DAMAGE MONITORING OF AIRCRAFT STRUCTURES MADE OF COMPOSITE MATERIALS USING WAVELET TRANSFORMS

MOLCHANOV DMITRII SERGEEVICH

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Abstract

Due to the significant increase in composite materials that can be used in aviation structural elements, there is a strong need for their operational control. It is estimated that a significant part of the average modern aircraft lifecycle costs is related to inspection and repair, thus it is important to perform efficient and cost-effective maintenance and monitoring techniques to reduce lifetime costs. This study is concerned with integral state monitoring of aircraft structures made from composite materials. It deals with techniques for damage monitoring and quality control, equipment observation, planned prototype testing and research into the vibration properties of different composite structures. Operation, maintenance and condition forecasting of components, such as aircraft composite blades, airplane spoilers, ailerons, aircraft airframe components, are the areas that should be properly investigated, in order to enhance the future of the industry.

The aim of this research is to investigate usable signs of vibration characteristics that can reflect the effects of the damage and integral changes of advanced composite structures. The main goals are a universal approach to integral condition monitoring for all kinds of composite materials and research into the vibration property alterations of a new generation of composite materials during their operation. The modern generation of large aircraft can be designed with all-composite fuselage, frames and wing structures. The main advantages of composite materials are their high strength, relatively low weight, corrosion resistance and flexibility in implementation. Control and diagnostics of this kind of composites require deep knowledge of composite structures, materials, their failure behaviour, and tooling. Aerospace structures are suffering from damage as a result of fatigue, overloading, partial or integral material destruction and degradation in

consequence of environmental factors, and extemporaneous incidents such as seismic events or impacts.

There is also uncertainty connected to understanding the outcome of operational damage of aircraft composite structures. Non-destructive inspection and evaluation techniques are recommended in many cases, but still, represent significant downtime and labour costs and, in many cases, require highly skilled personnel to perform them. Linked to structures and onboard built-in structural health monitoring systems could be used for improving the reliability and safety of composites while reducing lifecycle costs and improving the design and manufacture processes. However, they also have their own disadvantages like the cost of implementation, cost of operation of the system itself and impact to the structure during production and maintenance.

This research is therefore mainly focused on vibration properties of advanced composite materials and simple control procedures that can be conducted by an engineering technician during light maintenance checks (including both routine and detailed inspections). The decision on the schedule for the checks to be performed can vary by aircraft type, the cycle count, or the number of hours flown since the last check. Another important subtask is the prediction of the object condition in operation. A significant part of the research is concerned with the collection of statistical information, and experiments with different objects made of composite materials, using the proposed methodology. An additional part is linked to the optimization of equipment for the future demands of the industry in operational control and diagnostics.

It is concluded that the technique of combining wavelet analysis is an effective and appropriate tool for vibration analysis to determine the modal parameters of free and forced oscillations, especially in the integral control of composite structural elements. The novel aspect of the research is the practical experimental work that has been executed on real advanced composite material objects (metal-polymer-metal composites as well), and its subsequent analysis.

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Nomenclature

$\mathbf{a}(\boldsymbol{t})$	signal function
$\approx\boldsymbol{\omega}$	approximate frequency
ω	Frequency
$\boldsymbol{\zeta_j}$	coefficient of damping
$\boldsymbol{\alpha_j}$	initial amplitude $(\mathrm{t} = 0)$
$\boldsymbol{\varphi_j}$	phase shift of the jth mode
σn	nominal stress
F	force applied
A	area of contact
Wt	weight percent
$\mathbf{X_i}(\boldsymbol{\omega})$	frequency response function in the form of speed or acceleration for the i-th degree of freedom
$\boldsymbol{\alpha_{NDI}}$	defect sufficient size
$\mathbf{t_1}$	Initial value of nondestructive detection period for structure in its lifetime
$\mathbf{t_{crit}}$	critical period in

$\boldsymbol{\alpha}_{90/95}$	probability-of-detection
$\boldsymbol{\psi(t)}$	denotation of mother wavelet
$\bar{\boldsymbol{\psi}}(\boldsymbol{t})$	complex conjugate number to $\psi(t)$
$\boldsymbol{a}$	wavelet scale parameter
$\boldsymbol{b}$	wavelet shift parameter
$\boldsymbol{f(t)}$	signal function
$\hat{\boldsymbol{f}}(\boldsymbol{\omega})$	Fourier transform of the function
K	diagnostic parameter
[K]	allowable value of the diagnostic parameter
$\mathrm{A_j(t)}$	natural oscillation frequency 1
$\mathrm{\Phi_j(t)}$	natural oscillation frequency 2
$\mathrm{b_0}$	fixed time value
$\mathrm{\omega_j}$	the relevant frequency for jth mode
f_n	discrete function
ω^*	fixed frequency
$a(s)$	parametric-written line
$b(s)$	parametric-written line

db4	designation of Daubechie wavelet
db9	designation of Daubechie wavelet
PP/PE	polyolefin polymer
$(\boldsymbol{n})$	number of freedom degrees
$[\boldsymbol{H}]$	transfer function matrix
Fj$(\boldsymbol{\omega})$	effect of j-th FD function
FD	freedom degree
$\boldsymbol{i}$	freedom degree object
Hij (ω)	function matrix
AFR	amplitude-frequency response
EMA	experimental modal analysis
$(\boldsymbol{n})$	number of freedom degrees
$[\boldsymbol{H}]$	transfer function matrix
Fj$(\boldsymbol{\omega})$	effect of j-th FD function
FD	freedom degree
[K]	stiffness matrix
[M]	mass matrix

{u}	displacement vector
{ù}	acceleration vector
f_{ip}	the calculated value of (i) natural frequency
f_{ie}	the experimental value of (i) natural frequency
a_i	weight coefficients
$\boldsymbol{i}$	number of freedom degree
(φ)	phase of the oscillation
N_R^2	noise power of input signal
N_V^2	noise power of output signal
$A\overline{P}$	average autocorrelation function
V	measured signal on the surface of the blade
R	reference signal

Chapter 1: Introduction

Research background

Aircraft airframe components exposed to high amounts of tension and stress during the operation. The integrity of a structure could be easily endangered by minor flaws that can lead to catastrophic events. Carbon laminates and sandwich composites and glass fiber composites are large parts of present aircraft's components, however, the aviation community is filled with unreliable and incorrect information about their safety and operational stability. It is a fact that the behavior of the composite structures in operation can be very different compared to equivalent metal structures. The combination of metal and polymer in a composite is a very specific area of intense research. The behaviour of metal-polymer-metal sandwich composites in operation is a big issue. It has been proven, that compared to metals, composites present less fatigue and corrosion, but undetected subsurface damages may stay undetected for a long period of time and can result in sudden avalanche failures. Therefore, there is extreme importance in an innovative inspection process capable of identifying the condition of these materials [1]. The original contribution of the present research is in the investigation of the existing techniques and methods and their combinations applicable to new materials under question and creation of a methodology based on analysis and data obtained. The use of a combination approach for condition monitoring of different types of advanced composites can provide the result test data which can be used for a better understanding of their behaviour in operation.

Implementation of elements made from composite materials (CM) into aircrafts design occurred gradually and very carefully. At first, only unstrained members (access hatches, doors, chassis elements, etc.) were made from CM. Subsequently, carbon fiber flaps, spoilers, ailerons, has become an ordinary aircraft design parts.

The problem of products operation, made from CM in the power frame of the wing and fuselage is a finally not resolved question. Currently, aircrafts such as Airbus A350 XWB and Boeing 787 Dreamliner or MC-21 have fuselage made of CM. The same as modern A-380, which has CM and frames made of polymer composite materials. This systematic implementation approach was chosen for several reasons:

1. Composite materials anisotropy - material properties could be significantly different depending on the direction of loads application. Since the power elements of the structure perceive the entire load spectrum: distributed aerodynamic, distributed mass, concentrated loads, it becomes very difficult and sometimes impossible to choose such an orientation of fibers so that the material can absorb the above loads during the designated resource with an adequate margin of safety.

2. Conditions of aircraft operation, among temperature deviations and time factors, have a strong influence on the mechanical properties of CM. In comparison with metal ones, CM are also subjects of the destructive aggressive influence of temperature and external conditions.

3. Another reason is the rapid growth in air traffic. Related factors are a continuous increase of new aircrafts, lack of qualified flight and engineering staff, and a high cost of error in calculating power elements strength at the stage of design.

4. Low modulus of resilience among with hygroscopicity (ability to absorb water, which, freeze at low temperatures, and breaks the layers of material), toxicity, low operational manufacturability (long duration and complexity of repair) are still factors which badly influence the whole picture of CM aircraft components usability.

5. The significant cost of CM products. Despite the fact that there is a constant increase in the application, some CM remains more expensive than metal products due to the high cost

of raw materials and more complex production cycle. This ultimately increases the final cost of the aircraft. CM are characterized by high damping ability, which determines their good resistance to cyclic and vibration loads. In world practice, products based on polymer CM (PCM) are most widely used. From a semi-finished products, it is possible to obtain more complex spatial-geometric configurations of parts and products, opposite to structural metal materials and their alloys, thereby eliminating multiple technological joints, improving reliability and performance. All elements, for example of a frame compartment (plating, longitudinal stringer set, struts and walls, transverse frames and stiffeners) could be assembled and connected in one curing (polymerization) process.

Till present days the process of cyclic fatigue growth for damaged aircraft composites and their residual strength under operational loads are not fully investigated. Modern composites are usually designed without damage growth criterion with many knockdown factors included to cover unknown/untested effects. Their optimization could not be achieved according to the no damage growth criterion. In 2009, the U.S. Federal Aviation Administration (FAA) presented a slow-growth approach to certifying composite, adhesively bonded structures and bonded repairs which could improve the situation and is worthy for the research [2].

Defects in composites

Many types of defects can occur during the manufacturing process or in operation during the component life cycle of composite material. Various processes could cause a wide range of defects, the most common of which is “porosity”. Little voids may be extraordinary high-stress concentrators. Porosity may be caused by inappropriate curing parameters (inappropriate deviations of temperature during the process, process duration time, pressure, vacuum bleeding of the resin, etc). Levels of porosity can be critical, as they affect many parameters of the mechanical characteristics, such as interlayer shear stress. Resin-impregnated fiber layers (pre-pregs) are made manually or by the means of automated production lines. Any of these variants potentially has the possibility for the inclusion of foreign bodies during the production process. Modern manufacturing processes involve the infusion of resin into pre-formed dry fibers in moulds. These processes added new types of defects such as fiber displacement or waviness both in the material plane and outside the plane. According to R. A. Smith: “Stitching of fiber tows, to hold them in place and prevent misalignment during cure, can itself introduce numerous regularly-spaced sites for void formation” [3]. Another big problem for honeycomb structures is poor bonding and disbonds as a result. These defects are often issues in the skin-to-adhesive and adhesive-to-core interfaces.

The impact is the most recent in-service damage. In laminates, when composite constructed as monolith this can lead to matrix damage, resulting in delaminations of the layers. Critical delaminations could stay invisible for a long period of time, in other cases the structure can be visually damaged - “barely-visible impact damage” (BVID). Sandwich structures are not an exception, they also suffer from the matrix cracks and delaminations during impact. Another defect for honeycomb sandwich structures is a fillet-bond failure, it occurs when the bond layer suffers from different factors. Crushed cores occur when the energy of the impact is transferred to the core, this can lead to relatively high compressive strength reduction but also stay invisible [3].

Influence of defects in composites

Abnormalities can be created in composite materials either during in-service operations or during production processes. These abnormalities should be considered as a defect, that can be represented as a function of the intended use of the material and the significance of the deviation on the required performance.

> “All defect types are known to adversely affect performance in some way. However, the type and size of the defect that needs to be found can only be set for each application based on the results of mechanical destructive tests and detailed knowledge of how such defects grow, if at all, in the expected service environment. This process sets the acceptance criteria for manufacturing and in-service defects”
>
> Taken from [3].

The possible impact of the defects to the structure must be assessed before significant acceptance and deviation criteria can be established for subsequent operation. The determination of the initial (prior to use) condition of the composite material is important for understanding the process of properties deviation during the operation.

The anisotropy can be considered, both as an advantage and disadvantage of composite materials. This feature can bring exposure to states of stress in the presence of geometrical discontinuities. Another factor that can reflect the more complex nature of a failure description in comparison with traditional materials is their distinctive heterogeneity. The composite structure can consist of unidirectional plies which in turn are composed of different phases, namely the matrix and the fibers. Observing global failures, the propagation of any damage occurs through a mechanism that is only similar to a crack in a global sense [4].

As an example for fiber-reinforced composites, five damage modes can modify the local stress distribution and as a consequence strongly influence the evolution of damage [5]. These modes are:

1. Transverse matrix cracking (A)
2. Delamination (B)
3. Longitudinal matrix cracking (C)

4. Fiber degradation (D)
5. Fiber debonding (E)

Early-stage transverse matrix cracking (A) is connected to the low transverse strength of unidirectional plies oriented transverse to the loading force direction. Longitudinal matrix cracking (C) is the secondary matrix dominated failure. The appearance of this mode is possible at higher loading conditions, due to the opposition expressed by the fibers in the transverse ply to the Poisson shrinkage during longitudinal tension loading. Fiber degradation (D) depends on fiber tensile strength, time of the force exposure, and environmental factors. Delaminations (B) between the composite plies, the same as debonding around the end of a fractured fiber (E) are created by interlaminar debonding stresses (Figure 1).

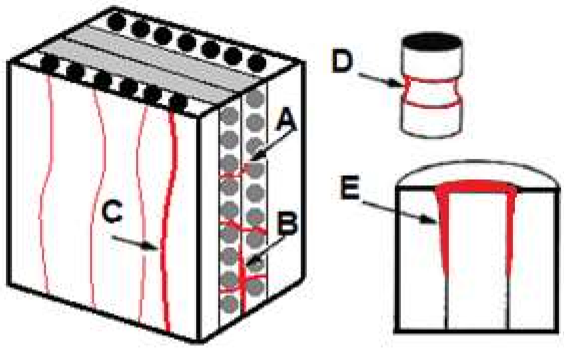


Figure 1. Damage modes modifying the local stress distribution in fiber-reinforced composites: transverse matrix cracking (A); delamination (B), longitudinal matrix cracking (C), fiber degradation (D), fiber debonding (E) [5].

In the case of metal-polymer-metal sandwich composites, possible failure modes are more relevant for special loading conditions. Like an example bending by the means of electromagnetic forming (EMF) causes a variety of possible failures.

Shear, tensile and compressive failures for these composites are usually expected at the edges during the bending (Figure 2**a**). However, compressive failure takes place in the vicinity of the sample middle. Tensile failure by cracking normally takes place in the outer skin sheet in the centerline of the sample. So-called Gull-wing bend in bending multilayered sheet material can also take place under special conditions as shown in Figure 2b. This type can occur during the local bending of the bending arm at the contact point due to poor adhesion.

