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im. Tadeusza Kościuszki

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Marek Słoński, PhD, DSc, Eng.
Professor of Cracow University of Technology
Chair of for Computational Engineering
Cracow University of Technology

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Review Report on the PhD thesis submitted to the
Scientific Board of the Szewalski Institute of Fluid-Flow Machinery
Polish Academy of Sciences

to attain the
Degree of Doctor of Philosophy (Ph.D.)
(w dziedzinie nauk inżynieryjno-technicznych w dyscyplinie inżynieria mechaniczna)

entitled

"Guided Wave-Based Methods for Delamination Identification Enhanced by Deep Learning"

Author:
Saeed Ullah, M.Sc. Eng.

Supervisor:
Paweł Kudela, D.Sc. Ph.D. Eng.

At the beginning, I would like to congratulate Mr Saeed Ullah and the thesis supervisor Professor Paweł Kudela for a very interesting topic of the research carried out in this thesis. I could recognise a great effort involved in running presented in the thesis multi-threaded experimental research program. The Candidate has shown analytic rigor in presenting the results of the work reliably and comprehensively. I hope that my remarks will positively influence the final presentation of results during the defense.

The review report was prepared on the basis of the decision of the Scientific Board of the Szewalski Institute of Fluid-Flow Machinery Polish Academy of Sciences dated 19.12.2023.

The presented review report is organized in the following sections:
1) project background,
2) thesis structure and content,
3) analysis of the work,
4) list of queries and
5) summary and final evaluation statement.

1) Project background

Recent progress in machine learning methods such as deep learning offers the opportunity to be implemented for guided waves based structural health monitoring (SHM) and non-destructive testing (NDT). This can be attributed to the current limitations of classical methods of signal processing for the extraction of damage-related features from signals propagating in structural elements.

Thus, the subject of the PhD thesis "Guided Wave-Based Methods for Delamination Identification Enhanced by Deep Learning" by Mr Saeed Ullah is closely related to the studies of whether deep neural networks can be effectively used as a tool for monitoring the technical condition of a thin structural component. For this purpose, images of propagating Lamb waves in thin-walled elements of the structure are used and the convolutional deep recurrent neural networks are aimed at finding anomalies of propagating waves caused by structural damage and indicating their position in the monitored element.

2) Thesis structure and content

The thesis consists of 8 chapters, and it comprises 131 pages, 7 tables, 45 figures and 237 publications. It begins with Chapter 1 which presents a problem statement, purpose of the study, objectives and motivation, thesis contribution and thesis organization.

Chapter 2 introduces Structural Health Monitoring (SHM) and its applications, with a particular emphasis on the utilization of Guided Waves (GWs) for monitoring composite materials. It also outlines various techniques for damage detection and localization using GWs. Furthermore, this chapter includes a review of literature on GW-based damage detection in composite structures.

Chapter 3 shifts its focus to the application of Artificial Neural Networks (ANNs) in the field of Guided Wave-based Non-Destructive Testing and Structural Health Monitoring (NDT/SHM). This chapter explores the distinctions between artificial intelligence, machine learning, and deep learning, detailing the operational mechanisms of ANNs and providing insights into optimal training practices for neural networks. Various types of ANN algorithms are discussed, alongside an examination of ANN-based approaches in GW-based NDT/SHM for composite structures.

Chapter 4 focuses on the description of the process of generating a synthetic dataset mimicking the complete wavefield of Lamb waves propagating through a Carbon Fiber Reinforced Polymer (CFRP) plate. This dataset encompasses wave interactions, structural boundaries, and discontinuities, like damage. Additionally, the chapter introduces data preprocessing and details the dataset splitting process for subsequent chapters.

Chapter 5 outlines the initial task of this research, which is delamination identification, employing a deep learning approach and a convolutional long-short term memory (ConvLSTM) recurrent neural network model. The ConvLSTM model is introduced and discussed in detail. The effectiveness of the proposed approach is evaluated through numerical test cases, showcasing its ability to predict unseen cases accurately. Additionally, experimental data, including single and multiple Teflon inserts mimicking delamination scenarios, is used to evaluate the generalization capabilities of the developed ConvLSTM model.

Chapter 6 outlines the second objective of this research, which is the reconstruction of full wavefields of Lamb waves using a Deep Learning (DL) approach. It discusses the necessity of employing a super-resolution based method for reconstructing full wave fields from low-resolution to high-resolution. The evaluation of the proposed super-resolution approach is detailed, incorporating numerical test cases to illustrate its effectiveness in predicting unseen data. Additionally, the results obtained from the proposed super-resolution based approach are compared with those from the conventional compressive sensing technique.

Chapter 7 outlines the third objective of this research, which involves simulating the full wavefield for delamination identification using a DL-based approach. The creation of full wavefield data through a DL-based surrogate model is detailed. The evaluation of this approach is discussed, encompassing numerical test cases to showcase its effectiveness in predicting previously unseen data. Additionally, the outcomes of the DL-based surrogate model are compared with those of the delamination identification task described in Chapter 5.

Chapter 8 summarizes the discoveries and insights gleaned from this dissertation. Additionally, it delineates potential avenues for future research that stem from the findings presented in this work.

3) Analysis of the work

The main goal of the experimental investigations was to develop an innovative AI-driven diagnostic system for delamination identification in composite laminates based on the propagation of Lamb waves and deep neural networks allowing the replacement of classical methods of signal processing that are considered here to be ineffective.

