Nondestructive Testing of Thin Composite Structures for Subsurface Defects Detection Using Dynamic Laser Speckles

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ABSTRACT
A novel nondestructive testing method for subsurface defects detection in thin composite structures using dynamic laser speckles is proposed. In this method, a laminated composite panel containing a subsurface defect is excited by a frequency scanned ultrasonic (US) wave and is illuminated by an expanded laser beam. If one of resonant frequencies of the defect coincides with the US frequency, a local area (a region of interest or ROI) of the panel optically rough surface, placed directly above the defect, begins to vibrate, and the sequences of difference speckle patterns containing the spatial response from the defect are recorded. The formation of this response is caused by both decorrelation and speckle blurring within the local speckle pattern generated by the vibrating ROI at its opposite tilts. The accumulation of difference speckle patterns increases the intensity of the spatial response. This method differs from similar ones in that defects are detected using dynamic speckle patterns of a composite rough surface, illuminated by a single expanded laser beam. The verification of the proposed method was performed using a hybrid optical-digital experimental breadboard to test composite panels containing artificial subsurface defects, as well as a real defect.

KEYWORDS
Subsurface defects detection; laminated composite; dynamic speckles; speckle pattern; tilt angle

1. Introduction
Composite materials are widely used in machines, aircrafts, vehicles, buildings, etc. However, the presence of several components in composites with different physicochemical and mechanical characteristics contributes to the formation of various surface and subsurface defects, including delaminations, cracks, voids, inclusions, matrix cracking, etc. Therefore, the problem of detecting subsurface damage and defects in composite structures is very relevant [1]. Several nondestructive testing (NDT) techniques can detect subsurface defects in composites with a certain level of confidence [2]. They also include hybrid optical-acoustic NDT techniques, in which the composite
structure is excited by an ultrasonic (US) wave, and its probing is carried out using optical radiation. These techniques can be divided conventionally on two basic directions. The first direction uses scanning laser beam to monitor the composite surface excited by US waves, and the second one uses the expanded laser beam illumination of the excited surface area to record fringe patterns (speckle interferograms), shearograms, holograms, and speckle patterns. Resonance spectroscopy technique that uses a laser vibrometer scan of each point of a studied specimen surface area is a promising representative of the first direction [3-5]. This technique is based on the concept of Local Defect Resonance [3,4] and allows detecting subsurface defects at their resonance frequencies. The second direction analyzes accumulated fringe patterns of the surface area and potentially possesses a higher operational speed. Additive-subtractive electronic speckle pattern interferometry (ESPI)/shearography [6,7], synchronized reference-updating ESPI [8], and time-average digital holography [9] techniques use speckle interferograms, shearograms, and digital holograms of the composite surface excited by US waves for detection of subsurface defects. Experimental breadboards of interferometric and holographic systems created on the basis of these techniques were developed for testing artificial defects made in the form of flat-bottomed holes [6-11] and real subsurface defects [11]. Let us note that such interferometric and holographic systems are very sensitive to external vibrations and air/heat fluxes. The shearographic system based on the additive-subtractive ESPI technique is insensitive to vibrations [7,10]; however, the identification of subsurface defects in such systems still remains a problem that is often difficult to solve. Another problem attributable to these systems consists in speckle decorrelation of two subtracted fringe patterns. This obstacle does not allow to detect relatively large defects due to the low visibility of correlation fringes or their absence, if the vibration amplitudes of a surface area above the subsurface defect become more than several tens of microns. In addition, all these systems have complex equipment that complicates or prevents their application for NDT of composite structures in real setting. Let us note that the accumulation of speckle patterns obtained by illumination of the studied test surface only by an expanded laser beam without a reference beam is widely used in speckle imaging techniques to detect the blood flow phenomena and agro-cultural products aging [12-14].