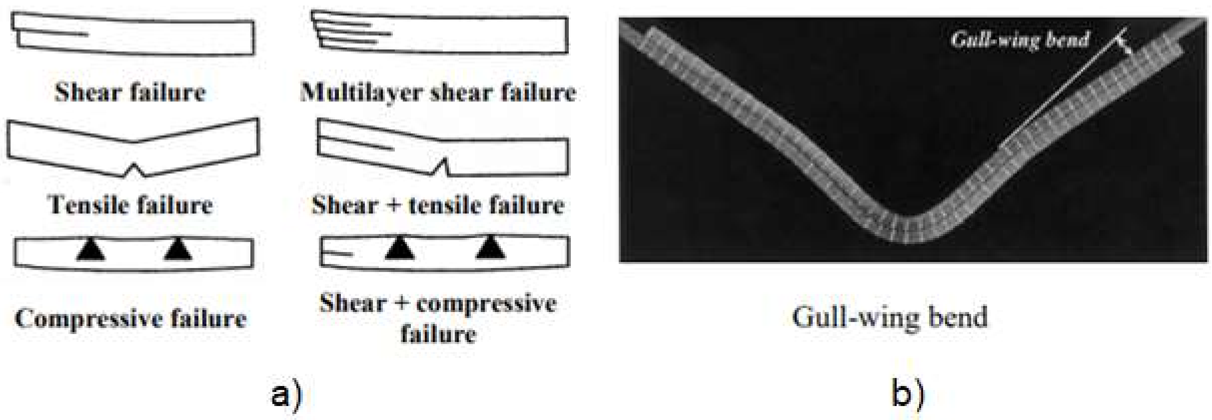


Figure 2. a) Possible failure mechanisms from bending multilayered materials according to DIN 14130 [6] as well as b) Gull-wing bend phenomenon due to the shear strain of the core/adhesive layer [6].

Observing the present situation in aircraft operation, it could be declared that the use of different non-destructive evaluation (NDE) approaches still allow to check the condition of composite material to identify damage modes. To consider (NDE) techniques for composite materials, it is necessary to accept that some of the defects should have a considerable size for the possibility of their detection. This is important because composite applications are the most demanding due to the necessity of reducing weight as much as possible. At the same time, these assumptions could be not valid for different applications or composite types [3].

In-service defects

In-service failures of composite materials depend on several processes and most important of them are connected to the environmental factors and particular materials properties. Such mechanisms of degradation like fatigue, impacts, static overloading, overheating, lightning strike, humidity, and temperature effects are most common [7]. Despite the differences in mechanisms by which defects are initiated and grow, there is a limited number of defect types. The most critical of them are:

- Delaminations (delamination buckling, splitting, etc.)
- Bond failures
- Cracks (large scale, interlaminar cracks and microcracks)
- Ingress of moisture or particles
- Fracture of fibers
- Buckling of fibers
- Interface failures between matrix and fibers.
- Failure between layers
- Failure between core and layers in sandwiches

One of the in-service most common defects requiring detection is the presence of delaminations. It can be caused by many factors like impact or fatigue damage. Disbonding can be found by the means of different techniques but still, there is no method available to measure adhesive strength during operation. Cracks should be detected before they will lead to delamination growth and a critical stage occur. It is likely to find a high density of cracks as a sign of delamination growth by the means of ultrasonic inspection as an example. In a situation when delaminations are oriented at right angles to an ultrasonic wave propagated at normal incidence into a laminate, they are ideally aligned for detection by ultrasonics [3]. Their presence can be detected by the reflected sound or by the corresponding loss of transmitted energy.

Different defects require various methods for their detections. The ingress of moisture can not only affect the mechanical properties that are matrix dependent but also can reduce the residual strain of composite structure. Interlaminar cracks may be caused by moisture and sharp temperature fluctuations. Measuring of moisture by the means of infrared thermography or by ultrasonic velocity should be connected to the design, with the designation of the possible tolerances. Depending on the type and application of composite structure these judgments may be different. As an example, the delaminations in composites with short fibers are not as important as cracks, which can be located along the fibers [3].

One of the most important requirements for aircraft structures is to ensure safe operation for the entire life cycle in combination with high weight efficiency. The significant cost of the structure and the requirements for its reliable operation within the established or intended resource lead to the need of solving the problem of the longest period of its safe operation until the maximum possible service life will be reached for the individual components and structural elements, as well as the aircraft in general. The main factor in solving the problems related to the strength of aircraft structures is occupied by the issue of optimizing the problems connected to the maximum possible fatigue life and safe operation of the structure with the minimum weight characteristic of components and assemblies.

The limiting state of the main carrier element of the structure, the structural unit as a whole, and its individual elements can be characterized by various criteria due to the difference in the consequences to which it leads. However, in all cases, the basic requirement is to ensure flight safety.

The analysis and systematization of external loads with the subsequent assessment of the aircraft lifecycle or the power components of the airframe design have the ultimate goal to make the most accurate verdict of the arising tense state. It is extremely important for the evaluation of a possible state with an emerging and developed crack. The limiting state by the criterion of crack initiation or by the criterion of the achievement of the crack size, at which the fast uncorrectable final destruction of the structural element is realized, can be achieved when the structural element is stressed. Its evaluation is carried out based on various information.

The question about what size of a fatigue crack is worth attention should be determined by the condition for achieving the ultimate state of the body with a crack and the capabilities of the methods and means of non-destructive testing used in practice to identify cracks. Based on the ideas about the duration of the crack development process and the possibilities of non-destructive methods and means of control, as well as the availability of the control points themselves, this problem can be addressed directly in the framework of the above-considered question of the relative survivability of the material. The vitality of the main power elements of the structure is sufficient for the introduction of reasonable and cost-effective reliable periodic monitoring. However, even in structural elements of the same type, fatigue cracks may occur as a result of damage to the surface of a part in different sections and zones with different load concentrations. Under these conditions, the strategy for determining the periodicity of the inspection, the choice and justification of the method and means of control cannot be considered from general positions. It is necessary to analyze the features of the control according to different criteria, such as accessibility of the control zone, the geometry of the part, location of the crack, periodicity of inspections taking into account the kinetics of crack growth in the control zone, sensitivity of the method and cost of the control procedure. The intensity of checks and their complexity can overlap the impressive effect of the operation of the structural element on the principle of safe damage.

Research hypothesis

Considering the information above, we can affirm that high requirements for future advanced composite materials dictate strict regulations of such materials in operation. The search for alternative, fast, and low cost combined techniques for integral monitoring of advanced composites is a modern issue. For safety reasons and to ensure the operational stability of an aircraft or vehicle or an element during its life-cycle the effects of damages should be investigated by using a special approach, a data processing technique, and different types of composites. The modification of production technology for composites also can lead to a change in the structure of the material and therefore can greatly affect the properties of the material and its behaviour during operation. The tendency for damage accumulation, as well as the stability of the vibration characteristics for these materials, are the areas of research. Experimental models and experimental data will be used to investigate structural damages of modern composites (including composite materials with polymer matrixes, applications with the addition of carbon nanotubes and metal-polymer-metal sandwich composites), which will be helpful to predict their remaining capabilities. The research will allow to create a modern method of vibration analysis for diagnostic of the aircraft operational elements, made of different composite materials. It is expected that the study and collected information will not only help to solve a problem of long life for certain composite materials practical use but also will help to add data for the future composite materials industry as a whole.

One of the research aims is to detect simple signs, which allows us to monitor the composite aircraft element's condition in time and give a decision on its further possible operation. Composite structure element condition depends on many factors like production quality, operating conditions, personnel qualification, etc. While constant monitoring of the aircraft composite structure behaviour is essential for safety, there is a great chance of detecting signs of integral changes inside the structure, as an example due to state-dependent mechanical failures. Current research starts by investigating existing composite materials testing techniques, where different techniques are used to capture data for all stages of testing. Some usual test methods including tensile testing, compression testing, shear testing, fatigue testing, thermal analysis, and others are designed to investigate composite's properties due to mechanical abuse conditions in after production period, where a quasi-static loading approach is often used. Post-failure structural analysis of composite is an important technique where composite failure patterns, including deformation, crack or fracture are used to understand detailed failures and their effects on composite object degradation. NDE methods are further step connected to control in operation. In this research we use NDE vibration monitoring techniques in combination with continuous wavelet transforms both with modeling by the means of finite element analysis. The methods used are the following:

- Monitoring of alterations in the integral state of aircraft structures made of composite materials.
- Using wavelet transforms for the construction of the 3d finite function spectrum.
- Determination of the modal parameters of free oscillations.
- Using of Fourier Transforms for vibration spectrum construction.
- Using scanning Vibrometer, vibration generator and additional equipment to ensure the experimental results.

Experimental work and simulation for validation of experimental results are detailed in this thesis. Based on the above overview following hypotheses are used for damage monitoring of aircraft structures made of composite materials:

- There are usable features of vibration characteristics that can reflect the effects of damage and integral changes of advanced composite structures.
- NDE vibration-based technique in combination with Fourier and mainly wavelet transforms is an appropriate universal technique for fast composite element control and diagnostics in operation.
- A wide range of composite materials can be tested and monitored by the method proposed in the research.
- Experimental modal analysis can be useful for the determination of material models parameters for calculating the modal characteristics of polymer-metal sandwich sheets and metallic mono-materials composite products. As well as, solving the problem of minimizing the discrepancy between the calculated natural frequencies and the experimental ones.
- The severity of the outcome depends on operating conditions as well as loading type.

Research objectives

The following objectives were set to develop a base for the modern method of vibration analysis for diagnostic of the aircraft operational elements, made of composite materials.

- Analysis of the practical and theoretical areas of damage control for the aircraft elements made of composite materials.
- Theoretical and experimental studies of the influence of structural damage of composite materials on their vibration characteristics.
- The selection of the vibration diagnostic parameters and detecting the signs of damage of the structures made of composite materials.
- Experimental evaluation of the method sensitivity to failure degree.

- Developing of the operating diagnostics technique for the damage monitoring of aircraft structures made of composite materials.
- The approbation of technique on different modern composite materials.
- The development of NDT testing equipment set for monitoring of various composite materials in operation.
- The development of a principle for an express-test device for aircraft composite materials based on the proposed methodology.

Thesis structure

This chapter covers the background and rationale of this research where safety aspects of composite materials are discussed in relation to some operational and production defects and their effects. Emphasis is given to highlighting composite materials safety use, fast and adequate integral evaluation of their condition in operation. The following paragraphs cover chapters detailing the research outline.

Chapter two focuses on existing techniques and their applications for the aerospace industry; considering the needs for composite parts monitoring for efficient and safe operations. Different approaches where the main purpose is to understand more about composite performance estimation in cases of all kinds of abuse conditions were considered. Existing methods, along with their technological techniques, relevant results, conclusions extracted from those results, and drawbacks are reviewed in detail. The literature review includes analysis of the practical and theoretical areas of damage control for the aircraft elements made of composite materials. It can give an opinion on advanced composite materials and their inspection, an overview on SHM, and NDT techniques.

Experimental methodology, analysis of existing methods of vibration diagnostic, and preliminary results with fundamental parameters and a part of the experimental set-up are discussed in chapter three. Features of building information systems for non-destructive testing tasks of all types of equipment are discussed in depth where the formation of the test set up with particular devices also discussed. Information processing and presentation of processing results in a form suitable for analysis and further interpretation are also presented which mostly link to initial testing with various configurations. Information received and the formation of a decision according to the state of the controlled object and the possibility of its normal functioning or forecasting its residual resource is discussed in detail for further analysis.

Chapter four discusses the significant results obtained from different sets of experiments where details of test scenarios are included. This chapter presents the explanation of behaviour during loading conditions, with initial and final results of vibration response in the case of composite object condition changes. The methodology is tested on various applications including modern ones. In particular, this chapter identifies parameters useful for failure analysis, behaviour deviations, and their monitoring.

Experimental results and their discussion are presented in chapter four. It begins from the interpretation of obtained data according to information from chapter three. Experimental results with aircraft blades and their discussion results with CNT/Polymer applications and mainly research of vibration properties of metal-polymer-metal composite materials are the main core elements of chapter four. It also contains information on the methodology and results of the experimental modal analysis for metal-polymer-metal composites, thermography testing, the simplification of the vibration method and the conclusion of experimental results.

Chapter five, explains the novel aspects of this study that include major techniques used, results, and their impact and limitations of this research. The recommendation for future work is also included in this chapter in great detail.

Chapter 2: Literature Review

2.1 Introduction

This chapter covers the background and available literature related to the problem of damage monitoring of aircraft composite structures. Main articles, materials, and works, which were investigated and were used as a research basis, were represented here. The literature review suggests that there are three main categories on which the research should be focused, including analysis of the practical and theoretical areas of damage control for the aircraft elements made of composite materials, inspection of composites, and validation of results. The focus is given to critically discuss available research outcomes that link to this research and citing the results. This chapter clarifies the rationale of this research.

According to research aims, one of the main goals of this research is to develop a base for a modern method of vibration analysis for diagnostic of the aircraft operational elements, made of composite materials (including new composite materials with carbon nanotubes and metal-polymer-metal composites). The absence of statistical data referred to i) the operational stability, ii) combined alternative ways of the state detection, and iii) prediction of the state in time are still open problems for the operation of composite materials. The search for a simple, cheap universal approach for the integral estimation of different composite materials is still a priority goal. A solution that combines control and diagnostic features for new materials before the start of their operation, would save enormous time and material expenditures. To achieve this goal, at first, it is necessary to make an analysis of the practical and theoretical areas of damage control for the aircraft elements made of composite materials. The following information gives an opinion at the present situation in after production testing and damage monitoring of aircraft structures made of composite materials. As stated by Saba et al., “The many types of composite materials used in aerospace applications include thermoset and thermoplastic composites, laminates, fiber-reinforced composites, sandwich-core materials, resins, films, and adhesives. The future of materials science appears to involve a heavy focus on composites” [8]. Before any composite material gets into operation, it always goes through the procedure of after production tests. Test verdicts are often used for the selection of the field of application, quality control procedures, and for prediction of material behaviour during specific conditions. According to advisory circular AC 21-26A (U.S. Department of Transportation (Federal Aviation Administration)): “The quality system should include procedures that ensure the quality of incoming materials, the control of in-process manufacturing methods, and testing performed to evaluate the end product for conformity to design requirements.”

Logical rules presented in this simple advisory circular states that the quality system standards should contain applicable information for nondestructive and destructive tests during the manufacturing process and product final acceptance. It is underlined, that the standards that determine the choice for the acceptance or rejection of manufacturing defects and damage should also take into account the process and inspection capability. This should be based on the AC 20-1 07 applicable airworthiness standards which have approved data under the results of proof-of-structure evaluation tests [8].

A wide range of mechanical tests is a constant feature for full characterization of the properties of anisotropic and inhomogeneous composite materials, for use in demanding structural applications. As an example, to determine the bulk properties we require tension, compression and shear tests. Open hole tension/compression (OHT/OFC), inter-laminar fracture toughness, compression after impact (CAI), and fatigue tests are other test types used to explore more complex properties. Tests need to be conducted over a range of environmental conditions such as different range of temperatures, high humidity levels, and immersions in fluids [8].

Composites' testing for aerospace applications is one of the most severe and important areas of testing. Organizations that undertake composites testing for aerospace applications face a number of challenges. Four main challenges are:

- All tests should be conducted in compliance with the wide range of standards
- All equipment should be maintained and be able to demonstrate accurate alignment of grips and fixtures
- All samples should be quickly and efficiently checked in order to cover a wide range of tests while maintaining high productivity
- The test environment should be correctly maintained

<u>Comment:</u> This is the first iteration of control, which help to understand initial properties. There are still several testing methods for modern composites.

2.2 Analysis of the practical and theoretical areas of damage control for the aircraft elements made of composite materials.

2.2.1 Advanced composite materials.

One of the most significant issues for the next composite materials generation is finding the best possible technique for control and prediction of advanced composite materials in operation. As described by Saba et al., "New materials can be defined as materials which have yet to be applied in an 'as-designed' application in aviation" [8]. Among them, metal matrix composites (MMCs), ceramic matrix composites (CMCs) have already been in some flight tests but still needs acceptance for many reasons [9]. The following characterization of some modern composite is presented next.

