ACOUSTIC METHODS

Impact Damage Detection in Laminate and Honeycomb CFRPs using Lamb Wave Ultrasonic Sensing

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Abstract—The paper presents the results on application of Lamb waves based technique for impact damage detection and severity identification. The PZT network operates in the round-robin mode changing the actuator and sensor roles of the transducers in order to detect the response of the system in the presence of damage. The monitoring is performed via the analysis of three parameters: change of the amplitude (dA), change of the energy (dP) and cross-correlation (NCC) of the signals in baseline and damaged state. Testing of laminate CFRPs shows that the damage location is estimated with an error of 5–15 mm, while the computed Damage index is linearly dependent on the applied impact energy. For honeycomb CFRPs the NCC parameter do not provide accurate results, however, other parameters allow identification within the 5–20 mm error and reflect accurate data on the severity of the damage.

Keywords: non-destructive testing, structural health monitoring, ultrasonic testing, Lamb waves, impact damage, carbon fiber reinforced polymers

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INTRODUCTION

Non-destructive testing is a field of science and engineering that has great relevance for safety in many industries. But ensuring safety by NDT is often associated with a stop of operation and brings economic losses due to the unit downtime. So in industries demanding high quality inspection the Structural Health monitoring (SHM) concept becomes of great importance [1–4]. The development of SHM in aerospace is a serious engineering task that got a boost with the design of the aircrafts with wide CFRP usage (Boeing 787 and Airbus A350XWB) in main load-bearing structures: wings, fuselage, empennage, etc. The operation of such aircrafts has shown that the aircraft suffers large amount of external impacts of different origin: debris on the runway, thunderstorms, bird strikes, low-quality or improper maintenance, etc. Such events lead to the formation of damages the vast majority of which are classified as barely visible impact damages (BVID) and do not lead to the urgent operation halt. The BVID of carbon fiber reinforced polymers are complex internal structure defects combining delamination, fiber breakage and pull out, and matrix debonding. Thus due to operational loading and environmental effect the BVIDs can evolve to large-scale weakened areas which are more difficult to repair or even they can become a threat to load bearing capacity of the structure. Thereby the monitoring systems that can provide timely data on the emergence of damages are of great importance in aerospace.

The scientists and engineers examine various physical principles to be utilized in SHM: vibration [5–7], ultrasonic waves [8], thermography [9, 10], eddy currents [11, 12], electromagnetism [13], etc. In the case of aerospace the SHM development task is more complicated due to hard limitations of the aircraft weight: the installed sensors, wires, and electronics can nullify the advantages of SHM application [14, 15]. Thus opposite requirements for reduced weight and high safety promote using of the most high-tech solutions. For example, the aerospace considers acoustic emission [16–20], fiber-optic strain gauging [21–23], and other methods to be used in monitoring systems. Artificial neural networks are studied extensively to process raw data and provide efficient decision making. Recently, an increasing number of studies has been devoted to the investigation of ultrasonic Lamb waves in SHM [24, 25]. Due to low attenuation these waves can

Fig. 1. Sketch of the specimen instrumented with PZT network.

cover extensive areas, that is extremely important in aircraft industry, where the area of CFRP skins can be very large. Lamb wave ultrasonic methods are widely studied for the detection of impact damages in composites [26, 27]; the optimal networks of transducers are investigated [28–30]. However, the physical mechanism of Lamb waves propagation is quite complex [31, 32] requiring consideration of many factors such as the stability of the adhesive layer and the degradation of its properties [33, 34], temperature deviations [35, 36], sensor failure [37], etc. as it can significantly affect the quality of obtained data and reduce the monitoring efficiency.

The technique for monitoring of impact damages studied in the paper was developed earlier and applied on the honeycomb specimen [38, 39]. The algorithm was established using the artificial damages and subsequent multiple impact damaging of the specimen.

The present paper is a result of application of this technique for monitoring of different materials using modified testing procedure. The aim of the paper is investigation of the algorithms of detection of impact damages with different severity in laminate and honeycomb CFRPs using Lamb waves.

