Nondestructive Evaluation of Composites Using Model Based Design

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Abstract

There is a practical interest among composite materials manufacturers to high-speed accurate non-destructive evaluation (NDE) technology for voids inspection when these voids are natural components of such complex structures like resin insulated layer of double-sided copper-clad laminates. Model based design (MBD) of NDE system is one of principal solutions for voids inspection in such composites [1-4]. This work presents a MBD approach to voids inspection based on MEMS high frequency ultrasonic transducers with dry point coupling extensions [5-7], finite element analysis (FEA) of waves propagation through complex structures by COMSOL, modern digital signal processing (DSP) and artificial intelligence (AI) tools together [8-10].

Keywords: Model Based Design, COMSOL, MATLAB, Ultrasonic Transducers, DSP.

1. Introduction

The detection method is based on application of surface and bulk high frequency ultrasonic waves using MBD for design of transducers with dry compiling elements (DPC) and modern digital signal processing (DSP) and artificial intelligence (AI) techniques implemented to voids detection, recognition and classification.

Strength of the approach is in many advantages comparing with conventional nondestructive detection of voids. This approach allows avoiding difficulties with high resolution and inspection speed. It based on new design of miniature ultrasonic transducers with dry point contact (DPC) coupling elements, which provide a reliable acoustic contact between testing materials and sensors, speedy testing procedure.

Uniqueness of the approach is in application of MBD for optimal design of miniature DPC transducers with high frequency responses and for analysis of surface and bulk ultrasonic waves propagation in small specimens, which contain combination of different material with and without voids. MBD models will be applied for training of AI network for detection of voids and decision making about size and position of those voids and mapping of testing specimens. Complexity of testing material and configuration of specimen is presented in Figure 1.

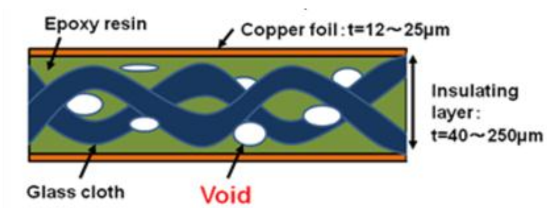

Figure 1. Specimen model: thickness of the insulating layer is 40-250 µm, copper foil id 12-25 µm, and panel size 600X600 mm

2. Modeling & Simulation

The presented geometrical model does not allow building of a sufficient analytical model for NDE of resin due to complexity of acoustic waves propagation in the specimen. Solution of this problem is MBD using finite element analysis (FEA) of ultrasonic pulses propagating in specimens with and without voids. Some preliminary FEA models of ultrasonic pulse propagating through specimens are presented in Figure 2:

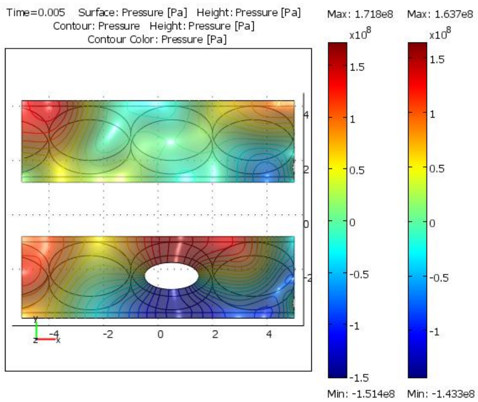

Figure 2. Preliminary FEA models of specimens without (upper figure) and with void (lower figure) showing propagation of ultrasonic pulse

NDE of the specimens can be performed by high frequency miniature DPC transducers which will be automatically manipulated in complience with a special algorithm. The miniature DPC transducers will generate bulk acoustic waves for two-sided testing and surface waves for one-sided testing. Design of miniature DPC transducer is shown in Figure 3:

