Warsaw, 20 March 2024

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Review of the PhD thesis
M.Sc. Eng. Saeed Ullah
„Guided wave-based methods for delamination identification enhanced by deep learning"

1. Base of eleboration

The basis for the review is the letter of Professor Grzegorz Żywica, Deputy Director for Scientific Issues at the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences, dated January 18, 2024, and the attached doctoral dissertation of Mr. M.Sc. Eng. Saeed Ullah entitled "*Guided wave-based methods for delamination identification enhanced by deep learning*".

The work was created at Mechanics of Intelligent Structures Department of IMP PAN. The PhD student's supervisor is Dr. Hab. Paweł Kudela from Mechanics of Intelligent Structures Department.

2. Topics of work

The thesis deals with development of an neural network-based diagnostic system for identification of delamination in composite structures with aid of ultrasonic guided waves. The proposed methodology addreses three aspects of delamination identification namely: generation of full wavefield dataset for training (step 1), reconstruction of full wavefields of Lamb waves from low-resolution images (step 2) and simulation of the full wavefield using deep autoencoder (step 3). The individual stages of the proposed methodology can be characterized as follows:

Step 1. introduces a synthetic dataset of elastic wave propagation by using time-domain spectral element method.
Step 2. begins with low-resolution input frames with minimal number of scanning points fed into deep learning model to achieve image transformation to high-resolution.
Step 3. applies convolutional autoencoder for generating comprehensive full wavefield data and then utilizes particle swarm optimization for delamination identification.

All three steps of delamination identification are current research topics and constitute an important part of the living trend of health monitoring of composite structures. The proposed methodology was analyzed on many numerical and experimental examples of carbon fiber reinforced composite plates (CFRP) and took into account various sizes of delamination. Therefore, the topic of the dissertation has significant engineering potential. Undertaking such a specific research topic should be considered fully justified.

3. Scope and content of the thesis

The dissertation has 120 pages and it was written in English. It is divided into 8 chapters ending with a list of literature. The bibliography contains 237 items, including items co-authored by the PhD candidate, which are indexed in the Scopus database. Additionally, the PhD candidate published his works in renowned journals from the current list of MNiSW (*Mechanical Systems and Signal Processing* and *Engineering Applications of Artificial Intelligence*). He also published three chapters in the books and 3 conference papers in the prestiguous conferences devoted to SHM.

In chapter 1, serving as an introduction to the PhD dissertation: problem statement, purpose of the study and motivation are presented. The chapter introduces fundamental concepts of Structural Health Monitoring (SHM) and Non-Destructive Evaluation (NDE). It also presents a main thesis of the study and two additional sub-theses.

Chapter 2 serves as a general overview of measurement techniques used in guided wave-based SHM and NDT of engineering structures. The chapter provides also a short description of the most frequently used types of sensors such as piezoelectric transducers, fiber optics, microelectromechanical systems (MEMS) or scanning Laser Doppler Vibrometers (SLDV). Finally, the chapter contains a literature review of GW-based SHM and NDE techniques dedicated to composite structures.

Chapter 3 is devoted to a brief survey of the literature on artificial neural networks. After introducing a short historical view the chapter describes learning and training processes of classical architectures of neural networks ie. Convolutional and Recurrent Neural Networks (CNNs and RNNs). Finally, the last section of the 3rd chapter provides information about deep learning techniques applied in GW-based SHM/NDE.

In chapter 4 the PhD candidate described a synthetic dataset generated for simulating propagation of Lamb waves in carbon fiber reinforced composite plates. The dataset has been generated using a parallel implementation of spectral element methods based on Mindlin-Reisner theory. Determined in such a way dataset serves as a replacement of the experiments usually conducted with aid of Scanning Laser Doppler Vibrometry (SLDV) in transverse direction of the plate. 475 different delamination scenarios were analyzed resulting a collection of dynamic responses of composite plates discretized in spatial domain with 500 x 500 grid points and in time with 512 sampling points.

Chapters 5, 6 and 7 are the most important chapters of the thesis. In chapter 5 PhD candidate provides details of the proposed deep learning based methodology for detecting, localizing and quantifying different types of delamination in various damage scenarios. The proposed approach is utilizing the Convolutional Long Short-Term Memory (ConvLSTM) neural architecture allowing for simultainous analysis of spatial and temporal correlations. The proposed ConvLSTM network was trained on the dataset introduced in chapter 4. Both numerical and experimental cases were investigated related to single and multiple delaminations.

Chapter 6 focuses on a deep learning approach for improving the spatial resolution of the measurments obtained by SLDV. This research was motivated by time consuming measurements of high resolution images needed for accurate predition of delamination. For that purpose the PhD candidate intoduces neural network consisting of a series of residual dense blocks (RDB) allowing to increase the resolution from 32 x 32 grid points to 512 x 512 points. The chapter is ended with

comparison of the proposed methodology with classical compressive sensing techniques showing the superiority of the proposed residual dense network over SPGL1 compressive sensing algorithm.

Chapter 7 describes a deep learning based approach for simulation of the full wavefield for delamination identification. For the purpose of reduction of the computational effort related with time-domain finite element simulations on a dense meshes the PhD candidate proposes a deep ConvLSTM autoencoder, which is trained in a three steps. In the first step features are extracted from all of the delamination cases. In the second step full wavefield frames in a healthy plate combined with information about location of the delamination are used for training the encoder. Finally, in the third step evaluation of the proposed neural network is performed on data, which was not used in the training process. The last stage of the overall algorithm proposed for delamination identification is application of Particle Swarm Optimization. The effectivenes of the proposed methodology has been compared with approach described in chapter 5 showing similar accuracy.

