Numerical investigation of innovative nonlinear ultrasonic spectroscopy for detection and sizing interface defects in composites

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Abstract

The article is devoted to innovative nonlinear acoustic techniques of non-destructive testing (NDT) of composites. Modern composites have a very complex inhomogeneous structure with a large number of interface bond-lines. Along these bond-lines there are interface defects, such as delaminations, microcracks, debonding and weakening of adhesive bonds. This leads to the necessity of distinguishing from each other a signal from given defects and a signal from interface bond-lines. The task becomes more complicated because interface defects have a very small thickness of micro or even nanoscopic scale. Conventional techniques of ultrasonic testing have a very low sensitivity of these defects detection. The article describes a novel acoustic-mechanical approach to numerical modeling of nonlinear acoustic interaction of ultrasonic wave with interface defect. The results of computer simulation of this nonlinear acoustic interaction are analyzed. A simple technique of nonlinear ultrasonic spectroscopy is suggested for detecting and sizing the interface defects.

Keywords: composite material, interface defect, nonlinear wave/defect interaction, nonlinear ultrasonic spectroscopy, modeling and simulation, numerical method, opposite phased transducer, subharmonic and superharmonic, period-doubling bifurcation.

Introduction

Novel composites are advanced engineering materials with wide application prospects: from sporting goods up to aerospace industry and nuclear power. For example, in commercial aircraft such as the A380 and Boeing 787 fiber metal laminates (Glare®, TiGr®) and carbon fiber composites (CFRP, CFRP/Titanium and CFRP/Aluminum hybrid materials, etc.) are widely used. Ceramic matrix composite structural systems are desirable for shielding nuclear power plants. Interfaces in composites influence the material's mechanical behavior significantly and limit their useful properties. This is resulted from interface defects along bond-lines of various elements of composite material structures: delaminations, microcracks, debonding and weakening of adhesive bonds. These defects occur both during manufacturing and operating composite materials.

Interface defects have a very small thickness of micro or even nanoscopic scale. Opposite surfaces of these defects are in close proximity, or even touch each other. By the action of external ultrasonic wave acoustic transparency and reflectivity of interface defect are evolved in space (along the defect's surface) and in time due to nonlinear wave/defect interaction. Therefore conventional techniques of ultrasonic NDT have very law sensitivity of detection of nonlinear interface defects because they are almost transparent to ultrasound.

During the last 10 years the techniques of composite testing have used ultrasonic phased array and laser interferometer for in-production and in-service tasks. These techniques either don't take into account nonlinear wave/defect interaction [1-4] or use complex non-standard equipment [5, 6]. The article suggests a simple technique of ultrasonic spectroscopy for detection and sizing nonlinear defects considered above. Using only standard electronic equipment is one of the advantages of this technique. Therefore the technique will find its worth in industrial applications of NDT.

Cognitive barrier for conventional theory and application of ultrasonic NDT

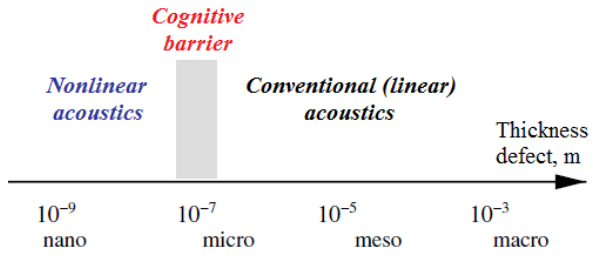

Fig.1. **Illustration of the applicability of linear and nonlinear acoustics for NDT, depending on the thickness defect**

Before modeling nonlinear interface defect we should understand the conditions leading to transformation of conventional (linear) behavior of defect to nonlinear one by the action of external ultrasonic wave. Various known models agree that a defect may be completely closed by the compressing load. The load produces a strain in the surrounding medium approximately equal to the ratio of the defect thickness h to its length L at the equilibrium state. This actually means that a defect is approximately L/h times softer than the surrounding medium [7]. Thus for the defect of millimetric length $L = 10^{-3}m$ and submicrometric thickness $h = 10^{-7}m$ compression half-wave with typical acoustic strain $\varepsilon = 10^{-4}$ produces its closing with respect to equilibrium state. Defect becomes transparent to ultrasound. Otherwise tensile half-wave produces gap between the defect surfaces, often referred to as "defect opening". In this case ultrasonic wave is reflected from soft boundary of defect. This is resulted in the state referred to as "non-classical" nonlinear wave/defect interaction (or contact acoustic nonlinearity) where theory and application of conventional (linear) acoustics meet with an insurmountable cognitive barrier (Fig.1). Here the main conventional postulates are not applicable because they are based on the principle of superposition of waves:

- non-interacting secondary sources of waves (Huygens–Fresnel principle and Kirchhoff integral theorem);
- decomposition of complex wave on non-interacting sine-wave harmonics (Fourier transform).

