Multiple robots (robotic centers) and systems. Remote sensing and non-destructive testing

Роботизированные комплексы и системы. Технологии дистанционного зондирования неразрушающего контроля

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RESEARCH ARTICLE

Detection of defects in printed circuit boards by the acoustic emission method

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Abstract
Objectives. Defects in the form of layering may occur during lamination in the production of multilayer printed circuit boards (MPCB). These defects cannot be detected by optical and electrical methods of output control. However, they can lead to breaches of the mechanical mode of operation and failures while running radioelectronic devices. In order to detect such defects, the acoustic emission (AE) method is proposed. This is based on the occurrence and propagation of acoustic waves in MPCBs caused by the presence of defects. The aim of this study is to investigate the possibility of using the AE method to detect defects in multilayer printed circuit boards. These defects can occur, in particular, in the lamination process.
Methods. A mechanical processes modeling program (for research on the MPCB model) and various samples of two-layer printed circuit boards with pre-introduced defects (for experimental studies) were used to study the propagation of acoustic signals in the MPCB in the presence of defects. A solenoid mounted on the MPCB was used as a source of acoustic signals, while a piezoelectric sensor was used to receive signals. Data processing was carried out by comparing AE signals obtained for a serviceable MPCB sample and for MPCB samples with defects.
Results. Simulation of the acoustic signal propagation in MPCBs in serviceable and faulty (with a rectangular defect in the form of delamination) states was carried out to show the difference in the received signals at the sensor installation point. Experimental studies were also conducted to examine the AE method applicability for detecting defects of various sizes and quantities.
Conclusions. The studies demonstrated that the AE method allows the presence of defects in MPCB occurring during the lamination process to be detected effectively and reliably. This study proposes a new approach to non-destructive testing of MPCB using the AE method. This method significantly increases the reliability of MPCBs and the efficiency of their production processes.

Keywords: acoustic emission, multilayer printed circuit board, defect detection, delamination, non-destructive testing

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НАУЧНАЯ СТАТЬЯ

Обнаружение дефектов в многослойной печатной плате методом акустической эмиссии

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Резюме

Цели. При производстве многослойных печатных плат (МПП) в процессе ламинирования в них могут возникать дефекты в виде расслоений. Они не обнаруживаются оптическими и электрическими методами выходного контроля, но в процессе эксплуатации радиоэлектронного средства могут вызвать нарушения механического режима работы и привести к отказам. Для обнаружения таких дефектов предлагается использовать метод акустической эмиссии (АЭ), основанный на возникновении и распространении акустических волн в МПП, вызванных наличием дефектов. Целью данного исследования является изучение возможности использования метода АЭ для обнаружения дефектов МПП, возникающих, в частности, в процессе ламинирования.

Методы. Для исследования распространения акустических сигналов в МПП при наличии дефектов использовались программа моделирования механических процессов (для исследования на модели МПП) и различные образцы двухслойных печатных плат с заранее внесенными дефектами (для экспериментальных исследований). В качестве источника акустических сигналов использовался соленоид, установленный на МПП, а для приема сигналов – пьезоэлектрический датчик. Обработка данных проводилась путем сравнения сигналов АЭ, полученных для исправного образца МПП и для образцов МПП с дефектами.

Результаты. Проведено моделирование распространения акустического сигнала в МПП в исправном и неисправном (с прямоугольным дефектом в виде расслоения) состояниях, которое показало различие полученных сигналов в точке установки датчика. Также были проведены экспериментальные исследования с целью изучения применимости метода АЭ для выявления дефектов различного размера и количества.

Выводы. Исследования показали, что метод АЭ позволяет достаточно эффективно и достоверно обнаруживать наличие дефектов в МПП, возникающих в процессе ламинирования. В данном исследовании предлагается новый подход к неразрушающему контролю МПП с использованием метода АЭ, который может значительно повысить надежность МПП и эффективность процессов их производства.

Ключевые слова: акустическая эмиссия, многослойная печатная плата, обнаружение дефектов, расслоение, неразрушающий контроль

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Авторы заявляют об отсутствии конфликта интересов.

INTRODUCTION

Multilayer printed circuit boards (MPCBs) are an important component in many electronic devices. As such, their quality control is critical to ensure the reliability and functionality of the devices. One of the most important steps in MPCB production is the lamination process. This involves joining multiple layers of copper-clad dielectric material, in order to form a multilayer board[1]. Laminating is prone to defects such as delamination, cracks, and voids which can degrade the PCB electrical and mechanical properties.

A variety of non-destructive testing methods such as X-ray inspection, optical microscopy, and ultrasonic inspection have been developed to detect defects in MPCBs. However, these methods have limitations in terms of cost, time, and accuracy. The non-destructive acoustic emission (AE) method has attracted increasing attention in recent years due to its high sensitivity, real-time monitoring capability and non-contact defect detection capability[2].

Acoustic emission is a phenomenon associated with the generation of elastic waves as a result of a sudden and localized energy release within the material [1]. The AE waves can be captured and analyzed, in order to obtain information about the location, magnitude, and type of defect in MPCB material. Using the AE method for detecting defects in MPCB has been investigated by scientists and experts [2–4].

This study considers the possibility of applying the AE method to detect defects occurring in MPCB lamination process. A solenoid is used as a source for generating AE signals, and a piezoelectric plate is used as a sensor for capturing signals. The signals obtained for the defective and serviceable MPCBs are compared, in order to evaluate the efficiency of the AE method for detecting defects.

The aim of the study was to develop a non-destructive testing method for detecting defects in MPCB occurring during the lamination process. This can significantly improve the reliability and efficiency of MPCB production. The work investigates whether the AE method can effectively detect defects in MPCB which may be formed during the lamination process. If this is so, then what are the advantages and limitations of this method compared to other existing ones.

LITERATURE REVIEW

Several studies have investigated the use of AE method for detecting defects in PCBs. Zhao et al. (2015) used the AE method for detecting defects in PCB during the hole drilling process [5]. It was discovered that AE signals can be used to distinguish between different types of defects such as incomplete hole, burr, and breakthrough. Liu et al. (2018) developed a method for detecting delamination in MPCB using AE [6]. This method used a pencil lead breakage as an AE source and a piezoelectric transducer as a sensor for detecting AE signals. The result showed that AE signals can be used to detect the presence and location of delamination in MPCBs.

Chen et al. (2020) investigated the use of AE method for detecting defects in flexible PCB [7]. For this purpose, a piezoelectric sensor was used to detect AE signals generated by needle puncture of a flexible PCB. It was found that AE signals can be used to determine the location and severity of the defect and that this method is sensitive to defects as small as 0.5 mm.

Although previous studies have shown the potential of the AE method for detecting defects in PCB, there are still problems in its implementation in diagnostic practice. One of the problems is the need to use complex algorithms for processing and analyzing different types of signals and noise [8, 9]. Another problem is the selection and optimization of the AE source and AE sensor placement which can affect the sensitivity and accuracy of the method [10].

Despite these problems, the AE method for detecting defects in MPCBs has significant advantages. The AE method is a non-destructive and non-contact method which can be performed in real time without the need

[1] Pokrovskaya M.V., Popova T.A. *Materials and structural elements of the REM.* Textbook. Part 1: *Material science and structural materials.* Moscow: RTU MIREA; 2021. 200 p. (in Russ.).

[2] Nosov V.V., Yamilova A.R. *Acoustic emission method.* Textbook. St. Petersburg: Lan; 2022. 304 p. (in Russ.).

for expensive equipment[3] [11, 12]. The AE signals can provide information about the location and type of defect, allowing the root cause of the faulty state to be identified and the quality control of MPCB production to be improved [13–15].