According to the latest industry analytical forecast reports for 2017-2027 made by Dr. Richard Collins (source IDTechEx [10]), modern composite materials can be divided into a few simple areas (Figure 3).

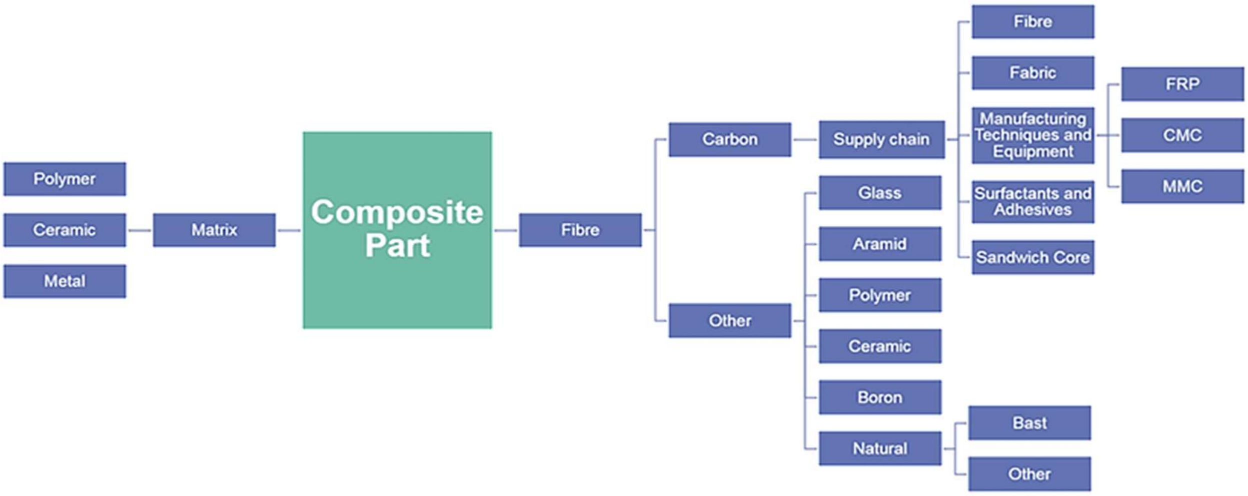


Figure 3. Advanced composite materials classification 2017 [10]

Ceramic matrix composites (CMCs)

Advanced ceramic matrix composite components can make a huge impact on the aircraft engines in the nearest feature. Due to high thermal resistance, their major application is connected with aircraft engine hot sections (combustion chamber and turbine parts). Implementation of CMCs in combustion chambers can allow increasing work temperatures and as a result, raise the fuel-efficiency. These composites also have improved mechanical characteristics, that can avoid the limits of monolithic ceramic materials [8].

Metal matrix composites (MMCs)

While polymer matrix composites FRP (CFRP) composites are widely used in different airframe applications, there is still place for metal matrix composites, usual aluminum alloys, titanium, and even steel materials. MMCs can have titanium, steel or aluminum matrix with oxides, nitride or carbide reinforcement, etc. These composites can overcome many limited properties of monolithic materials. Potential applications of MMCs are aircraft fuselage parts, aircraft highly loaded surfaces as helicopter rotor blades and turbine fan blades [8].

Metal-polymer-metal sandwich composites (MPMs)

Metal-polymer-metal (MPM) sandwich structures could also provide an innovative alternative for existing materials due to reduced weight with improved stiffness characteristics. Different composition of aluminum alloy, steel and polymer layers in a sandwich can provide desired characteristics. This can be made in purpose for many reasons, including cost and simplicity of production, strength vs density characteristics (Figure 4) and strength vs maximum service temperature (Figure 5). Following graphs were made according to information from works made by R.J.H. Wanhill and G.H. Bray [10].

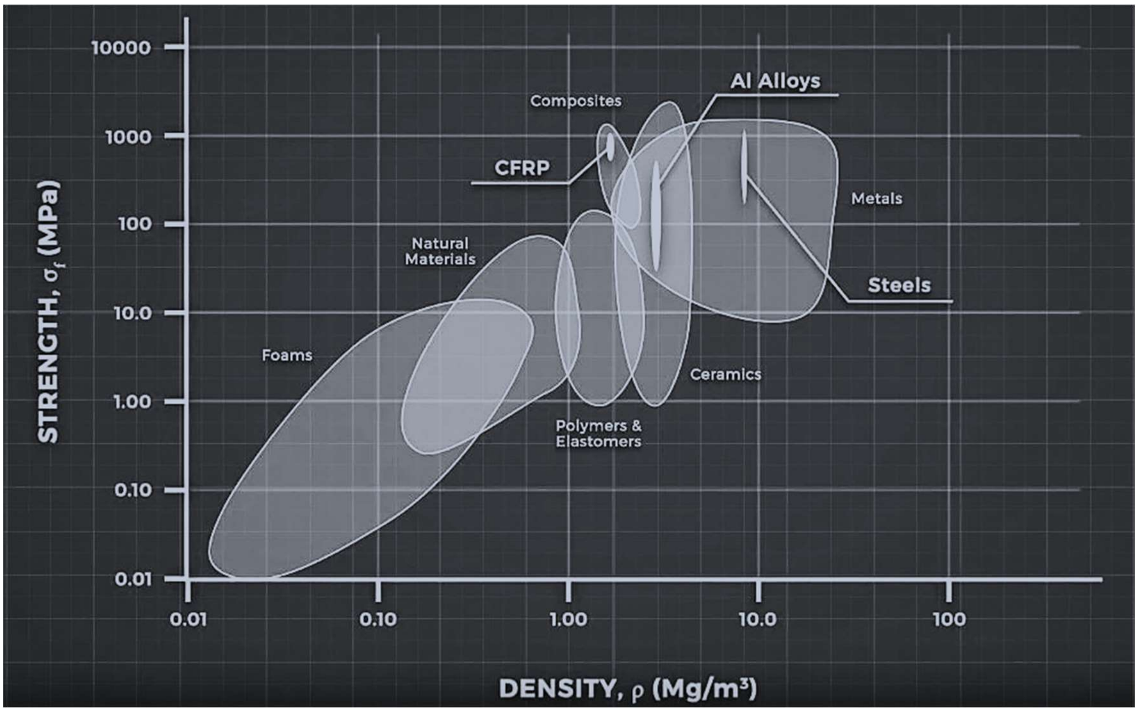


Figure 4. Strength vs density of different materials [10].

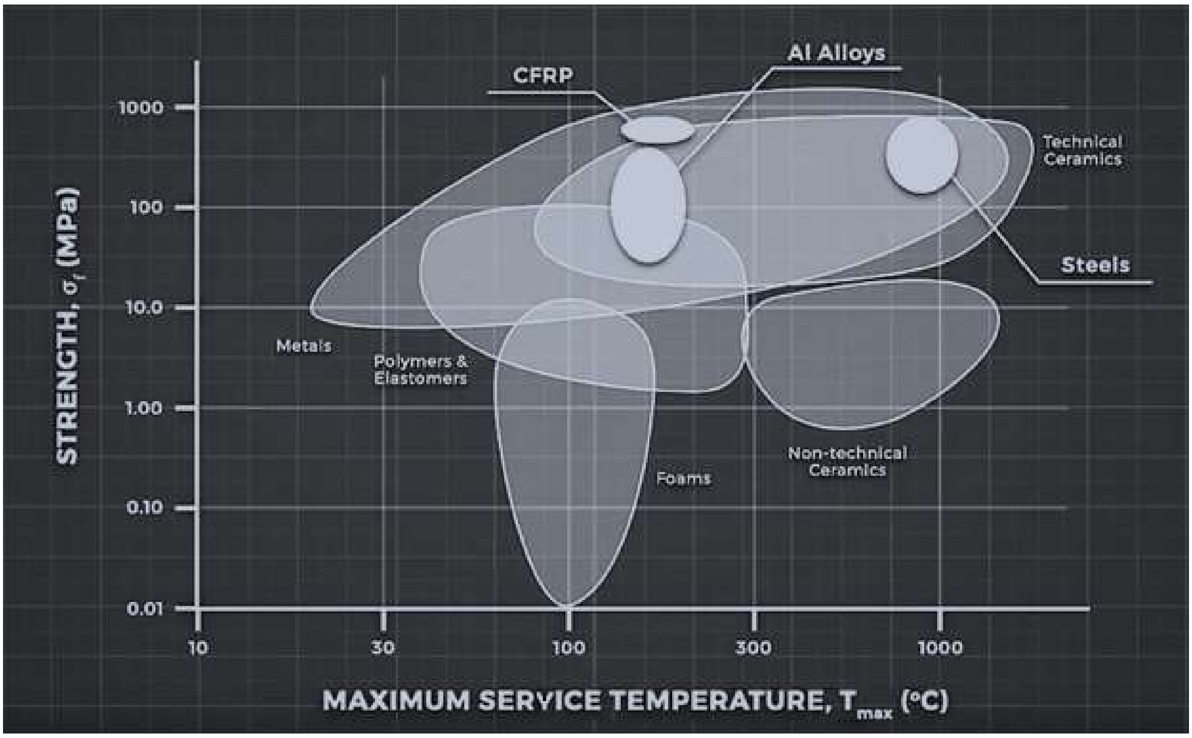


Figure 5. Strength vs maximum service temperature of different materials [10].

The composites of this kind can be used in secondary flight surfaces as aircraft spoilers or door hatches, they have good damping characteristics, relatively cheap in production, can have no problems with transmitting energy during the possible lightning strikes. Due to high stiffness and strength, good forming behaviour and damping properties, MPM structures have good potential specifically in applications for automotive, aerospace, and vehicle industries [11].

High formability and universality are other big advantages of these composites. High formability can be achieved by using simple production procedures for shaping to even complex geometries. The design of mechanical properties for these composites is possible by using adapted materials (different metals, thickness combinations between core and cover materials) and rules of mixtures. Potential for integration of functions is also a benefit.

In the last decade, wide research was carried out on developing light-weight materials with improved mechanical properties, for instance, comparable specific stiffness and strength, improved isolation, superior vibration and sound damping properties. To satisfy the increasing demands, metal-polymer-metal laminates have been numerously developed [12].

LITECORE® products used in the automotive industry proved its efficiency with a remarkable increase of bending stiffness, optimal weight, and thickness characteristics (Figure 6) [13]. Specific features like high thermal conductivity and more important for this research - good acoustic isolation are properties that outline these type of modern composites among others. A good example is the reduced acoustic loads of automotive products from Bondal® [14;15] compared to a conventional solid sheet, shown in Figure 7.

	Thickness	Weigh (kg/m²)	Bending stiffness
Steel	0,75 mm	5,8	100 %
Aluminium	1,0 mm	2,7	79 %
LITECOR®	0,20/0,40/0,20 mm = 0,80 mm	3,5	106 %
LITECOR®	0,25/0,40/0,20 mm = 0,85 mm	3,9	129 %
LITECOR®	0,25/0,60/0,20 mm = 1,05 mm	4,2	209 %

Figure 6. LITECORE® characteristics in comparison with usual automotive steels [14].

MPMs are very appropriate materials for this research. Due to the new, not fully developed technology of production, the various defects may arise in new promising metal-polymer-metal sandwich composites. Another reason for choosing MPMs is its good damping characteristics. As a result, experimental metal-polymer-metal sandwich composites have been chosen as one of many samples for the research (detailed information on experiments is presented in Experimental results and discussion sections in Chapter 4).

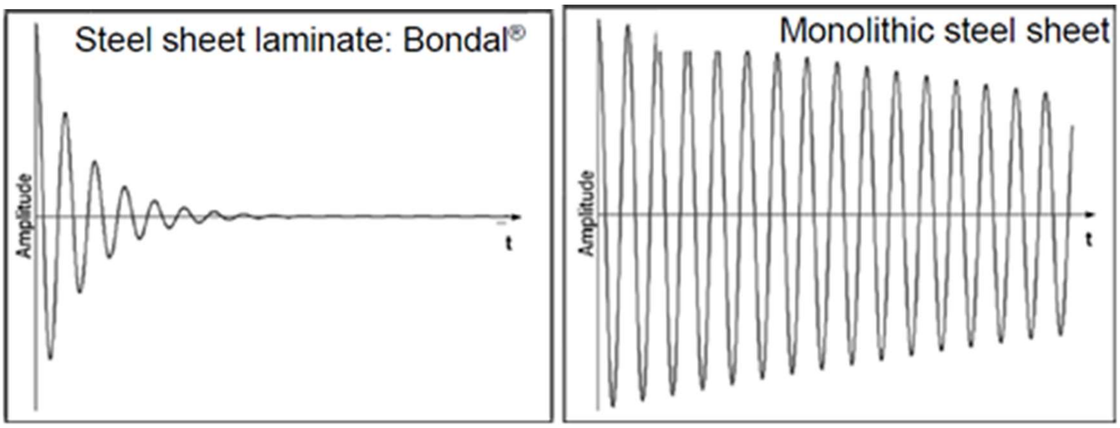


Figure 7. Damping properties of Bondal® compared to a monolithic steel sheet. (Source: Mohamed Abd El Hamid Harhash Doctoral thesis 2018 “Forming Behavior of Multilayer Metal/Polymer/Metal Systems”) [16].

Another interesting area is carbon nanotube (CNT) technology in the composite industry. Carbon nanotubes applications in composites could be considered as a new field in modern structural materials. There is a huge potential in use for electronics and shielding in the aircraft industry. Carbon nanotube technology has many applications for aerospace, defense electronics, and new structural materials. Basic and useful data can be found in work made by Dr. Marcio Loos [17]. In his work, he separately underlines the use of CNTs for the improvement of polymer properties. A more important feature is EMI shielding, as an example, carbon-based composite aircraft fuselage parts often get residual current from lightning strikes. In practice design engineers usually use metal mesh to protect the aircraft, but the residual current is still present. Lightweight materials with carbon nanotubes are being used for EMI shielding and shielding internally. It provides better shielding with basically less the weight of a coat of paint, and shield the internals of a carbon fiber-based aircraft structures. Carbon nanotubes have the tensile strength of carbon fiber, at the same time they are quite flexible. The strain to failure is high because the brittleness is low. They are able to be in a fabric like a format where they can be put into the composite components, or be the composites themselves. According to prospect in [8]: “One can imagine that the surface of a wing would be both structural, it would de-ice itself, it could be the antenna, it could report back to the aircraft and say ‘we are or we are not integral’, you have enormous numbers of multifunctional applications that carbon nanotube technology can bring to aircraft and spacecraft”.

At present, all civil, mechanical and aerospace structures might be damaged by impacts, overloading conditions, fatigue, and deterioration of material properties forced by environmental factors. Damages also place in question the ability of the structure to perform its basic functions. For these reasons, many structural systems undergo routine inspections and maintenance to ensure stable operation and extend the lifespan. Identification and further characterization of material damages without ruining the integrity of the material are made by the means of Non-Destructive Evaluation (NDE) or Non-Destructive Testing (NDT) (Lockard, 2015) [7], (Sandeep Kumar Dwivedi et al., 2016) [18].

General non-destructive evaluation (NDE) methods include the use of eddy currents (Xin Li 2013) [19], acoustic emission (Gholizadeh et. al. 2015) [20], ultrasonic inspection (Peng, W., Zhang, Y., et. al 2012) [21], radiography (Tan et. al. 2011) [22], infrared thermography (Vavilov et. al 2015) [23] or just basic visual inspection and evaluation (Mouritz 2003) [24].