This cognitive barrier may be completely overcome by a nonlinear intelligence that has been formed as Nonlinear Science during past few years. Here numerical methods should be used for computer simulation because analytic methods either do not provide an appropriate solution (so the discussed nonlinearity is also called "non-analytical") or require a significant simplification of the original nonlinear system. On the other hand experimental research is very expensive.

Nonlinear interface modeling

Nowadays to obtain physic-mathematical description of nonlinear wave/defect interaction we usually use:

- mechanical approach based on spring-mass modeling;
- approach of electromechanical analogies, leading to mechanical diode-based modeling.

The article proposes a more clear novel acoustic-mechanical approach to nonlinear interface modeling. The separations between defect surfaces and the form of the asperities, which can be opened or closed by incident ultrasonic wave, are different for various local pairs of interface points along interface defect.

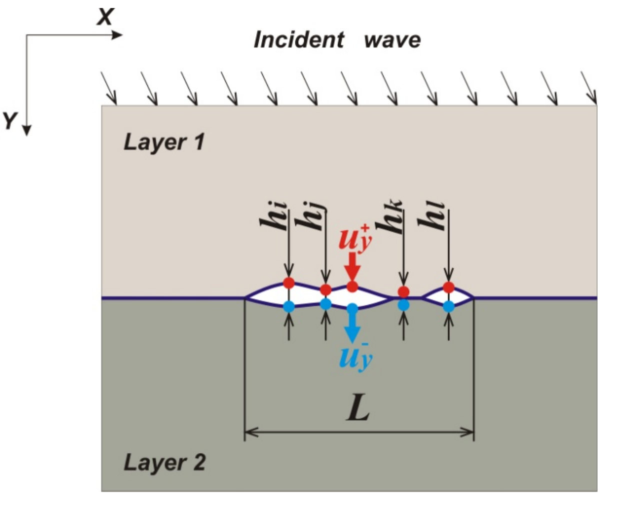

Fig.2. **Interface defect schematization: h and L – equilibrium thickness and length, u_y - normal particle displacement by the action of incident wave, ●● - pair of interface points**

Fig. 2 shows that in real defects distances between interface points for various pairs are not equal, for example $h_i \neq h_f \neq h_t$ and $h_k = 0$. By the action of incident wave defect surfaces are displaced. For initial study let defect surfaces be absolutely smooth. Consider the local transfer of wave energy between two layers of composite material. It depends on the difference between the values of the normal particle displacements u_y^+ and u_y^- for the corresponding pair of interface points. Obviously the opening/closing of mechanical contacts between interface points corresponds to the absence/presence of nonlinear acoustic contact (NAC) between them:

$$\text{NAC is absent, if } \begin{cases} u_y^+ < 0 \text{ and } u_y^- > 0 \\ u_y^+ - u_y^- < h \text{ for } u_y^+, u_y^- > 0 \,. \\ \left|u_y^-\right| - \left|u_y^+\right| < h \text{ for } u_y^+, u_y^- > 0 \end{cases} \quad (1)$$

NAC is present in all other cases.

This condition takes into account the evolution of acoustic transparency and reflectivity as a function of variability of thickness h along nonlinear defect. Condition (1) for "non-classical" acoustic nonlinearity can be easily included in the numerical method described in [8].

Remarks on numerical solution

Taking into account the transverse orientation of absolutely smooth interface defect with respect to the direction of incident wave, for initial study consider only the longitudinal ultrasonic wave/defect nonlinear interaction without regarding mode conversion. The initial first-order differential equations are written in velocity-stress form. Then the motion equation and the continuity equation become:

$$\frac{\partial v}{\partial t} + \frac{1}{\rho}\operatorname{grad}\sigma = g \,, \quad (2)$$

$$\frac{\partial \sigma}{\partial t} + \rho c^2 \operatorname{div} V = q \,, \quad (3)$$

where σ – elastic stress of longitudinal ultrasonic wave, $V = (v_x, v_y)$ - particle velocity vector, ρ – material density, c – velocity of longitudinal wave, g and q - external actions, t - time.