MATERIALS AND METHODS

There were two types of specimens used for testing of ultrasonic technique for the detection of barely visible impact damages. The first type is a laminate carbon fiber reinforced polymer with the following layup: $[90_G/0/-45/90/+45/0]_S$. The specimens were produced with prepreg unidirectional carbon fiber fabrics using vacuum bagging and autoclave pressing (on the outer surfaces of the CFRP the glass fiber protective layer marked with “G” letter was placed). The total thickness of the 32-ply CFRP is 5.2 mm. The size of the specimen is $300 \times 300 \text{ mm}^2$. This specimen will be further denoted with “L” letter.

The second specimen is a sandwich with aluminum honeycomb filler and CFRP skins with the following layup: $[90_G/0/-45/90/+45/0]_S$. Each 12-ply skin is about 1.7 mm thick and the total thickness of the specimen is about 18.2 mm. The size is the same as for the laminate specimens – $300 \times 300 \text{ mm}^2$. They are denoted as “H” specimens below.

Each specimen was instrumented with two networks (on the front surface to be impacted and on the rear surface) of PZT transducers allowing both actuating and sensing. The network had a size of 4×4 with a 45 mm offset from the specimen boundary and a step of 70 mm. The sketch depicting the PZT network is shown in Fig. 1. The PZTs transducers used are AW1E12G-190EFL1Z by Audiowell with the diameter of 9 mm and thickness of ceramic layer of 0.19 mm bonded to the steel substrate. The use of two similar PZT networks on both surfaces allow us to estimate the possibility to detect damage of the outer surface of structure from the sensing system installed inside and protected from the environmental conditions. This is quite important for honeycomb CFRP which has higher attenuation of the ultrasonic waves traveling from one skin to another by aluminum honeycomb core. 3M DP490 epoxy adhesive was used to bond the transducers on the surface of CFRP specimens.

The waveform used is 5 cycles of sine modulated by Hanning window. The frequency distribution of the waveform results in moderate dispersion during wave propagation compared with sine or pulse signal. This makes the analysis of the obtained results easier because the reduced dispersion allows classifying the components of the received waveform, e.g. direct passed wave and edge reflections. The actuating and sensing hardware are arbitrary waveform generator AWG-4105 and 4-channel USB oscilloscope Handy-scope HS4 correspondingly. AWG-4105 allows generating waveforms with amplitude of 10 V which was enough for the experimental testing of the ultrasound technique for $300 \times 300 \text{ mm}^2$ CFRP specimens. However the magnitude of sensed signal for honeycomb specimens was insufficient, thus the high-frequency amplifier was used for oscilloscope.

During the preliminary tests of “actuator-sensor” pairs bonded on the surface of CFRP specimens the frequencies of 100 and 300 kHz were chosen. According to the literature data of Lamb waves dispersion curves and simulation of ultrasonic waves propagation in LAMSS-Composites software [40] it was established that 100 kHz frequency corresponds to the A0 mode with a wavelength of 18 mm while the S0 mode is negligible. At 300 kHz S0 is generated much better (9 mm diameter transducer is comparable to the half of wavelength) instead. However A0 is also presented with much lower amplitude. The A0 mode wavelength at 100 kHz is quite large compared to the size of the BVIDs but it was expected that the waves would interact with such BVIDs with increased attenuation. This phenomenon is due to decrease of stiffness and emergence of defects like delamination, matrix cracking, fiber breakage, etc.

It should be noted that literature review [41] and the tests conducted earlier by the authors show that the difference in wave propagation velocity in 0 and 90 fiber direction differs by 1–3% thus the anisotropy of the specimens with quasi-isotropic layup can be neglected.

In order to increase the S/N ratio the received signals were averaged 100 times. The signal acquisition by HS4 oscilloscope was triggered by the reference signal from the generator using the first channel of the oscilloscope. Three remaining channels were used for data capturing. Each position of the generator (one of the 12 transducers) requires the data from 11 sensors to be captured thus the relay box was designed for sequential registering the data from all sensors. The relay box allows changing the generator position simplifying the experimental procedure. Summary there are 132 signals for the 4×4 pattern of PZTs to be captured. Using of two frequencies and testing of two sides resulted in the set of 528 waveforms for ultrasonic testing of one specimen.