> “Depending upon the structural system, the cost associated with systematic time-based NDE inspection and maintenance can be substantial relative to the total life-cycle costs of the system. For commercial and military aircraft, it is estimated that 27% of the average life cycle costs are related to

inspection and repair. In addition, there is a corresponding opportunity cost associated with the loss in operational availability during maintenance"

Taken from [25;26].

The existence of a large number of non-destructive testing methods and their variation plays an important role in composite materials testing field (Scott & Scala, 1982) [27]. Today, there are only two categories on which NDT methods for composites could be based for operational control use. The first one is the direct estimation of their physical and mechanical properties with material defects detection. This category is good for applications like measurement of dynamic mechanical analysis (DMA) [28], measurement of damage failing initiation and subsequent damage evolution [29] or measurement of delaminations (Ghadermazi et al. 2015) [30]. The second category is the determination of structural components integrity. A good example for aerospace composites are applications for the detection of cracks and debonding (Giurgiutiu, 2016) [31] or fiber breakage for composites reinforced by carbon nanotubes (Narita et al. 2014) [32]. Both categories of existing methods are inevitably and strongly depend on the human factor.

In work [33], M.E. Ibrahim narrowly explains the basic information on damage tolerance and probability-of-detection (POD) during non-destructive testing for marine composite structures. Figure 8 shows a damage tolerance curve, which gives the typical growth of a defect in an in-service engineering structure. It should be mentioned that still during routine non-destructive testing, the defect is likely to be missed until it reaches a sufficient size, commonly called '$\boldsymbol{\alpha}_{\mathbf{NDI}}$'.

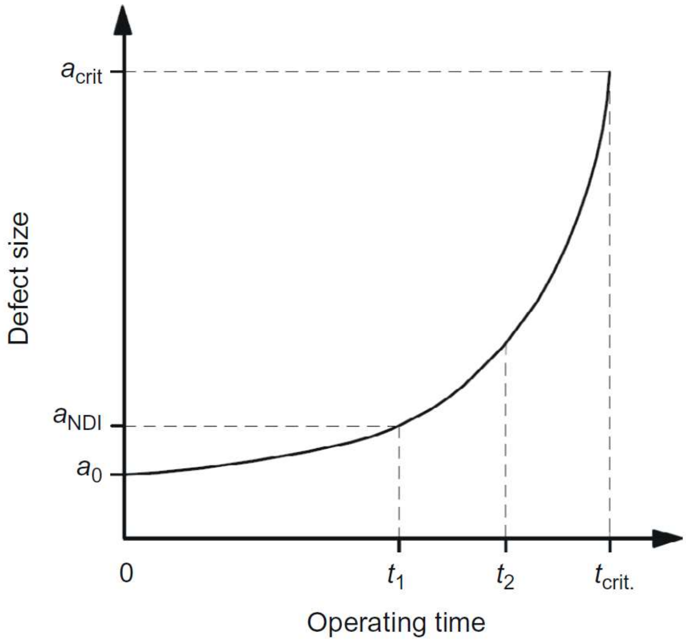


Figure 8. Damage tolerance curve, showing the increasing rate of growth of a defect of size $\boldsymbol{\alpha}$, and nondestructive detection period from $\mathbf{t_1}$ to $\mathbf{t_{crit}}$. Operation time $\mathbf{t_{crit}}$ and defect size $\mathbf{a_{crit}}$ are points of failure conditions [33].

It is suggested that there will be no defect in the structure greater than $\boldsymbol{\alpha_{NDI}}$, at the point in the period of time $\mathbf{t_1}$ in the lifecycle of the component during the common inspection. The time of failure can be determined in the case when the time period between $\mathbf{t_1}$ and $\mathbf{t_{crit}}$ and the growth characteristics of the life-limiting defect in the component are known. The probability of failure would be significantly increased when a large defect is missed during the initial inspection at $\mathbf{t_1}$. M.E. Ibrahim underlines that: “The most rigorous way to establish confidence in an inspection method is to perform an NDT reliability study, in which the probability-of-detection (POD) for a set of inspection parameters can be obtained” [33]. Figure 9 presents a probability-of-detection curve,

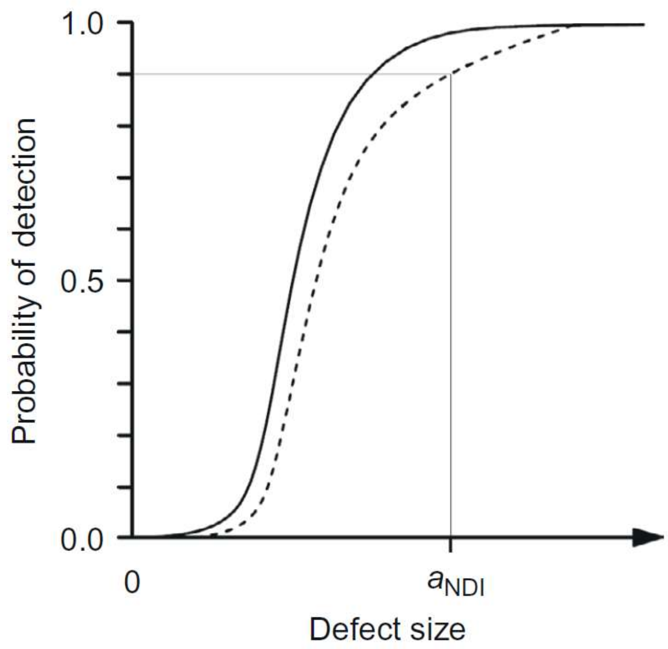


Figure 9. Probability-of-detection curve produced from hit-miss NDT data, showing the derivation of $\boldsymbol{\alpha}_{\mathbf{NDI}}$ at $\boldsymbol{\alpha}_{90/95}$. The light grey line intersects the 95% statistical confidence limit at POD = 0.9 [33].

where $\boldsymbol{\alpha}_{\mathbf{NDI}}$ is identified with the parameter $\boldsymbol{\alpha}_{90/95}$, the defect size for which the POD = 0.9, demonstrated with a 95% statistical confidence (dashed line).

POD curve form and minimum reliably detectable defect size $\boldsymbol{\alpha}_{\mathbf{NDI}}$ parameters can be defined from statistical data. The probability of localized simulated defect detection by the means of the well-known calibrated equipment is much higher than the detection of the unlocalized defect.

Measurement of an $\boldsymbol{\alpha}_{\mathbf{NDI}}$ requires many iterations of "blind" inspections. During inspections of this kind, the inspector should not know the location or true size of the defect.

Proper application of probability-of-detection information depends on the right estimation of the purpose of inspection. There are some important points that are commonly misunderstood or misinterpreted by researchers and practitioners in NDT and related fields:

- A POD curve is not “transferable”. NDT reliability trial results are specific to the inspection, flaws, specimens, inspection conditions and NDT equipment used. It can be concluded, that the range of inspectors typical range of human factors is likely to occur in future inspections. That is why a single curve cannot be presented as the universal POD for ultrasonic inspection in composites;
- The POD of a specific inspection can vary in case of using different means;
- The value of $\boldsymbol{\alpha}_{\mathbf{NDI}}$ is normally chosen to be $\boldsymbol{\alpha}_{90/95}$. Statistics show that 90% of defects of size $\boldsymbol{\alpha}_{\mathbf{NDI}}$ can be detected by NDT.

Taken from [33]

The technique of non-destructive evaluation should be selected on the basis of the larger defect among others, that inspector could miss, this larger defect is the life-limiting factor for the component. It has been suggested that a technique able to inspect a thick composite should be able to at least resolve a 5% anomaly in the through-thickness direction of the structure with high reliability [34].

Specifically for the aviation industry, maintenance procedures are performed in accordance with the design methodology adopted for vehicle components. The main design methodologies are safe-life and damage tolerant. For safe-life design, the operational lifespan of structural components is estimated through a statistical analysis [35]. Inspection is not provided for this methodology, because components are simply replaced prior to its defined design life period. Due to this reason, a safe-life is the least economically profitable methodology. It is also irrespective to incident damage, that can badly influence the residual resource of the component. The overwhelming majority of modern aircraft are designed in accordance with damage-tolerant methodology. This methodology uses models to predict the appearance of damage in various components under certain loading conditions [36].

The main function of a structural health monitoring (SHM) system is based on a collection of periodical dynamic measurements by the means of an integrated or attached network of sensors. The sensors, located in specially designated places are measuring the damage sensitive features. These features can be used to find a solution for direct or inverse problems by system models or by recognition algorithms applied in the statistical scheme for analyzation of the structural condition of the system [36].

Opposite to SHM, the nondestructive evaluation and preventive maintenance are performed by the means of separate NDT equipment at regular time intervals to determine the initial damage and prevent its growth until the critical situation. Maintenance based on damage-tolerant methodology should be executed when the system has been damaged beyond tolerable levels. The best variant is when a planned scheduled check is replaced by the integration of the embedded SHM system, which can perform continuous on-line diagnostics as well as forecasting functions. Potentially, perfectly integrated structural health monitoring system can increase the operational availability, extend the lifespan of an aircraft, improve life safety and significantly reduce life cycle costs. A well-designed SHM system can save 40% of expenses related to inspection time and 20% of expenses on maintenance procedures [37]. The main goal of the structural health monitoring system is damage detection and characterization. Damage detection and its proper identification can be organized into a hierarchical pattern which was made by Rytter A. [38].

- Level 1 (Damage Detection): Recognition that damage exists within the structure
- Level 2 (Localization): Identification of the geometric position of damage
- Level 3 (Classification): Classification of damage type when multiple damage scenarios exist
- Level 4 (Assessment): Quantification of damage extent
- Level 5 (Prediction): Estimation of residual life of the structure.

Taken from [38]

Damage identification in accordance with an SHM paradigm involves progressive stages. As described by Matt, H. M., [39] and Sathya, R., & Abraham, A. [40], this sequential process consists of five stages: 1) operational evaluation, 2) data acquisition, 3) signal processing, 4) feature extraction, 5) statistical pattern processing (Figure 10).

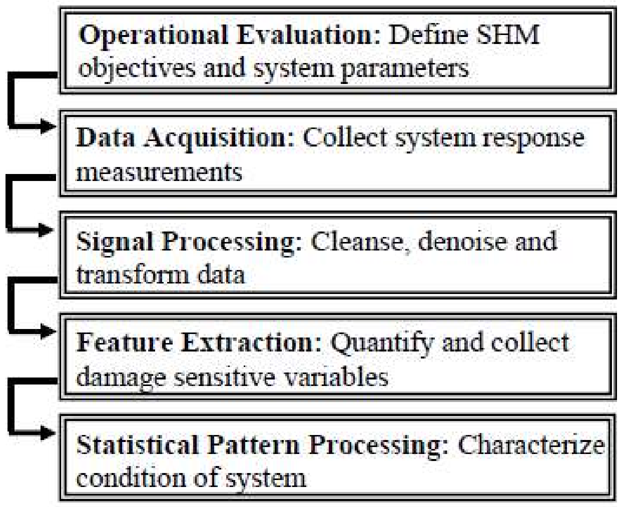


Figure 10. SHM based damage identification process [39].

Operational assessment includes the estimation of the economic and life safety factors of the system, the determination of damage in the structure, the determination of the external environment features in which the structure is exposed, and how this can interact with the availability of receiving the reliable data. Before data collection, the type, number, and location of sensors should be determined by taking into account the adopted damage characteristics and the statistical analysis process [41]. As stated by Raghavan et al., “Signal processing, which includes data cleansing, denoising, and data transformation, is paramount in the damage identification procedure. Common methods of data cleansing and denoising include digital or analog filters, signal averaging and more recently, the use of the discrete wavelet transform” [42].

Reliable quantification and collection of data that can reflect the presence of damage are challenging tasks. They require careful selection of functions that can take into account the maximum sensitivity to the specific damage while ensuring their sensitivity to the variance of operational and environmental factors. Severe memory and processing limits of onboard applications are dictating the use of low-dimensional and computationally simple functions [39].

The algorithms used for final system condition characterization are divided into two categories: supervised learning and unsupervised learning [37]. Supervised learning is based on structural models and experimental data, which can classify the defect or provide further analysis. Unsupervised learning is mainly focused on the indication and comparison of parameters that show deviations in normal operational conditions. It is more appropriate for rapid diagnosis and does not require collecting large amounts of data. The unsupervised learning approaches are demonstrated in a number of works [40-45]. Regarding this research, it is important to consider diagnostic features as global or local. Global diagnostics are generally relative with measurement of vibrations at low frequencies. These vibrations might be acquired by passive or active methods. Passive methods only record vibrations during operation. Active methods use different tools as vibration generators to create and then measure the reflected vibration by different types of certainly located sensors [36]. When using vibration measurement, the verdict about the condition of the structure is usually made according to deviations in modal parameters. Modal parameters are mode shapes, natural frequencies, and damping characteristics. These parameters are used in direct or inverse solutions in various supervised learning model-based methods [46,47,48]. In these cases, an analytical or numerical approach with finite element (FE) analysis can be used. The direct solution usually interacts with modal features from known damage characteristics. Intercomparison is achieved through a number of iterations with models until the moment when calculated data will match acquired test data. The inverse solution consists of computing the damage parameters by inputting the measured modal response characteristics into the model The inverse solution needs calculation of the damage parameters by entering the measured characteristics of the modal response into the model [47].

Although model accuracy is important for model-based, vibration-based methods, using the model is not necessary for low-frequency vibration methods. Instead, the direct comparison of damaged and undamaged vibration characteristics of the structure can be provided [48]. This is then covered by the unsupervised learning category. There are a lot of works connected to global model-free vibration-based methods that used forced vibrations with low-frequencies under 80-100 kHz [49;50]. This kind of method is only relevant to relatively strong and usually visible damages. Local SHM diagnostic methods can be applied for the detection of small damages with the use of frequencies up to 1000 kHz. In more detailed consideration there are active and passive diagnostics. Active local diagnostics implies the availability of an active adjustable source of excitation (device), while local passive diagnostics based on the impact monitoring.

Generally, passive approaches use piezoelectric sensors for impact monitoring or acoustic emission caused by structural integrity deterioration. Localization of damage can be estimated using simple triangulation algorithms. Dynamic models and neural networks can be used providing better accuracy. The main drawback of the passive approach is the requirement of continuous monitoring of the system. Also, every passive method demonstrates the difficulty to accurately identify damage in large segmental structures which may be anisotropic, non-prismatic sandwich-type systems connected to stiffening elements. All the models that can characterize the return signals of rectangular piezoelectric transducers to guided ultrasonic waves were well described by (Raghavan & Cesnik, 2005) [42]. As an example, this data can help to develop a method for improved passive damage detection. In order to find the best possible solution for control and diagnostic needs among existing methods, the clarification and analysis of the advantages and disadvantages of nondestructive inspection techniques are presented next.