Condition (1) and Eq. 2, 3 are associated by numerical integration:

$$u_y^{\text{new}} = u_y^{\text{old}} + v_y^{\text{new}} * \Delta t \,, \quad (4)$$

where new and old – indexes for new and previous steps of integration, Δt - step of integration in time.

A numerical algorithm for solving the system of Eq. 1– 4 was described in the article [8]. It is differing a little only at the phase of nonlinear defect opening when defect becomes soft boundary and condition (1) is true. In our case, the discrete analogue of the continuity equation (3) along this defect is excluded from the system of equations. Rapid exclusion (3) from the equation system leads to generating false high-frequency oscillations of small amplitude. To damp these false high-frequency oscillations the artificial viscosity is added to the numerical algorithm.

Computer simulation and discussion

When ultrasonic pulse passes through a nonlinear defect the tensile half-wave has some delay and the compression half-wave doesn't have any delay [8]. Further numerical investigation prompted us to use this phenomenon to amplify nonlinear processes in wave/defect interaction. Fig. 3 shows computer simulation results of passing ultrasonic pulses with opposite polarity (I, II) through a nonlinear interface.

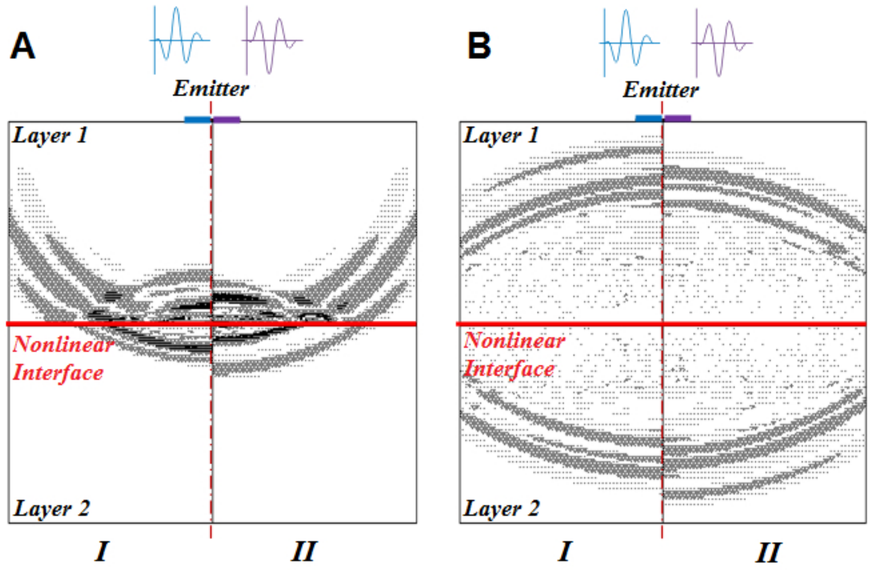

Fig.3. **Comparison of passing ultrasonic pulses with opposite polarity (I, II) through a nonlinear interface: A – at the moment of wave/defect interaction, B – after wave/defect interaction**

We clearly see the tensile half-wave is delayed for passed ultrasonic pulse and the compression half-wave is delayed for reflected one.

Carried out simulations allow us to see that application of opposite phased transducer (OP-probe) [9] has a high efficiency in amplifying the nonlinear processes for nonlinear ultrasonic spectroscopy (NUS) of composite structures. Firstly OP-probe was designed for ultrasonic technique of precise localization and sizing of linear defects [10]. OP-probe consists of positive and negative emitters generating two phase-reversed pulses with fundamental frequency f_0 (Fig.4).