The proposed technique was evaluated for possibility of detection of damage position and severity of impact of varying energies. The specimens were impacted according to the ASTM D7136 standard using a drop weight technique. The 2 kg impactor having a hemispherical striker tip with a diameter of 16 mm was used. The impact energies were 10, 15 and 20 Joules for laminates while honeycomb CFRPs were impacted with 2 and 4 Joules.

Before the impact testing the ultrasonic monitoring was performed creating the baseline set of signals. After the impacting of the specimens, the same procedure was performed resulting in the set of signals for the damaged state. The mathematical comparison of these sets of waveforms allows to detect the presence of a defect and its location as well as to estimate roughly the severity of the damage.

Numerical evaluation of the ultrasonic signals in order to detect the changes occurring due to impact damaging of the CFRP was performed by calculation of the set of informative parameters (between the signals for two states—damaged and baseline): difference of maximums of envelopes, normalized correlation coefficient and energy difference.

The calculation of the signal envelope of the received signal is performed using Hilbert transform in the frequency domain. On the first step the n -point Discrete Fourier Transform (DFT) of the N -length signal is calculated and spectrum values $X(m)$ corresponding to the negative frequency are zeroed. The values $X(0)$ and $X(N/2)$ are divided by 2. Then the reverse N -point DFT is performed. The signal has real and imaginary parts. The values of envelopes are determined as the absolute values of the obtained signals. The difference of envelopes maximums dA is calculated as follows:

$$dA = \frac{A_{\text{bas}} - A_{\text{dam}}}{A_{\text{bas}}}, \quad (1)$$

where A_{bas} is an envelope maximum for the baseline state signal and A_{dam} is an envelope maximum for the damaged state signal.

Normalized correlation coefficient is obtained by the following equation:

$$NCC = 1 - \frac{\left| \sum x_{\text{bas}} x_{\text{dam}} \right|}{\sqrt{\sum x_{\text{bas}}^2 \sum x_{\text{dam}}^2}}, \quad (2)$$

where x_{bas} and x_{dam} are the signal magnitudes of the baseline and damaged states correspondingly.

In order to obtain the power spectrum the DFT was performed and the values of the spectrum were calculated by the expression:

$$Pow(i) = 10 \log \sqrt{X^2(2i) + X^2(2i+1)}, \quad (3)$$

where X are values of the Fourier spectrum. Then for each signal the energy within the range of $0.4f$ was calculated:

$$P = \sum_{-0.4f}^{0.4f} Pow(i), \quad (4)$$

where f is a point corresponding to the central frequency of the signal. Then for two signals the difference dP is calculated:

$$dP = \frac{P_{bas} - P_{dam}}{P_{bas}}, \quad (5)$$

where P_{bas} is an envelope maximum of the baseline state signal and P_{dam} is an envelope maximum of the damaged state signal.

After the testing the database for each specimen contains the following data: locations (coordinates) of PZT transducers, sets of registered signals for all actuator-sensor pairs, informative parameters calculated by comparison of baseline and damaged state data. Then using developed software the data is processed and analyzed in order to obtain the location and severity of impact damage. The algorithm of processing is described below:

- (1) the wave paths are sorted according to the ascending of absolute relative change of dA , dP or NCC value in assumption of higher attenuation due to presence of damage;
- (2) in the sorted list the first N paths are chosen (in the present paper 10 and 20 paths were used for comparison);
- (3) for each pair of wave paths the coordinates of intersection points are obtained;
- (4) then according to the equations (6) and (7) the coordinates of the position of the damage and its severity are calculated.

The coordinates of impact damage are calculated using equation:

$$r = \frac{\sum r_i w_i}{\sum w_i}, \quad (6)$$

where r_i are coordinates of i -th intersection point of wave paths, w_i are values of chosen informative parameters. The damage severity is assessed using dimensionless damage index (DI):

$$DI = \frac{\sum w_i}{n}, \quad (7)$$

where w_i are values of chosen informative parameters, n is a number of wave paths. The higher the DI the more severe the damage is. Both coordinates of the damage and DI can be obtained using each informative parameter (dA , dP , or NCC).

