

Damage monitoring of aircraft structures made of composite materials using wavelet transforms

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Abstract. The present article is dedicated to the study of the acoustic properties of composite materials and the application of non-destructive testing methods to aircraft components. A mathematical model of a wavelet transformed signal is presented. The main acoustic (vibration) properties of different composite material structures were researched. Multiple vibration parameter dependencies on the noise reduction factor were derived. The main steps of a research procedure and new method algorithm are presented. The data obtained was compared with the data from a three dimensional laser-Doppler scanning vibrometer, to validate the results. The new technique was tested in the laboratory and on civil aircraft at a training airfield.

1. Introduction

As a result of a significant growth in the use of composite materials in aviation structural components there is a strong need for increased capability for the operational monitoring and inspection of such components. The main impact of this research lies in the management and operation of future composite aircraft components. The data, which was obtained, can help to develop a universal non-destructive testing method, and as a result, improve aviation safety. The condition monitoring of modern passenger aircraft with complex composite material components, and the prediction of the operational state of such components, will be one of the major aviation operational tasks of the next decades.

During the preliminary research it was concluded that wavelet analysis is the most effective and appropriate tool for the vibration analysis for the determination of the modal parameters of free oscillations, especially in the integral control of a composite structural aircraft component, during the operational inspection. Wavelets can be combined, using a “reverse, shift, multiply and integrate” technique called convolution, with portions of a known signal to extract information from the unknown signal. The present research represents a “shift” technique with the use of the variable list of the wavelet family, such as Morlet, Gabor and Daubechies wavelets [1].

Other diagnostic and NDT methods, materials and results have been studied in detail to verify the correctness of the chosen research method [2-8].



The aircraft components of interest in the research were: propeller blades (figure 1); Yak-42 aircraft spoilers (figure. 2); and different types of honeycomb construction.



Figure 1. Propeller blades with different operation time.

Propeller blades with different surface conditions and geometry were tested. The fully composite blade with an Aluminum alloy ring at the attachment point is a perfect example of a modern hybrid composite structure. Each blade was made from pre-preg material using different types of epoxy resin. These blades are commonly used in small civil aviation aircraft, especially in hydro-aeroplanes, trikes, trainer aircrafts, etc.. The life of each blade, according to passport data, is, on average, no more than 600 flight hours. Yak-42 aircraft spoilers, made from a three layer reinforced honeycomb construction, were also tested in lab and on the training airfield.

2. Theoretical basis

The wavelet transform can be regarded as a three-dimensional spectrum, where time is given on the X – axis, frequency on the Y – axis, and the Z – axis represents the amplitude of harmonics with a given frequency at a given time. There are two main features that make the continuous wavelet transform (CWT) particularly attractive. First, in most cases, the vibration modes are automatically separated, thus providing the natural frequencies. This means that the values of the instantaneous frequencies and damping parameters can be easily obtained. Second, the most significant information is preserved in the CWT line highs and ridges (the high amplitude areas of the CWT figure). It should be noted that for the appropriate choice of the wavelet family, CWT wavelets can serve as a filter for separation of free oscillations.

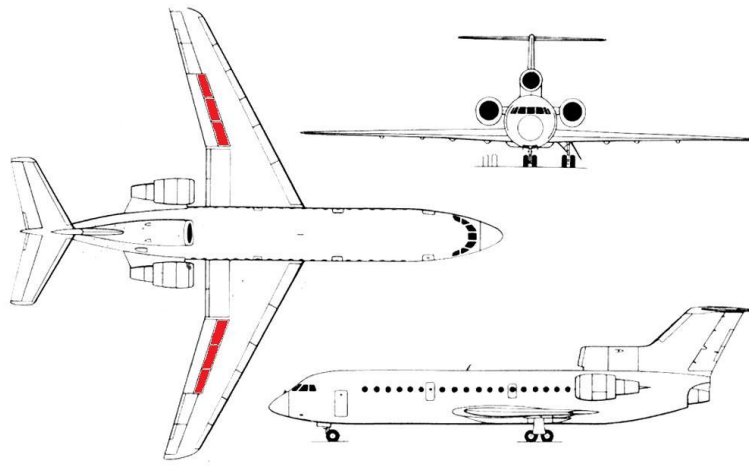
To illustrate the proposed method, we analyze a simple case of a linear system with two degrees of freedom (figure 3). This shows the principle for obtaining instantaneous frequency and damping parameters through the use of CWT (calculated only for ranges).