MODELING OF ACOUSTIC SIGNAL PROPAGATION IN MPCB

Initial data for modeling

In order to verify the effectiveness of the analytical simulation, *ABAQUS*[4] software was used for the numerical analysis of the accuracy of the piezoelectric sensor response in the MPCB model. Plate modeling MPCB is made of FR 4 foil-coated fiberglass (WAVGAT authorization store, China) having 0.2 × 0.15 × 0.0015 m in size. The characteristics of FR 4 material are presented in Table 1.

Table 1. Material parameters of the studied MPCB

Material	Density, kg/m^3	Elastic modulus, hPa	Poisson ratio
FR 4	1850	24	0.136

Transient excitation is required to model the defect effect on the AE signal propagation. In this paper, AE signal is excited using the time dependence function for excitation force $F(t)$ (Fig. 1) [15] represented mathematically as follows:

$$F(t)=\begin{cases}F_{\max}\left(t/t_e\right), & t\le t_e,\\ F_{\max}(2-t_e t), & t_e\le t\le 2t_e,\\ 0, & t\ge 2t_e,\end{cases}$$

where t_e is the time of achieving the maximum value of excitation force $F_{\max}$.

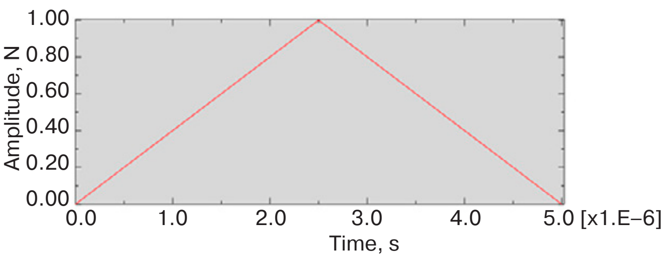

Fig. 1. Function *F*(*t*)

[3] Sych T.V. *The perfection of the acoustic-emission control technology based on the finite-element analysis of the acoustic path.* Diss. Cand. Sci. (Eng.). Moscow: SGUPS; 2016. 149 p. (in Russ.).

[4] https://www.3ds.com/products-services/simulia/products/abaqus/. Accessed August 30, 2023.

The schematic diagram of the sensor and AE signal source arrangement as well as the model in the *ABAQUS* software are shown in Fig. 2.

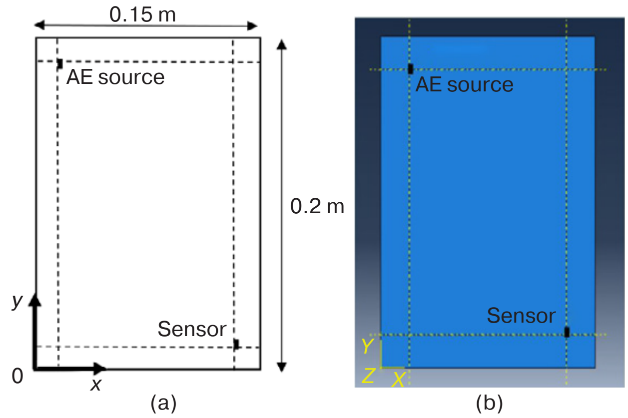

Fig. 2. The schematic diagram of the sensor and AE signal source arrangement (a) and the model in the *ABAQUS* software (b)

In order to model the presence of a delamination defect in the MPCB sample, a rectangular area 3 × 3.7 cm was created in the *ABAQUS* software. The MPCB model with a rectangular defect is shown in Fig. 3.

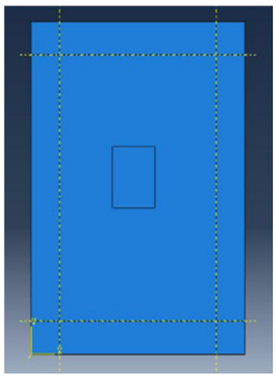

Fig. 3. The MPCB model with rectangular defect of 3 × 3.7 cm in size

The simulation studies wave propagation and piezo sensor response to AE signals generated by a virtual solenoid in the presence of a defect. The resulting signals are used for further analysis and comparison with the signals received from the MPCB sample without defect. The experimental results enable the possibility of using this approach for detecting defect in MPCB to be evaluated.

Modeling result

The acoustic wave propagation at certain time instants (0.12, 0.32, 0.64, 0.84, and 1.16 μs) in the absence of defect in MPCB is shown in Fig. 4.

The sensor signal received in modeling in the absence of a defect in MPCB is shown in Fig. 5.

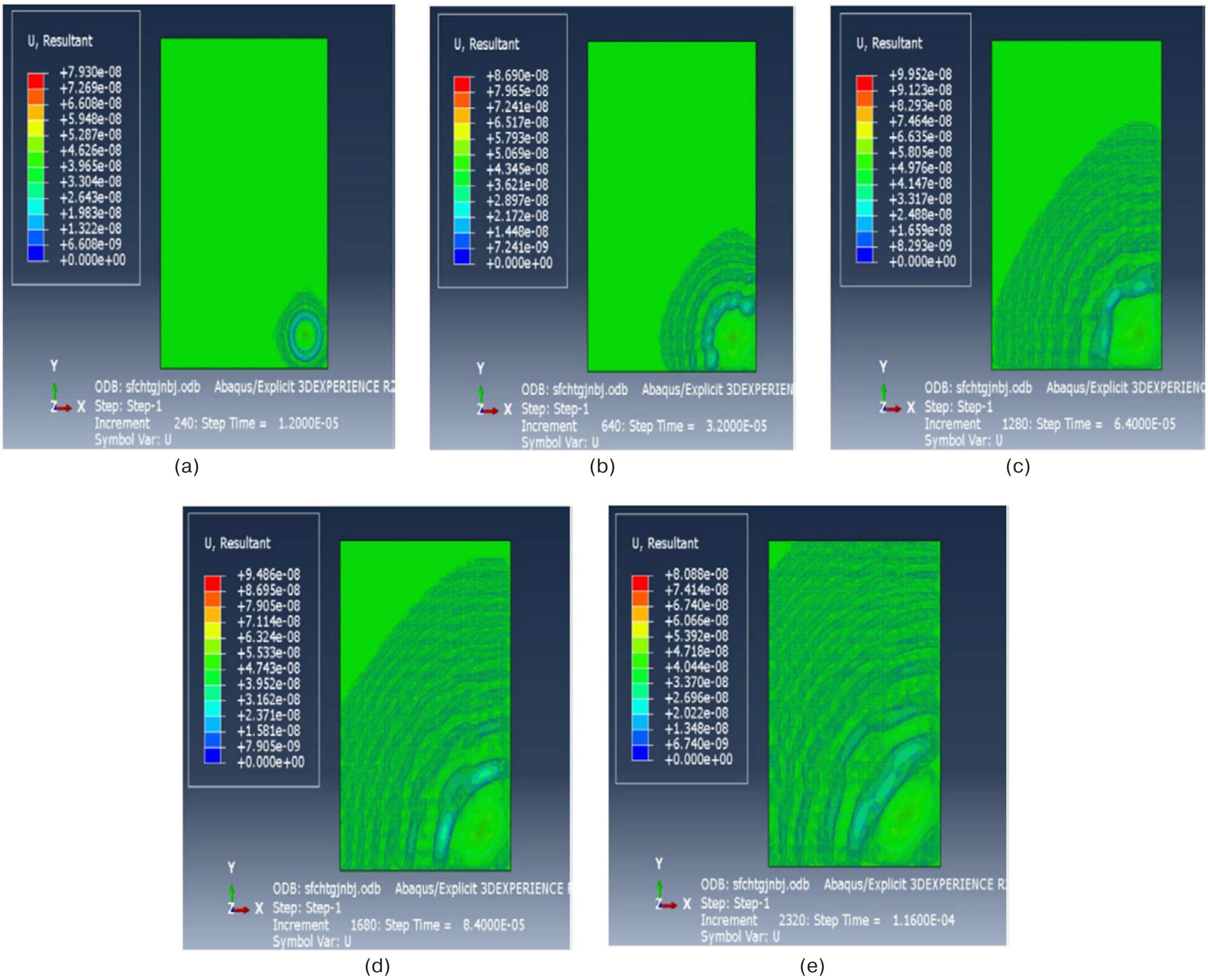

Fig. 4. Acoustic wave propagation in MPCB in the absence of a defect at time instants: (a) 0.12 µs, (b) 0.32 µs, (c) 0.64 µs, (d) 0.84 µs, and (e) 1.16 µs