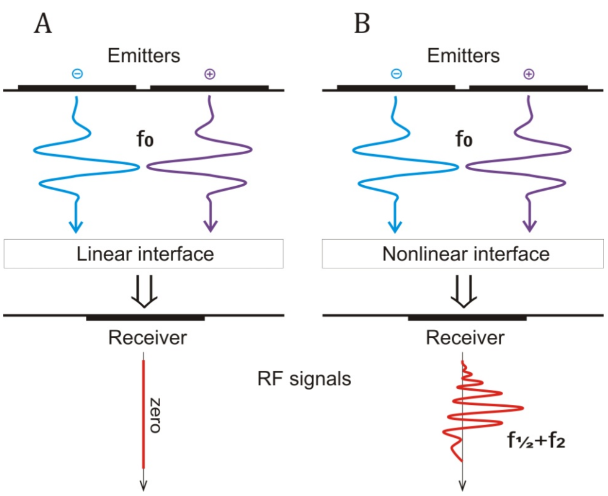

Fig.4. **Illustration of OP-probe radiating linear (A) and nonlinear (B) interface**

While OP-probe radiating linear interface or defect (Fig.4-A), by the sum of two echoes of reversed phases, the received RF-signal is zero. For ideal nonlinear interface the received RF-signal includes subharmonic $f_{1/2} = 1/2 f_0$ and superharmonic $f_2 = 2 f_0$ (Fig.4-B). Thus OP-probe "damps" fundamental harmonic f_0, which characterizes the linear component of wave/defect interaction, and amplifies the amplitude of subharmonic $A(f_{1/2})$ and superharmonic $A(f_2)$, thereby amplifying the nonlinear component of wave/defect interaction significantly.

Let us consider two examples to evaluate efficiency of OP-probe for NUS of complex composite structures. The first example concerns testing carbon fiber composites (CFRP) (Fig.5). The second example concerns testing fiber metal laminates Glare® (Fig.6). These complex composite structures are widely used in modern aerospace industry.

In the first example one case corresponds to using conventional probe (Fig.5-A), another case corresponds to using OP-probe (Fig.5-B). Compare the obtained amplitude-frequency spectrums of received RF-signals for testing CFRP. Due to different orientation of carbon fiber filaments there exist delaminations with non-intermittent (I) and intermittent structures (II, III). Moreover intermittent structures may include nonlinear microdelaminations (II) or various combinations of nonlinear microdelaminations with linear (non-transparent) ones (III).

For computer simulation the following parameters are used:

- simulation area is 10λ at 7λ, where λ - wavelength;
- material density $\rho = 2{,}1 \times 10^{-3}\, g/m^3$ and velocity of longitudinal ultrasonic wave $c = 2{,}85$ mm/µs;
- total size of probe equals 5λ;
- parameters of delamination intermittent structure are $l_1 = l_2 = 0{,}25\lambda$;

- for initial study equilibrium thickness h of nonlinear delaminations is zero.

In Fig. 5 we clearly see that OP-probe amplifies the amplitude of superharmonic $A(f_2)$ with respect to the amplitude of fundamental harmonic $A(f_0)$ and activates generating the subharmonics $f_{1/2}$ Moreover for delamination structures of I and III types the amplitude of fundamental harmonic $A(f_0)$ for OP-probe is close to zero.

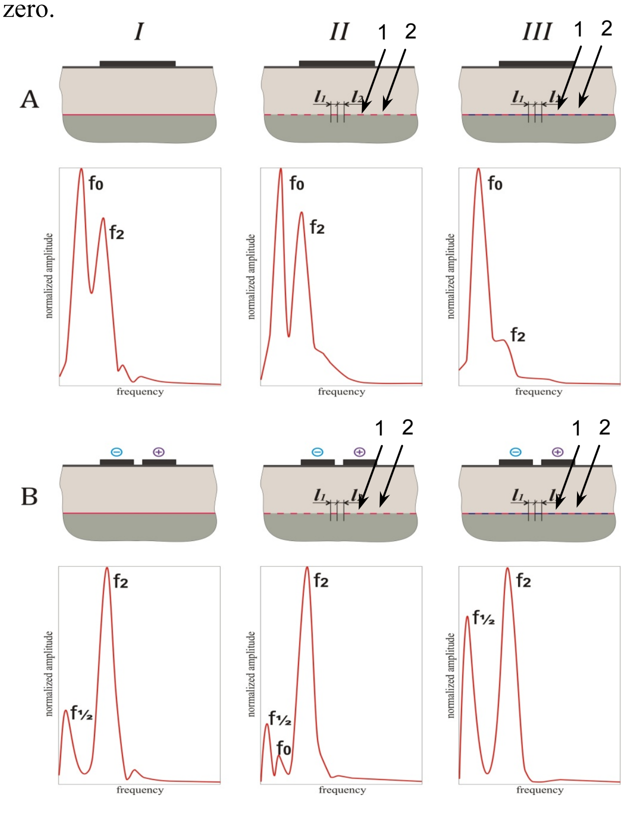

Fig.5. **Comparison between conventional probe (A) and OP-probe (B) for detection CFRP-delaminations of various structures (I, II, III): 1 (red) - nonlinear part of delamination; 2 (blue) - linear (non-transparent) part of delamination (red and blue in the electronic version)**

These results led to the idea of creating novel techniques NUS, based on analyzing ratio of the amplitudes of fundamental harmonic $A(f_0)$, subharmonic $A(f_{1/2})$ and superharmonic $A(f_2)$.