Therefore, an urgent problem is the development of simpler methods and technical means suitable for use in natural conditions. To this end, we propose a NDT method for detecting subsurface defects in laminated composite structures excited by US waves using an optical imaging system, in which only a single expanded laser beam illuminates the composite optically rough or spray-painted surface. Dynamic speckle patterns generated by light reflected from the surface produce the final flaw map after digital processing. The experimental breadboard that implements the proposed method has
confirmed its reliability. This method is close to other laser speckle imaging techniques that use the tilt of a surface area to analyze vibrations and thermal stresses in beams, membranes, and other specimens and structural elements. These techniques are based on the speckle decorrelation of tilted moving rough surfaces. Gregory [15] has shown how tilt topology variations on a scatter surface may be separated from linear displacements. Jones and Wykes found the dependence between complete speckle decorrelation and value of the out-of-plane surface tilt [16]. Spagnolo et al. showed that the out-of-plane tilt of a vibrating specimen surface leads to speckle decorrelation between two recorded speckle patterns, generated by the static rough surface and the same vibrating one [17]. The places of surface tilts of the square aluminum plate surface corresponded to bright spots indicating the occurrence of speckle decorrelation. Wong [18] studied the influence of surface tilt on the speckle decorrelation in defocusing image plane during flexural surface vibrations of steel cantilever beam and a circular plate with clamped periphery. Keene and Chiang [19] proposed the technique for imaging the anti-nodes of vibrating square membranes surfaces using the LASCA technique [12] and the gradient vector for localization of the contrast reduction. However, in these techniques, the problem of detecting subsurface defects in composite materials was not considered or mentioned. Most likely, Bruno et al. [20] were the first to demonstrate the ability of the speckle decorrelation technique produced by the surface tilting to detect a subsurface defect in a composite. During the experiment, only the object laser beam illuminated the surface of the carbon epoxy composite laminate containing debond, intentionally introduced during the manufacturing cycle. The debond, sized about 10 × 10 mm, was thermally stressed by an infrared lamp. The spatial response from the debond was initiated after the digital subtraction of two speckled images captured during the transient thermal deformation. Authors noted that this technique is efficient if the high-power (about 6 W) single mode laser source is used. The need to use a powerful infrared lamp and a powerful laser to implement this method significantly limits the possibilities of its using in full-scale and even in laboratory conditions. This technique does not use advantages of the additive-subtractive ESPI/shearography [6,7] and synchronized reference-updating ESPI [8] techniques, which allow to produce the final flaw map by accumulating the similar fringe patterns recorded during the US excitation of the studied composite panel.

The proposed NDT method for subsurface defects detection in laminated composite structures accumulates the advantages of the above-mentioned ESPI techniques and the laser speckle imaging ones. In particular, it combines the accumulation of initial speckle patterns to increase the intensity of final flaw maps, on the one hand, with speckle decorrelation of a local speckle pattern (LSP) generated by a tilted local area (a region of interest or ROI) of the vibrating composite optically rough surface located above the defect, on the
other. This combination allows a fundamentally new result to be obtained, since the speckle decorrelation leads to speckle blurring within the LSP and its extraction from the surrounding background in the final flaw map. On the contrary, speckle decorrelation within the local fringe pattern of the flaw map is extremely undesirable for the aforementioned ESPI, shearography, and digital holography techniques, since in this case the flaw map is completely degraded and the spatial response from the defect disappears. Thus, this method is novel and has distinctive characteristics in comparison with similar techniques.

2. Method for Subsurface Defects Detection

Techniques for analyzing speckle fluctuations have been successfully used to research blood flow [12], freshness and aging of agricultural products [14,17], kinetics of a surface corrosion [21], paint drying [22], and in-plane rotation of diffuse objects [23]. These techniques use the time evolution of laser speckles generated by the surfaces of biological or technical objects that are stationary or perform in-plane motions. Our method of subsurface defects detection in laminated composite structures is based on out-of-plane motion of separate local surface areas, that is ROIs, placed directly above the subsurface defects.

As shown in [3–5,24], the flexural US waves arise in thin composite structures and excite flat bottom defects at their resonance frequencies. According to the LDR concept [3,4], the constructive interference of flexural waves inside the defect leads to the formation of standing waves at resonant frequencies [5]. If the US wave excites a composite structure at the resonant frequency of the sought subsurface defect, the out-of-plane resonant vibrations of the ROI occur in a direction transverse to the direction of propagation of the US wave. Since the US harmonic excitation works in a frequency scanning mode, all defects that possess resonant frequencies in the given range became generate vibrations of the ROI. The optically rough surface of a given area of the composite structure is illuminated with coherent or quasi-coherent light, and a series of speckle patterns generated by this area can be recorded in an optical system at any moment of time during the ROI vibrations. Typically, oscillations at frequencies that are resonant for a subsurface defect located in this area are absent or very small outside the ROI placed above this defect. The spatial structure and contrast of the local part of the speckle pattern, in other words, the local speckle pattern (LSP) generated by the ROI, changes synchronously with the ROI vibrations. The rest of the speckle pattern area generated by the surface part surrounding the ROI remains virtually
unchanged. This difference between the LSP and the rest of the speckle pattern area make it possible to select the LSP or its part and to detect the subsurface defect.