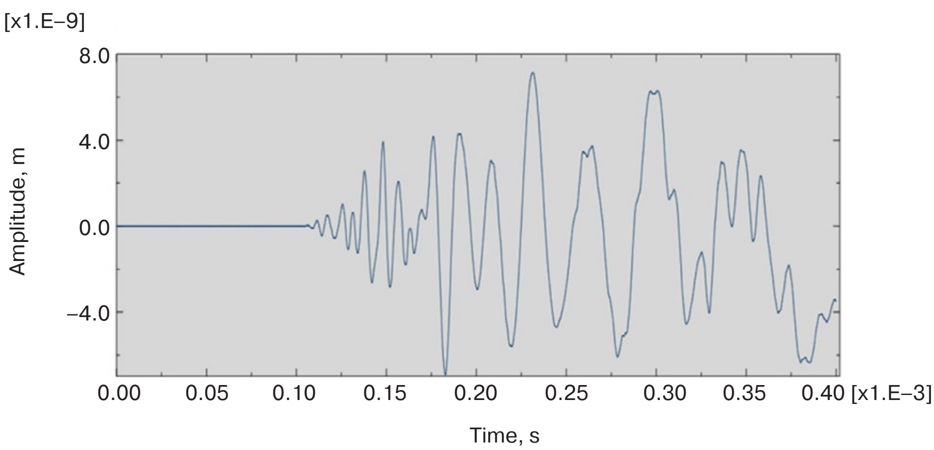

Fig. 5. Sensor signal in the absence of defect in MPCB

Similarly, in the presence of a defect in MPCB (defect in the form of the 3 × 3.7 cm rectangle), the process of acoustic wave propagation through MPCB at the same time instants (0.12, 0.32, 0.64, 0.84, and 1.16 µs) and the sensor signal are shown in Figs. 6. and 7, respectively.

Next, the sensor signals are compared for the absence and the presence of the defect (Fig. 8).

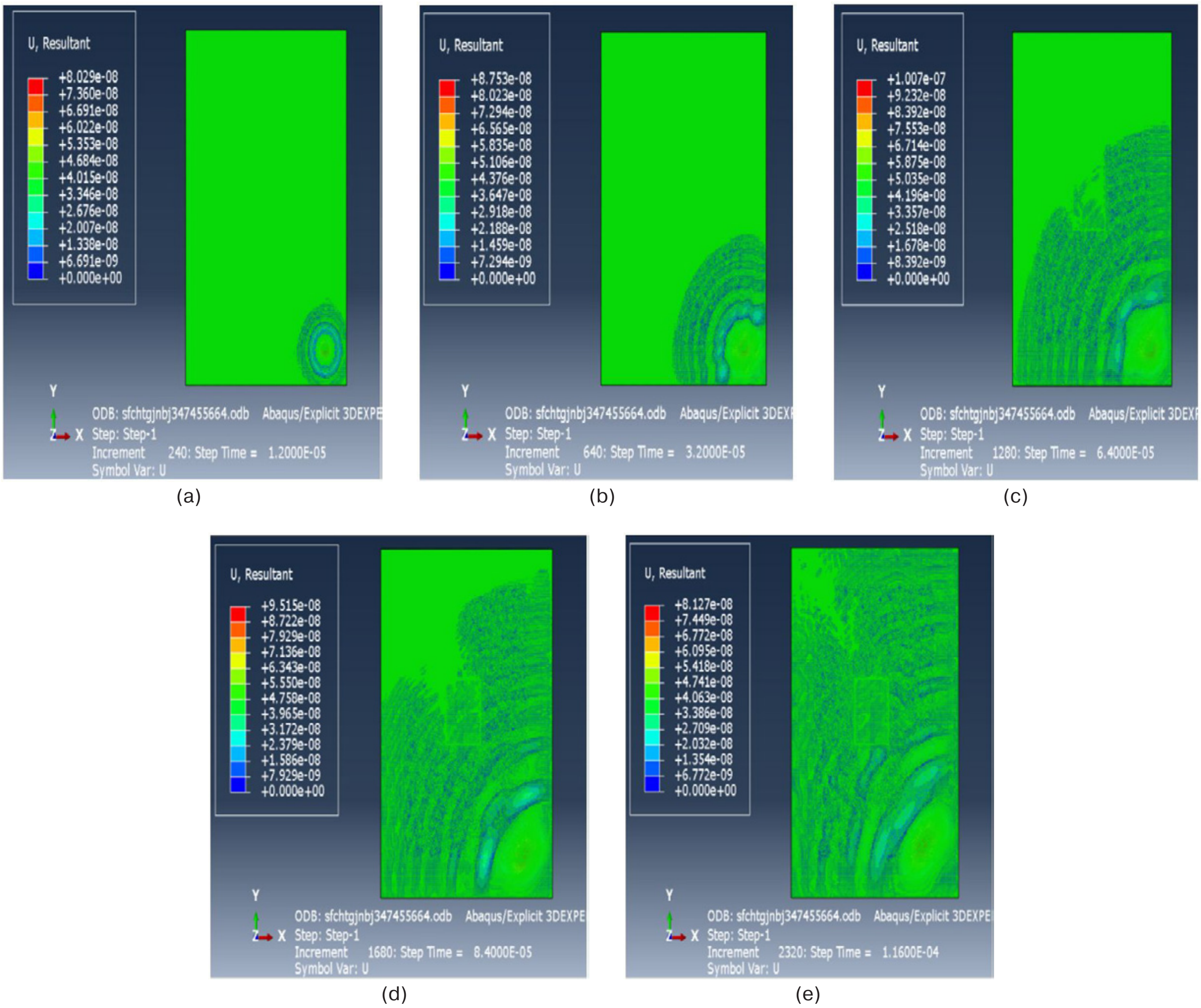

Fig. 6. Acoustic wave propagation in MPCB in the presence of the 3 × 3.7 cm defect at the following time instants: (a) 0.12 µs, (b) 0.32 µs, (c) 0.64 µs, (d) 0.84 µs, and (e) 1.16 µs