2.2.2 Nondestructive Inspection for Composites

Selection of NDI methods

The selection priority for mobile NDI methods for fast in-service inspection of composite aerospace structures is their cogent practical use. A good example of applications of Composite NDT for aerospace can be found in the work made by (Liew 2011) [51]. Many NDI methods were down-selected (and put at the end of analysis) because of these criteria, e.g. laser-ultrasonic because of its complexity and high cost, radiography because of its complexity, danger to human and safety precautions, and some other techniques because of the sensitivity to vibration. Even despite this, such methods are included in the analysis and are presented further in the text to show the whole modern picture. Finally, the following NDI methods were selected for inclusion in the inspection program:

- Visual inspection.
- Vibration analysis, mechanical impedance inspection.
- Ultrasonic inspection (different types with a variety of equipment handheld UT camera, dry-coupling roller probe, phased array UT, etc.).
- Shearography inspection.
- Thermography inspection.
- Low-frequency vibration methods

Visual Inspection

A visual inspection is the number one used inspection method for in-service inspections. On average 80-90% of inspections are still visual. It is a cheap, simple, and fast method. Overwhelming damage types as penetration damages, scorches, stains, dents, abrade, or chips in the composite surface, making the damage visible. When damage is detected, the affected area should be inspected using additional means (mirrors, magnifying glasses, borescopes, and flashlights). This equipment is used to enlarge defects that otherwise might be missed and to allow visual inspection of areas that are not easily accessible. The most common defects that can be detected with the visual inspection are disbanding, blisters, wrinkles, discoloration, core, and resin defects (due to overheating, lightning strike, impact damage, etc.).

In a detailed comparison to the simple visual inspection, SHM systems still have obvious disadvantages. SHM system complexity depends on desired functionality characteristics, it is closely connected to the size and complexity of the structure [52]. SHM systems can have hardware and software failures that require routine system maintenance. A proper SHM system should automatically analyze the data to provide actionable information that locates potential damage for the identification of the correct maintenance vector. Another simple but important consideration is dedicated to the personnel requirement for monitoring and analyzing the system output. Opposite to this factor, visual inspection requires only average prepared personnel for the execution of the fast inspection procedures. The existence of an SHM system alone without the necessary organizational commitment cannot deliver the benefits and even can lead to creating a false sense of correct operation. Inspection events are discrete and infrequent, while SHM systems have the potential to periodically generate the information. Certain types of structural faults can be detected only by one or another approach. An advantage of inspection is that it is not limited to the detection or assessment of a specific type of damage. The inspection approach involves an integral evaluation of the entire structure without wide knowledge of structural defects. An example of this would be the assessment of cracks, where both formation and propagation must be considered. As stated by Sohel Rana and Raul Fangueiro., “Visual inspection cannot find internal flaws in the composite, such as delamination, disbonds, and matrix crazing. More sophisticated NDT techniques are needed to detect these types of defects. Audible Sonic Testing (Coin Tapping) sometimes referred to as audio, sonic, or coin tap, this technique makes use of frequencies in the audible range (10 Hz to 0 Hz)” [53]. In the case when highly experienced personnel executing the procedure of inspection, tap testing could be a very accurate technique. It is perhaps still the most common technique used for the detection of delamination and/or disbonds. A good early summary review of visual inspection with a connection to vibration-based damage identification methods was done by He, M Y; Hutchinson, J. W. [54]. Regarding tap testing, a certain idea explains the simplicity and usability of technique: “The method is accomplished by tapping the inspection area with a solid round disk or lightweight hammer-like device and listening to the response of the structure to the hammer” [55].

Tap testing is often performed as a part of visual testing. Tap test procedure with a tap hammer presented in Figure 11.

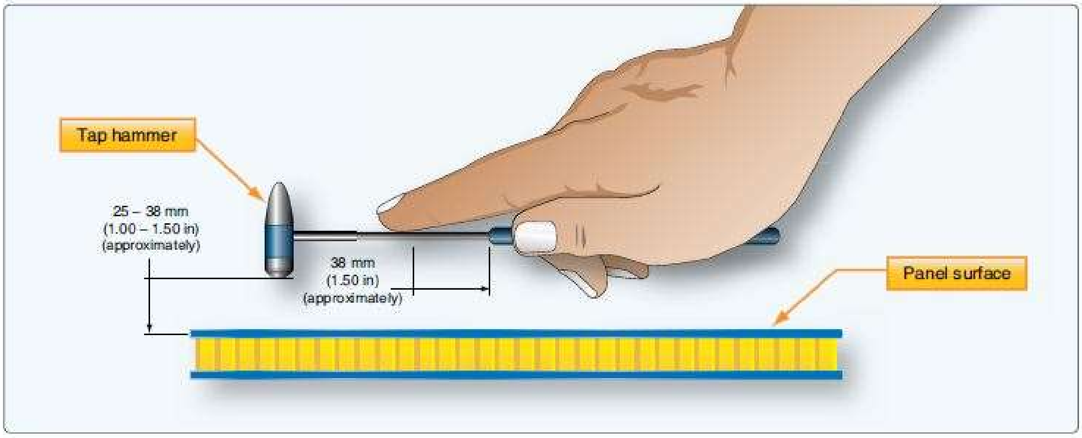


Figure 11. Tap test with a tap hammer [55].

Another obvious statement in [55] says: “Clear, sharp, ringing sound is indicative of a well-bonded solid structure, while a dull or thud-like sound indicates a discrepant area”. This accurate affirmation explicates, that the human ear of well trained and experienced personnel can easily detect the alterations in reflected sound. The tapping rate needs to be rapid enough to produce enough sound for any difference in sound tone to be discernible to the ear of the performer. This type of testing could be very effective on honeycomb sandwiches with thin face sheets thin skin stiffener bond lines and near the surface of thick laminates (in rotorcraft blade supports as an example). One most significant disadvantage of the method is the possibility that changes within the internal elements of the structure might produce pitch changes that could be interpreted as defects even by the highly experienced inspector, when in fact they should exist according to design.

It should be summarized that the inspection should be executed in a quiet area (which is mostly impossible during fast maintenance checks) and by experienced personnel familiar with the part’s internal configuration. The tap testing is not reliable for structures that contain more than four layers. It is often used to find the damage on thin honeycomb face sheets [56].

An automated tap test is virtually a manual tap test with the addition of solenoid, which is used instead of a hammer. It can produce multiple strikes in a limited area. The transducer can record the force and time signal functions of the impactor. The magnitude of the force depends on the properties of the impactor itself, applied energy, and mechanical properties of the structure. The duration of the strike changes proportionally the structure rigidity, but not depend on the magnitude of the impact force. A signal from a non-defective area is used for calibration, and any deviation from this signal indicates the presence of damage.

Advantages:

- Fast procedure;
- Ease of use;
- Simplicity and availability of equipment.
- A universal approach for a big area of composite structures

Disadvantages:

- Failure to detect defects in multi-walled composite structures, with thick skins, etc.;
- Failure to detect defects in products made of laminated plastics, lying at a depth of more than 10 mm.
- The curved surfaces are difficult to control;
- High probability of recent missed/misinterpreted ‘large damage’ events;
- Not perfect technique (requires the use of additional means);
- Personnel should be well trained and have the experience to eliminate the human error factor.

Comment: Visual inspection is still the main and most commonly used method of nondestructive inspection for composites. It is still simple, cheap, easy for operation in many conditions, but it needs good skills of the maintenance crew and not always reflect the real condition of the structure, because it highly depends on the human factor.

Ultrasonic Inspection

Ultrasonic testing is a very useful tool for the detection of internal delamination, voids, or inconsistencies in composite materials not otherwise discernible by visual/tap methods. There is a variety of ultrasonic techniques, which use sound wave energy with different frequencies above the audible range (including complex ultrasonic guided wave structural health monitoring systems [57]. Ultrasonic waves unlike electromagnetic waves require a medium-range for propagation. Few types of particle motion, or modes of propagation, can be supported in solid materials [3]. If we consider longitudinal waves (or compressional waves), then the particle motion would be parallel to the direction of propagation. An interesting study of subsurface longitudinal waves in composite materials was made by A.Pilarski and J.L.Rose [58].

We know that only compressional waves are supported in fluids. Ultrasound waves are also modified by environment boundaries, defects presence, and by the material itself during propagation. The influence of these factors and their interactions can have a complex character. The nature of each interaction depends on parameters as the relative size of the defect or inclusion to the wavelength of sound and its localization. Previously mentioned R.A. Smith with D.A Bruce, L.D. Jones, A.B. Marriott, L.P. Scudder, and S.J. Willsher, in their work [59] gave an affordable explanation on important acoustic effects during the use of ultrasonic inspection for composites those can affect the final picture of the reflected signal.

Like it was mentioned, the sound-wave that propagates through the material can be modified by this material in many different ways. Wave energy may be damped because of dispersion inside the material, or dissipation from the interrogating waves (from inclusions and voids). Energy loss of this kind is usually affecting the frequency, which can be reflected in changes of propagating acoustic waveform shape. When an ultrasound wave goes through two diverse materials with unequal acoustic transmissivity, a part of the wave is transmitted across the boundary and some part of it is reflected. Wave characteristics as amplitudes and phases depend on the change in acoustic impedance across the material boundaries. With the increase of acoustic impedance, more energy will be reflected and less of it will be transmitted across the boundary.

In case of defect presence, there will be a local change in acoustic impedance. When dimensions of the defect are larger than the sound wavelength, the caused reflection will be relatively equal to the reflection at a boundary. In this scenario, the diffraction will be less than the specular reflection. When dimensions of the defect are of the same order of magnitude as the sound wavelength, it will cause scattering of energy from the interrogating wave because of the diffraction effects. In case when defect dimensions are smaller than the magnitude of the sound wavelength, the sound wave may stay relatively unchanged. There is also a possibility that insignificant amounts of energy will be scattered or reflected in different directions which can cause the attenuation of the wave [3].

A high-frequency sound wave may be directed normal to the surface, along the surface, or at some angle to the surface. The reflected sound is then monitored during its route through the structure for deviations and changes. Ultrasonic wave energy also can be either absorbed or reflected back to the surface. This energy is registered by receiving transducer and can be converted into useful data on the display of appropriate equipment. This data allows the operator to evaluate the difference between good and bad values. There are also updated standards, that are established for calibration of the ultrasonic equipment and procedures. As an example ASTM E2580 – 17, "Standard Practice for Ultrasonic Testing of Flat Panel Composites and Sandwich Core Materials Used in Aerospace Applications" [60]. This standard should be used under requirements of standard guide ASTM E2533 - 17e1 [61], for nondestructive testing of polymer matrix composites used in aerospace applications. It is obvious that outlined concepts only work fine in a special environment. It is rather more difficult to implement them in a repair environment given the vast number of different composite components installed on the aircraft and the relative complexity of their construction. In service, the environment factor should be taken into account when we talk about deviations in composite structures conditions during exploitation. As an example, after repair or after in-service damage, nobody can predict the behaviour of a certain composite structure with high accuracy. It should be mentioned that there is a variaety of ultrasonic techniques (Figure 12) with different ultrasonic techniques standards [55].

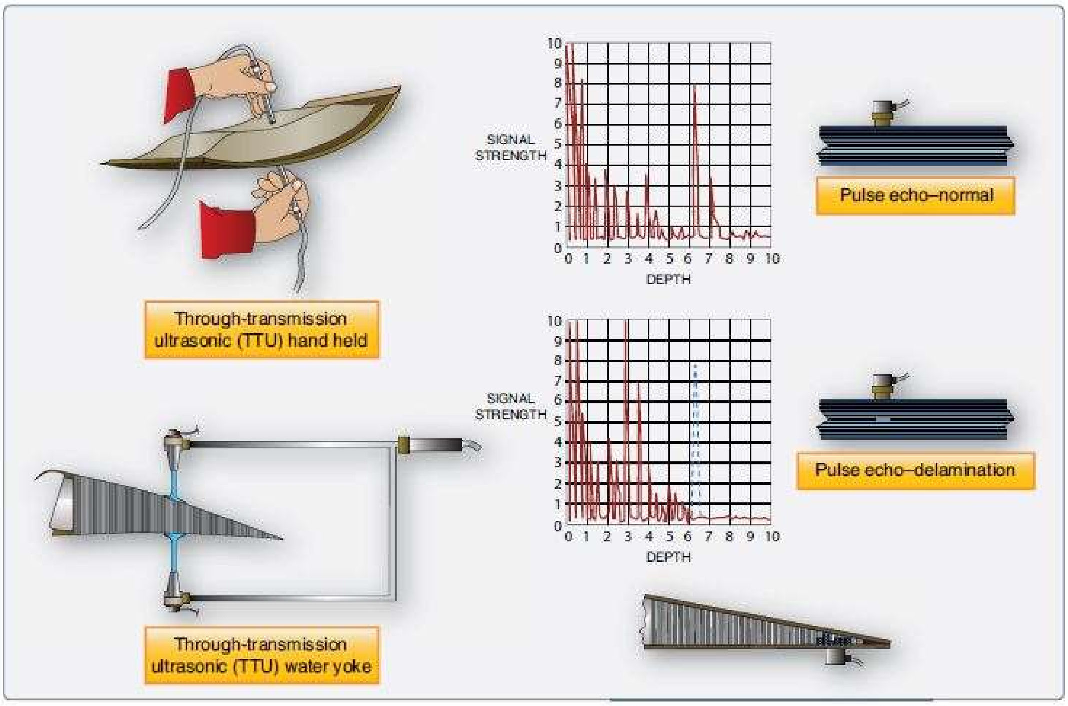


Figure 12. Ultrasonic testing methods [55].

Ultrasonic C-scan inspection

Fiber-reinforced polymer composites can be easily scanned by ultrasonic C-scan to provide a base-line inspection. This type of inspection is one of the primary production inspection techniques for composite structures after manufacturing. Figure 13 shows the C-scan equipment and an example of the base-line inspection for the composite structure. So-called immersion and water-jet methods can be used to make a two-dimensional amplitude map [59].

Figure 13. Ultrasonic C-scan equipment (left) and an example of the composite structure inspection (solid laminate with 3 T-shaped stiffeners; pulse-echo inspection with monitoring of the back wall-skin reflection) [62].

Phased Array Inspection

Phased array is an ultrasonic inspection technique for composites which works according to the same principle of operation as the pulse-echo. This technique requires at least 64 simultaneously working transducers. Its primary goal is the detection of flaws.

Advantages:

- Identification of defects in glue and solder joints;
- Versatility;
- Ease of use;
- The curved surfaces are easy to control;
- Simplicity and availability of equipment.

Disadvantages:

- Failure to detect defects in the skin thickness greater than 3 mm and 1.7 mm for composites with steel or aluminum combinations;
- Failure to detect defects in the details of a full homogeneous material;
- Failure to detect defects in products made of laminated plastics, lying at a depth of more than 20 mm.
- Need for contact liquid;
- High labor input;
- Not effective for identifying all types of disbonds.

Radiography inspection

Radiography inspection is a very useful NDI method which basically presents the interior area of the composite structures transparent to low energy X-rays. X-rays are passing through the structure and absorbed by a sensitive film or by a sensor shield. Received images can reflect the whole inside condition picture. Inspector is just analyzing its integrity and identify a wide range of invisible undersurface defects, as delamination in corners (except delaminations in a plane normal to the radiation direction), core defects, water ingression, etc. Although it is one of the most informative NDI methods for the detection of composite materials defects, it is almost inappropriate for the fast in-service inspection procedures. According to safety regulations, its use near aircraft is strictly prohibited. [55].

Neutron radiography inspection

Neutron radiography is additional to the X-ray radiography technique, which allows detecting light elements such as hydrogen found in corrosion products and water. The same as radiography inspection neutron radiography is a nondestructive imaging technique that visualizing the internal characteristics of the composite structure. Differential attenuation of neutron radiation can be registered and mapped for further visualization. Detailed information can be found in sources [55;63].

Comment for radiography:

Advantages:

- The speed of the results process;
- Ability to store the history of results;
- High reliability.

Disadvantages:

- The presence of radioactive sources;
- The high cost of the equipment;
- Requires highly skilled operator;
- The need to obtain a special permit for tests;
- High labor intensity;
- The need to remove the units (surfaces, panels, etc.) from the plane;

- Determine only the location of the water zones. The amount of water in the unit can not be measured.