Analysis of publications devoted to temporal changes in dynamic laser speckles during surface vibrations suggests that two factors mainly affect the structure and contrast of speckles. The first factor is caused by shift of the spatial frequency in the lens aperture plane leading to the transformation of the speckle pattern spatial structure [20,25,26]. The second one is caused by the out-of-plane motion of the diffuse surface, which directly leads to decrease in the speckle contrast and to speckle blurring [27].

Transformation of the LSP generated by the ROI during its vibrations occurs due to the ROI elements tilt, leading to a shift of the spatial frequency in the lens aperture plane located in the optical imaging system [25,26]. Decorrelation between the transformed LSP and the initial one can result in the local speckle contrast reduction in the resulting speckle pattern, if an estimator of speckle patterns sequences is chosen well. Let us analyze the influence of the ROI out-of-plane displacements on the LSP transformation in the image plane. Suppose the ROI element tilting during the ROI vibration has a flat surface. Complex amplitudes of the LSP part generated by the ROI element before and during its tilt in the image plane can be expressed respectively as

\[ \tilde{a}(r) = \tilde{g}(r) \otimes p(r), \]  

\[ a(r) = g(r) \exp(-j2\pi \Delta vr) \otimes p(r), \]

where \( r = (x, y) \) is the point in the LSP part; \( \tilde{g} \) and \( g \) are the complex amplitudes of the LSP parts before and during the ROI element tilt in the geometric optics limits; \( p \) is the point spread function of the optical imaging system; \( \Delta v = (\Delta v_x, \Delta v_y) \) is the spatial frequency change corresponding to the amplitude spectrum shift in the aperture plane, \( \otimes \) is the convolution symbol.

An optical scheme of imaging and recording speckle patterns generated by the thin composite structure’s surface area containing the ROI and tilted ROI element is shown in Figure 1.

Fourier spectra of the amplitudes \( \tilde{a} \) and \( a \) expressed by Equations (1) and (2) are given as

\[ \tilde{A}(v) = \tilde{G}(v)P(v), \]  

\[ A(v) = G(v)P(v + \Delta v), \]
where $\nu = (v_x, v_y)$ is the spatial frequency, $P$ is the pupil function of the lens aperture. Equation (4) shows that the amplitude spectrum shift in the lens aperture plane is caused by the object tilt. The linear dependence of tilt angle $\alpha$ of the ROI element (see Figure 1) as a function of $\Delta\nu$ is expressed as [25,26]

$$\Delta\nu = \frac{1 + \cos \theta}{\lambda} \frac{1}{M} \alpha,$$

(5)

where $\lambda$ and $\theta$ are the wavelength and incidence angle of coherent or quasi-coherent light, respectively, and $M$ is the lateral demagnification of the imaging system. This equation shows that the maximum spatial frequency shift $\Delta\nu_{\text{max}}$ corresponds to the maximum tilt angle $\alpha_{\text{max}}$ of the ROI element. Therefore, the largest frequency shift of the amplitude spectrum in the lens aperture leads to the largest change in the LSP spatial structure.

Theoretical models have been developed that describe nonlinear elastic effects of the LDR, which can be features both at damage locations [28] and at all points of the composite surface [24]. The damage in the form of a flat-bottomed defect can be treated as subsurface defect with thin composite layer between them and the ROI. This layer between the subsurface defect and the ROI can be simplistically interpreted as a thin membrane with clamped boundary conditions. Suppose the subsurface defect is a rectangular shape and its ROI is an optically rough surface of the thin clamped rectangular
membrane of the same dimensions as the defect. In simplified linear approximation without taking into account applied nonlinear transverse forces and other physical parameters, the shape function of a perfect rectangular membrane out-of-plane vibrations can be expressed as [19,29]:

\[ u_{k,n}(x', y', t) = A_{k,n} \sin \left(2\pi f_{k,n} t + \varphi_{k,n}\right) \sin \lambda_k x' \sin \mu_n y', \quad (6) \]

where \( k, n \) are the modes of eugenfrequencies \( f_{k,n} \) of the membrane vibrations; \( \varphi_{k,n} \) is the phase shift of vibrations; \( \lambda_k = \frac{k\pi}{l}, \mu_n = \frac{n\pi}{m}; \) \( l, m \) are the sides of rectangle membrane, \( A_{k,n} \) is the amplitude of the membrane vibrations, and \( x' \) and \( y' \) are the coordinates of the input plane of the imaging system, i.e., the composite surface plane.