$$f(t) = \sum_{j=1}^2 A_j(t) \cos \Phi_j(t), \quad (1)$$

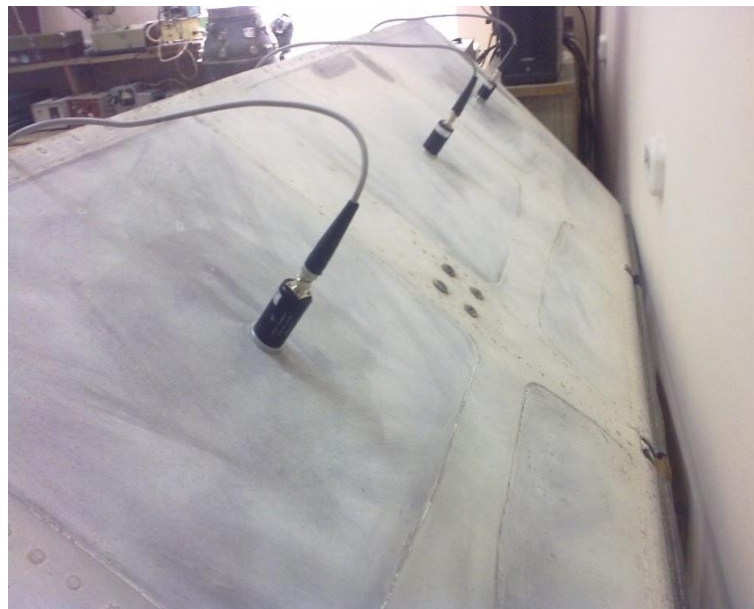
where $A_j(t) = \alpha_j \exp(-\zeta_j \omega_j t)$, and $\Phi_j(t) = (1 - \zeta_j^2)^{\frac{1}{2}} \omega_j t + \varphi_j$ and ω_j are the natural oscillation frequencies, with damping coefficient, ζ_j ; initial amplitude, α_j ; and the phase shift of the j^{th} mode, φ_j .

Table 1. Values used in the linear system example

$\alpha_1 =$	α_2	ζ_1	ζ_2	ω_1	ω_2	φ_1	φ_2
0.5	3.0	0.03	0.045	40π	156π	0.5π	0.5π



(a)



(b)

Figure 2. (a) Yak-42 passenger jet with spoilers shown in red;
(b) Yak-42 spoilers in lab during the testing.