RESULTS AND DISCUSSION

The section presents the experimental results obtained after investigation. Table 1 presents the data on studied specimens. The laminates and honeycombs are designated as L and H correspondingly.

In order to describe operation of the experimental technique the detailed results for the specimen L2/20 are provided. Figure 2 shows the 4×4 sensor network with a generator defined in lower corner: possible wavepaths and the differences of the maximums of envelopes between baseline and damaged states are shown. This example corresponds to the dA equal to 0.41, i.e. the drop of amplitude by ~41% for "actuator-sensor" pair 10→5 of the L2/20 specimen.

It can be seen that the neighboring sensors 4 and 6 show drops of 12 and 23% correspondingly. The change of the signals in presence of damage for other sensors is quite low. The example of initial waveform with a corresponding envelope for L2/20 specimen is shown in the upper plot in Fig. 3. Lower plot describes the envelopes for both baseline and damaged state and the difference between maximums is graphically shown.

Fig. 2. Example of dA distribution for L2/20 specimen and specified position of the actuator.

Figures 4 and 5 show the examples of damage detection for specimens L3/10 and L4/15 impacted by 10 and 15 Joules correspondingly. Each small colored dot corresponds to the damage location prediction calculated by (6). This dot array is calculated for each combination of testing frequency, side of the CFRP specimen, amount of calculation paths and informative parameter (red for NCC; green for dA ; and blue for dP). Thus there are $2^3 = 8$ damage location prediction points for each informative parameter. These points are used to obtain the resulting X and Y coordinates which are plotted as crossed circles of the corresponding color.

Quantitative results for all laminate specimens are summarized in Table 2. It can be seen that the technique allows detecting the location damage with an errors of 5–15 mm. Monitoring of the impacted side and back surface provides the same results about impact damage prognosis. The scatter of Δ_{avg} for any parameter is nearly the same allowing to conclude that all of them can be utilized in damage location procedure. The last column in the table shows the Damage Indexes calculated by the equation (7) and averaged for each informative parameter. These DI have different ranges of variation. DI_{dA} is the simplest to analyze varying from 0 to 1, where 0 stands for an absolutely non-damaged state resulted from the comparison of baseline and damaged ultrasonic data with no amplitudes changes while 1 is obtained if the all damaged signals will be nullified. Each number between 0 and 1 describes the average drop of amplitude of signals used for damage location. The same idea is for DI_{dP} except that the energy of the signals is calculated and compared instead of amplitude. Both these parameters are aimed to detect higher attenuation

Table 1. Specimens and impact parameters

Specimen	Impact energy, J	X , mm	Y , mm
L1/10	10	180	180
L2/20	20	180	180
L3/10	10	150	220
L4/15	15	150	220
L5/10	10	220	220
L6/15	15	220	220
H1/2	2	180	180
H2/4	4	180	180
H3/2	2	150	220
H4/4	4	150	220
H5/2	2	220	220
H6/4	4	220	220

Fig. 3. Shapes of the baseline waveform (upper plot) and graphical representation of envelopes difference for baseline and damaged states.

Fig. 4. Experimental results of impact damages detection for laminate specimen L3 impacted by 10 J.

Fig. 5. Experimental results of impact damages detection for laminate specimen L4 impacted by 15 J.

Fig. 6. Damage index dependence versus impact energy for laminate specimens.

of the Lamb waves in presence of damage. DI_{NCC} varies in the range of 0 to 1 as well, but demonstrates different behavior because the correlation can change due to different reasons, like phase shift. The 0 value stands for absolutely non-damaged state while 1 for damaged but the dependence within this range is highly nonlinear. Thus DI_{NCC} for the damages obtained due to 15–20 Joules impacts reach 0.8–0.9 but the BVIDs obtained are quite small. Thus it can be concluded that NCC will have very low classification ability for larger damages.

Figure 6 presents DI_{dA} for all laminate specimens are presented. The data are fitted using linear function resulting in good linear dependence of the damage index versus impact energy.

Then Lamb wave ultrasonic testing of all honeycomb specimens has been performed. The preparation and testing procedure for honeycomb specimens was absolutely the same as one utilized for laminates but the results showed some differences.

