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Non-contact excitation and focusing of guided waves in CFRP composite plate by air-coupled transducers for application in damage detection

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Abstract

Guided waves have been utilized in Structural Health Monitoring (SHM) and Non-Destructive Testing (NDT) for many years. The vast majority of applications are based on contact wave excitation by using a group of piezoelectric transducers attached to the surface of a structure. However, in some cases piezoelectric transducers cannot be used directly on the structure and non-contact wave excitation methods are preferable. The paper presents the results of laboratory investigations utilizing air-coupled excitation with the use of ultrasound transmitters. The response of the specimen under various excitations by ultrasound transmitter array (UTA) was investigated. Various number of actuators and their configurations were considered. Moreover, various methods of wave focusing have been analysed. Next, the experimental verification of guided wave based damage detection system with proposed air-coupled excitation is presented. The wave sensing was non-contact as well. For this purpose the Scanning Laser Doppler Vibrometer (SLDV) was used. Full wavefield images and wave profiles for various excitation were prepared. The influence of ultrasound transmitter configuration and focusing method on the energy of induced wave was highlighted on RMS maps. Tests were carried out on the CFRP plate with dimension 500 x 500 x 1.5 mm. The delamination damage in a form of 15 x 15 mm Teflon tape insert was analysed.

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Keywords: guided waves; air-coupled excitation; non-destructive testing; ultrasound transmitter

1. Introduction

In issues related to structural integrity problems, risk and reliability assessment, apart from fracture mechanics, fatigue, materials science, Non-Destructive Testing methods play a significant role. One of the common and widely used NDT technique is guided waves method (Staszewski (2004), Giurgiutiu and Soutis (2010), Rose (2004)). The variety of damage detection algorithms which utilize guided waves method are known and applied with success. They

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are utilized successfully to damage detection and localization in both composite (Zhao et al. (2007), Ostachowicz et al. (2014), Song et al. (2009)) and metallic (Jurek et al. (2008), Yu et al. (2015)) structures.

One of the main disadvantage guided waves method is necessity of assembly of wave actuators. For this reason to the surface of monitored structure transducers and wiring systems should be mounted. It could limit functionality of the structure and make its service difficult. For this reasons, non-contact methods of excitation and sensing of guided wave are desirable.

Moreover in some cases like large objects testing or high-temperature applications, there is a need to use a fully non-contact damage detection system. The PZT piezoelectric transducers are the most common devices used for guided wave excitation. Among the advantages (low cost, the possibility of embedding in the structure, energy efficiency, reliability, compactness) also have disadvantages and limitations in application. Their usefulness is limited when interference in the surface of the analysed object is not allowed or when the test is carried out at high temperature. The significant disadvantage of PZT transducers is their vulnerability (Mueller and Fritzen (2017)). A very common defect is the breakage as a result of various causes, like an impact, caused by a tool drop, or high bending moments acting on the brittle ceramic material. Moreover the cyclic loading may cause transducer fracture (Taylor et al. (2014)). The another source of limitation in PZT application is the possibility of transducer debonding. Complete or partial detachment of the transducer from the structure, can be caused either due to weak bonding conditions or by a crack or degradation of the bonding layer as an effect of environmental exposure, cycling loading, high temperature influence. Moreover the need to excite a wave in many variable locations or in large areas requires the use of an alternative to PZT method of guided waves excitation. In such cases, the non-contact methods are utilized. For this purpose laser techniques are employed. There are known two main ways to excite waves - by laser ablation (Canle et al. (2017), Hosoya et al. (2017)) or thermoelastic excitation (Jhang et al. (2006), Castaings and Hosten (2008)). Thermoelastic waves are generated by a localized sudden temperature rise induced by pulse laser radiation on the surface of analyzed structure. The main disadvantage of this approach is that amplitudes of generated waves are small. The impulse excitation generated using laser ablation may realize guided waves with large amplitudes over a broad range of frequencies. However non-contact laser techniques allow to generate only pulse excitation and are very expensive.