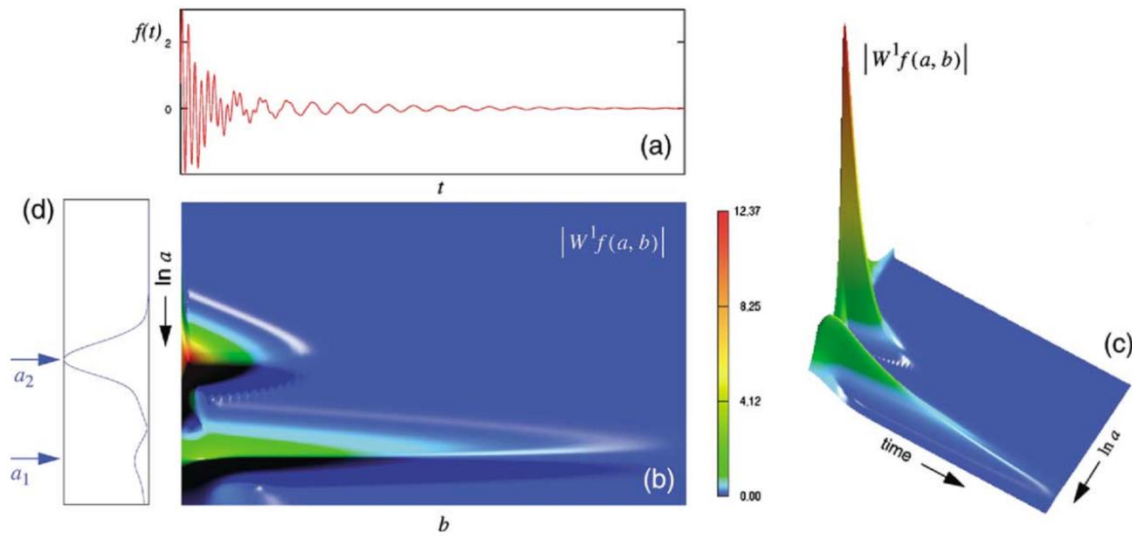


Figure 3. Linear system with two degrees of freedom: (a) Function $f(t)$; (b, c) Wavelet transform; (d) Free oscillation frequency.

Figure 3 (a) shows the reaction to the impulse excitation during the time interval ($0 \leq t \leq 1$). The first-order derivative for the CWT wavelet analysis was selected to be equal to

$$\psi_1(t) = (-t + i\omega_0)e^{\frac{-t^2}{2}}e^{-i\omega_0 t}, \quad (2)$$

with $\omega_0 = 5$. Figures 3 (b) and (c) show two a 2D and a 3D view of the CWT, from which the modes of oscillation can be clearly identified; however, the proposed method does not require a complete calculation of the CWT. It is only necessary to perform the calculation for a fixed time, b_0 , figure 3 (d), and evaluate the scales a_1 and a_2 for the maximum deformation: $a_1 = 4.159 \times 10^{-4}$; $a_2 = 1.046 \times 10^{-2}$. The relevant frequencies, ω_j , and damping parameters, ζ_j , can be determined by the following formula [9]

$$\alpha_j \sqrt{1 - \zeta_j^2} \omega_j = \omega^* \quad \text{and} \quad \zeta_j \omega_j = -m_j. \quad (3)$$

3. Methodology and experimental results

The data obtained was validated by comparison with data from a Polytec PSV-400 scanning Vibrometer (figure 4). The method of the procedure contains several iterations combining direct Fourier transformation and CWT, (figure 5).

Using a direct Fourier transform – first iteration, (figure 6), to check the dependence of the vibratory acceleration on the frequency, can be used to indicate the presence of a defect.

Figures 7, 8 and 9 illustrate the features of the CWT before and after the appearance of the artificially created defect in the reference honeycomb structure. There is a clear difference between

the CWT result for the object before and after the appearance of the defect. The differences marked in yellow highlight the changes in particular areas.



Figure 4. Polytec PSV-400 scanning Vibrometer.

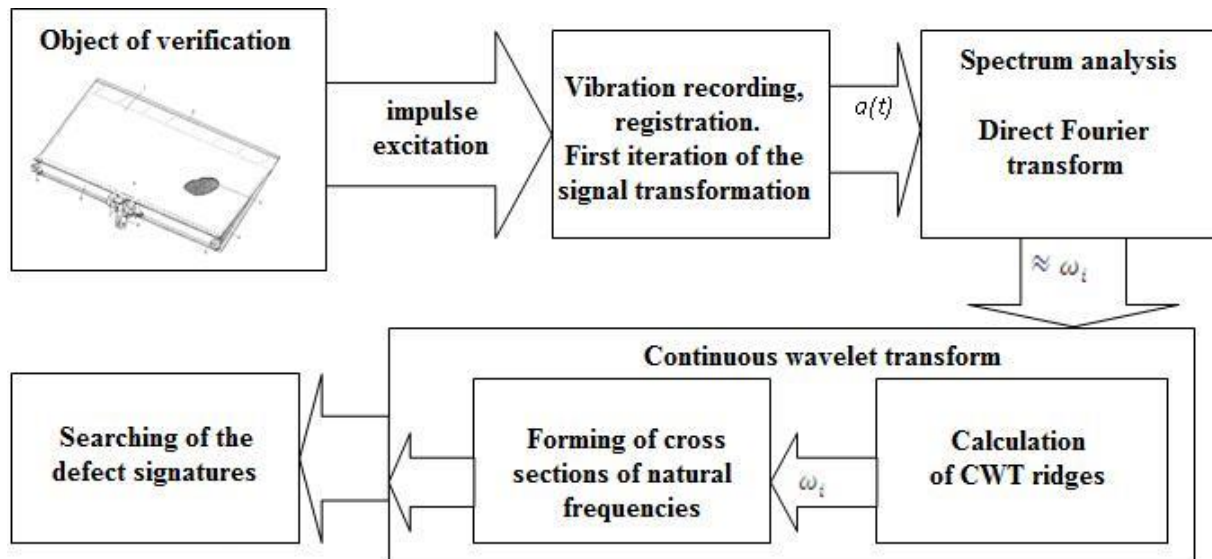


Figure 5. The main steps of the procedure (Algorithm).

