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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

"Feasibility study of artificial intelligence approach for delamination identification in composite laminates"

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

At the beginning, I would like to congratulate Mr Abdalraheem A. Ijjeh and the thesis supervisor Professor Paweł Kudela for a very interesting topic of the research carried out in this thesis. I recognise an enormous effort involved in running a multi-threaded experimental research program. I know how much time and effort it takes to carry out this kind of work. The research concerned numerous aspects and used several experimental tools, including several deep neural network models for delamination identification. The Candidate has shown great rigour 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 defence.

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 on July, 14th 2022.

The presented review report is organised in the following sections: 1) project background, 2) a general description of the manuscript, 3) analysis of the work of the Author in the thesis 4) list of queries and 5) final evaluation statement.

1) Project background

Recent progress in artificial intelligence methods such as deep representation learning offers the opportunity to be implemented for elastic waves based non-destructive testing (NDT) and structural health monitoring (SHM). It can be attributed to the limitations of standard methods of signal processing for the extraction of damage-related features from signals of propagating waves.
Thus, the subject of the PhD thesis "Feasibility study of artificial intelligence approach for delamination identification in composite laminates" by Mr Abdalraheem A. Ijjeh is related to the studies of whether deep neural networks can be an effective tool in monitoring the technical condition of the thin structural components. For this purpose, signals/images of propagating elastic waves in thin-walled elements of the structure are used. The models of convolutional and recurrent deep neural networks are aimed at finding anomalies of propagating elastic waves caused by damage and indicating their position.

2) Thesis structure and content

This PhD thesis starts with an introduction to the research goals, then presenting the state of the art, describing the methodology and experiments and finally, presenting results with discussion. The thesis consists of 6 chapters, and it comprises 126 pages, 11 tables, 82 figures and 167 publications. It begins with an introduction to the subject, which presents the background and motivation of the research. The following Chapter 2 presents the state of the art in guided waves based SHM for composite materials. This review is based on 76 recent publications and is followed by a short summary. In Chapter 3, the Candidate gives a short description of machine learning models, citing 41 papers and books and then presents related works for data-driven SHM/NDT, based on 29 papers. Chapter 4 describes acquisition of the synthetic dataset, methodology and applied deep neural networks models. Chapter 5 shows obtained results with detailed discussion. Chapter 6 presents conclusions and suggests future work.

3) Analysis of the work

The main goal of the experimental investigations was to develop an 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 models were considered for the AI-driven diagnostic system: five fully convolutional network architectures (Residual UNet, FCN-DenseNet, VGG16 encoder-decoder, Pyramid Scene Parsing Network and Global Convolutional Network), a recurrent neural network called Autoencoder ConvLSTM and the residual dense network. In my opinion, the information presented about these models was gathered skilfully. The description of the architectures show their applications potential. In the manuscript, the author refers to the recommendations for using these models found in the cited works. State of the art summarises 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 were as follows from 1 to 3:

Aim 1. Delamination identification using fully convolutional networks (FCN).

The Candidate in his research explored a one-to-one approach using five models of fully convolutional networks (FCNs) for pixel-wise image segmentation by classifying each pixel of the input image as damaged or not. The FCN models were trained on input images representing energies computed from full wavefield signals of Lamb waves propagating in carbon fibre reinforced polymer (CFRP) plates. The applied models were appropriately selected, and their description was carefully presented. Chapter 5.2 is dedicated to the presentation of the results.

In my opinion, the experiments were carried out with great care, and the results were presented in a clear manner. Moreover, it should be noted that the scope and diversity of the conducted segmentation tests significantly expanded the Candidate's research competences, enriching his experimental background.

Aim 2. Delamination identification in the CFRP plate based only on animation of the full wavefield of Lamb wave propagation.

The Author in this research applied a many-to-one approach with a recurrent neural network called Autoencoder ConvLSTM for identification of single and multiple delaminations in CFRP plates. The model was trained on sequences of images representing the full wavefield of Lamb wave propagation animation. Chapter 5.3 presents the results. The performed and discussed experiments, enabled the Candidate to identify the positive effect of using a sequence of full wavefield frames and recurrent neural network to perform pixel-wise segmentation and identification of delaminations in CFRP plates. It is probably the first implementation of deep recurrent neural networks utilising Lamb wave propagation animations for delamination identification with semantic segmentation.

The trained model performed very well on the numerically generated animations, and it also showed generalisation capability in real-world applications.

Aim 3. Super-resolution image reconstruction for recovering the high-resolution full wavefield of Lamb wave propagation from low-resolution measurements using deep neural networks.

In this section, the Candidate tested an end-to-end framework for full wavefield reconstruction of propagating Lamb waves from spatially sparse SLDV measurements of resolution below the Nyquist wavelength using deep learning super resolution (DLSR) method. An end-to-end approach is used in which a deep neural network is trained on a numerically generated dataset and tested on an experimental dataset acquired by SLDV performed on a plate made of carbon fibre reinforced polymer (CFRP) with embedded Teflon inserts simulation delaminations. In Chapter 5.4 the Candidate presents the results.

The Author achieved his goal, tested and assessed the suitability of the residual dense network for reconstruction of propagating Lamb waves.

4) List of queries

1) After getting acquainted with this thesis, I believe that a more appropriate dissertation title would be: "Feasibility study of deep neural networks for delamination identification in composite laminates".

2) In my opinion, the better structure of the thesis would be by presenting each application of deep neural networks in one chapter, starting from description of methodology and ending with discussion.

3) 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 Bayesian model selection method. In my opinion, it is an important aspect in the presented applications.

4) In the state-of-the-art, you do not refer to the applications of Bayesian deep neural networks for SHM/NDE and specifically for delamination identification. Bayesian approach is considered to be useful for uncertainty quantification. Have you found in the literature any reports on the possibility of using Bayesian deep neural networks as a prospective replacement for the standard deep neural networks in the context of data-driven SHM/NDT?

5) Summary and final evaluation statement

The manuscript prepared by Mr Abdalraheem A. Ijjeh presents an experimental program that contributes to the application of artificial intelligence approach for delamination identification in composite laminates. Comprehensive experimental program conducted by the Candidate and the diversity of the identification tests significantly expanded the Candidate's research competences, enriching his research skills.

The Author achieved three goals of the doctoral dissertation by exploring five models of fully convolutional networks (FCNs) for pixel-wise image segmentation by classifying each pixel of the input image as damaged or not. Moreover, he pointed at the possible use of recurrent neural networks (RNNs) 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.

Without doubt, 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 Abdalraheem A. Ijjeh, the Author of the thesis entitled: "Feasibility study of artificial intelligence approach for delamination identification in composite laminates" 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 Abdalraheem A. Ijjeh 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.

Kraków, 3.11.2022