Table 2. Results of laminate specimens testing

Specimen	X , mm; Y , mm	Parameter	X_{avg} , mm	Y_{avg} , mm	ΔX_{avg} , mm	ΔY_{avg} , mm	Δ_{avg} , mm	DI
L1/10	180; 180	NCC	176.8	185.7	3.2	−5.6	6.5	0.4
		dA	165.3	180.3	14.7	−0.3	14.6	0.092
		dP	171.9	177.1	8.1	2.9	8.6	0.000461
L2/20	180; 180	NCC	173.4	193.6	6.5	−13.7	15.1	0.82
		dA	171.3	185.5	8.7	−5.5	10.3	0.212
		dP	164.6	190.9	15.4	−10.1	18.9	0.001210
L3/10	150; 220	NCC	151.5	222.0	−1.5	−2.0	2.5	0.59
		dA	151.2	204.7	−1.2	15.3	15.4	0.098
		dP	145.3	216.2	4.7	3.8	6.0	0.000408
L4/15	150; 220	NCC	150.8	220.4	−0.8	−0.4	0.9	0.88
		dA	145.3	218.4	4.7	1.6	4.9	0.142
		dP	142.8	202.5	7.2	17.5	18.9	0.000613
L5/10	220; 220	NCC	216.1	217.0	3.9	2.9	4.9	0.51
		dA	217.7	211.5	2.3	8.5	8.8	0.080
		dP	209.4	210.4	10.6	9.6	14.3	0.000479
L6/15	220; 220	NCC	212.8	218.6	7.2	1.4	7.3	0.82
		dA	216.4	224.9	3.6	−4.9	6.1	0.129
		dP	214.1	221.0	5.9	−1.0	6.0	0.000830

Fig. 7. Experimental results of impact damages detection for honeycomb specimen H1 impacted by 2 J.

Fig. 8. Experimental results of impact damages detection for honeycomb specimen H2 impacted by 4 J.

Firstly it has been found that damage location procedure using NCC parameter provides unreliable results for any H specimen. The calculation of the damage prediction points for every combination of frequency, side of the specimen and number of wavepaths provides high scattered set of points which after averaging resulted in X and Y which are very close to the center of the specimen (150; 150). Above said can be seen in Figs. 7 and 8. For both specimens H1/2 and H2/4, as well as for remaining H3–H6, the scatter of red dots is high and the averaged damage prediction is nearly in the center.

Secondly the testing of honeycomb specimens showed that damage prediction points obtained by the network on the rear side (opposing the side of the impact) demonstrate high scatter for dA and dP informative parameters. This can be seen for nearly all honeycomb specimens and it should be concluded that the detection of the damage on the side opposite to external impacted surface is not possible when using such technique. The detailed results of high scatter of rear side network location are shown in Table 3 while for laminates such data has not been provided due to similarity of the numbers for front and rear PZT networks.

Fig. 9. Damage index dependence versus impact energy for honeycomb specimens

Thus for the calculation of averaged X , Y coordinates for dA and dP parameters only the front PZT networks has been used. All the results are summarized in Table 4. It can be seen that the damage location prediction error for dA varies within the range of 10–20 mm while dP has higher scatter of Δ_{avg} : 4–35 mm.

Damage indexes for various parameters have been calculated showing the sensitivity and classification ability as well as for laminate specimens (Fig. 9). The scatter of the DI_{dA} is higher than for laminates but the direct dependence is clearly distinguishable.

Table 3. Comparison of front and rear networks damage location for the honeycomb specimen H6/4

Specimen/Impact Energy, J	Parameter	Side	Δ_{avg} , mm
H6/4	dA	Front	18.9
		Back	56.3
	dP	Front	23.1
		Back	64.9