The maximum tilt angle \( \alpha_{\text{max}} \) causes maximum shift of spatial frequency \( \Delta \nu_{\text{max}} \) in the lens aperture plane and, accordingly, the largest transformations of the LSP. To find the locations of maximum gradient within the vibrating ROI, we can use Equation (6) to estimate the spatial distribution of the magnitude of the gradient vector \( \nabla u_{k,n} \) in the same way as was done for clamped rectangular membranes in [19]. For this purpose, we rewrite Equation (6) for the mode (3,3) of the rectangular membrane as

\[ u_{3,3}(x', y', t) = A_{3,3} \sin \left(2\pi f_{3,3} t + \varphi_{3,3}\right) \frac{3\pi x'}{l} \sin \frac{3\pi y'}{m}, \quad (7) \]

and after differentiation by coordinates \( x' \) and \( y' \) we obtain

\[ ||\nabla u_{3,3}|| = A_{3,3} \sin(2\pi f_{3,3} t + \varphi_{3,3}) \times \]

\[ \times \sqrt{\frac{9\pi^2}{l^2} \cos^2 \left(\frac{3\pi x'}{l}\right) \sin^2 \left(\frac{3\pi y'}{m}\right) + \frac{9\pi^2}{m^2} \sin^2 \left(\frac{3\pi x'}{l}\right) \cos^2 \left(\frac{3\pi y'}{m}\right)}. \quad (8) \]

If the ROI is square and \( l = m = 1, f_{3,3} = 1/T_\nu, t = T_\nu/4, \varphi_{3,3} = 0, \) where \( T_\nu \) is the vibration period, Equation (8) is given as

\[ ||\nabla u_{3,3}|| = A_{3,3} \sqrt{9\pi^2 \cos^2 (3\pi x') \sin^2 (3\pi y') + 9\pi^2 \sin^2 (3\pi x') \cos^2 (3\pi y')} \]. \quad (9) \]

The spatial distribution of the membrane nodes and antinodes for the mode (3,3) calculated by Equation (9) is shown in Figure 2, where nodes are depicted by bright spots and antinodes by dark ones.

The tilt of the ROI elements by the angle \( \alpha \) and the corresponding shift of the spatial frequency \( \Delta \nu \) according to Equation (5) lead to the transformation of the LSP generated by the ROI and to the decorrelation between the initial
LSP and the transformed one. The dependence of the tilt-induced decorrelation on the spatial frequency shift $\Delta \nu$ can be defined using the Yamaguchi correlation factor (YCF) for a circular aperture [27]

$$C_Y = \frac{4}{\pi^2} \left[ \arccos \left( \frac{|\Delta \nu|}{D_v} \right) - \frac{|\Delta \nu|}{D_v} \sqrt{1 - \left( \frac{|\Delta \nu|}{D_v} \right)^2} \right]^2,$$  

(10)

where $D_v$ is the lens aperture diameter in the frequency domain and

$$D_v = D/\lambda z,$$  

(11)

where $D$ is the lens aperture diameter; $z$ is the distance from the lens aperture plane to the matrix sensor of the digital camera (DC).

The YCF can be calculated using Equation (5), if the corresponding parameters of the optical imaging system and the spatial frequency shift $\Delta \nu$ are known. Note that the transformed LSP parts generated by the ROI tilted elements are completely decorrelated with the corresponding parts of the initial LSP generated by the flat ROI if $\Delta \nu_t = D_v$, where $\Delta \nu_t$ is the minimum frequency shift at which the YCF reaches zero. In this case, Equation (5) becomes

\[\text{Figure 2.} \text{ Spatial distribution of the mode (3.3) gradient for the square clamped membrane surface (i.e., the ROI). Membrane nodes are depicted by bright (white) spots and antinodes by dark (black) ones.}\]


\[ D_v = \frac{1 + \cos \theta}{\lambda} \frac{1}{M} \alpha_t. \]  
(12)