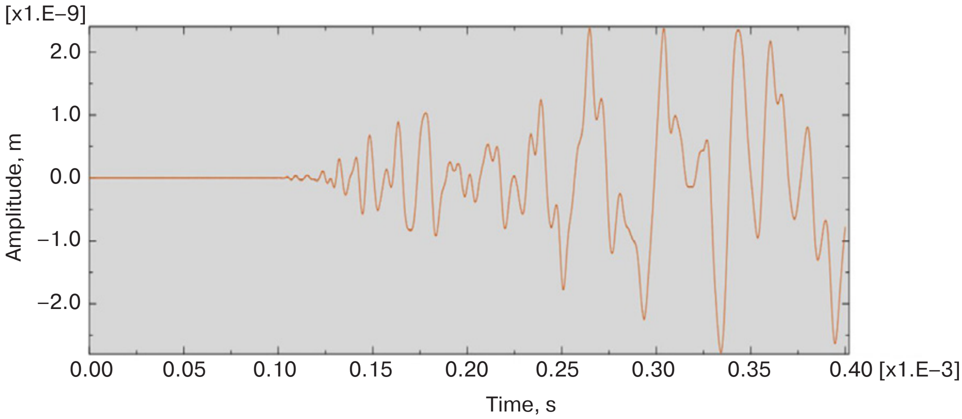

Fig. 7. Sensor signal in the presence of a defect in MPCB

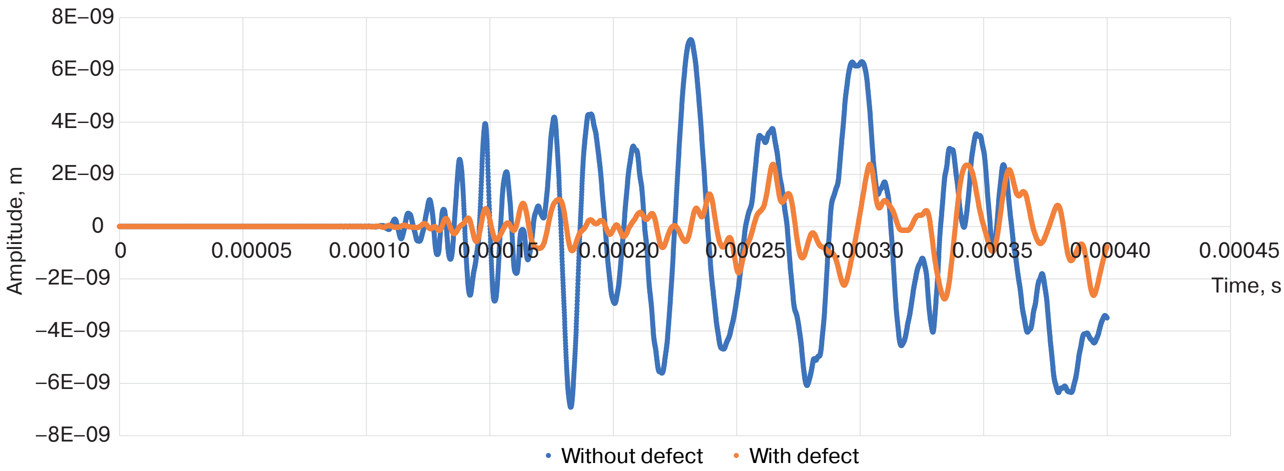

Fig. 8. Comparison of AE signals from the sensor with and without a defect in MPCB

The comparative results of the signals show that the presence of a defect causes distortion in the wave propagation process. This results in significant differences (several times) in the signal amplitude and signal arrival time compared to the case without a defect.

EXPERIMENTAL STUDIES ON A TWO-LAYER PRINTED CIRCUIT BOARD

Experimental setup description

An experimental setup was designed for this study (Fig. 9). It consists of: UNO R3 ATMEGA16U2 + MEGA328P chip for Arduino UNO R3 with breadboard and USB cable (1) (IGMOPNRQ module store, China); a piezoelectric plate of 27 mm in diameter (2) (KY WIN ROBOT store, China); V3 power key (3) (Amperka, Russia); 12 VAC source (4) (Teslocom, Russia); TAU-0520 solenoid tuned to 10 Hz frequency (5) (Amperka, Russia); two-layer printed circuit board (6) (WAVGAT authorization store, China); computer equipped with *Audacity* software[5] used for capturing and analyzing acoustic signals (7).

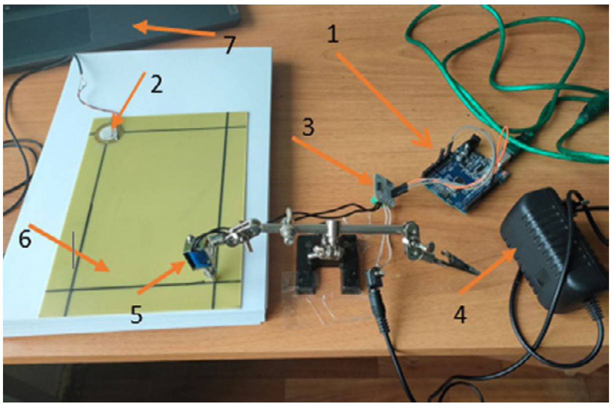

Fig. 9. The experimental setup

The technical characteristics of the acoustic signal sensor are given in Table 2. The image and view of the sensor are presented in Fig. 10.

[5] https://www.audacityteam.org/. Accessed August 30, 2023.

Table 2. Sensor parameters

No.	Parameter	Parameter value
1	Resonant frequency	3.5 ± 0.5 KHz
2	Resonant resistance	<300 Ohm
3	Static capacity	28000 pF ± 30%
4	Storage temperature	from −30 to +70°C
5	Plate material	copper
6	External diameter *D*	27 ± 0.1 mm
7	Internal diameter *d*	20 ± 0.2 mm
8	Thickness *t*	0.15 ± 0.05 mm
9	Thickness *T*	0.35 ± 0.05 mm

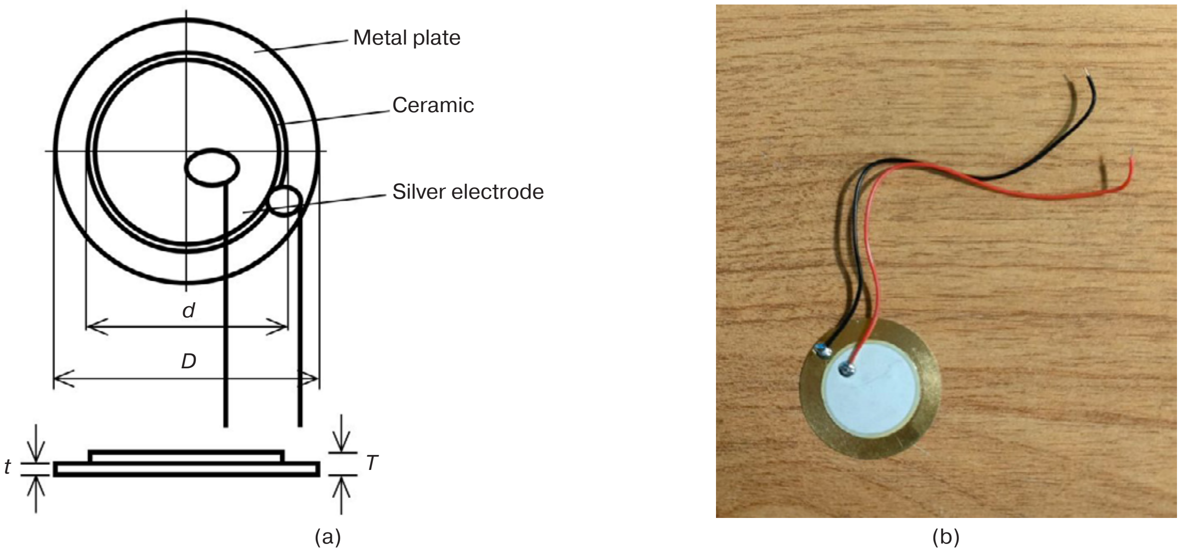

Fig. 10. Drawing (a) and view (b) of the piezoelectric sensor of acoustic signals

In the experimental study, a piezoelectric plate was placed on the MPCB surface and was used to capture sound waves propagating after the solenoid impacts on the MPCB. The working mechanism of the piezoelectric sensor operates in the presence of mechanical motion in the solenoid only. In its absence, no electrical signal is generated. This approach allows the level of external noise to be significantly reduced, since the possibility of signal recording occurs only when the solenoid impacts on the MPCB.

Experimental results in the absence of a defect in PCB

Audacity software is used for acquiring and processing the signals. The software uses a normalized representation of acoustic signals as floating point numbers from −1 to +1; where −1 stands for the minimum possible sound level; while +1 represents the maximum one. This type of representation allows *Audacity* to accurately represent the full range of sound levels, while avoiding any potential loss of accuracy which might occur with integer-based representations. In addition, it simplifies mathematical operations on audio signals such as mixing and processing, since all signals are represented on the same scale.