Table 4. Results of testing of honeycomb specimens

Specimen	X , mm; Y , mm	Parameter	X_{avg} , mm	Y_{avg} , mm	ΔX_{avg} , mm	ΔY_{avg} , mm	Δ_{avg} , mm	DI
H1/2	180; 180	NCC	145.8	140.5	34.1	39.5	52.2	0.27
		dA	186.3	168.3	−6.3	11.7	13.3	0.025
		dP	177.2	183.3	2.8	−3.3	4.3	0.000178
H2/4	180; 180	NCC	159.1	162.0	20.9	18.0	27.6	0.31
		dA	173.6	188.0	6.4	−8.0	10.2	0.052
		dP	176.4	187.6	3.6	−7.6	8.4	0.000472
H3/2	150; 220	NCC	165.7	186.0	−15.7	34.1	37.5	0.18
		dA	151.2	200.5	−1.2	19.5	19.5	0.026
		dP	177.2	196.9	−27.2	23.1	35.7	0.000328
H4/4	150; 220	NCC	152.6	200.4	−2.6	19.6	19.8	0.29
		dA	161.2	219.6	−11.2	0.4	11.2	0.074
		dP	149.5	197.0	0.5	23.0	23.0	0.000432
H5/2	220; 220	NCC	192.3	190.8	27.7	29.2	40.3	0.2
		dA	206.7	206.3	13.3	13.7	19.0	0.038
		dP	209.1	210.6	10.9	9.4	14.4	0.000368
H6/4	220; 220	NCC	189.9	188.5	30.1	31.5	43.6	0.33
		dA	207.1	207.2	12.9	12.8	18.1	0.056
		dP	206.0	205.8	14.0	14.2	19.9	0.000592

CONCLUSIONS

The experimental technique utilizing Lamb waves for BVID detection of CFRP has been studied. Piezotransducers adhesively bonded to the surface were used to actuate and detect the Lamb waves. The round robin testing of laminate specimens shows that all informative parameters allow detection of damage location prediction within the range of 5–15 mm. The damage index shows linear dependence on impact energy. Finally both front and back surfaces can be used for PZT system having a little effect on accuracy. NCC can be used to detect the damage but correct evaluation of severity degree using this parameter is complicated.

Testing of honeycomb specimens showed sufficient prognosis accuracy in the range of 5–20 mm in spite of the larger scatter than for laminates. The monitoring of damages by the PZT on the side that is opposite to the impacted one is more complicated and the accuracy is much less due to the presence of aluminum honeycombs and their large thickness. Thus the Lamb waves are insensitive to damages on the opposite side. Damage Index allows to classify the damage severity. NCC parameter cannot be used for honeycomb CFRP because of the influence of phase shift on the NCC value.

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REFERENCES

1. García Márquez, F.P. and Peco Chacón, A.M., A review of non-destructive testing on wind turbines blades, *Renew. Energy*, 2020, vol. 161, pp. 998–1010.
2. Schubel, P.J., Crossley, R.J., Boateng, E.K.G., and Hutchinson, J.R., Review of structural health and cure monitoring techniques for large wind turbine blades, *Renew. Energy*, 2013, vol. 51, pp. 113–123. <https://doi.org/10.1016/j.renene.2012.08.072>
3. Qing, X., Li, W., Wang, Y., and Sun, H. Piezoelectric transducer-based structural health monitoring for aircraft applications, *Sensors (Switzerland)*, 2019, no. 3, pp. 1–27.