Inserting (11) into (12), we obtain

\[ \alpha_t = \frac{MD}{z(1 + \cos \theta)}, \]  
(13)

where \( \alpha_t \) is the threshold tilt angle, i.e., the minimum tilt angle at which the YCF between the transformed parts of the LSP generated by the ROI containing tilted elements and the corresponding parts of the initial LSP generated by the flat ROI reaches zero. This equation allows calculate the threshold tilt angles \( \alpha_t \) using the imaging system, which scheme is represented in Figure 1. According to (13), the angle \( \alpha_t \) can be calculated, if the parameters of the imaging system \( D, \theta, M, \) and \( z \) are known. In particular, if \( \theta, M, \) and \( z \) are constant values, the angle \( \alpha_t \) is linearly depends on the aperture diameter \( D \) and tends to zero as \( D \) decreases.

The membrane nodes and other ROI elements reaching maximum tilt during vibrations, generate the maximum decorrelation in respective parts of the LSP. Locations of these LSP parts with a certain degree of error reflect the location of the indicated ROI nodes and other ROI elements. Correlation comparison of two LSPs that are recorded in two opposite phases of the vibrating ROI leads to contrast changes in these parts. Accumulation of sequences of such LSPs can result in the formation of the spatial response from the defect.

The second factor affecting the LSP changes is connected with out-of-plane motions of the ROI directly leading to decreasing the speckle contrast and speckle blurring. If the surface is motionless, the spatial coherence between optical waves reflected from the surface does not change and has a constant level. If the surface starts to vibrate, the optical waves during the vibration cycle acquire randomly phase differences caused by the phase distortions introduced by the moving rough surface [30]. As a result, the spatial coherence of the ROI imaging is reduced, and the LSP generated by the ROI loses its contrast. In addition, the recording of a speckle pattern generated by a surface containing the vibrating ROI always has a finite exposure time, and time-averaging of dynamic speckles during their recording leads to an even greater speckle blurring in the resulting speckle pattern, which we will call the flaw map.

Results obtained for rectangular test subsurface defects can be widening on circular ones. The surface layer above such a defect within the ROI can be treated as a circular membrane, and by using the vibration equation for a thin clamped circular membrane given, for example, in [29], we can find the locations of nodes in the circular ROI for resonant US frequencies.
3. Technical Implementation of the Method

The hybrid optical-digital (HOD) experimental breadboard with US excitation of studied laminated composite panels was developed for validation of the proposed method. In this breadboard, US waves generated by a wide-band piezoelectric transducer (PZT) in acoustical contact with the panel are propagated in a thin composite panel. US waves are introduced to the PZT from an US generator and scanned in the range from 10 kHz to 150 kHz. If a subsurface defect is present in a composite panel, flexural waves excite it when the scanning US wave frequency coincides with the fundamental or one of the multiple resonant frequencies of the defect. A ROI placed above of this defect begins to vibrate at a resonant frequency as a clamped membrane. Although this statement is true only for ROIs placed over well-shaped defects extending along the composite layers directions, the proposed method can also detect irregular subsurface defects such as internal debonds and fiber break, as will be shown below.

During the ROI vibrations, two accumulated odd and even speckle patterns with intensity distributions $I_{n,o}(i,j)$ and $I_{n,e}(i,j)$, where $n$ is their number ($n = 1, 2, \ldots, N$) and $i,j$ are the pixel numbers, are recorded with the help of the HOD breadboard. These speckle patterns are produced by accumulating the sequences of $K$ initial speckle patterns (ISPs) $I_{kn1}(i,j)$ and $I_{kn2}(i,j)$, where $k = 1, 2, \ldots, K$. The ISPs $I_{kn1}(i,j)$ are registered by a DC during the frame time $T_{n,o}$, at the time gap $\tau$ within each vibrating cycle equal to the US wave period $T_{us}$. The time gap for ISPs $I_{kn1}(i,j)$ lasts when the amplitude of the vibrating ROI corresponds to the US wave amplitude passing its maximum. The ISPs $I_{kn2}(i,j)$ are registered by the same DC during the frame time $T_{n,e}$ at the same time gap $\tau$, which lasts when the amplitude of the vibrating ROI corresponds to the US wave amplitude passing its minimum. Thus, the ISPs $I_{kn1}(i,j)$ are formed at the maximum tilt of the ROI elements in one direction relative to the flat surface of the composite, and ISPs $I_{kn2}(i,j)$ at the maximum tilt of the ROI elements in the opposite direction. The odd speckle pattern $I_{n,o}(i,j)$ is accumulated during the time $T = T_{n,o}$ of the odd frame and the even one $I_{n,e}(i,j)$ is accumulated during the time $T = T_{n,e}$ of the even frame $(T = T_{n,o} = T_{n,e})$, that is