The area of the defect in the reference honeycomb construction was gradually increased, from approximately 1% to 5% of the internal honeycomb construction space. To create the defect, water was injected water, and subsequently frozen, to cause the delamination between the honeycomb core and the layers. After that, the water was vaporized, and the sample was weighed to ensure that there was no remaining water in the construction.

The works [10-14] guided the authors in the interpretation of the CWT signal images.

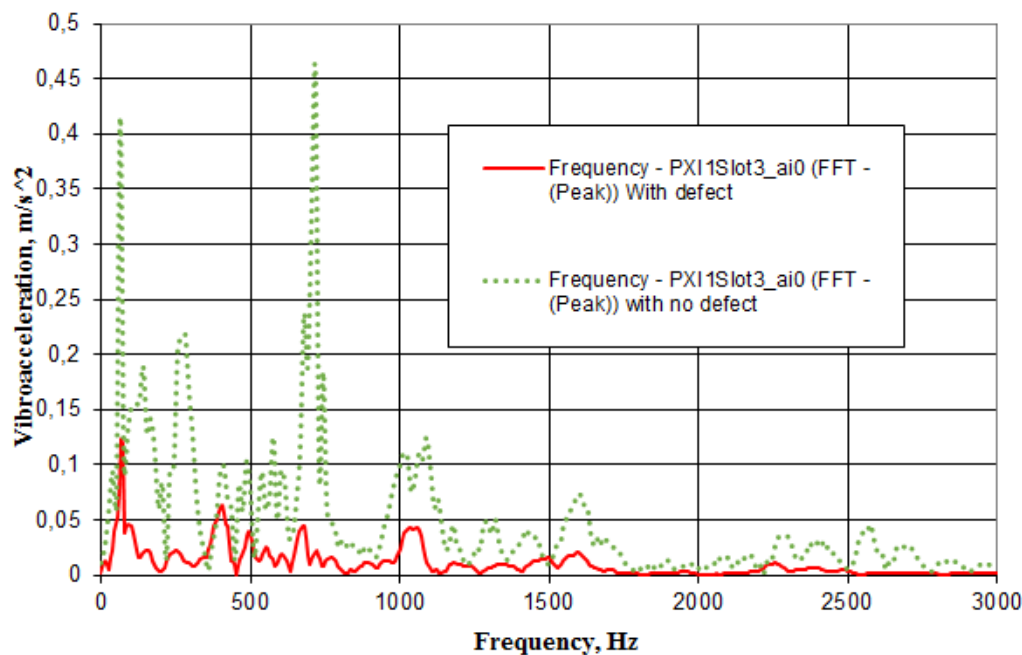


Figure 6. Graph of Vibratory acceleration, with and without the defect.

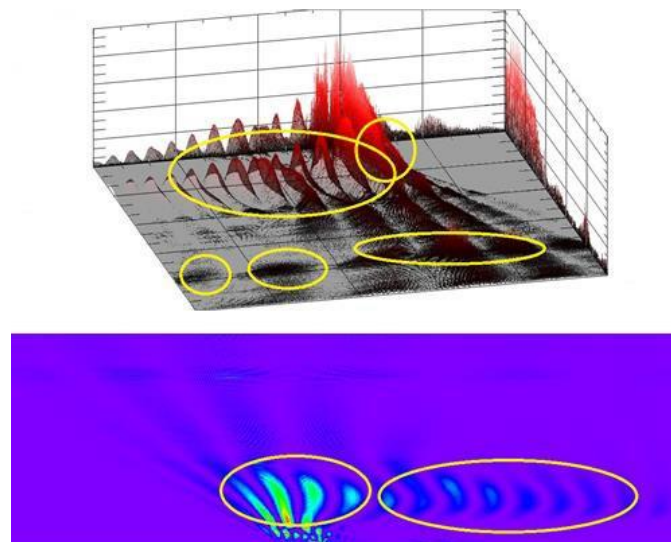


Figure 7. CWT 3d and Scalogram – honeycomb construction with no defect.