Composite structures are often complex and formed by layers of dissimilar materials. Examples of such structures are fiber metal laminates Glare®, which include aluminum alloy and glass fiber reinforced plastic lamina. The second example (Fig.6) illustrates the developed novel technique of NUS for detection and sizing interface delamination in Glare®.

For computer simulation the following parameters are used:

- simulation area is 10λ at 7λ, where λ - wavelength in aluminum alloy;
- for aluminum alloy (layer 1) material density $\rho = 2{,}78 \times 10^{-3}$ g/mm^3 and velocity of longitudinal ultrasonic wave $c = 6{,}42$ mm/µs;
- for glass lamina (layer 2) material density ρ = 1,98 $\times 10^{-3}$ g/mm^3 and velocity of longitudinal ultrasonic wave $c = 3{,}96$ mm/µs;
- total size of probe equals 3λ;
- distance from probe to interface equals 6λ;
- for initial study equilibrium thickness h of nonlinear delamination is zero.

The obtained results demonstrate high efficiency of novel technique NUS based on analyzing ratio of the amplitudes of harmonics $A(f_2)/A(f_0)$ for the received RF-signals in comparison with conventional amplitude technique. In Fig. 6 we clearly see significant increasing in sensitivity of this technique for detection of defect tip. Moreover using OP-probe leads to amplifying the ratio $A(f_2)/A(f_0)$ when it moves over nonlinear defect. A conventional probe doesn't provide such amplifying.

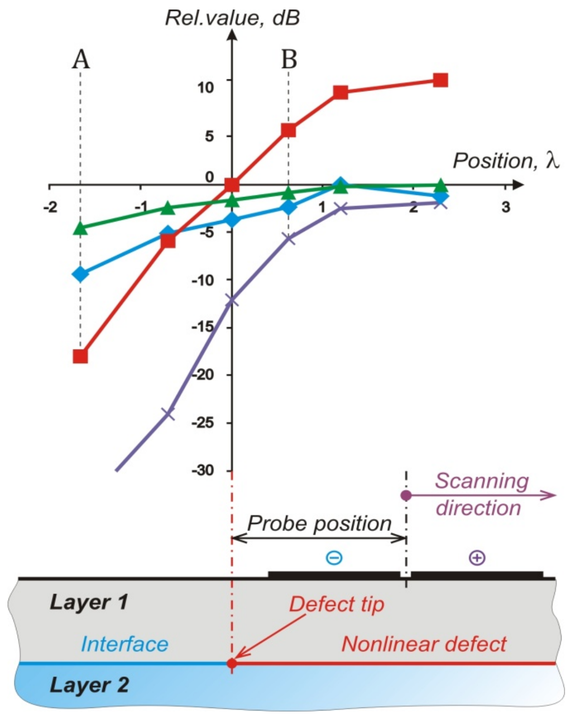

Fig.6. **Comparison of amplitude and spectral techniques for detection of interface delamination in Glare ®: ▲ , □ amplitudes of received RF-signals for conventional probe and OP-probe; + , ■ - ratio of amplitudes of harmonics $A(f_2)/A(f_0)$ of RF-signals for conventional probe and OP-probe**

Fig. 7 shows dynamics of relative changing amplitudes of fundamental harmonic $A(f_0)$, subharmonic $A(f_{1/2})$ and superharmonic $A(f_2)$ while OP-probe is moving over a tip of nonlinear defect. OP-probe positions correspond to notations in Fig. 6.