$$I_{n,o}(i,j) = \sum_{k} [I_{kn1}(i,j)], \quad I_{n,e}(i,j) = \sum_{k} [I_{kn2}(i,j)].$$

(14)

The procedure of the odd and even $n^{th}$ pair of SPs $I_{n,o}(i,j)$ and $I_{n,e}(i,j)$ registration is shown in Figure 3. Since $\tau \ll T_{n,o}$ and $\tau \ll T_{n,e}$, an optical shutter such as an acousto-optical deflector (AOD) or electro-optical modulator should be used to generate these time gaps.

In order to exceed the threshold of complete decorrelation between LSPs generated by the initial and tilted surfaces within the ROI, the maximum tilt angle $\alpha_{max}$ should be not lesser than the threshold tilt angle $\alpha_{o}$, that is, $\alpha_{max} \geq$
\[ I_{n,-}(i,j) = |I_{n,o}(i,j) - I_{n,e}(i,j)|. \] (15)
The descriptor is similar to ones used for estimation of dynamic speckles statistical characteristics [31]. Fulfillment of this descriptor allows reaching the speckle decorrelation and blurring of LSPs generated by a ROI due to its opposite out-of-plane displacements during the recording of \( n \)th odd and even speckle patterns \( I_{n,o}(i,j) \) and \( I_{n,e}(i,j) \). The resulting difference SP \( I_{n}(i,j) \) represents the initial flaw map containing the spatial response from the subsurface defect and the background generated by the composite panel surface area outside the ROI. To obtain a more intense and contrasting spatial response covering the accumulated LSP, we propose to register speckle patterns \( I_{n,o}(i,j) \) and \( I_{n,e}(i,j) \) \( N \) times \( (n = 1, 2, \ldots, N) \) and to sum up all obtained difference speckle patterns. As a result, we receive the cumulative difference descriptor to produce the flaw map, that is [11]

\[
I_{\sum}(i,j) = (\gamma N)^{-1} \sum_n [I_{n,-}(i,j)],
\]

where \( \gamma (N^{-1} \leq \gamma \leq 1) \) is the factor for choosing the optimum intensity level of the flaw map \( I_{\Sigma}(i,j) \).

The functional diagram of the HOD breadboard performing the procedure described above is shown in Figure 4. The breadboard contains a miniature Nd:YAG laser 1 \((\lambda = 532 \text{ nm}, P = 120 \text{ mW})\), an acousto-optical deflector (AOD) 2, a spread lens 3 illuminating the chosen area of a laminated composite panel 4, a lens “VEGA 2/20” 5 with an adapter ring, a 640 × 480 pixel DC “Sony-XCD-V60” 6, an US generator 7, a wide-band piezoelectric transducer (PZT) 8, a control unit 9, and a laptop 10. A US wave with a scanning frequency in the range from 10 to 150 kHz is introduced from the US generator 7 to the PZT 8, which is in acoustical contact with the studied composite panel 4. If any resonant

![Figure 4. Functional diagram of the HOD breadboard.](image-url)
frequency of the subsurface defect matches the US frequency of the PZT 8, the ROI begins to vibrate with the same frequency. The recording of ISPs $I_{km1}(i,j)$ and $I_{km2}(i,j)$ is performed with the help of the AOD 2, which open the optical beam from the laser 1 for the time gap $\tau \ll T$ to illuminate the studied area of the composite panel surface using the spread lens 3. ISPs are accumulated on the DC sensor matrix that is opened by the DC shutter during the frame time $T$ to generate speckle patterns $I_{n,0}(i,j)$ or $I_{n,e}(i,j)$ (see Equations (14)). These speckle patterns are entered into the control unit 9, where the difference speckle pattern $I_n(i,j)$ is produced (see Equation (15)) and input to the laptop 10. In the laptop, all $N$ difference SPs are added to give the resulting flaw map $I_n(i,j)$ (see Equation (16)). In order to increase the signal-to-noise ratio and enhance the contrast, the digital image processing of the flaw map is performed.