4. Discussion

As might be anticipated, the new testing experimental procedure, carried out on the reference honeycomb structure, showed a reduction in the value of each natural frequency and an increase in damping at resonance as a result of the presence of damage. Visual features of the CWT 3d and scalogram indicate changes in the overall vibration picture of the signal, which can directly attributed to the integral damage condition of the object under investigation.

The aircraft components for which this procedure would be most applicable include spoilers, propeller blades and different types of honeycomb constructions.

It was found that the master blade mode shapes at resonant frequencies are practically the same in comparison with a blade following an operating time of 500-600 flight hours (figure 10).

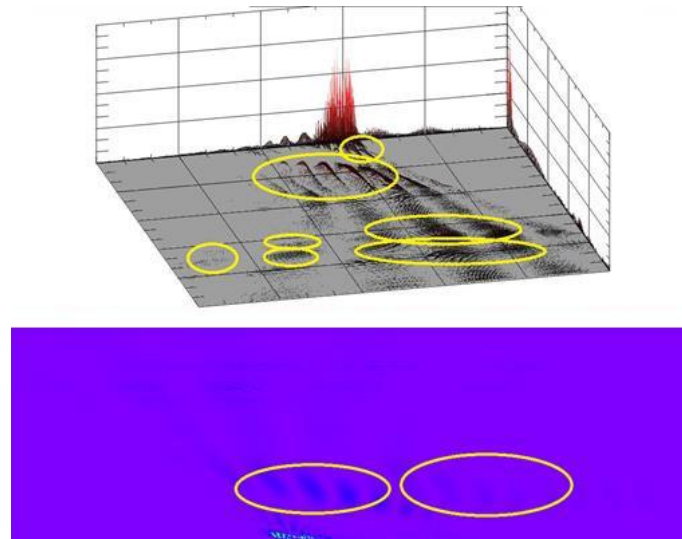


Figure 8. CWT 3d and Scalogram, honeycomb with 1% artificially created delamination.

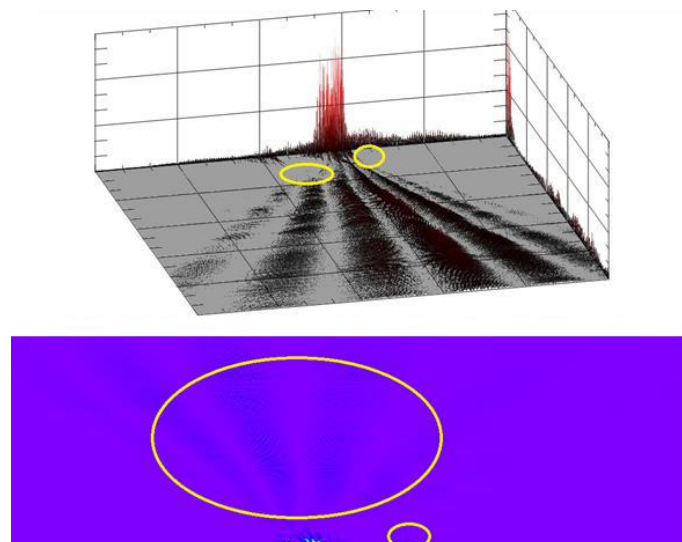
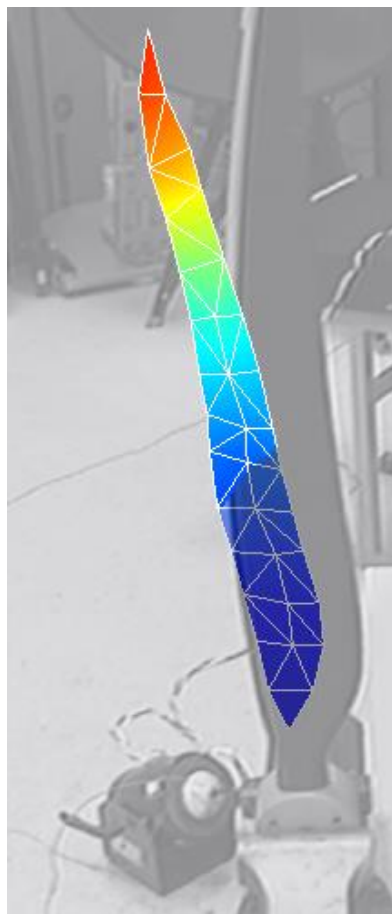