Firstly, experimental studies are conducted on a two-layer PCB without defects. Three mechanical shocks were generated by the solenoid impacting PCB (with an interval of 3 s between shocks), and the acoustic signals were recorded by the piezoelectric sensor (Fig. 11). The comparison of the resulting signals is shown in Fig. 12. It was found that the signals received after three shocks are the same, thus indicating the PCB material uniformity.

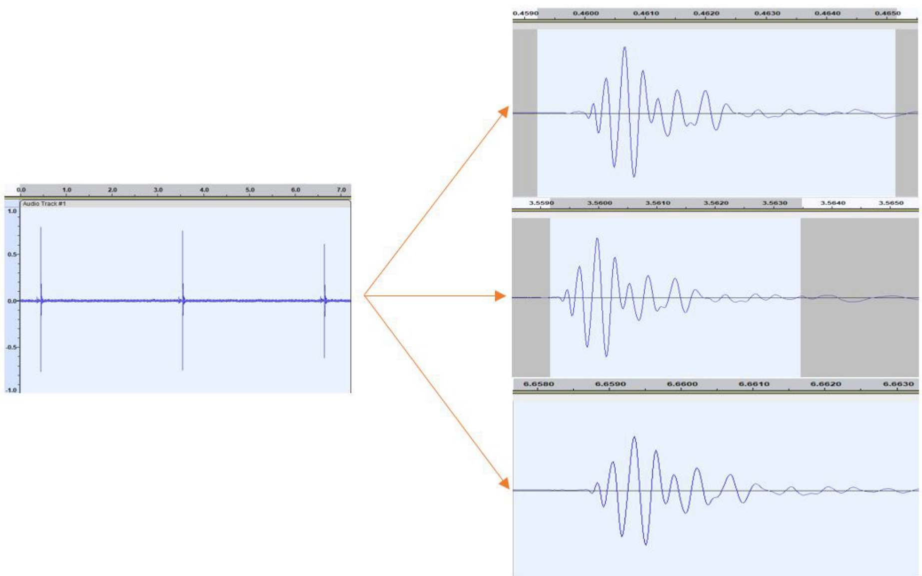

Fig. 11. The signal received from the sensor after 3 shocks in the absence of a defect

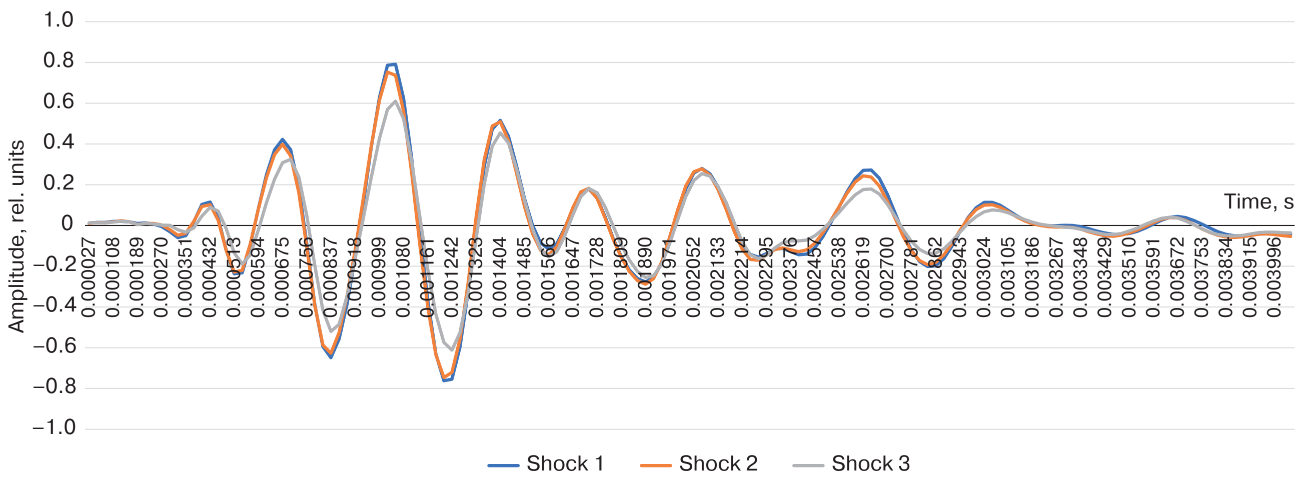

Fig. 12. Comparison of sensor signals after 3 solenoid shocks on PCB without a defect

Experimental results in the presence of a defect in PCB

Next, experiments were performed on a board with a rectangular defect of 3 × 3.7 cm shown in Fig. 13. Three mechanical solenoid shocks on PCB were recorded in the same way (Fig. 14), followed by the comparison of the resulting signals with the signal received in the absence of the defect.

The presence of a defect is detected by comparing the results with the result in the absence of a defect. The comparative result is shown in Fig. 15.

The comparative results show significant differences in signals in the presence and absence of a defect. This indicates that the defect affects the acoustic wave propagation and acoustic signals received by the sensor significantly.

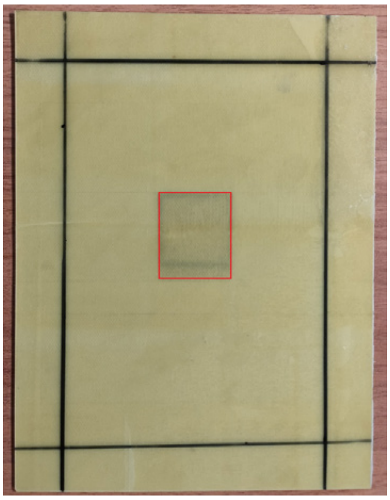

Fig. 13. PCB with a rectangular defect of 3 × 3.7 cm (the defect is marked with a red frame)