Thermography inspection

Thermal monitoring includes all the methods in which temperature sensors are used to measure temperature changes for the parts being tested. The basic principle of thermal control is to measure or map surface temperatures as heat passes from, to, or through a test object [55]. All thermography inspection methods are based on different thermal conductivities between normal, defect-free areas and areas with defects.

Typically, the structure is heated to raise its temperature by various means and then observed for the determination of the heating effects. When areas without defects conduct heat more efficiently than areas with defects, absorbed or reflected the amount of heat can locally show the condition of the structure. The type of defects affecting thermal properties includes disbonds, cracks, water ingress, impact damage, thinning of panels [63].

Significantly large areas can be monitored by thermography from reasonably long distances, without any contact with the object (Figure 14). This type of inspection can detect various defects like porosity, disbands, delaminations, corrosion, relatively huge cracks, core damages, diffusivity, and systematic wall thinning [64]. A good overview of thermography methods can be found in work [65], made by Swiderski and Szudrowicz.

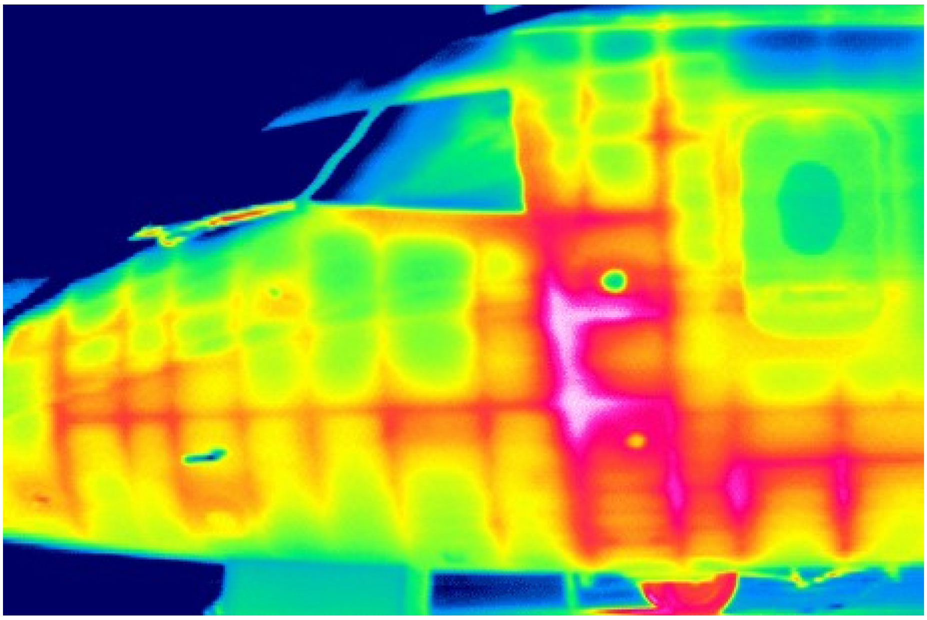


Figure 14. Picture of the heated aircraft structure under inspection.

Thermal methods are the most effective ones for thin laminates defects, near-surface defects, and inside moisture identification.

The advantages of the thermal control (or thermography) are:

- Remote (IR-systems: thermal, thermal flaw systems). The test could be applied from distance.
- High speed of information processing;
- High test performance;
- High linear resolution;
- The ability to control a single and two-pronged approach;
- Theoretical possibility to control a wide range of future materials;
- Multivariable nature of the test;
- The possibility of a complementary combination with other forms of non-destructive testing; compatibility with conventional information processing systems;

- The possibility of in-line monitoring and the creation of automated process control and management.

Disadvantages of thermal control:

- Inability to determine the amount of water in the cellular structures;
- The need to heat the object before the test;
- High cost of high-resolution equipment;
- Ineffective to identify disbands in composites.

Laser Ultrasonic methods of NDE. LUCIE

The most interesting variant of modern ultrasonic NDT methods is laser ultrasonic. As described by Bentouhami et al., "Airbus and EADS started a French regional project aiming to prepare the future for NDT of CFRP components. TECNATOM with the cooperation of iPhoton Solutions providing such system with the most advanced and flexible laser ultrasonic system in the world" [66]. The Laser Ultrasound for Composite InspEction (LUCIE) system main components are: interferometer, scanner, generation, and detection lasers. (Figure 15).

Figure 15. LUCIE in iPhoton Solutions' facility [66].

Description of the LUCIE system LUCIE is based on the iPLUS™ technology from iPhoton Solutions. This technology uses commercial articulated robots to position the scanning head for laser-ultrasonic inspection of composite components. The articulated robot is located on a linear axis with the generation laser. The generation laser beam is transmitted to the scanning head using an articulated beam delivery system made of rigid tubes connected by rotating joints equipped with mirrors. The flexibility provided by the articulated robots gives LUCIE the ability to inspect parts of a large variety of sizes and shapes. Furthermore, the iPLUS™ III configuration, two beam delivery systems tied together on the robot and the cantilever of the linear axis, gives LUCIE the additional capability to inspect features inside large composite parts like an aircraft fuselage.

The generation laser is a transversely-excited atmospheric CO_2 laser running at a maximum repetition rate of 400 Hz. This CO_2 laser was designed to maximize the laser generation of ultrasonic waves and to make it suitable for industrial applications and environments. Pulse durations are approximately 70 ns (the laser provides up to 350 mJ per pulse at 400 Hz). An improvement over previous versions of this laser was introduced with LUCIE: the side-arm hot catalyst. This new catalyst provides faster and more reliable gas recombination from the previous in-vessel room-temperature catalyst, making the laser even more reliable for industrial applications. The detection laser is a non-planar ring oscillator. This laser is combined with a fiber laser amplifier and can provide up to 800 W of peak power. Each iteration the fiber laser amplifier output is adjusted shot-to-shot to provide the optimized level of collected light on the detectors. The interferometer is a dual-cavity confocal Fabry-Perot. This approach was shown to provide the best sensitivity in the ultrasonic bandwidth of interest for composite inspections (1 to 10 MHz). LUCIE also benefits from a new stabilization approach. The new approach uses a reference beam that is counter-propagated inside the interferometer and hence ensures perfect stabilization independent from collected light levels.

Taken from [66].

Figure 16. Inspection of the test fuselage component by LUCIE. 1. LUCIE 2. Testing sample (with different thickness) 3. Operators room [66].

The optical scanner is a two-dimensional galvanometer attached to an independent articulated robotic arm that can scan areas up to 2,25 square meters (Figure 16). A wide range of airframe composite material structures can be scanned with LUCIE. Aero industry can also use the data acquired with LUCIE for the design of new aircraft systems. Perfect adaptation to large area external and internal composite components is the main benefit of this system. Potentially, in combination with modern programming software and with connection to relevant databases this could be a self-learning system, with an automatic inspection option [66]. Benefits and drawbacks of this method are as follows:

Advantages:

- Low labor costs;
- High speed of information processing;
- Ability to store the results;
- High reliability.
- High accuracy;
- No additional tools;
- Fault detection areas with very complex geometry;
- High degree of automation control;

Disadvantages:

- High energy costs;
- A massive block of excitation;
- The high cost of equipment;
- Man appearance near the surface under study is unavailable. The danger of injuries (robotized equipment, high energy laser beams, etc.);
- The need for detaching of surfaces for the diagnosis;
- The inability for rapid diagnostic directly on aircraft;
- Strict requirements for locations in which the control is carried out.

Low-frequency vibration methods

There are two different kinds of low-frequency vibration methods. The first one is a global assessment when the whole structure is forced by vibration to determine its natural frequencies. A good example of a global assessment is an old railway wheels test. During the strike on the wheel, the whole construction can resonate giving information about natural frequencies. The second one is a local assessment when the investigation of the vibration modes can be executed. A good illustration is searching for voids and beams in the wall during the tap tests. Local methods are more appropriate for the inspection of composite materials [56;67]. During simple tap by coin or hammer, the performer listens to the sound reflected from the surface. An experienced operator can identify defects with good reliability. The significant disadvantage of the method is its high dependency on the human factor. An instrumented hammer can be used for a more sophisticated tapping method. During the use of this type, the reactive force of the tap device can be represented as a function of time after the strike. Various types of defects will cause different deviations in the reflected signal. Inspection of the structures may be conducted by different excitation techniques and using continuous or wobble frequencies. Potentially, this allows forming a map of a scanned object [3]. However, there is still a huge area for deep research for vibration methods, when we talk about not only low frequencies, but overall deviations in a signal picture with the time scale. It is obvious that by the means of modern structural dynamic imaging using piezoelectric actuation and laser Doppler vibrometry this can be accomplished [67;68;69]. Based on the information provided, it is necessary to choose the optimal method of vibration analysis and to select the diagnostic parameters. The explanation of certain advantages for certain vibration techniques is given further in detail.

2.2.3 Analysis of existing methods of vibration diagnostic. The main types of analysis of vibration signals and their applications.

Vibration analysis is commonly understood as the study of the functional dependencies of measured vibration parameters on one or several independent variables. The most commonly used variables are time, frequency, spatial coordinate or sequence number in a group of independent vibration measurements (Figure 17).

Among all types of vibration analysis as a function of time, the shape of the vibration signal is most often analyzed in practice. The most widely used of the frequency analysis types are spectral and synchronous frequency vibration analysis. Many tasks of spatial analysis are associated with determining the shape of the oscillation of a structure or the coordinates of defects in extended systems. Group analysis of vibration signal parameters is often used to determine threshold values in diagnostic models. The vibration of working machinery and equipment usually contains a large number of components of different origin. Therefore, to study it, either statistical methods of signal analysis are used, or separate components of vibration are preselected, which are then examined by deterministic or statistical methods of analysis. The vibration of non-working machines and structures, excited by artificial sources of oscillatory forces, is most often investigated using the methods of analyzing deterministic vibrations.

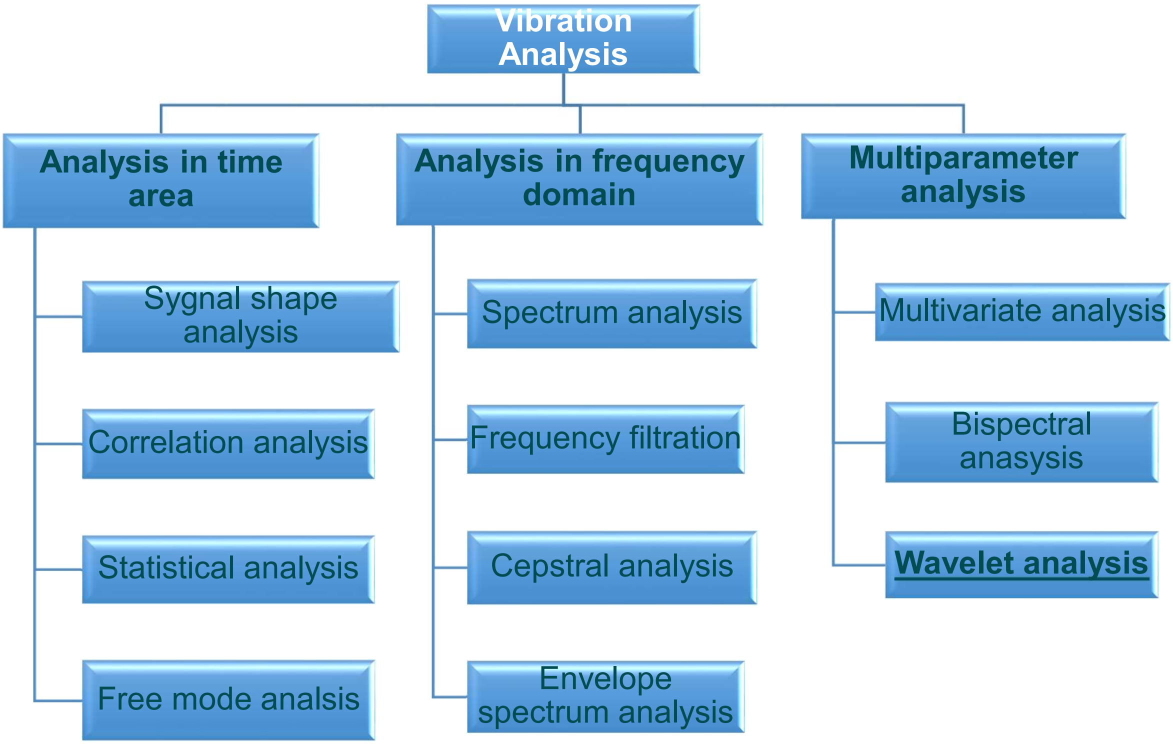


Figure 17. The main types of vibration analysis.

A significant number of components in the vibration signal of most diagnostic objects is usually determined by the fact that in each object there are many different sources of oscillatory forces of different nature and with different properties. The result of diagnostics, including the form of vibration, directly depends on how successfully the task of dividing the vibration signal into components of different nature has been solved. There are, however, such diagnostic tasks when the vibration of a diagnosed object is excited by only one external source, and the form of oscillatory forces is simple and known in advance. In this case, to study the waveform of vibration, it is not necessary to divide it into separate components. Such a case, for example, is the excitation of its own damped oscillations by a separate shock pulse. Form analysis of damped oscillations allows obtaining diagnostic information, which is determined by the natural frequency and direction in which the shock is made and the vibration is measured [70].

In some cases, the form of a complex vibration signal is analyzed without first decomposing into components. Naturally, this uses statistical methods of signal analysis. During the statistical analysis of complex signals, most of the diagnostic information can be lost. However, this analysis can be used, for example, to quickly evaluate the symmetry of vibration relative to its average value. The asymmetry of the vibration signal may, on the one hand, appear at various kinds of impacts in the object of diagnostics, and on the other hand, will be a consequence of nonlinearity and overloads in the measuring and analyzing structures. In addition, as a result of the statistical analysis of a complex signal, it is possible to quantify the deviation of the real distribution of its values from the normal distribution law.

Not always an analysis of the vibration waveform is understood as research only as a function of time. In some cases, when analyzing the form of vibrations, their spatial coordinates are also used. The simplest example is the analysis of the shaft orbits movement in bearings, for which the shaft vibration is measured relative to the fixed part of the bearing in two mutually perpendicular directions. This analysis allows to detect several types of defects and determine the degree of their danger for several revolutions of the shaft.

The high speed of making diagnostic decisions is a distinctive feature of all methods of analyzing of oscillations shape. At the same time, these methods are focused on the detection of only certain types of defects or resonances that most strongly affect the vibration signal. To detect a wider range of defects, those vibration signal analysis methods are applied that accumulate information over a long time.

One of such methods is frequency (spectral) analysis of vibration, which allows to divide a signal into components of different frequencies, excited by different sources of oscillatory forces that have different nature and different properties.

Most often, spectral analysis methods are used to study the vibration of devices and equipment of periodic action. Physically, spectral analysis can be viewed, as parallel filtering of a signal using many filters of different frequencies and determining the power of its individual components or their root-mean-square value at the output of each filter. Mathematically, the spectrum is the result of decomposing a signal into frequency components using a digital Fourier transform. Only for simple periodic vibration signals, the analysis of its shape and spectrum gives almost the same amount of information. For complex signals, the amount of information obtained using the Fourier transform is many times larger than the information obtained from analyzing their shape.

It is not always the object of diagnosis with a constant frequency for the entire measurement of vibration. As an example, when we have unstable rotation frequency of an object, during the use of a typical spectral analysis, due to a violation of the vibration signal frequency, it does not give the desired results.

