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Rzeszów, March 15, 2024

REVIEW
The doctoral dissertation of **Saeed Ullah, M.Sc., Eng.**
Guided Wave-Based Methods
for Delamination Identification Enhanced by Deep Learning

1 Formal basis and the subject of the review

The basis for the review is a letter from the Vicedirector of Scientific Issues of the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences, prof. Grzegorz Żywica. The letter is dated January 9, 2024 (signature: RN-42I-6l23) and regards the assignment of this opinion to me.

The dissertation by Saeed Ullah, M.Sc. Eng. (from now on referred to as the Author) is entitled "Guided wave-based methods for delamination identification enhanced by deep learning" and is written under the supervision of Paweł Kudela, PhD, DSc, Eng. The dissertation deals with the problem of delamination detection in composite structures, it focuses on the issue of using modern tools from the field of Machine Learning to analyze Lamb waves propagation in a composite rectangular panel and the possibility of drawing conclusions about possible delaminations.

2 General characteristics of the dissertation

The topic of the dissertation is the detection of delamination in composite panels using Machine Learning tools. The Author proposes an interesting procedure for recognizing the damage occurring in the analyzed element based on the analysis of elastic wave propagation using Deep Neural Networks (DNN). The dissertation analyzes various aspects of the studied phenomenon, not only the diagnosis associated with the recognition of the damaged state, localization, and identification of delamination parameters, but also DNN-based support for experimental testing in the form of transformation of the results of measurements made for a sparse grid of measurement points into results corresponding to those made for a dense measurement grid.

The issue analyzed in the dissertation can be included in the rapidly developing area of Structural Health Monitoring, or more precisely–as the Author clearly indicates–in the SHM-related issue described as Non-Destructive Testing (NDT). The subject of the dissertation is well-chosen, up-to-date, and relevant both from the point of view of scientific discipline of mechanical engineering development and prospects for future utilization.

The dissertation is 141 pages long (including the title page, acknowledgments, lists of tables and figures, and the literature) and is divided into eight chapters. The literature consists of 237 items.

Chapter 1 is the introduction, in which the Author presents the motivation for taking up this topic, gives a general characterization of the problem, and presents the thesis of the work and its objectives. The main thesis and two sub-theses are formulated as follows:

> **Main thesis**: It is possible to develop DL methods that surpass conventional full wavefield processing methods for delamination identification in composite laminates.
>
> **Sub-thesis 1**: It is possible to develop a DL-based super-resolution method that significantly reduces the data acquisition time by the SLDV.
>
> **Sub-thesis 2**: It is possible to develop a DL-based surrogate method that can be efficiently utilized in the inverse problems of delamination identification.

In this chapter, the Author also introduces the three main issues that will be analyzed later in the dissertation: delamination identification, reconstruction of full wavefields of Lamb waves, and surrogate model-aided simulation of full wavefield for delamination identification.

Chapter 2 of the thesis is an introduction to the problem of Structural Health Monitoring, mainly from the point of view of applying Guided Waves (GW) propagation. Chapter 3 presents essential information on Artificial Neural Networks, including deep networks, in applications related to SHM and NDT. Chapter 4 is the last introductory chapter, and it contains the description of the acquisition of a synthetic dataset that resembles the full wavefield of Lamb waves propagating in a Carbon Fiber Reinforced Polymer (CFRP) element.

Chapter 5, "DL-based delamination identification by using animation of guided wave propagation," is the first of three chapters presenting the Author's own work. In this chapter, the Author deals with detecting delamination in a rectangular composite element. The proposed procedure is built using data obtained from numerical simulations and tested on actual data obtained from experimental measurements. The source of information used for delamination detection is a series of images depicting the successive stages of Lamb wave propagation (called in the dissertation an animation) in the analyzed element; as a tool for analyzing these images and for inference, the Author will carve out ConvLSTM deep networks. It should be emphasized that the proposed procedure has been later verified on data obtained from experiments.

Chapter 6, "DL-based super-resolution approach for the reconstruction of full wavefields of Lamb waves," presents the ancillary task of artificially increasing the resolution of images representing Lamb wave propagation. The rationale for increasing the resolution is the need to reduce the time-consuming nature of experimental measurements made using laser Doppler vibrometry and the associated abandonment of a very dense grid of measurement points, the use of the approach developed by the Author and discussed in this chapter allows a post-measurement increase in the resolution of the images of Lamb wave propagation. Deep neural networks are used to accomplish the task, as in the previous chapter.

Chapter 7, "DL-based approach for the simulation of full wavefield for delamination identification," presents another approach related to reducing the time consumption necessary to perform delamination identification using deep networks. This time, the Author presents the construction, learning and verification of surrogate models to replace lengthy numerical simulations necessary for data preparation for learning and testing deep networks for delamination detection.

The work closes with Chapter 8, which presents a summary of the results achieved and future plans, as well as a final chapter containing the list of the literature used.