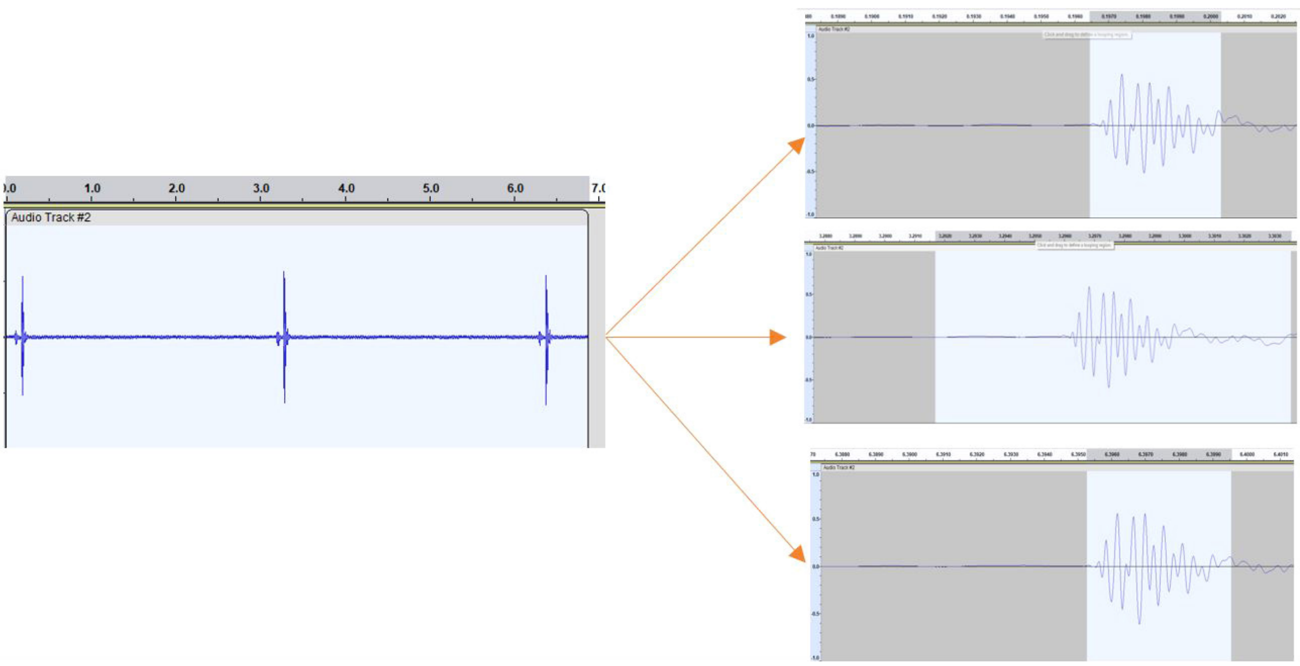

Fig. 14. The sensor signal after 3 shocks in the presence of a defect

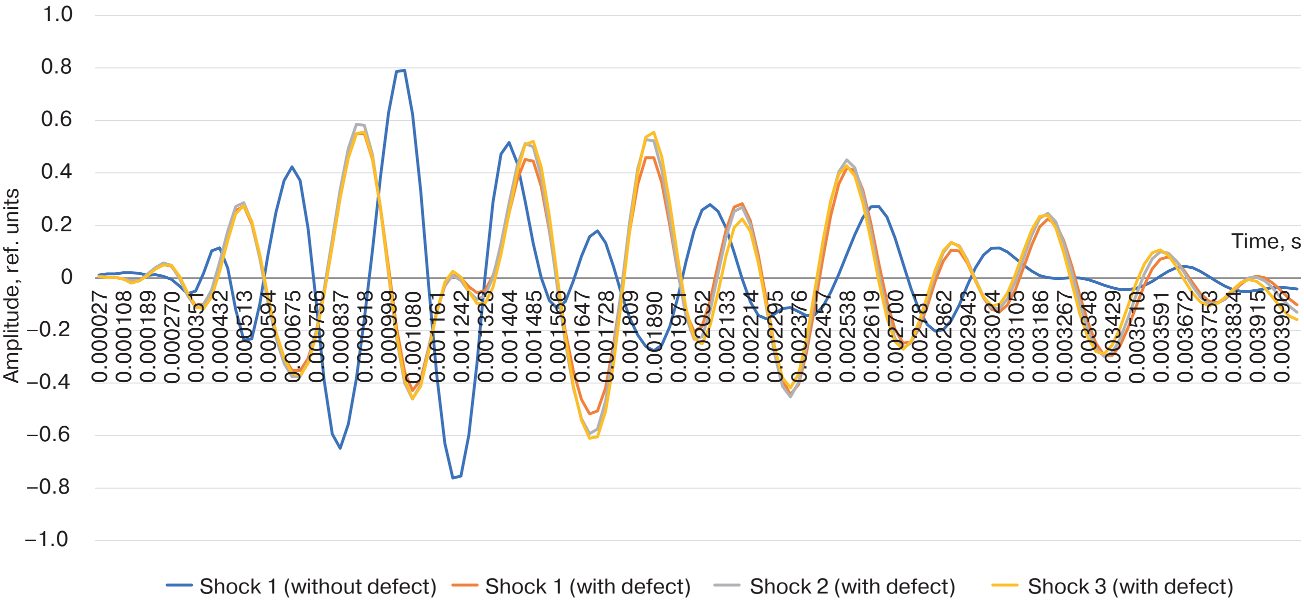

Fig. 15. Comparison of the sensor signals at 3 solenoid shocks on PCB having a 3 × 3.7 cm defect with the signal for PCB without defect

Research of the sensor sensitivity to defects of different sizes

In order to study sensor sensitivity to defect detection, two-layer PCB with defects in the form of squares with different side sizes: 4, 5, 6, and 7 mm were designed. Three mechanical shocks were applied sequentially to MPCB with a defect, while the signals from the sensor were compared with the signal for MPCB without a defect. The research results are shown in Figs. 16–19.

Signals relating to the 4 × 4 mm and 5 × 5 mm square defects were found to be similar to those for PCB without defects, thus indicating the sensor's inability to detect these types of defects. However, the signals for the 6 × 6 mm and 7 × 7 mm square defects show significant differences when compared to PCB without defects, thus indicating the capability of the sensor to detect these types of defects.

Next, the effect of the number of 5 × 5 mm square defects on the sensor's capability to detect defects was investigated. For this reason, PCBs with two (Fig. 20), three, and four 5 × 5 mm square defects were designed. Then three mechanical shocks were applied sequentially to the boards and the sensor signals were recorded (Figs. 21–23).

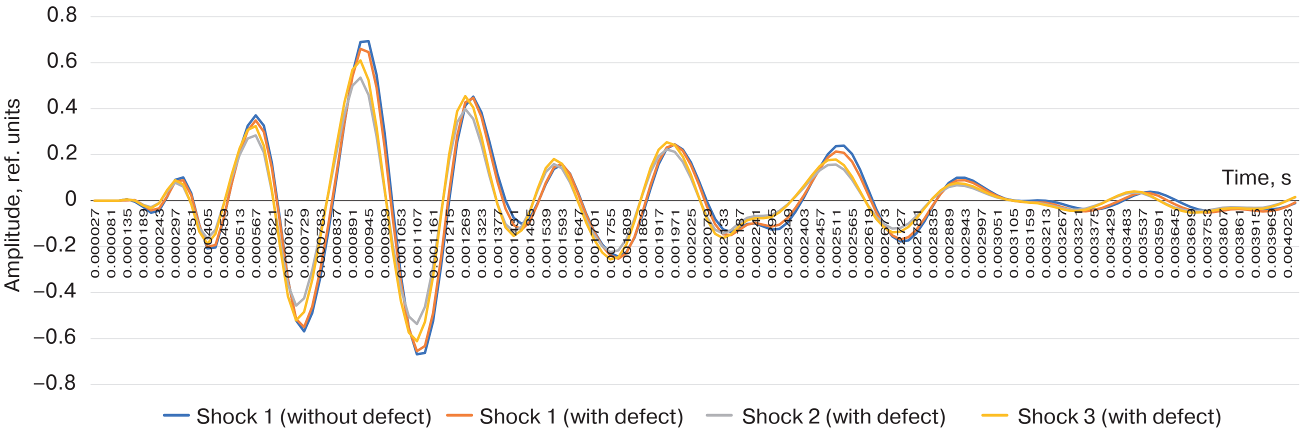

Fig. 16. Comparison of sensor signals for 3 solenoid shocks on PCB having a 4 × 4 mm defect with the signal for a serviceable PCB