An alternative method of non-contact excitation of guided waves are ultrasonic air-coupled transducers (ACT) (Gomez Alvarez-Arenas et al. (2016), Harb and Yuan (2016), Rheinfurth et al. (2012)). In this approach ACT was used as a sources of acoustic wave. It is assumed that the acoustic wave front impacts the surface of testing structure and generates the Lamb wave (Fig. 1). It allows to set unlimited locations of the source of excitation.

However, due to the lack of fluid couplant, it is important to determine optimal actuator-structure configuration. The distance and angle of the actuator relative to the surface of tested structure are crucial from the point of view of generated wave parameters. Professional air-coupled transducers used in NDT applications require specialized electronic equipment for actuation. In this research, experimental verification of usefulness of resonance-based commercial ultrasonic transmitters as a guided wave actuators is presented.

2. Laboratory measurements

2.1. Experimental setup

The laboratory setup is presented in Fig. 1. The excitation signal was generated by TTi TG1010 signal generator and amplified by Piezo Sytems EPA 104 linear amplifier. Further an amplified signal was sent to wave actuator. The sample response was registered by Scanning laser Doppler vibrometer. This device enables non-contact measurement of displacements as well as velocities of vibrating surface. Full field of propagating guided waves in 375 x 375 equally spaced points was acquired. Vibrometer scanning head was located about 2.5 m in front of the investigated specimen. The reflective tape was mounted on the sample surface to obtain a good quality of response signals in LDV measurements.

Tests were carried out on the Carbon Fiber Reinforced Polymer (CFRP) plate with dimension 500 x 500 x 1.5 mm with artificial delamination (Fig. 2a). In this purpose, during manufacturing process 15 x 15 mm teflon tape insert between composite layer was introduced. It should be noted that the purpose of the study was not to detect and localize the damage but to verify the possibility and efficiency of non-contact excitation with the use of ultrasonic transmitter.

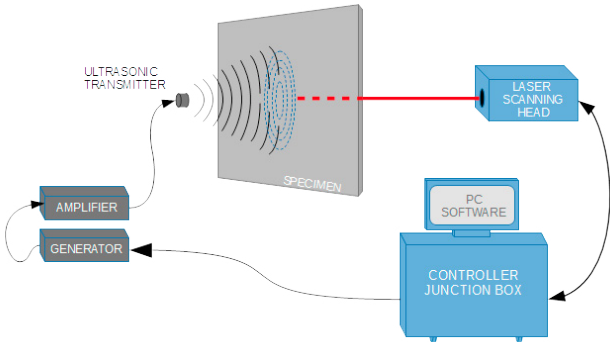

Fig. 1. Diagram of elastic wave excitation by ultrasonic air coupled transmitter and laboratory setup schem.

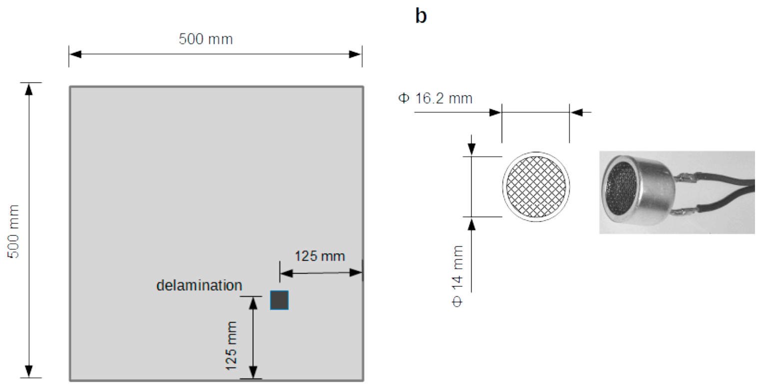

Fig. 2. (a) specimen diagram; (b) ultrasonic air coupled transmitter.

2.2. *Wave excitation*

As the acoustic wave actuators commercial, low-cost resonance-based ultrasonic transmitter 40ST-16 (Fig. 2b) were used. The resonant frequency of used transducers is 40 kHz, capacity is 2000 pF and the sound pressure generated 300 mm from its front cover reach 115dB.

In order to increase the energy of the generated excitation an ultrasonic transmitters array (UTA) was used. An array of 36 transmitter was prepared in circular configuration presented in (Fig. 3). Transmitters were stably mounted in a flat plate in holes drilled in strictly fixed positions. As an excitation signal the package of 10 cycle sine wave, modulated by Hanning window was used.