After OP-probe axis passes defect tip, arising of subharmonic $f_{1/2}$ (position O) is followed by rapid increasing in its amplitude $A(f_{1/2})$ (position B). This results from the beginning of interaction between nonlinear defect and the second phase-reversed pulse radiated by OP-probe. So period-doubling bifurcation is occurred. This phenomenon isn't studied enough to apply in NDT but it is of great practical interest. Subharmonic waves are generated only at nonlinear parts of defect whereas superharmonic waves may have many different nonlinear

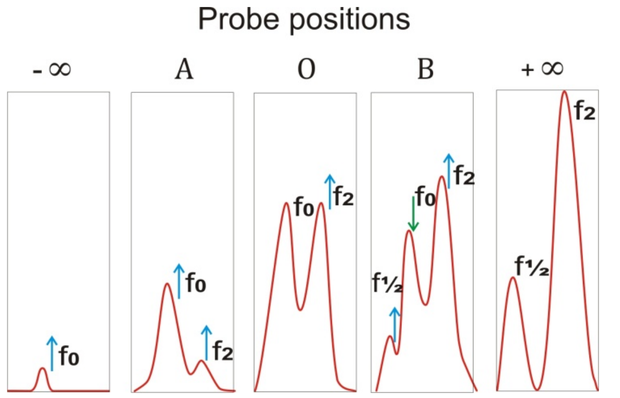

Fig.7. **Relative change of amplitudes of fundamental harmonic $A(f_0)$, subharmonic $A(f_{1/2})$ and superharmonic $A(f_2)$ for OP-probe**

sources (piezoelectric transducer, coupling liquid, electronics etc). Since subharmonic waves have much higher signal-to-noise (S/N) ratio than superharmonic waves, they are potentially useful for precise sizing closed defects. Obviously numerical methods let this phenomenon be applied in innovative techniques of NDT.

In article the examples concern the practical tasks of aerospace industry. Obviously the obtained results are suitable for other industrial applications of NDT, for example, detection of closed micro-cracks in composite tube for cooled system of nuclear power plants [11, 12].

Conclusions

Summarizing the above results we come to the following:

The article proposes a more clear novel acoustic-mechanical approach to nonlinear interface modeling. This approach takes into account the evolution of acoustic transparency and reflectivity as a function of variability of thickness h along nonlinear defect. By using such an approach numerical interface models are developed. These models can be used both to understand the fundamental physical processes underlying the nonlinear acoustic effects, and to develop qualitative or quantitative techniques for non-destructive evaluation of micro-inhomogenous materials.

2. Simulation results show efficiency of novel techniques for nonlinear ultrasonic spectroscopy (NUS). These techniques are based on analyzing ratio of the amplitudes of fundamental harmonic $A(f_0)$, subharmonic $A(f_{1/2})$ and superharmonic $A(f_2)$.

3. A novel technique of NUS is proposed for detection and sizing interface defects in composite materials by using opposite phased transducer (OP-probe). Due to using OP-probe some energy is transferred from fundamental harmonic in subharmonic and superharmonic. This improves sensitivity of NUS by increasing the S/N ratio at registering superharmonics and generates period-doubling bifurcation for subharmonics.

4. OP-probe has a very simple design compared with ultrasonic phased array (for ex.), allows air-coupled measurements, and requires only standard electronic testing equipment. All this contributes to substantial cost savings during the NDT.

It should be noted that computer simulation adds a new dimension to scientific investigation and has been established as investigative research tool which is as important as traditional approaches to theory and application.

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Inovatyvios netiesinės ultragarsinės spektroskopijos, skirtos tarpsluoksniniams defektams surasti ir matmenims įvertinti, skaitmeninis tyrimas

Reziumė

Aprašomi inovatyvūs akustiniai neardomieji kompozitų bandymų metodai. Šiuolaikiniai kompozitai turi labai sudėtingą nehomogeninę struktūrą ir joje labai didelį tarpsluoksninių sujungimo linijų skaičių. Išilgai šių linijų gali būti įvairių tarpsluoksninių defektų, tokių kaip atsisluoksniavimai, mikroplyšiai arba klijuotinių sujungimų susilpnėjimas. Todėl svarbu atskirti signalus nuo sujungimo linijų ir konkrečių defektų. Šis uždavinys labai sudėtingas, nes tokie defektai yra labai ploni - mikro- arba nanometriniai. Tradiciniai ultragarsiniai metodai tokiu atveju nepakankamai jautrūs. Straipsnyje aprašomas naujas netiesinės akustinės bangos sąveikos su tarpsluoksniniu defektu skaitmeninio modeliavimo metodas. Šis paprastas tokiems defektams surasti ir matmenims nustatyti metodas pagrįstas netiesine ultragarsine spektroskopija.

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