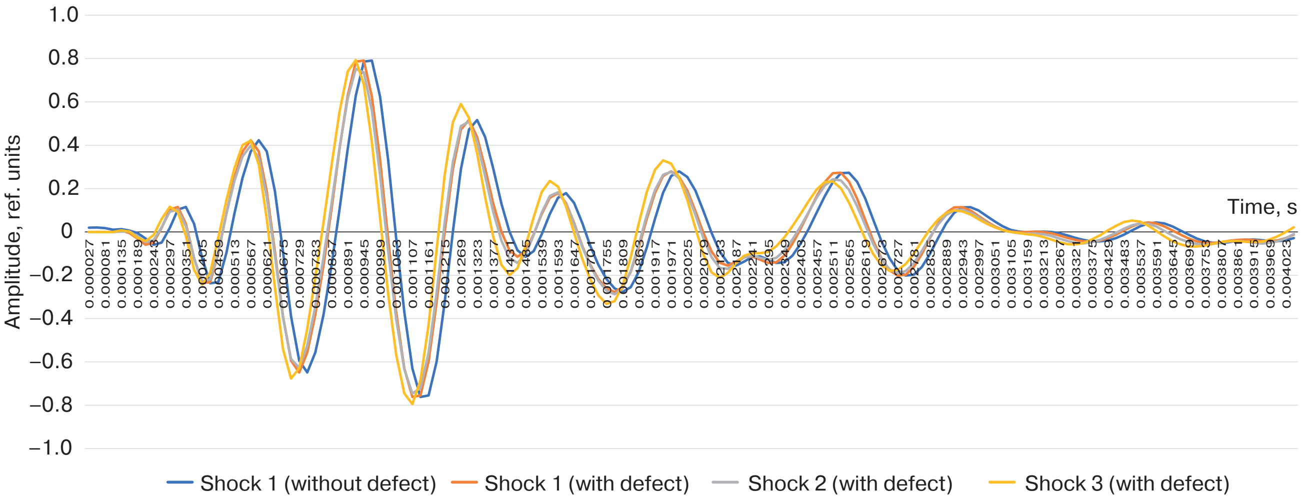

Fig. 17. Comparison of sensor signals for 3 solenoid shocks on PCB having a 5 × 5 mm defect with the signal for PCB without defects

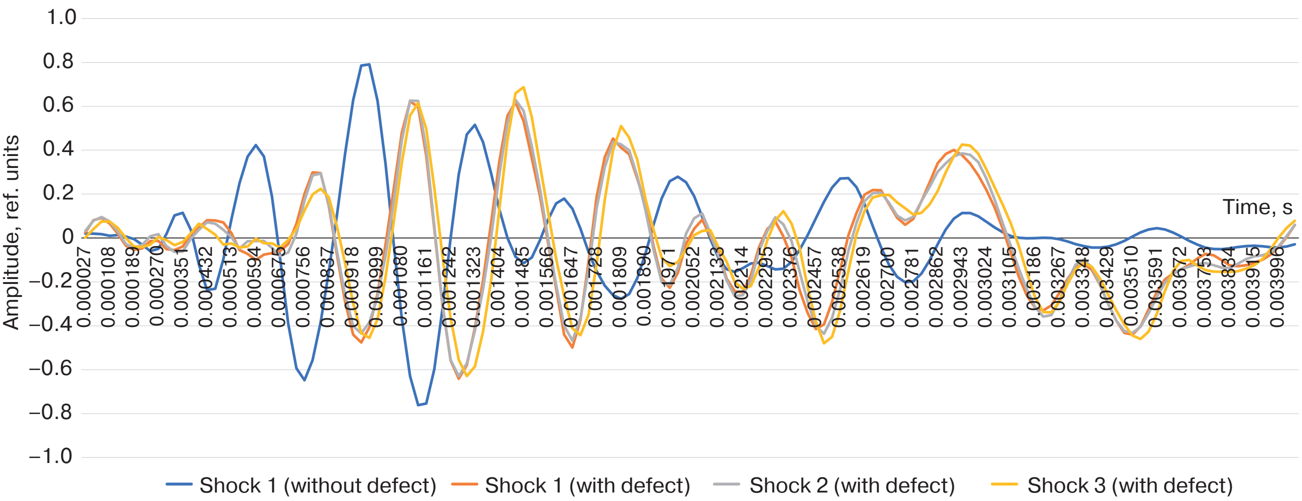

Fig. 18. Comparison of sensor signals for 3 solenoid shocks on PCB having a 6 × 6 mm defect with the signal for PCB without defects

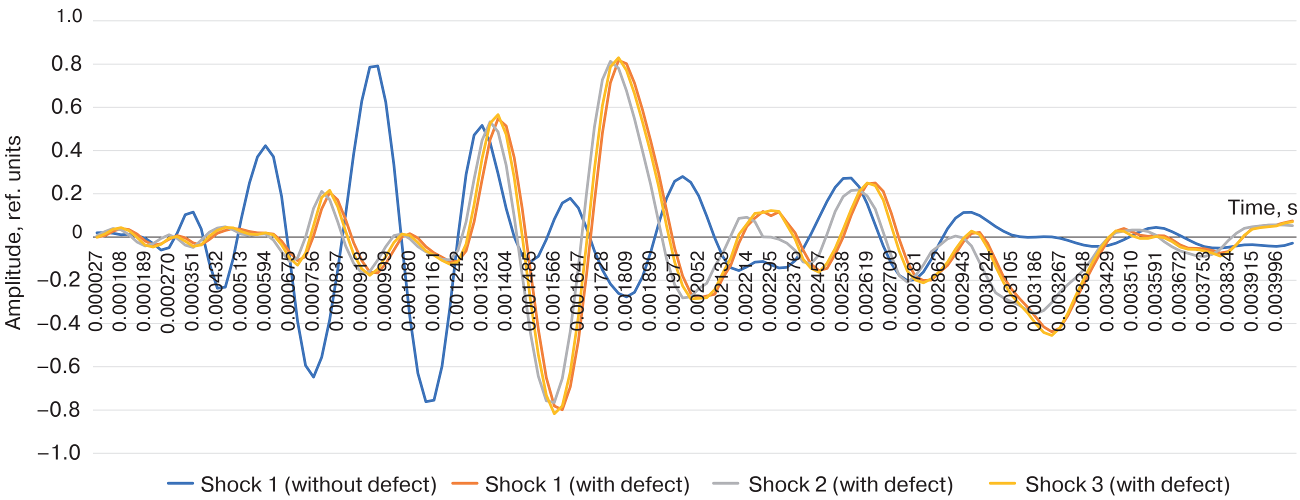

Fig. 19. Comparison of sensor signals for 3 solenoid shocks on PCB having a 7 × 7 mm defect with the signal for PCB without defects

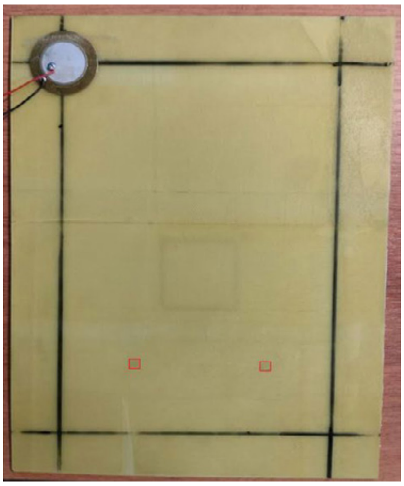

Fig. 20. PCB with two 5 × 5 mm square defects
(marked with a red frame)

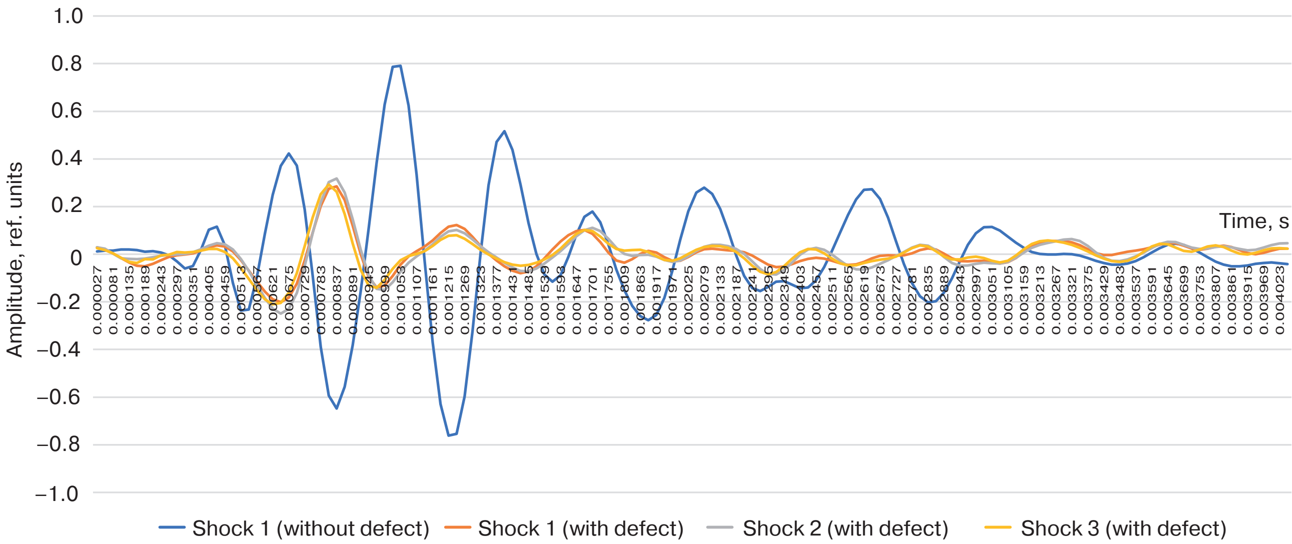

Fig. 21. Comparison of sensor signals for 3 solenoid shocks on PCB having two 5 × 5 mm defects
with the signal for PCB without defects