The optical imaging system of the created HOD breadboard was synthesized with taking into account the optical schemes for formation of speckle patterns from the tilted optically rough surface see [20,25,26] and Figure 1. In this system, the threshold angle $\alpha_t$ is reached between the vibrating ROI tilted elements if they are in antiphase with each other and reach a maximum gradients in opposite directions of out-of-plane displacement. In this case, the tilt angle $\alpha$ shown in Figure 1 is $\alpha = \alpha_{\text{max}}/2 \geq \alpha_t/2 = \alpha_{\text{thr}}$. If we know the parameters of the optical imaging system such as $D$, $M$, $z$, and $\theta$, we can calculate the threshold angle $\alpha_{\text{thr}}$ using Equation (13) obtained for calculating $\alpha_t$, that is

$$\alpha_{\text{thr}} = \frac{MD}{2z(1 + \cos \theta)}, \quad (17)$$

The parameters of the synthesized optical imaging system have such values: $M = 0.0893$; $z = 22.5$ mm; focal length of the lens “VEGA 2/20” $F = 20$ mm; $f_x = 2, 2.8, 4, 5.5, 8, 11, 16$, where $f_x$ is the $f$-number; $D = F/f_x$; $\theta = 27.0^\circ$. Substituting these values in Equation (17) and choosing $D = 5$ mm, we obtain that $\alpha_{\text{thr}} = 0.30^\circ$, whereas $\alpha_t = 0.60^\circ$. Dependences “$\alpha_{\text{thr}}$ versus $\theta$” for given $f$-numbers $f_x$ are depicted in Figure 5. These dependences increase very weakly with increasing the angle $\theta$. Therefore, it is enough to choose the angle $\theta$ in the range from $5^\circ$ to $30^\circ$ and there is no need to choose this angle less than $5^\circ$. Indeed, if $\theta \leq 5^\circ$, the threshold angle $\alpha_{\text{thr}}$ practically does not change for all $f$-numbers of the lens, and therefore, it makes no sense to decrease the angle $\theta$.

A twofold decrease in the threshold angle $\alpha_{\text{thr}}$ makes it possible to expand the capabilities of the HOD breadboard in detecting subsurface defects, in particular, those of larger sizes and lying on greater depth from the composite surface. Moreover, due to a twofold decrease in the threshold angle we can significantly reduce the power of US waves and, respectively, the power of the US generator used in the HOD breadboard.
The very simple configuration of the HOD experimental breadboard and its low sensitivity to external actions due to the absence of a reference beam (see Figure 4) opens up wide possibilities for the practical application of devices based on it for nondestructive evaluation of composites.

4. Experimental Verification

Experimental verification of the proposed method for subsurface defects detection in thin composite structures was performed using the created HOD experimental breadboard with US excitation and test specimens of laminated composite panels. In order to perform the first series of experiments, square and circular flat-bottomed holes were drilled in a 6 mm thick fiberglass multilayer panel СГЭ-1 containing 0.3 mm thick fiberglass fabric layers with the addition of epoxy resin as a thermosetting binder. A close analogue of the composite СГЭ-1 is a glass-reinforced epoxy laminate material FR-4. The holes 5 mm deep were drilled from the side opposite to the side of the panel illumination with the laser beam. To demonstrate the experimental results, a rectangular part of the panel with dimensions of $57 \times 43 \text{ mm}^2$ was chosen. This area contained one square subsurface defect with a side of 22 mm, parts of two circular defects with diameters of 20 and 12 mm, as well as one real disbond that was formed between the layers during the panel preparation. The PZT was positioned along a vertical line passing through the center of the square defect. US excitation of the panel was realized from 10 to 150 kHz. The propagation direction of the UV wave exciting a square ROI that can be considered as

\[ \alpha_{\text{thr}} \text{ versus } \theta \]

**Figure 5.** Dependencies “$\alpha_{\text{thr}}$ versus $\theta$” for $f$-numbers 2, 2.8, 4, 5.6, 8, 11, 16 of the lens “VEGA 2/20.”
a clamped square membrane at the frequency of the membrane mode (3,3) is schematically shown in Figure 6(a). The ROI above the defect is excited in the transverse direction, and the ROI nodes vibrate and tilt in this direction along the three dashed lines. Under such conditions, the LSP, that is, the spatial response from this defect, at the multiple frequency $f_{3,3}$ should consists of four optical bright spots along each line, i.e. contain a $4 \times 3$ matrix of bright spots.