In Chapter 8, which ends the dissertation, the PhD candidate briefly summarizes the obtained research results. In this chapter he also indicates directions for future works.

4. Evaluation of the thesis

The dissertation is devoted to the deep learning based delamination identification of composite plate structures, taking into account its applications in the civil, mechanical and aerospace industries. Such a research topic is currently investigated and fit well into the research direction related to modern methods of structural health monitoring.

The doctoral candidate proficiently uses the methodology of conducting scientific research in the discipline of mechanical engineering, i.e. 1) he begins his work by outlining broad issues; 2) formulates and analyzes individual tasks, discusses their variants and special cases; 3) develops numerical solution methods and verifies them on a number of representative tasks; 4) proposes and analyzes the possibility of practical implementation of the developed methodology; 5) discusses the literature background and places its results in it. This research pattern, reflected in the structure of the dissertation, confirms the scientific maturity of the PhD candidate.

The following should be considered interesting and significantly original elements of the dissertation:

- Development of the novel deep learning - based methodology for identifying delamination in composite plates with aid of ultrasonic guided wave technology.
- Selection of an appriopriate neural architectures, including Convolutional Long Short-Term Memory (ConvLSTM) network allowing for precise identification of delamination using animation of the full wavefield.
- Generation of sofisticated dataset used for training of the proposed neural network architectures and consequntly for determining the identification of damage in the structure.
- Verification of proposed methodology on various delamination scenarios involving both numerical and experimental cases.

What is particularly noteworthy is the wide scope of the research conducted, which covers three different stages of delamination identification (detection, localization and quantification). These topics requiring the use of various methods of numerical analysis and experimental techniques. The thematic scope and structure of the work prove the PhD student's proficiency in theoretical and

experimental research work.

The dissertation is of the nature of basic research, however, the methods developed relate directly to real engineering problems and their application potential should be assessed as very important. This applies both to the possibility of implementing proposed delamination identification methodology, as indicated in the work, as well as to checking their reliability and effectivens in various types of delamination occuring in different cases.

5. General comments and questions

The reviewer did not notice any major errors or omissions in the dissertation. The following comments and questions are of a debatable nature and are intended to contribute to increasing the transparency and cognitive value of the dissertation.

- The first question is related to the metrics used for evaluation of the obtained results. In page 56 the PhD candidate introduced a metric known as *Intersection over Union (IoU)*. Generally this is correct metric, however misses an important information about detected delamination, namely it does not distingush between ***false positive*** *and* ***false negative areas***. In damage detection it would be good to know if the error of the identification give the size of the damaged area on a safe side. It means that usally we prefer to overestimate the size of the damage than underestimate it. Therefore, the question arises here: ***What other than IoU metric could be used here to avoid this potentially problematic situation?***

- The second question is basically connected with the first one and refers to Table 5.2 (page 61). Additionally to *IoU,* second introduced in the dissertation metric is *percentage area error (ε).* In table 5.2 we can find that for case number 2 we have *IoU* = 0.89 and ε = 5.4%, but for case number 3 there is IoU = 0.86 and ε = 16.9%. **Why for such close values of *IoU* we have such a big discrepancy in *ε*?**

- Page 45 (chapter 4) introduces a numerical model of the delamination in the composite place. The delamination in this model takes elliptical shape. However, in experimental studies (page 62) real delamination is implemented in a form of square Teflon insert. **What is the influence of this different shape on reflection of the Lamb wave from delamination? Does it have any effect on training and prediction stages?**

- Forth issue is related to the assumed (known) time instance of the initial interaction of the wave propagation and delamination. Essentially, is it equivalent to known location of the delamination. In real experimental testing this location is unknown. ***Would it be possible to replace this assumption with a kind of trigger, which initiates image aquisition when the reflection from delamination is detected?***

- Final remark is connected with computational complexity of the proposed methodology. *How many Parameters and Hyperparameters are involved in the proposed neural architectures? What is approaximate time needed to train introduced neural architectures?*

6. Typographical errors

The dissertation is prepared in English. Its English language and composition are clear and do not require any corrections. Further comments are not of a substantive nature, but only of a technical and editorial nature.

- Page 24, "*given* X_n" should be replaced with "*given* X_i".
- Page 25, "*i=1, 2 , 3, ...,* X_n" should be replaced with "*i=1, 2, 3, ..., n*"
- Page 46, equation (4.1), "*j-1*" should be replaced with "*j=1*".
- Page 53, equation (5.1), "*where (*) indicates an element-wise multiplication*" should be replaced with "*where (*) indicates convolution operator*".
- Page 79, wrong description of the figure (6.4), on vertical axis should be "*PSNR values*" instead of "*IoU values*". The same with figure (7.4), page 90.
- Page 112, reference [117], mistake in the title of the book "*Principles of Neurodynamics*"
- Page 117, references [192] and [193] indicate the same article.
- Page 117, reference [194] is missing information about Journal or Database.
- Page 117, the first Author's surname of reference [195] is Shi.

7. Conclusions

Doctoral dissertation of Mr. Saeed Ullah concerns current topic in the field of structural health monitoring: deep learning-based delemination identification using guided waves. In solving the research problems, the PhD candidate used the methodology of conducting scientific research and demonstrated the ability to conduct it independently. The achieved results should be considered original and interesting for the wider scientific community. The dissertation generates further research problems, which confirms its importance. The critical remarks presented in the review are of a technical nature and do not reduce the value of the work.

The reviewed dissertation is an original solution to a scientific problem and meets all the requirements for doctoral theses by the applicable Law on Higher Education and Science of July 20, 2018 (Journal of Laws 2018, item 1668).

I declare the scientific work of Mr. Saeed Ullah is suitable for the open discussion and after a successful defense I suggest giving the PhD title.