Figure 9. CWT 3d and Scalogram, honeycomb with 5% artificially created delamination.

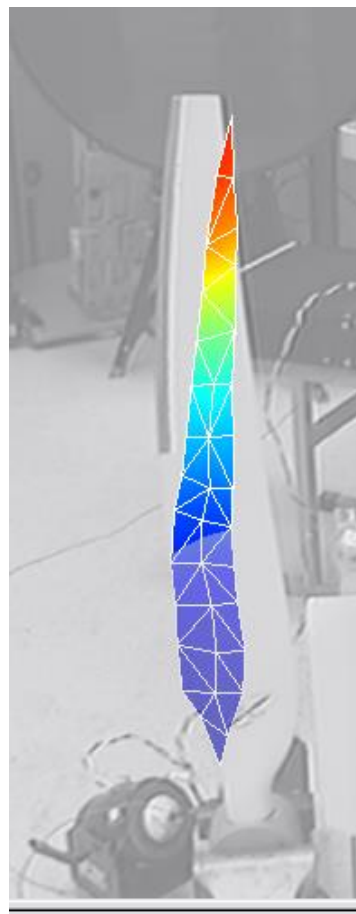
Vibration speed and vibratory displacement are presented (figure 11). It is shown that there is an increase in the vibration speed on some certain frequencies.

5. Conclusion

This research indicates that wavelet based NDT analysis could provide a basis for determining damage levels in structural composite aerospace components, and thus a means to decide whether a component is still fit to be operational.

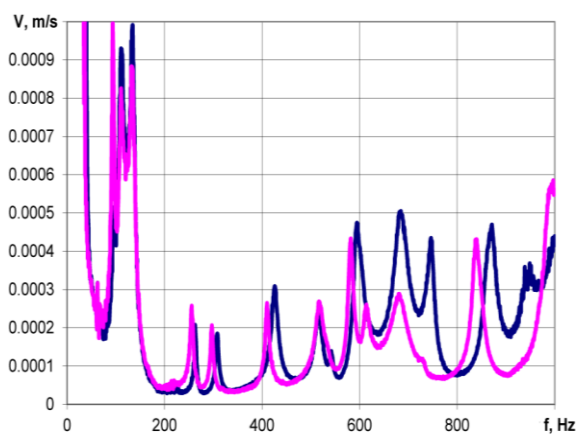


(a)

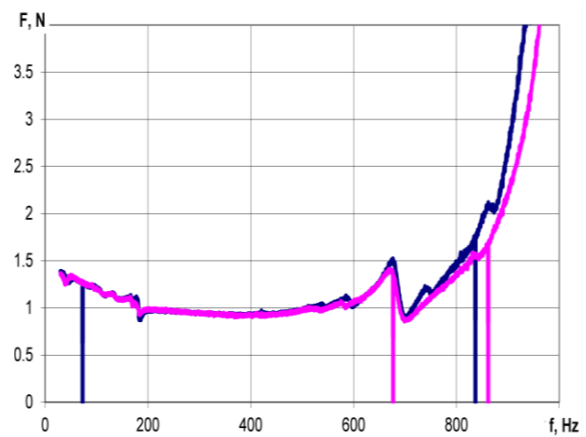


(b)

Figure 10. Blade mode shapes obtained using a 3 dimensional laser-Doppler scanning vibrometer
(a) Master blade
(b) Blade with 500-600 flight hours.



(a)



(b)

Figure 11. Comparison of master blade (pink) and blade after 500-600 hours operation (blue).
(a) Vibration speed and (b) Vibratory displacement.