During the experiment, the square defect was detected in the mode (3,3) of the membrane at the frequency $f_{3,3} = 70$ kHz. The resulting flaw map generated with the help of the cumulative difference descriptor (16) is shown in Figure 6(b). The same flaw map after standard digital processing is shown in Figure 6(c). As we see, the obtained spots practically coincide with simulated maximum tilt gradients, or nodes, shown in Figure 2. Figure 6 (c) also highlights the disbond area located between the square defect and two circular defects.

The second series of experiments was performed on the similar fiberglass panel СТЭФ-1. Round and square flat bottom holes of various sizes and 1 mm depth were drilled from one side of the panel. A 1 mm thick fiberglass layer was glued to the panel from the side of the drilled holes. In the HOD breadboard, the resulting composite fiberglass panel was illuminated with a laser beam from the side of the glued fiberglass layer. During the US excitation of the panel, we have detected a LSP from a ROI placed above a 10 mm diameter circular subsurface defect. A flaw map depicting this LSP at the defect resonant frequency $f_{01} = 25.6$ kHz is shown in Figure 7(a). The annular shape of the LSP shows that the vibrations of the ROI correspond to vibrations of the circular membrane on the fundamental mode (0,1), since the ROI maximum tilt is reached at
its edges. So, the ring in the LSP appeared due to the ROI tilts. In the center of the LSP, there is a small light response, which appears most likely due to the speckle blurring caused by the ROI out-of-plane vibrations. The same flaw map after low-pass filtering is shown in Figure 7(b). The LSP diameter of the in Figure 7(a) is 10.3 mm.

Real subsurface defects in composite and hybrid metal composite structures were also detected using the HOD experimental breadboard. In particular, we analyzed the defectiveness of a thin metal-composite joint applied in aviation industry. We found the rupture of one of these layers in the 4 mm thick carbon fiber-reinforced polymer composite panel, which is a part of an element of the metal-composite joint, shown in Figure 8(a). The panel fracture was caused by the tension of this joint up to 4,500 Kg using a tension testing machine. The response on this defect within an outlined in Figure 8(a) rectangular area is sharply extracted after standard digital image processing, as it is observable in Figure 8(b).

5. Conclusions

Compared to other similar optical-digital methods for detecting subsurface defects, the proposed method produces the flaw map using sequences of dynamic speckle patterns. Formation of speckle patterns in an optical system does not demand the use of a reference beam, and the composite surface is illuminated only by single expanded laser beam. Therefore, this method is simpler than the similar ESPI/shearography and digital holography techniques [6–10]. Moreover, the method is not such sensitive to vibrations and other external influences. The proposed method is implemented using the HOD experimental breadboard, which is simpler than systems built on the basis of the aforementioned
techniques. This breadboard also lacks complex optical elements and units that are necessary to produce a reference beam for ESPI and digital holography or a shear for shearography. A cheap laser and even narrow-band LED can be used in devices created on basis of this method, since the coherence length of optical waves is not a decisive factor in the formation of speckle patterns.

In comparison with well-known systems for detection of subsurface defects based on the ESPI/shearography and holography techniques, the created HOD breadboard can detect defects during much higher vibration amplitudes, which allow detecting larger defects, and thereby expands the capabilities of the NDT of composite structures. Such peculiarity is caused by a distinctive feature of the proposed method, which consists in the use of speckle blurring and decorrelation of speckle patterns. On the contrary, the speckle decorrelation is one of the significant obstacles in the detection of defects by the ESPI and digital holography techniques. These techniques are very sensitive to vibrations and other external actions, and the speckle decorrelation rigidly limits displacement range of studied surfaces. Shearography due to shear of the object wave is not so sensitive to external actions and is not sensitive to rigid body motions. However, the speckle decorrelation also influences on its performance.

And, finally, devices built on the basis of the proposed method can be used in in situ applications for solving many problems of the NDT due to their simplicity and low sensitivity to vibrations and other external factors.
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Disclosure Statement

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