In this case, synchronous frequency or spectral analysis of vibration should be carried out. For such analysis, it is necessary to measure in parallel the signals from the vibration measuring transducer and the shaft angular position sensor. Each of the filters (physical or mathematical) used for vibration analysis should have a frequency that is a multiple of the instantaneous frequency of the signal from the speed sensor, and in this case, the output of any filter determines the root-mean-square value of that vibration component that is synchronous to the frequency of rotation or its harmonics (sub-harmonics).

There are a number of diagnostic tasks when it is necessary to measure and analyze the amplitude-frequency characteristics of a mechanical system, exciting its vibration by oscillating forces of varying frequency. In this case, the methods of synchronous frequency analysis of vibration are used, and its result is the dependence of the amplitude and phase of a certain vibration component on the oscillating force changing in the frequency range. Such analysis is most often used to study low-frequency resonances of machines with nodes of rotation.

Spectral analysis methods are used to study many types of oscillatory processes and not just the signal from the output of a vibration measuring transducer. Such a process can be a vibration signal or one of its parameters if it periodically changes in time. The most important characteristic of vibration is power and not just the power of the vibration signal, but only those components that are of the same nature and are pre-allocated from the vibration signal.

The type of power fluctuations analysis of pre-selected vibration components of the same nature, called spectral analysis of the vibration envelope, is widely used in vibration diagnostics. However, spectral analysis of the vibration envelope began to call the analysis of the oscillations connected not to the power, but the root-mean-square value of the high-frequency component of the vibration of the same nature, which does not change the physical basis of the obtained results. The main errors in the use of spectral analysis of the vibration envelope are due to the fact that many analysis tools do not have the ability to pre-divide the vibration signal into components of different nature. The main advantages of this type of analysis are associated with its use to study the properties of random vibration excited by mechanical, aerodynamic and hydrodynamic friction.

The main types of vibration signal shape and frequency analysis were listed above for measurement at one point of vibration control of a device or equipment. The operations of spectral analysis are linear and reversible, i.e. there are direct and inverse Fourier transforms linking the time waveform to the frequency one. Considering that in practice the Fourier transform is performed in digital form, and the computing power of analyzing devices and systems is continuously growing, to analyze the waveform began to consistently apply the operations of spectral Fourier transform, extract the vibration components of the same nature from the spectrum, and then restore the waveform vibrations of this nature.

For joint analysis of vibration in two or more spatially separated points, nonlinear methods of signal conversion are used. That is why there are no universal methods for spatial analysis of vibration signals, and it is necessary to optimize the set of used analysis methods for solving each of the diagnostic tasks.

The problems of studying the shape of oscillations of machines and equipment at the frequency of forced oscillations are most often determined by the complexity of creating oscillatory forces at the frequency under study. To study the waveforms of devices or equipment at frequencies other than those naturally induced during operation, sources of harmonic oscillatory forces, often called vibrator generators, are used. Their attachment to the object under study changes the mechanical properties of the object and, consequently, the form of its oscillations. In this regard, it is necessary to take special measures to compensate for the influence of the vibrator on the mechanical properties of the object under study.

The problem of studying the shape of oscillations of various objects at resonant frequencies is somewhat easier to solve. Such questions are solved by the methods and means of modal analysis, designed primarily to study the forms of an object's natural oscillations. This method is based on the principle of reciprocity, which allows swapping the point of application of oscillatory force and the point of measurement of vibration. The vibration of an object is excited by shock pulses successively at all points where it is necessary to determine the shape of the object's vibrations, and the response to the shock excitation is measured by a vibration sensor installed in the place where an oscillating force acts on the object. To build an object's vibration waveform at each of the natural frequencies, special software is used, the input data for which are the impact parameters measured by the force sensor built into the impact hammer, the shock response parameters measured by the vibration sensor, and the coordinates of the impact points.

A very important section of vibration analysis is a statistical description of the measurement results of various vibration parameters in a group of independent measurements. This group usually includes either data from periodic measurements of the vibration of the same control object, or measurements made at the same points of a large number of identical objects operating under identical conditions. The task of such analysis is usually to identify the law of distribution according to values of vibration parameters which are being monitored and to determine the main points of distribution, on which the threshold values in diagnostic models depend. In addition, the task of statistical analysis of periodically measured vibration parameters of the same object can be the construction of trends characterizing the change of monitored parameters over time and a short-term forecast of these changes.

Usually, the results of statistical analysis of various vibration parameters are periodically measured in defect-free equipment. This fits well into the normal law of distribution of random variables, which is characterized by only two quantitative estimates - the average value and variance.

In the presence of developed defects in the test object, the distribution law of periodically monitored vibration parameters may differ from normal due to the appearance of certain tendencies of time variation of these parameters. In such cases, trends of changes in monitored vibration parameters are analyzed.

In addition to these typical methods for analyzing vibration signals used in monitoring and diagnosing devices and equipment, special methods, including many parametric methods for describing and analyzing signals, have recently been used to qualitatively evaluate vibration.

Applications for multidimensional vibration analysis are as follows:

• Spatial analysis of “photographs” of diagnosable objects obtained using contactless optical, thermal, and other types of radiation converters.

• Acoustic and hydro-acoustic location, dealing with the spatial detection in homogeneous environments of weak acoustic signals against the background of strong uncorrelated noise.

• Investigation of the diagnostic parameters obtained from the vibration signal as functions of independently controlled characteristics of the diagnosed equipment.

• Multidimensional display of vibration spectra of the diagnosed equipment measured over long time intervals.

For the study of stationary vibration with a constant power of random and periodic components in time, methods of spectral analysis of signals based on the Fourier transform are most often used.

When studying non-stationary vibration, the results of spectral analysis of a signal segment must be tied to a point in time corresponding to the center of this segment (instant spectrum), and the analysis itself must be performed repeatedly at certain time intervals. In this case, the wavelet transform is used.

The current level of development of the means of computing and processing information allows to fundamentally change the methods of modeling, identification and diagnostics in mechanical engineering, introduce into the practice of studying the damping properties of machines and mechanisms statistical methods of analysis and thereby significantly improve the quality and reliability of the experimental data processing results. In particular, the problem of introducing new information technologies has been successfully solved in the field of automated study of vibration signals of machines based on digital spectral analysis [71]. However, obtaining a reliable estimate of the technical condition of a dissipative mechanical system based on the analysis of the dissipation of oscillation energy characteristics during its operation or strength industrial testing still remains the most important problem in mechanical engineering. Traditional methods used for the determination of dissipative characteristics usually use the results of several measurements, either the envelope of the amplitudes of the oscillations or the amplitude-frequency characteristics in the resonance curve method [72;73].

Among the known methods for determining the characteristics of the scattering of vibrational energy is the method of damped oscillations. It consists of a recording of the vibrations of free damped oscillations of a mechanical system, which determine the logarithmic decrement (attenuation factor) of oscillations.

2.2.4 Development of a method for damage monitoring based on vibration characteristics

The choice of strategy and methods depends on a number of factors. Most important is the ultimate goal of diagnosis, which depends primarily on what stage of the life cycle we determine the technical condition of the test object: at the stage of production, operation, or repair.

Periodic control of technical condition characteristics is most effective at the stage of operation. The prior goal is in time detection of nascent defects, identifying the cause and location of the defect, assessing the tendency to change the technical condition, and the duration of the repair work. At the same time, methods for analyzing vibroacoustic processes are used to form diagnostic signs [74].

Periodic individual control based on short-term forecasting of changes in vibroacoustic characteristics gives the greatest effect when diagnosing unique, expensive, or safety-related objects. It is so, because there is a fairly wide variation in characteristics between individual instances of the same object type, due to the variation in the quality of workmanship, assembly and operating conditions.

The essence of the proposed method is that during the life cycle of an object, the test dynamic effects simulated at its control points at certain time intervals. This allows us to get construction response to these excitations to judge the occurrence of a pre-failure condition over time.

Rigid characteristics of the structure are changing in the operation of composite material, this can be seen in harmonic excitations, in a certain frequency range due to the accumulation of damage (the appearance of “non-glue” zones as an example).

Wavelet transforms can better show the deviations in the signal. As a baseline amplitude and resonance frequency for the evaluation of the technical state, the calculated values or the values measured and stored for each device before its operation can be successfully used. The calculated values can be obtained using both the model constructed using the theory of oscillations and the finite element model.

At the same time, based on the information about the object, the task is to extrapolate its behaviour in the future and to establish the optimal moment for carrying out the next check of the technical condition or its operational termination.

Initially, the method is based on the analysis of free vibrations induced by mechanical shock at construction control points. The vibration signal is recorded by means of different equipment. To exclude random errors, repeated series of measurements are performed.

After that, from the received signal by using the fast Fourier transform, we obtain approximate values of the natural frequencies of oscillations. Then, by using continuous wavelet transform, sufficiently accurate values of modal parameters are determined at the natural frequencies of oscillations. The diagnostic parameter can be calculated based on the found values of the natural frequencies of oscillations and damping coefficients. After that, the obtained value of the parameter is compared with the maximum allowable value for the certain composite structure design. In the case when the experimentally obtained value of the diagnostic parameter exceeds the maximum allowable value, the test object is removed from service. When the condition of failure-free operation is performed, the obtained value of the diagnostic parameter is entered into the database to obtain the dynamics of its change with the operating time. After that, a statistical analysis can be performed and the product life can be determined until the next inspection.

2.2.5 Conclusions on the analysis of existing methods of vibration diagnostic

Within the framework of the task, an existing methods analysis was made for processing vibration signals and it was concluded that the most optimal method for analyzing free vibrations is continuous wavelet transform. In order to determine the natural vibration frequencies and the corresponding damping coefficients for calculating the diagnostic parameter, a method was developed for determining modal parameters based on the analysis of ridges and maximum lines of the wavelet transform module. Using the previously developed provisions, a method was proposed for diagnosing aircraft structures based on wavelet analysis of vibration signals. This method allows us to solve problems of operational diagnostics of the airframe design elements.

2.2.6 Selection of the optimal method of vibration analysis and diagnostic parameters.

The analysis of free vibrations caused by short-term pulsed excitation is most effective in evaluating of modal parameters of the structure. Only the amplitude of oscillation is a subject of variation in such excitations. For a short period of time, construction can oscillate near its natural frequencies. By attenuation of these oscillations, we can determine the damping characteristics [75].

There are various methods for approximate estimation of modal parameters, many of which work either in the time domain or in the frequency domain. For most nonlinear systems with several degrees of freedom, all these methods have limitations [76].

For systems that can display instantaneous frequency changes as a spread in the time domain, the combined time-frequency approaches are used. Frequency-time methods such as Wigner-Ville distribution (WVD) and Gabor transform were most commonly used. These approaches also have some drawbacks. The WVD has a false interference effect due to the quadratic form of the decomposition.

This deficiency can only be corrected by reducing the time-frequency resolution. The Gabor transform, although it gives an advantage in the optimal time-frequency localization according to the Heisenberg localization principle [77], also has the disadvantage of stationary windows, which is a common shortcoming for all window Fourier transforms.

Frequency-time methods are often used in conjunction with the Hilbert transform [78]. In this case, it is first necessary to separate the modes using a bandpass signal filter, which, however, may be inadequate in the case of nonlinearity. Taking into account the latest developments in wavelet analysis, a method of signal processing has been proposed. The main advantage of CWT is the possibility of obtaining information simultaneously in the time domain and scale by the means of adaptable windows [79]. CWT is a promising method for estimating modal parameters, on the basis of which, it is possible to build new methods for detecting defects in aircraft structures.

One of the first publications which described a defect-finding technique using the wavelet transform was the work by Addison, P.S: “Wavelet analysis for low strain integrity testing of foundation piles” [80]. Currently, there are some publications like [81-85], in the same direction.

2.2.7 The theoretical basis of wavelet transforms.

During the period of more than one hundred years, wavelet transforms were put into a rigorous mathematical framework and found different applications in various areas such as harmonic analysis, numerical analysis, signal and image processing, nonlinear dynamics, fractal and multi-fractal analysis, and many others [86].

The overall concept of wavelet transforms was formalized in the early 1980s in a series of papers made by Morlet et al. [87;88], Grossmann and Morlet [89]. Some significant works made by Meyer [90;91], Mallat [92;93], Daubechies [94;95], could be underlined among others. There is an accurate statement about wavelet transforms in [96]: “wavelet transforms can be designated, as integral transforms that used integration kernels called wavelets”.

Specifically, wavelets analysis history first began with a thesis by Alfred Haar [97]. Its present theoretical form was first proposed by Jean Morlet. Wavelet analysis has been developed mainly by Y.Meyer [91]. The main algorithm was developed by Stephane Mallat in 1988.

The Haar wavelet can be regarded as the simplest orthonormal wavelet basis, it is memory efficient, exactly reversible without the edge effects characteristic of other wavelets, and more importantly it is computationally cheap. The disadvantage of the Haar transform is that it can reflect only changes between adjacent pixel pairs. It uses just two scaling and wavelet function coefficients thus calculate pairwise averages and differences (Porwik, Piotr & Lisowska, Agnieszka. 2004) [98]. Interesting work for nonlinear vibration with the use of Haar wavelets was made by Jianyu Fan and Jin Huang [99].

The most popular wavelet family that can be used for texture feature analysis is probably the Daubechies wavelet family. This is due to its orthogonal and compact support abilities [94;95]. The use of overlapping windows results in a reflection of all changes between pixel intensities. Because of averages over more pixels, it is significantly smoother than the Haar wavelet. The most commonly used is Daubechies 4 or D4, the main feature of this wavelet is that its transform has four wavelet and scaling coefficients. The sum of the scaling function coefficients is also one, thus the calculation is averaging over four adjacent pixels [94;95].

Such called “Coiflets” or Coiflet wavelets were originally derived from the Daubechies wavelet. They have higher computational overhead and uses windows that can overlap even more. It uses six scaling and wavelet function coefficients and for the same reason of an increase in pixel averaging, wavelets are smoother. As an example, this increases capabilities in such image-processing techniques like de-noising of different images. Due to the filters, this calculates both averages and differences using the same format, only with six adjacent pixels. The Coiflet wavelet also follows the mirror technique [95].

Regarding non-stationary signals and images, wavelet transforms techniques could be powerful tools for compression, rebuilding, and modeling. They can be used for local capture, identification, and analyzation processes. By the means of a multi-scale, an infinite number of wavelets provide the possibility to explore aspects of data that other analysis techniques omit. A family of elementary functions is constructed by translation and dilation (or contraction) starting from a basic function, the mother, or analyzing wavelet. At first wavelet transforms were used in geophysics for analysis of seismic signals. Nowadays, they used very recently in the geophysical sciences. “The main properties that make wavelets very attractive are time-frequency localization, orthogonality, multi-rate filtering, and scale-space analysis. Wavelet theory involves representing general functions in terms of simpler building blocks at different scales and positions” [100].

There are two major features, that make continuous wavelet transforms especially attractive. The first one is the fact, that oscillation modes can be generally separated from each other. Due to this reason, natural frequencies can be detected more easily, which makes it possible to accurately obtain the values of the instantaneous frequency and damping parameters. The second one is that the main information of the wavelet is in the lines of maxima and ridges. For these purposes, we obtain a system of homogeneous differential equations, the physical meaning of the integrals of which are maxima lines or ridges [101-106].