3 The overall evaluation of the dissertation

The reviewed thesis presents a complex issue requiring the Author to be fluent in conducting numerical simulations, knowing how to build and apply modern artificial intelligence tools, and performing experimental tests. The Author has proven he is well-prepared and has the necessary knowledge and skills to perform all the necessary simulations, tests, and experimental measurements. The issue analyzed in the dissertation is important and topical regarding the scientific problem posed (detection of damage in the structure or in its components) and the tool used in the work (deep neural networks).

Each of the tasks set by the Author and presented in chapters 5 through 7 (namely delamination detection in composite elements, increasing the resolution of images showing the propagation of elastic waves, and finally, the construction of a surrogate model allowing to reduce the time-consumption required to build a procedure for delamination detection) is very well justified and described, each of them is also successfully solved by the Author of the dissertation. In each of those three cases, both the purpose and scope, the methodology for solving the problem, and the way of describing the results obtained are clear and correct.

The objectives of the work presented in the introduction have been achieved, and the theses have been proven. The Author of the dissertation has proven that he is well-prepared to conduct scientific work and can propose and implement an original solution to the research problem set before him.

Each of the three research tasks described in the dissertation is important and relevant, and each of them can also be considered original in terms of the approach used and the results obtained. These tasks are closely interconnected by the main problem analyzed in the work and the set of tools and methods used to solve them. Given the research interests of the author of the review, the most interesting is the construction of surrogate models (Chapter 7) and the experimental verification of the ConvLSTM-based approach for delamination detection (Chapter 5); however, as written above, each of the three tasks performed is important, and the solution of each of them deserves recognition.

4 Formal and critical remarks

The language of the dissertation is exact and readable. Even though it is not the mother tongue of either the Author of the dissertation or the reviewer, I had no problems understanding the Author. I have noticed only a few faults of minor importance; taking into account the volume of the thesis and the difficult, scientific subject matter of the work, the language is–to the extent that I can judge–excellent.

The review of the state-of-the-art and the literature review are up-to-date and written very well but slightly too elaborate. The introductory part of the thesis (chapters 1 through 4) occupies almost exactly half of the thesis; together with the literature list, it is already longer than the content-critical chapters 5 through 7. Moreover, the literature list (237 items) needs a number of corrections (e.g., some items are not complete [127], some are unreadable [117], in [112] the given name of the author is mistaken with the family name: it is not H. Simon but S. Haykin, some names are twisted in links to the bibliography: see page 18 and the description of [118]).

The preparation of a list of co-authored publications of the Author of the dissertation, separate from the literature list, deserves praise; four publications scientific journals (one in review), three conference talks, and the co-authorship of three chapters in monographs deserve recognition for a PhD student.

Graphically, the work is well prepared, the drawings are generally legible, and only in a few cases would adjustments be necessary (e.g., Fig. 7.3 on page 88 should be described in a larger font).

The only significant editorial remark concerns the surprising restarts of the page numeration, this means that there are two pages numbered as "i" and two numbered as "1"; this should never happen.

Substantive questions and comments:

1. A question concerning the authorship of the numerical data described in Chapter 4 raises. The chapter does not indicate the author of these simulations, which might suggest that the Author of the dissertation is the author of the data. However, the reference to the literature entry [194] suggests that these are data of a different authorship. While it is not a vital issue in the review of this particular thesis, this information should always be clearly explained in the doctoral dissertation.
2. Has the noising of the numerical data described in Chapter 4 been considered?
3. Rather low values of evaluation metric IoU given in Table 7.3 (and in some other places) suggest that the results, contrary to the Author explanations, could be better. I agree with the Author's explanations, but can it be concluded that the metric needs to be chosen better?
4. The thesis lacks the abstract in Polish.

5 Final conclusion

The Author has demonstrated an understanding of theoretical knowledge and the ability to plan, prepare, and conduct numerical simulations and experimental measurements. He has also demonstrated that he can independently and originally solve the research problem formulated as a delamination detection, supported by the advanced analysis of the measurement data and the creation of a surrogate model that speeds up important simulations.

With this in mind and considering also the comments formulated in this review, I conclude that the doctoral dissertation of Saeed Ullah, M.Sc. Eng., entitled "Guided wave-based methods for delamination identification enhanced by deep learning," meets the conditions specified in the Polish law (Ustawa z dnia 20 lipca 2018 r. Prawo o szkolnictwie wyższym i nauce, Dz. U. 2018 poz. 1668 z późniejszymi zmianami) for candidates for the PhD degree in the field of engineering and technical sciences in mechanical engineering (dziedzina nauk inżynieryjno-technicznych, dyscyplina inżynieria mechaniczna). The dissertation:

- **provides an original solution to a scientific problem of the development of DNN-based NDT procedure for delamination detection and identification,**
- **demonstrates the Author's general theoretical knowledge in the scientific discipline of mechanical engineering and the Author's ability to conduct independent scientific research.**

I am applying for acceptance of the PhD thesis "Guided wave-based methods for delamination identification enhanced by deep learning" and for admitting Saeed Ullah, M.Sc. Eng., to the next steps of the PhD procedure.

Bartosz Miller