4. Annamdas, V.G.M., Bhalla, S., and Soh, C.K., Applications of structural health monitoring technology in Asia, *Struct. Health Monit.*, 2017, vol. 16, no. 3, pp. 324–346.
5. Jamadar, N.I., Kivade, S.B., Dhande, K.K., and Pedada, S., Vibration based damage inspection in composite structures—A critical review, *Int. J. Eng. Sci. Innov. Technol.*, 2014, vol. 3, pp. 201–208.
6. Lakhdar, M., Mohammed, D., Boudjemaa, L., Rabia, A., and Bachir, M., Damages detection in a composite structure by vibration analysis, *Energy Procedia*, 2013, vol. 36, pp. 888–897.
7. Kernicky, T., Whelan, M., and Al-Shaer, E., Vibration-based damage detection with uncertainty quantification by structural identification using nonlinear constraint satisfaction with interval arithmetic, *Struct. Health Monit.*, 2019, vol. 18, pp. 1569–1589.
8. Beskhyroun, S., Wegner, L.D., and Sparling, B.F., Integral resonant control scheme for cancelling human-induced vibrations in light-weight pedestrian structures, *Struct. Control Health Monit.*, 2011, vol. 19, no. 1, pp. 55–69.
9. Talai, S.M., Desai, D.A., and Heyns, P.S., Infrared thermography applied to the prediction of structural vibration behavior, *Alexandria Eng. J.*, 2019, vol. 58, pp. 603–610.
10. Hwang, S., An, Y.K., and Sohn, H., Continuous-wave line laser thermography for monitoring of rotating wind turbine blades, *Struct. Health Monit.*, 2019, vol. 18, pp. 1010–1021.
11. Chen, G., Zhang, W., Zhang, Z., Jin, X., and Pang, W., A new rosette-like eddy current array sensor with high sensitivity for fatigue defect around bolt hole in SHM, *NDT & E Int.*, 2018, vol. 94, pp. 70–78.
12. Sodano, H.A., Development of an Automated Eddy Current Structural Health Monitoring Technique with an Extended Sensing Region for Corrosion Detection, *Struct. Health Monit. Int. J.*, 2007, vol. 6, pp. 111–119.
13. Witos, M., Zieja, M., Fallahi, N., Zurek, Z., and Kwasniewski, J., NDE and SHM of critical parts using magnetic and electromagnetic methods, *Acta Phys. Pol. A.*, 2018, vol. 133, pp. 697–700.
14. *Structural Health Monitoring (SHM) in Aerospace Structures*, Amsterdam: Elsevier, 2016.
15. Wang, Y., Qiu, L., Luo, Y., Ding, R., and Jiang, F., A piezoelectric sensor network with shared signal transmission wires for structural health monitoring of aircraft smart skin, *Mech. Syst. Signal Process.*, 2020, vol. 141, p. 106730.
16. Wildemann, V.E., Spaskova, E.V., and Shilova, A.I., Research of the damage and failure processes of composite materials based on acoustic emission monitoring and method of digital image correlation, *Solid State Phenom.*, 2016, vol. 243, pp. 163–170.