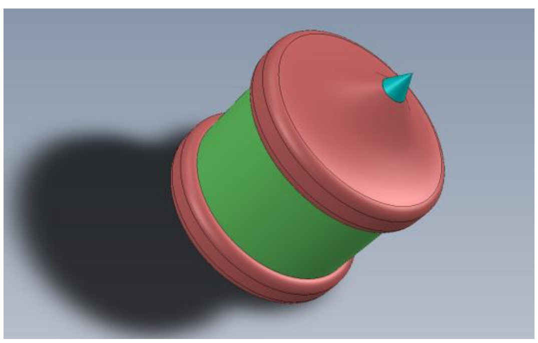

Figure 3. Design of miniature DPC transducer

A scheme of two-sided testing of a specimen is presented in Figure 4:

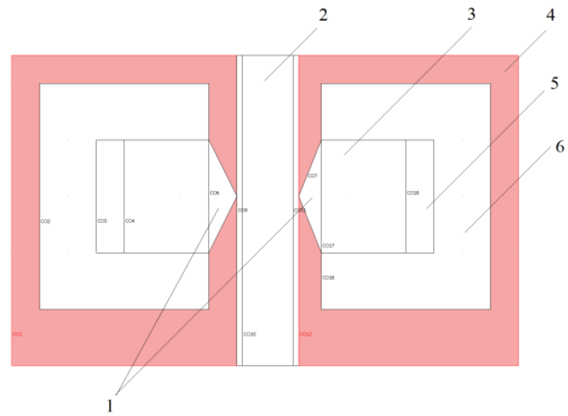

Figure 4. A scheme of two-sided testing of a specimen: 1 - DPC extentions; 2 - specimen; 3 - sensitive element (PZT); 4 - surrounding air; 5 - back mass; 6 - DPC housing

3. **Analysis & Tools**

The model contains realistic dimentions and physical properties of specimen (moduli of elasticity, density and acoustic attenuation parameters). MBD gives an opportunity to use ultrasonic pulses for specimen testing with different central frequency f. The NDE procedure is based on pattern differences for specimens with void and without voids. These differences are presented in Figure 5:

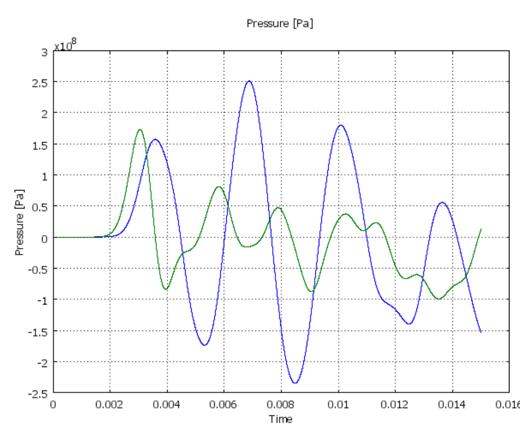

Figure 5. Patterns of bulk waves propagating through specimen without void(blue) and with void (green)

Modern DSP and AI tools will be applied for detecting and mapping of voids using MBD. As an example, these different patterns of ultrasonic pulses for central frequency f=1 MHz and void with diameter about d= 50 μm are demonstrated in Figure 6:

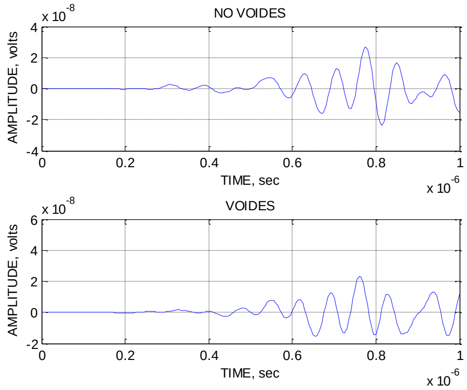

Figure 6. Patterns of bulk waves propagating through specimen without void (upper graph) and with void (lower graph)

Amplitude spectrums of these pulses are demonstrated in Figure 7:

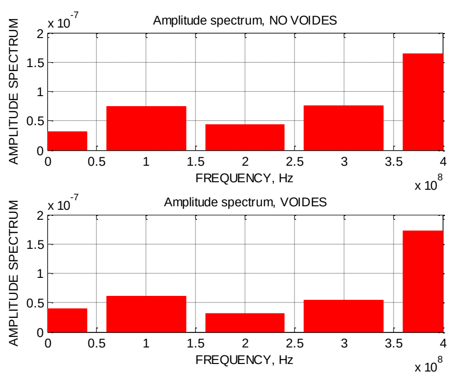

Figure 7. Amplitude spectrums of these pulses

Time-frequency patterns are presented in Figure 8:

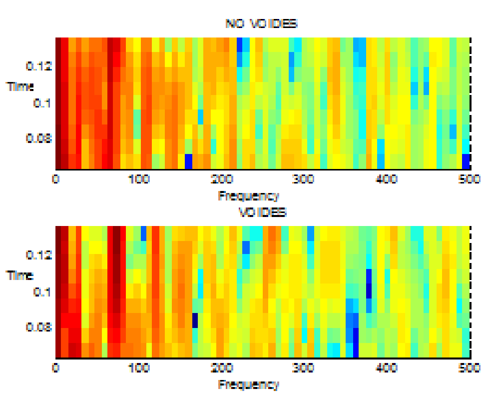

Figure 8. Time-frequency patterns of bulk waves propagating through specimens without void (upper graph) and with void (lower graph)

Wavelets fractal patterns are illustrated in Figure 9:

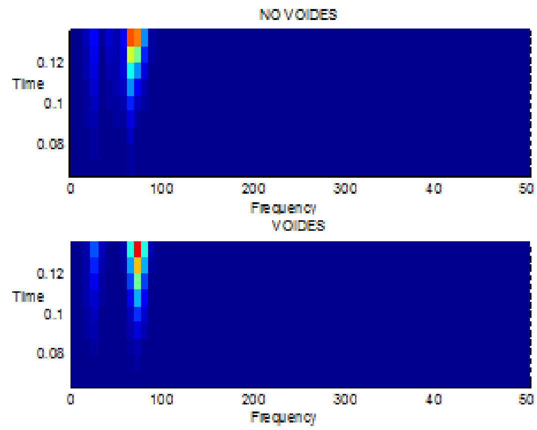

Figure 8. Wavelets fractal patterns of bulk waves propagating through specimen without void (upper graph) and with void (lower graph)

AI clustering tools will be applied for creating and training a neural network for evaluating and classification of patterns of acoustic waves propagating through specimens. An example of the self-organizing map (SOM) is presented below in Figure 9:

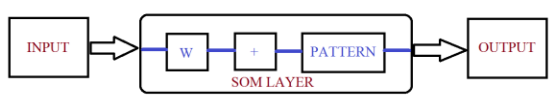

Figure 9. The network is trained with the SOM batch algorithm

Because this SOM has a two-dimensional topology, we can visualize in two dimensions the relationships among the four-dimensional cluster centers. Providing training of SOM for different acoustic waves propagating in specimens shown as neighboring distances in the training window in Figure 10:

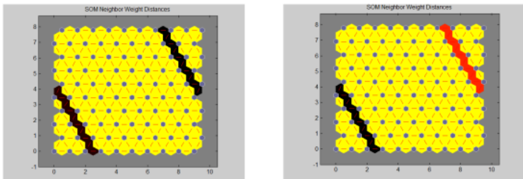

Figure 10. . Patterns of AI neural network for bulk waves propagating through specimen without void (left) and with void (right) indicated in red

