Improvement of the Sectional Elliptical Method procedure and its adaptation and implementation in the damage detection and location method.

• Development of a method for detecting damage in the transmitter's near field and a method for detecting multiple damages located at a short distance from each other.

• Carrying out analyses to determine the method of arrangement and location and configuration of piezoelectric elements in the context of possible damage localization.

Considering the scientific nature of the work, it should be stated that the doctoral dissertation of M.Eng. Kaleeswaran Balasubramaniam covers the requirements regarding the scientific and cognitive nature of the study.

4. Critical remarks

When analyzing the content of the dissertation, comments, and questions may arise. These are:

1. The study lacked analyses related to the sensitivity of the method. Since the detection and localization algorithm is multi-stage, the possibility of correct detection will depend on one of the stages in which the procedure will generate the most significant errors. If this is the first step of identification, you can expect potential errors to be transferred or even subsequent steps to be skipped due to failure to detect damage. In such cases, such an analysis is necessary to determine the range of the method's applicability.
2. Will the estimation technique based on the Time of Flight parameter used in the method be problematic in the case of many damages occurring near each other? How can the errors arising in this case affect the accuracy of damage identification?
3. Is the developed method resistant to the directionality of damage?

The above comments do not affect the substantive assessment of the doctoral student's work. The work results are presented correctly, and all conclusions relate directly to the research results and are formulated precisely. The questions posed above are debatable and aim to indicate problems that can be avoided in future research work.

5. Final conclusions.

Doctoral dissertation by M.Sc. Eng. Kaleeswaran Balasubramaniam is concerned with a significant and current research problem regarding detecting and localizing damage in construction materials.

The results of the work can be used in practice, which, in addition to its scientific value, makes the research utilitarian. The work contains scientifically important conclusions supported by results obtained on an actual facility.

In my opinion, the doctoral thesis entitled "Damage localization based on piezoelectric and fiber bragg grating Sensed guided waves" by M.Sc. Eng. Kaleeswaran Balasubramaniam meets the conditions for a doctoral dissertation. The reviewed doctoral dissertation is an original solution to a scientific problem that demonstrates the candidate's general theoretical knowledge in a given scientific discipline and the ability to independently conduct scientific work. It, therefore, meets the requirements specified in the Act on Scientific Degrees and Titles (Act of July 20, 2018, Law on Higher Education and Science, Dz.U. 2023 poz. 742).

The dissertation may be admitted for public defense and constitute the basis for awarding Kaleeswaran Balasubramaniam holds a Ph.D. in technical sciences in the discipline of mechanical engineering.