17. Barsuk, V.E., Stepanova, L.N., and Kabanov, S.I., Composite airplane construction acoustic emission testing during static loading, *Kontrol'. Diagn.*, 2018, no. 4, pp. 14–19.
18. Stepanova, L.N., Bataev, V.A., and Chernova, V.V., Studying the failure of a CFRP sample under static loading by the acoustic-emission and fractography methods, *Russ. J. Nondestr. Test.*, 2017, vol. 53, no. 6, pp. 422–429. <https://doi.org/10.1134/S1061830917060092>
19. Zhou, J., Mathews, V.J., and Adams, D.O., Acoustic emissionbased impact location estimation on composite structures, *Struct. Health Monit.*, 2019, vol. 18, pp. 1652–1668.
20. Zhao, W. and Zhou, W., Cluster analysis of acoustic emission signals and tensile properties of carbon/glass fiber reinforced hybrid composites, *Struct. Health Monit.*, 2019, vol. 18, pp. 1686–1697.
21. Guemes, A., Fernandez-Lopez, A., Daz-Maroto, P., Lozano, A., and Sierra-Perez, J., Structural health monitoring in composite structures by fiber-optic sensors, *Sensors*, 2018, vol. 18, p. 1094.
22. Bashkov, O.V., Romashko, R.V., Zaikov, V.I., Panin, S.V., Bezruk, M.N., Khun, K., and Bashkov, I.O. Detecting acoustic-emission signals with fiber-optic interference transducers, *Russ. J. Nondestr. Test.*, 2017, vol. 53, pp. 415–421.
23. Kwon, H., Park, Y., Kim, J. H., and Kim, C. G., Embedded fiber Bragg grating sensor based wing load monitoring system for composite aircraft, *Struct. Health Monit.*, 2019, vol. 18, pp. 1337–1351.
24. Weiland, J., Hesser, D.F., Xiong, W., Schiebahn, A., Markert, B., and Reisgen, U., Structural health monitoring of an adhesively bonded CFRP aircraft fuselage by ultrasonic Lamb Waves, *Proc. Inst. Mech. Eng. Part G. J. Aerosp. Eng.* 2020, vol. 234, no. 13, pp. 2000–2010.
25. Ong, W., Rajic, N., Chiu, W., and Rosalie, C., Lamb wave–based detection of a controlled disbond in a lap joint, *Struct. Health Monit.*, 2018, vol. 17, no. 3, pp. 668–683.
26. Sherafat, M.H., Guitel, R., Quaegebeur, N., Hubert, P., Lessard, L., and Masson, P., Structural health monitoring of a composite skin-stringer assembly using within-the-bond strategy of guided wave propagation, *Mater. Des.*, 2016, vol. 90, pp. 787–794. <https://doi.org/10.1016/j.matdes.2015.11.018>
27. Taleb, S., Rittmeier, L., Sinapius, M., Boubenider, F., and Schmidt, D., Experimental study of Lamb waves propagation inside an impact damage in the size of the used wavelength, *Russ. J. Nondestr. Test.* 2020, vol. 56, no. 2, pp. 141–150.
28. Lee, B.C. and Staszewski, W.J., Sensor location studies for damage detection with Lamb waves, *Smart Mater. Struct.*, 2007, vol. 16, pp. 399–408.
29. Tan, Y. and Zhang, L., Computational methodologies for optimal sensor placement in structural health monitoring: a review, *Struct. Health Monit.*, 2020, vol. 19, no. 4, pp. 1287–1308.
30. Ostachowicz, W., Soman, R., and Malinowski, P., Optimization of sensor placement for structural health monitoring: A review, *Struct. Health Monit.*, 2019, vol. 18, pp. 963–988.
31. Nedospasov, I.A., Mozhaev, V.G., and Kuznetsova, I.E., Unusual energy properties of leaky backward Lamb waves in a submerged plate, *Ultrasonics*, 2017, vol. 77, pp. 95–99. <https://doi.org/10.1016/j.ultras.2017.01.025>
32. Park, I., Jun, Y., and Lee, U., Lamb wave mode decomposition for structural health monitoring, *Wave Motion*, 2014, vol. 51, no. 2, pp. 335–347. <https://doi.org/10.1016/j.wavemoti.2013.09.004>
33. Attarian, V.A., Cegla, F.B., and Cawley, P., Long-term stability of guided wave structural health monitoring using distributed adhesively bonded piezoelectric transducers, *Struct. Health Monit.*, 2014, vol. 13, no. 3, pp. 265–280. <https://doi.org/10.1177/1475921714522842>
34. Schubert, K.J., Brauner, C., and Herrmann, A.S., Non-damage-related influences on Lamb wave-based structural health monitoring of carbon fiber-reinforced plastic structures, *Struct. Health Monit.*, 2013, vol. 13, pp. 158–176.
35. Wandowski, T., Malinowski, P.H., and Ostachowicz, W.M., Delamination detection in CFRP panels using EMI method with temperature compensation, *Compos. Struct.*, 2016, vol. 151, pp. 99–107. <https://doi.org/10.1016/j.compstruct.2016.02.056>
36. Dodson, J.C. and Inman, D.J., Thermal sensitivity of Lamb waves for structural health monitoring applications, *Ultrasonics*, 2013, vol. 53, no. 3, pp. 677–685. <https://doi.org/10.1016/j.ultras.2012.10.007>
37. Kullaa, J., Distinguishing between sensor fault, structural damage, and environmental or operational effects in structural health monitoring, *Mech. Syst. Signal Process.*, 2011, vol. 25, pp. 2976–2989.
38. Burkov, M., Lyubutin, P., and Byakov, A., Experimental application of Lamb wave technique for testing of CRFP, *AIP Conf. Proc.*, 2018, vol. 2051, article ID 020043. <https://doi.org/10.1063/1.5083286>
39. Burkov, M.V., Lyubutin, P.S., and Byakov, A.V., Lamb wave ultrasonic detection of barely visible impact damages of CFRP, *Russ. J. Nondestr. Test.*, 2019, vol. 55, no. 2, pp. 89–101.
40. Lamss-composites software. <http://www.me.sc.edu/research/lamss/html/software.html>. Accessed November 18, 2020.
41. Zhongqing, Su and Lin, Ye., *Identification of Damage Using Lamb Waves From Fundamentals to Applications*, Berlin: Springer, 2009.