In this study, the following deep neural network model was considered for the diagnostic system: a convolutional long short-term memory recurrent neural network called ConvLSTM. In my opinion, the information presented about the model was gathered skilfully. The description of the architecture shows their applications potential. In the manuscript, the author refers to the recommendations for using this model found in the cited works. State of the art summarizes in quite an efficient way the recent advances in data-driven SHM/NDT using machine learning models. It should be noted that it was a rather difficult task to prepare this literature review, taking into account the large number of recent papers on the subject.

The main aims of the experimental investigation in this thesis were:

1. Delamination identification using ConvLSTM model

The Author in this research task applied a convolutional long short-term memory recurrent neural network (ConvLSTM) for identification of single and multiple delaminations in Carbon Fiber Reinforced Polymer (CFRP) plates through semantic segmentation approach. This was applied by employing full wavefield animations of Lamb wave propagation, generated numerically, as input into the developed model to generate a comprehensive damage map. This is probably one of the first implementations of the ConvLSTM model employing Lamb wave propagation animations for delamination identification through image segmentation. In my opinion, the experiments were carried out with care, and the results were presented in a clear manner. Moreover, it should be noted that the scope and diversity of the

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conducted segmentation tests expanded the Candidate's research competences, enriching his experimental background.

2. Reconstruction of full wavefields of Lamb waves using RDN model

In the second research task, the Candidate tested an end-to-end framework for full wavefield reconstruction of propagating Lamb waves from spatially sparse SLDV measurements using a deep learning model called Residual dense network (RDN). This model has been developed to facilitate an end-to-end super-resolution technique concerning elastic wave propagation and its interaction with damage and structural boundaries. The process begins with acquiring a low-resolution input frame utilizing a uniform mesh grid with a minimal number of scanning points. These low-resolution frames are then fed into a RDN model, which transforms them into high-resolution frames. Subsequently, the predicted high-resolution frames can be input into the many to-one model to identify and characterize damage. The trained model performed very well on the numerically generated animations, and it also showed good generalization capability on the experimental cases.

3. Simulation of full wavefield for delamination identification using ConvLSTM autoencoder

This research shows a new approach centered on application of ConvLSTM-based autoencoder to predict the dynamics of guided wave propagation within composite structures containing different delamination scenarios and to solve an inverse problem using this model and particle swarm optimization (PSO) algorithm. At its core, this approach uses the rather sophisticated ConvLSTM autoencoder-based surrogate model, specially designed for generating comprehensive full wavefield data that mimics the behavior of propagating guided waves within these composite structures. This deep learning model, employed for predicting full wavefield patterns, marks its novel application within the domain of the inverse problem associated with delamination identification. The Author achieved his goal, tested and assessed the suitability of the model for simulation of propagating Lamb waves and solving the inverse problem of identification of single delaminations but only for numerical data. This approach was not tested against experimental data.

4) List of queries

After getting acquainted with the thesis I have few comments and questions:

1) In my opinion, at the beginning of the thesis, it would be good to include a list of abbreviations used in the thesis.

2) Has the Author considered introducing random noise into the inputs for a numerical model to simulate possible errors in measurements?

3) Why was it assumed that delamination occurs only between 3 and 4 layers?

4) One of the most important issues related to the application of deep neural networks is the proper tuning of hyperparameters such as learning rate, dropout rate, among others. In the thesis, the trial and error approach was used. Did you consider other methods for finding the best hyperparameters? One of the possible approaches could be the KerasTuner which is a hyperparameter optimization framework for

hyperparameter search. In my opinion, it is an important aspect in building deep learning models for the considered applications.

5) In Chapter 3, you shortly introduce Bayesian neural networks. Bayesian approach to neural networks is considered to be useful, especially for uncertainty quantification but computionally very demanding. Have you found in the literature any reports on using Bayesian deep neural networks as a prospective enhancement of the standard deep neural networks in the context of data-driven SHM/NDT?

5) Summary and final evaluation statement

The manuscript prepared by Mr Saeed Ullah presents an original experimental program that fully contributes to the application of deep learning models for effective signal processing in the context of delamination identification in composite laminates. Comprehensive experimental program conducted by the Candidate and the diversity of the research tasks significantly expanded the Candidate's research competences, enriching his research skills.

The Author achieved all three goals of the doctoral dissertation by exploring the ConvLSTM model for delamination identification in the CFRP plates based only on animation of the full wavefield of Lamb wave propagation. The investigation on super-resolution image reconstruction using deep neural networks has shown their application for recovering the high-resolution full wavefield of Lamb wave propagation from low-resolution measurements. And finally, the application of the ConvLSTM autoencoder-based surrogate model for simulation of propagating Lamb waves and solving inverse problem for delamination identification.

As the Candidate mentioned it in perspectives, further experimental studies would be necessary to identify other types of defects in CFRP structures. Many questions remained unanswered regarding the performance of the developed models if they are trained on experimental data and new datasets generated a higher excitation frequency or broadband frequency.

In my opinion, Mr Saeed Ullah, the Author of the thesis entitled: "Guided Wave-Based Methods for Delamination Identification Enhanced by Deep Learning" proved to have an ability to perform research and to achieve results of a scientific value. Moreover, the Candidate presented the capacity to implement scientific results in construction practice.

The thesis demonstrates that Mr Saeed Ullah meets the requirements laid down by the Polish law (Prawo o szkolnictwie wyższym i nauce, Dz. U. z 2020 r. poz. 85 z późniejszymi zmianami) for candidates for the degree of Doctor of Philosophy in the field of engineering and technical sciences in mechanical engineering (tytuł doktora nauk technicznych w dziedzinie nauk inżynieryjno-technicznych w dyscyplinie inżynieria mechaniczna). Taking into account the above, I am applying to the Scientific Board for admission of the Candidate to the next stages of the procedure of awarding the doctoral degree.

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