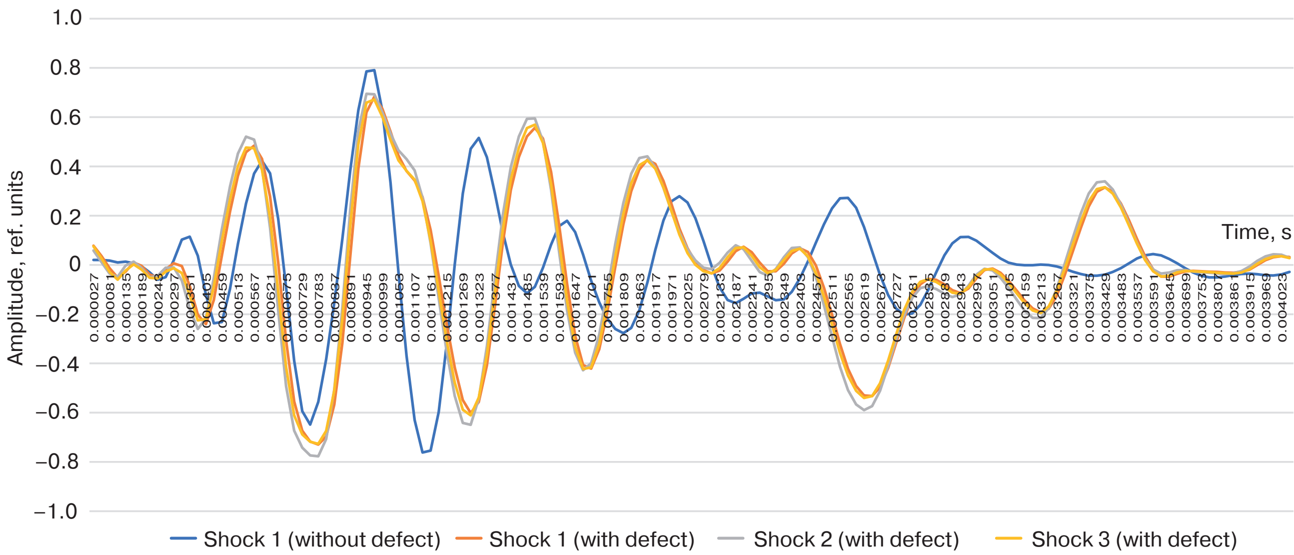

Fig. 22. Comparison of sensor signals for 3 solenoid shocks on PCB having three 5 × 5 mm defects
with the signal for PCB without defects

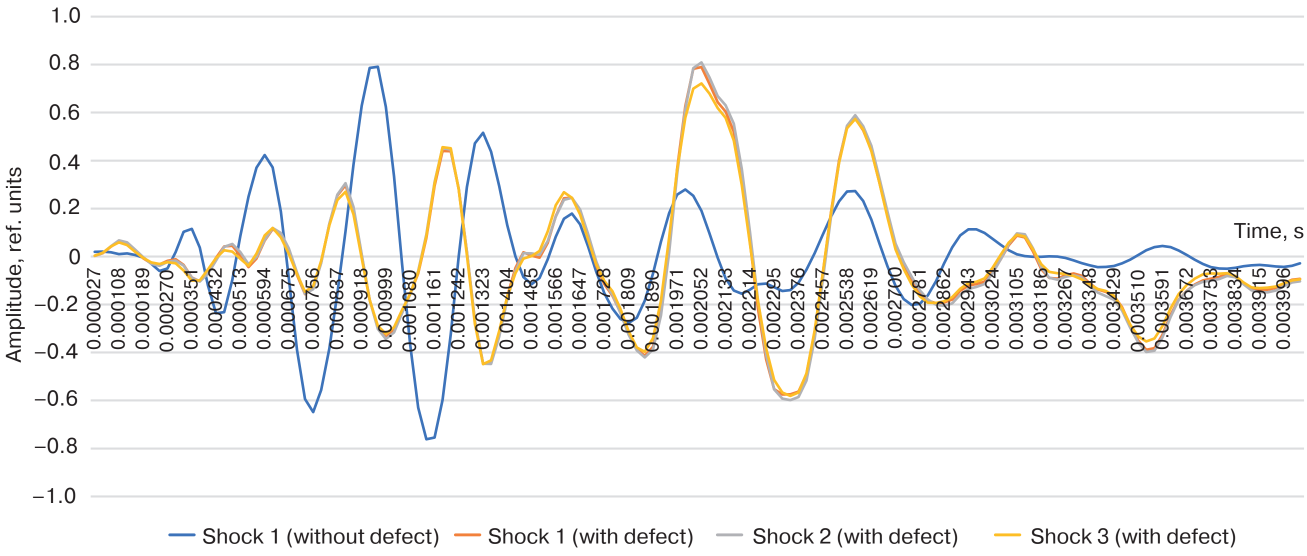

Fig. 23. Comparison of sensor signals for 3 solenoid shocks on PCB having four 5 × 5 mm defects with the signal for PCB without defects

Table 3. Studied defects and possibility of their recognition

Defect	Defect characterization (delamination)	Is it possible to use the AE method?
1	Rectangle 2 × 3 cm	Yes
2	Square 4 × 4 mm	No
3	Square 5 × 5 mm	No
4	Square 6 × 6 mm	Yes
5	Square 7 × 7 mm	Yes
6	Two squares 5 × 5 mm	Yes
7	Three squares 5 × 5 mm	Yes
8	Four squares 5 × 5 mm	Yes

The signals for each case were observed to be significantly different from those of PCB without defects. This suggests that the number of defects can affect the results obtained from the sensor.

The experiments showed the possibility of detecting defects in PCBs using the AE method. However, its sensitivity depends on the size and number of defects. The results also highlight the importance of analyzing the received signals to detect and localize defects in PCBs.

The final results on the possibility of recognizing the studied PCB defects using the AE method are shown in Table 3.

CONCLUSIONS

This paper examined the possibility of applying the AE method for detecting defects as delamination in MPCB. The modeling results for MPCB in serviceable and faulty states with a rectangular defect of 3 × 3.7 cm, as well as experimental studies for different sizes and number of defects were analyzed.

The approach developed herein allows for serviceable and faulty states of PCB to be recognized. It also helps determine the sensitivity of the AE method to the size of the defect being detected.

The research results permit the conclusion that the AE method can be applied in diagnosing the technical condition of MPCB, and that the results of physical tests are comparable to numerical experiments.

The authors continue to conduct further research towards developing a method for detecting defects in MPCB by using the AE method based on artificial neural networks. They also are working towards investigating the application of AE method in tests on the impact of harmonic vibration.

Authors' contribution. All authors equally contributed to the research work.

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