The method presented has the potential for critical life-cycle parameter identification, with a view to enabling life extension certification, based on acoustical structure health monitoring. It should be

mentioned that hardware and software can be used both for searching for defect signatures, and also for structural control. The data obtained during the test series indicated that the maintenance process is sufficiently frequent for predicting time to failure based on observed damage.

References

- [1] Daubechies I (1992) *Ten lectures on wavelets*, University of Lowell, Philadelphia: Society for Industrial and Applied Mathematics (SIAM)
DOI: <http://dx.doi.org/10.1137/1.9781611970104>
- [2] Blanas P and Das-Gupta DK (2000) Composite piezoelectric materials for health monitoring of composite structures. *Materials Research Society Symposium Proceedings*. Materials for Smart Systems III: Symposium, 30 Nov–2 Dec 1999, Boston, MA, USA, **604** 45–50
- [3] Koktavy P, Trcka T and Koktavy B (2011) Noise diagnostics of advanced composite materials for structural applications. *Proceedings IEEE 21st Int Conf Noise and Fluctuations*, 84–7
DOI: 10.1109/ICNF.2011.5994391
- [4] Makeev A and Nikishkov Y (2011) Material characterization and failure prediction for composites. *37th European Rotorcraft Forum*, 13–15 Sept 2011, Vergiate and Gallarate, Italy, **2**, 1164–70
- [5] Stifter D, Wiesauer K, Wurm M, Schlotthauer E, Kastner J, Pircher M, Götzinger E and Hitzenberger CK (2008) Investigation of polymer and polymer/fibre composite materials with optical coherence tomography. *Measurement Science and Technology*, **19**(7)
DOI: 10.1088/0957-0233/19/7/074011
- [6] Ecault R, Boustie M, Touchard F, Berthe L, Chocinski-Arnault L, Ehrhart B and Bockenheimer C (2011) Damage of composite materials by use of laser driven shock waves. *2nd Joint US–Canada Conf Composites*. Montreal, Quebec, Canada, 26–28 September 2011, **3**, 2583–96
- [7] Ben BS, Ben BA, Vikram KA and Yang SH (2013) Damage identification in composite materials using ultrasonic based Lamb wave method. *Measurement*, **46**(2), 904–12
- [8] Karabutov AA, Murashov VV, Podymova NB and Oraevsky AA (1998) Nondestructive characterization of layered composite materials with a laser optoacoustic sensor. *Proceedings SPIE*, San Antonio TX, ETATS-UNIS, 31 March 1998, **3396**, 103–11
- [9] Haase M and Widjajakusuma J (2003) Damage identification based on ridges and maxima lines of the wavelet transform. *Int J Engineering Science*, **41**, 1423–43
- [10] Destic F, Petitjean Y, Mollier J, Barbieri S and Sirtori C (2009) THz QCL - based active imaging applied to composite materials diagnostic. *34th Int Conf Infrared, Millimeter, and Terahertz Waves, IRMMW-THz*, Busan, Korea, 21–25 September 2009, 674–5
- [11] Kolodii BI and Lyaschuk OB (1995) Direct and inverse problems of electromagnetic diagnostics of flat-laminated composite materials with the use of a rectangular waveguide. *Materials Science*, **30**(2), 173–81
- [12] Kim F, Penumadu D, Siriruk A, Bunn J and Kardjilov N (2011) Three dimensional microstructure of polymeric composite materials used in sandwich structures using dual modality from combined high resolution X-ray and neutron tomography. *18th Int Conf Composite Materials*, Jeju Island, Korea, 21–26 August 2011, 1–6
- [13] Avdelidis NP, Moropoulou A and Delegou ET (2003) Applications of thermography in the assessment of masonry, airport pavements and composite materials. *Insight: Non-Destructive Testing and Condition Monitoring*, **45**(12), 836–40
- [14] Watson CC, Rhoads JF and Adams DE (2013) Structural dynamic imaging through interfaces using piezoelectric actuation and laser vibrometry for diagnosing the mechanical properties of composite materials. *ASME 2013 Dynamic Systems and Control Conference*, Palo Alto, California, 21–23 Oct 2013, 1–10