Two approaches were used to focus acoustic wave generated by ultrasonic transmitter.

First, time delay of generated signals was applied. The focusing point was designed to be 270 mm away from the UTA center point. The focusing point was aligned with the geometrical center of specimens back surface. Ultrasonic transmitters were divided into four groups, with various distance to the focal point. The division scheme is shown in Fig. 3a with the different colour assigned for each group. Time delays are compared in Tab. 1.

Table 1. Time delays for transmitter groups.

Transmitter number	Color	Time delay [μm]
1 - 8	red	0
9 - 24	yellow	22.4
25 - 32	blue	38.8
33 - 36	green	48.9

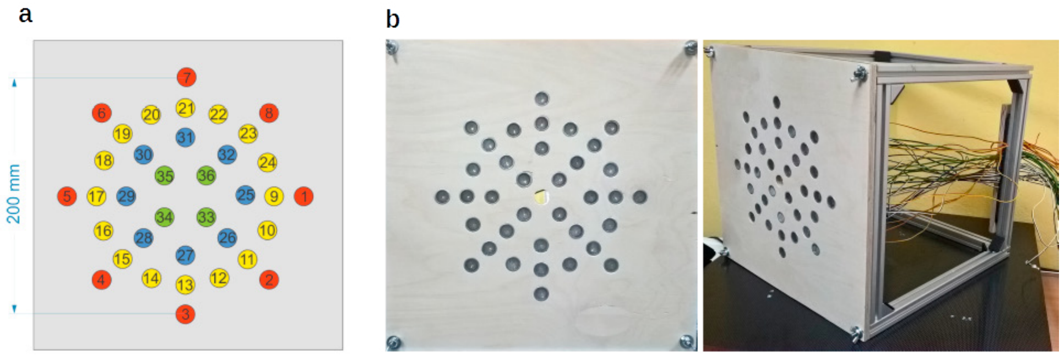

Fig. 3. Ultrasonic transmitter array (a) scheme; (b) photo.

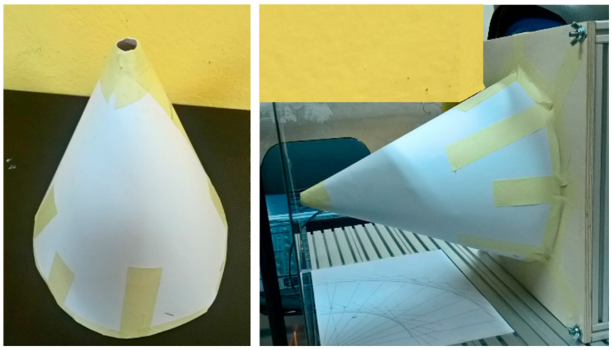

Fig. 4. Wave focusing with use of the cone.

Mechanical focusing of acoustic wave was also applied. For this purpose, a cone made of cardboard was used (Fig. 4). The diameter of the cone base was about 220 mm, so that all transducers were inside the cone. The diameter of the hole at the cone top was determined experimentally and was equal about 1 cm. During the measurements the cone was placed in such a way that its top was located 12 mm from the surface of the sample. Therefore, the distance of the UTA from the surface of the sample was 270 mm.

3. Results

Full wavefields of propagating guided waves were recorded. The results in the form of the selected frame of propagating waves taken from registered sequences of guided wave propagation in analysed sample are presented on Fig. 5. Three excitation cases were compared. Fig. 5a refers to excitation without focusing, while Fig. 5b and Fig. 5c concern excitation with focusing by time delay of excitation signals and with use of the cone respectively.

In all excitation cases it is difficult to distinguish delaminated region. Obtained results give limited possibilities of damage detection and localization. To increase the effectiveness of the method in non-destructive testing, it is necessary to use advanced algorithm. In the further works the application of the damage detection algorithm based on full wavefield processing in wavenumber domain (Kudela et al. (2015)) will be applied.

It is easy to notice that the usefulness of measurements for non-focusing excitation is limited. Due to the excitation impulse affects a large area of the sample, it is difficult to analyse the propagating wave.