4. Performance

Application of DPC transducers is a modern solution for monitoring of composites because it allows increasing productivity and repeatability. It is necessary to note that the ultrasonic (UT) methods are well developed and presented by a wide variety of tools and instrumentation. Still, there are several problems connected with application of ultrasonic methods for testing of nonmetallic or nonmagnetic materials. One of them is related to the design of ultrasonic transducers. Traditionally applicable transducers have plate contact with the testing material surface and require usage of a special coupling for creation of acoustic contact. These Coupling Plate Contract (CPC) transducers have several disadvantages: coupling is responsible for instability of test measurements repetition; application of CPC transducers is hindered on rough and curved surfaces; there is a possibility of an error (commensurable with their contact area) connected with determination of distance between two CPC transducers for surface testing. Coupling free DPC transducers allow avoiding these problems and increasing a number of ultrasonic NDT applications (see references below).

5. Use of COMSOL Multiphysics

This work was performed using COMSOL, MATLAB and Solid Works together.

6. Conclusions

- The purpose of NDE is to detect and evaluate size of voids in resins. Specimens may have different components like epoxy resin, glass cloth and cooper foils which mask voids for detection and classification. The problem of UT for voids detection is in high level of attenuation of acoustic signals in these materials, nonlinear effects during wave propagation, reflection and refraction as well as small size of specimen for nondestructive testing. Application of higher frequency of acoustic pulses will be used for increasing sensitivity of detection. The target is to detect voids with minimal size.
- The proposed approach will significantly increase speed of testing by application of miniature DPC transducers with robotic systems allowing automatize measurements and control. As a result NDE of specimen will need just seconds.
- This approach is expected to give increase of accuracy comparing with existing UT methods.
- Preliminary analysis of the approach shows ability to detect voids with size 50 μm. MBD may allow finding solutions and optimization of design of NDE for smaller voids detection.

7. References

1. Nesvijski, E.G. and Pochtoviic, G.Y., Waveguiding Extensions for Ultrasonic Testing of Composite Medium. Book: " Nondestructive Methods Testing of Civil Materials and Structures", Riga, Zinatne, 1982, p.59-66.
2. Nesvijski, E.G., On the Problem of Application of the Conic and Exponential Wave Guiding Extensions for Ultrasonic Transducers for Materials Testing. Journal: NASTA Technical Bulletin, Philadelphia, PA, USA, 1997 (ISSN 1079-8498), Volume 3, pp. 49-56.
3. Non-Destructive Testing in Civil Engineering 2000 (NDT-CE 2000), Ed. Taketo Uomoto, Elsevier Science, Tokyo, Japan, April, 25-27, 2000 (ISBN: 0080437176), pp. 323-330
4. Nesvijski, E.G. at al., "Ultrasonic Transducer". Patent SU 1298653, Bulletin of Inventors, No. 11, 1987.
5. Nesvijski, E.G., Nesvijski, T.E., Ultrasonic Testing of an Ice Specimen by the Dry Point Contact Transducers. Proceedings:

ASNT Fall Conference and Quality Testing Show Paper Summaries, Phoenix Arizona, USA, October 11-15, 1999, pp. 99-101.

6. Nesvijski, E.G., Dry Point Contact Transducers for Transfer Technology Applications. Proceedings: 1998 International Advanced Studies Institute (Science and Technology Series), Monterey, CA, February 10-13, 1998.
7. Nesvijski, E.G. at al., Robotic Test Bench for Ultrasonic Testing of Reinforce Concrete Structures. - "Construction and Architecture", Kiev, No. 1, 1981, p.17-18.
8. Nesvijski, E.G., NDTISS 99 Report. Journal: The e-Journal of Nondestructive Testing & Ultrasonics, February, 2000 (ISSN: 1435-4934).
9. Nesvijski, E.G. On Design of Ultrasonic Transducers and Accuracy of Velocity Measurements. NDT.net - February 2000, Vol. 5 , No. 02
10. Nesvijski E., Model Based Design and Acoustic NDE of Surface Cracks, NDT.NET Journal: The e-Journal of Nondestructive Testing & Ultrasonics, No.9, 2011, (ISSN 1435-4934)