For each excitation case root mean square (RMS) calculations were performed. All the above observations are confirmed on RMS maps (Fig. 6).

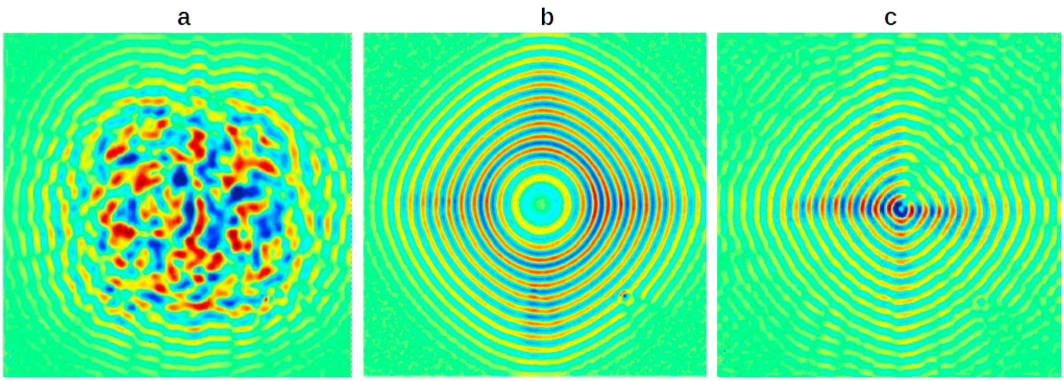

Fig. 5. Wave image: (a) without focusing, (b) with focusing by time delay of excitation signals, (c) with focusing with use of the cone.

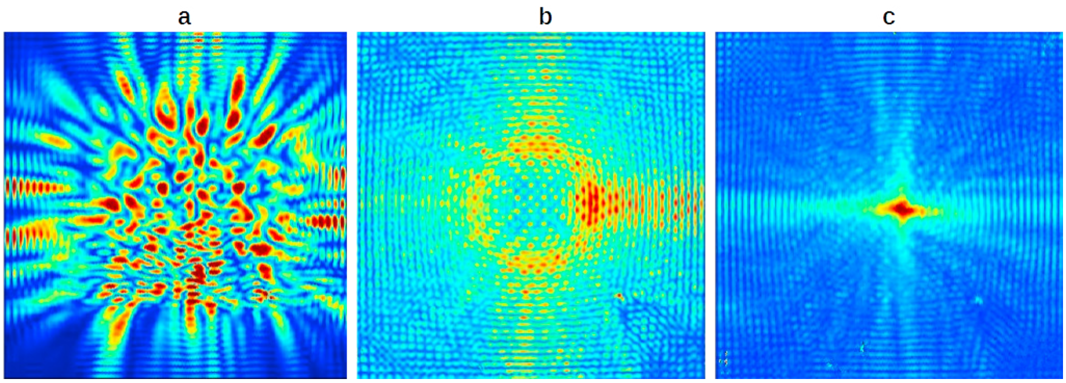

Fig. 6. RMS maps: (a) without focusing, (b) with focusing by time delay of excitation signals focusing, (c) with focusing with use of the cone.

4. Conclusions

The study aims to verify usefulness of low-cost commercial ultrasonic transmitters in non-contact guided waves excitation. It was confirmed that non-contact air-coupled excitation with the use of ultrasound transmitters could be an alternative way of elastic wave excitation. The laboratory test proved that low-cost commercial ultrasonic transmitters are a valid alternative to both contact excitation with PZT transducers and advanced professional air- ultrasonic air-coupled transducers. The main disadvantage of this approach is limited amplitude especially for excitation form a greater distance. To avoid this problem, an array of transmitter in various configuration can be used. It is planned to analyze ultrasound transmitter arrays (UTA) with different number of transducers and various configurations (circular, square, cross-shaped). Moreover two various methods of wave focusing were examined. In both cases an improvement in the generated extortion was obtained. Based on preliminary results it may be assumed that well designed UTA with properly tuned triggering of excitation signals or mechanical focusing is a valid alternative to contact excitation and may be used as a complementary component for non-contact laser guided waves excitation.

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