The basic principle of Continuous Wavelet Transform (CWT) is the decomposition of a signal into wavelets. Wavelets can be regarded as small oscillations that are highly localized in time. The Fourier Transform decomposes a signal into infinite length functions like sines and cosines. This technique is good but it effectively loses all time-localization information of the signal. The CWT's functions are scaled and shifted versions of the time-localized mother wavelet. This is a very good tool for the construction of a time-frequency representation of a signal, for mapping the changing properties of non-stationary signals, that offers an accurate explanation of its time and frequency localization. The following information is summarised from work made by Haase M and Widjajakusuma J [71;101].

According to equation:

$$Wf(a,b) = \frac{1}{a}\int_{-\infty}^{+\infty} f(t)\overline{\psi\left(\frac{t-b}{a}\right)}\,\mathrm{d}t \quad (a,b \in \mathbf{R}, a > 0) \tag{1}$$

CWT decomposes the signal $f(t) \in L^2(\boldsymbol{R})$ on elementary components $\psi\left(\frac{(t-b)}{a}\right)$, which are derived from a single mother wavelet $\psi(t)$ by reverse and shift techniques. Here $\bar{\psi}(t)$ is a complex conjugate number to $\psi(t)$, a – is a scale, b – is a shift parameter. The key point is the choice of $\psi(t)$, because it provides good localization in both physical and Fourier space. Unambiguous signal reconstruction is provided if $\psi(t)$ satisfies the admissibility condition:

$$C_{\psi} = \int_{0}^{+\infty} \frac{|\hat{\psi}(\omega)|^2}{\omega}\,\mathrm{d}\omega < \infty, \tag{2}$$

which reduces for $\psi(t) \in L^1(\boldsymbol{R})$ simple zero mean states

$$\int_{-\infty}^{\infty} \psi(t)\,\mathrm{d}t = 0 \tag{3}$$

The number of possible variants of the mother wavelet is infinite. Some of them are particularly suitable for identifying and describing irregularities in the signal or monotonicities in derivatives of the N-th order. For this, it is required that $\psi(t)$ be orthogonal to polynomials of the N-th degree. Then

$$\int_{-\infty}^{+\infty} t^k \psi(t)\,\mathrm{d}t = 0 \quad 0 \leqslant k \leqslant N \tag{4}$$

Complex-analytical wavelets are called progressive wavelets $\psi(t)$, as $\hat{\psi}(\omega) = 0$ for negative values ω, used to highlight instantaneous frequencies. The characteristics of two such wavelet families will be described next. Signal $f(t)$ can be reconstructed again using the inverse wavelet transform

$$f(t) = \frac{1}{C_\psi} \int_{-\infty}^{+\infty} \int_0^{\infty} Wf(a,b)\psi\left(\frac{t-b}{a}\right) \frac{\mathrm{d}a}{a^2}\,\mathrm{d}b \tag{5}$$

It should be noted that similarly to Fourier, continuous wavelet transforms are linear integral transforms and energy is conserved according to the Parseval theorem, i.e. scalar product and criteria within $L^2(\boldsymbol{R})$, till 2π coefficient. Consequently, CWT can also be performed in Fourier space according to the following expression

$$Wf(a,b) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \hat{f}(\omega)\mathrm{e}^{\mathrm{i}b\omega}\overline{\hat{\psi}(a\omega)}\,\mathrm{d}\omega \tag{6}$$

Here, we use the following condition for the Fourier transform $\hat{f}(\omega)$ of function $f(t) \in L^2(\boldsymbol{R})$

$$\hat{f}(\omega) = \int_{-\infty}^{+\infty} f(t)\mathrm{e}^{-\mathrm{i}\omega t}\,\mathrm{d}t, \quad t \in \mathbf{R} \tag{7}$$

Two wavelet families are presented next.

Each wavelet family is used for a specific purpose. Gaussian wavelet family may be reviewed first. This family is a derivative of the Gauss function. These wavelets are effective in recognizing abrupt transitions and abnormalities. Another one is the Morlet family. These wavelets are complex progressive wavelets. Their application allows selecting oscillation modes and measures the temporal change of the instantaneous frequency and the damping coefficient.

Gaussian family wavelets.

Gaussian wavelets of the n-th order of $\psi(t)$ are defined as

$$\psi_n(t) = \frac{\mathrm{d}}{\mathrm{d}t}\psi_{n-1}(t) \quad (n \in N), \tag{8}$$

Where $\psi_0(t) = e^{-t^2/2}$. (9)

After replacement, this can be represented as:

$$(n+1)\psi_n(t) + t\psi_{n+1}(t) + \psi_{n+2}(t) = 0. \tag{10}$$

For $\mathrm{n} > 0$, of $\psi_n(t)$ function, it satisfies the admissibility condition (2) and, thus, can be used as mother wavelets. Although the function $\psi_n(t)$ exists infinitely, it, like the Fourier transform, quickly decays to zero. As a result, good localization in time and frequency can actually be obtained. The second derivative has the name "Mexican hat." It was first used in computer vision to identify multi-scale boundaries [101]. Figure 18 presents the “Mexican hat” along with its Fourier transform. For the CWT signal $f(t)$, the $\psi_n(t)$ is used as the base component, the following abbreviation will be used in the following

$$Wf(a,b) = \frac{1}{a} \int_{-\infty}^{+\infty} f(t)\psi_n\left(\frac{t-b}{a}\right)\mathrm{d}t =: W^n f \tag{11}$$

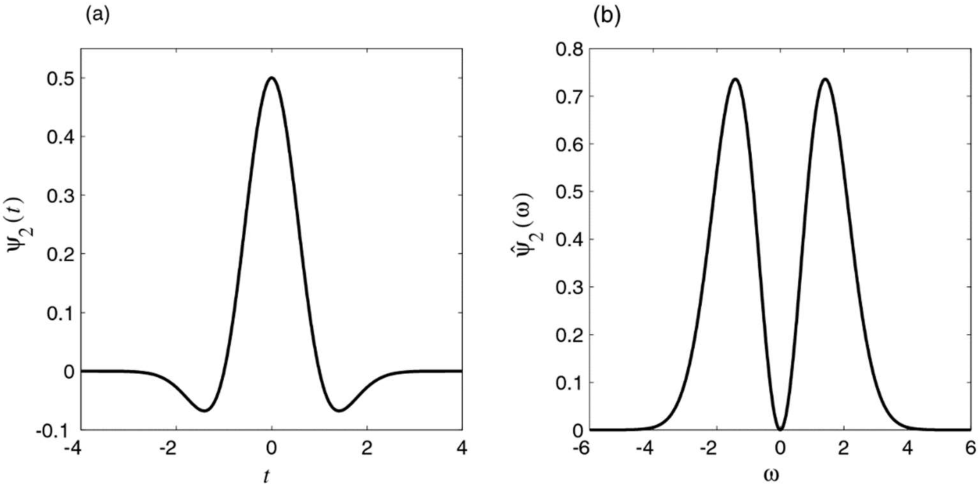


Figure 18. Wavelet $\psi_2(t)$ "Mexican hat" (a) and its Fourier transform $\widehat{\psi_2}(t)$ (b) [96].

The special properties of Gaussian wavelets can be used to obtain a partial differential equation for $W^n f$ [101]

$$\left(a\frac{\partial^2}{\partial b^2} - \frac{\partial}{\partial a} + \frac{n}{a}\right)W^n f = 0 \tag{12}$$

,

which will later be used to directly integrate the maximum lines.

It is important to obtain an equation in explicit form for the integral convolution for the discrete chosen function $f(t)$ (11). Then it is important to estimate $W^n f$ for any arbitrarily chosen separately point (a, b). Further, the need for this will be shown in order to effectively integrate the maximum lines. This method differs from the commonly used calculation methods of integral (11) as the inverse Fourier transform $f(\omega)\hat{\psi}(a\omega)$, where the full wavelet transform must be calculated for each fixed scale a.

Morlet wavelet families.

Unlike real-valued wavelets, complex wavelets are capable of distinguishing amplitude and phase, which makes it possible to measure the instantaneous frequency and its change over time. Next, we describe the family of complex wavelets that are derived from the classical Morlet wavelet.

$$\Psi_0(t) = \mathrm{e}^{-t^2/2}\mathrm{e}^{\mathrm{i}\omega_0 t} \tag{13}$$

This was the starting point for the wavelet analysis. In the beginning, it was used by Jean Morlet in the 70s for the chemical analysis of oil. This wavelet does not satisfy the admissibility condition (2) in a strict sense. Nevertheless, due to the rapid approximation of the envelope to zero, it can be considered as wavelet $\Psi_0(t)$ acceptable for $\omega \geq 5$. Unlike $\Psi_0(t)$, which depends on ω_0, all derivatives $\Psi_0(t)$ are derivatives in the strict sense.

$$\Psi_n(t) = \frac{\mathrm{d}}{\mathrm{d}t}\Psi_{n-1}(t) \quad (n \in N) \tag{14}$$

The main importance of applying Morlet wavelets family is their analytical meaning.

$$\hat{\Psi}_n(\omega) = 0 \text{ for } \omega < 0 \tag{15}$$

For a better understanding of this condition, we can consider the wavelet transform of the function $f(t) = cos\omega_1 t$. When substituting the Fourier transform of this function

$\hat{f}(\omega) = \pi[\delta(\omega + \omega_1) + \delta(\omega - \omega_1)]$ in expression (2) we get

$$Wf(a,b) = \frac{1}{2}\left[\mathrm{e}^{\mathrm{i}b\omega_1}\overline{\hat{\Psi}(a\omega_1)} + \mathrm{e}^{-\mathrm{i}b\omega_1}\overline{\hat{\Psi}(-a\omega_1)}\right] \tag{16}$$

which basically means that $|Wf(a,b)|$ oscillates in b direction. However, progressive wavelets that satisfy condition (15) do not perform these oscillations, which leads to the following relation

$$|Wf(a,b)| = \frac{1}{2}|\overline{\hat{\Psi}(a\omega_1)}| \tag{17}$$

For a Morlet wavelet, the Fourier transform is written as $\widehat{\Psi}_0(\omega) = \sqrt{2\pi}\mathrm{e}^{-(\omega-\omega_0)^2/2}$ and the correct localization of energy is observed in the region of the line $a = \omega_0/\omega_1$ [69]. Figure 19 shows the Morlet wavelet graph and its Fourier transform.

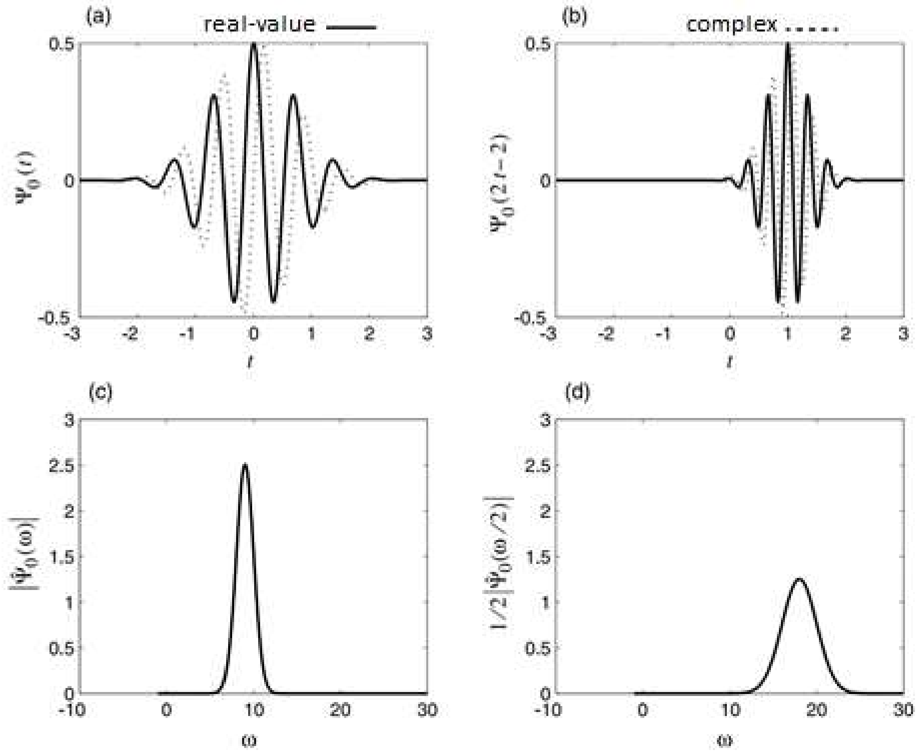


Figure 19. Morlet wavelets: (a) - $\Psi_0(t)$; (b) - $\Psi_0(2t-2)$; (c,d) - modules of the corresponding wavelet transforms [101].

With the same iterations with the Gaussian wavelets, we can write the recurrence equation

$$(n+1)\Psi_n(t) + (t - \mathrm{i}\omega_0)\Psi_{n+1}(t) + \Psi_{n+2}(t) = 0 \tag{18}$$

and partial differential equation

$$\left(a\frac{\partial^2}{\partial b^2} - \frac{\partial}{\partial a} - \mathrm{i}\omega_0\frac{\partial}{\partial b} + \frac{n}{a}\right)W^n f = 0 \tag{19}$$

for the Morlet family [87]. This equation allows us to calculate the wavelet transform for a discrete sampling function $f(t)$ in an explicit form. As noted above, this proves the existence of a direct integration solution for the ridges, which will be described later.

Wavelet transforms of asymptotic signals.

Any real-value signal $f(t)$ can always be written in the following form

$$f(t) = \sin\tilde{A}(t)\cos[\tilde{\Phi}(t)] \tag{20}$$

However, this form is not unambiguous. For originality, we can go to the analytic function

$$z(t) = f(t) + \mathrm{i}Hf(t) \tag{21}$$

where $f(t)$ is the real part, and the Hilbert transform $Hf(t)$ is the complex part, defined as

$$Hf(t) = \frac{1}{\pi}\int_{-\infty}^{+\infty}\frac{f(\tau)}{\tau - t}\mathrm{d}\tau \tag{22}$$

When calculating, $z(t)$ is completely described by its real part and its Fourier transform $\hat{z}(t)$ is equal to zero for negative frequencies. The canonical representation of the function f (t) can be written as

$$z(t) = A(t)\mathrm{e}^{\mathrm{i}\Phi(t)} \tag{23}$$

is unique if we take $\mathrm{A(t)} \geq 0$ and $\Phi(\mathrm{t}) \in [0,2\pi]$ [101]. This allows us to represent the instantaneous frequency as

$$\omega(t) = \Phi'(t) \tag{24}$$

where sign $'$ means time derivative t. The physical meaning of $\omega(t)$ can raise concerns in some cases, except for the cases when asymptotic signals with slowly varying $A(t)$ and $\Phi'(t)$ are considered [101]. In this case, the envelope $A(t)$ and $\omega(t)$ makes sense. CWT using Morlet family wavelets can be roughly replaced by the first term of the expansion in a series using the stationary phase argument.

$$Wz(a,b) = A(b)\mathrm{e}^{\mathrm{i}\Phi(b)}\overline{\hat{\Psi}(a\Phi'(b))} + \mathcal{O}\left(\frac{|A'|}{|A|}, \frac{|\Phi\Phi''|}{\Phi'^2}\right) \tag{25}$$

For a one-component signal (23), the wavelet transform module is localized in a curve area called the wavelet transform ridge. It is satisfying the condition

$$a = a_r(b) = \frac{\omega^*}{\Phi'(b)} \tag{26}$$

Where, ω^* means the maximum frequency of the $\Psi_n(\omega)$ function [101]. By substituting this expression into equation (25), we obtain the wavelet transform along the ridge approximated in proportion to the analytical signal $z(t)$ given in (23) with a constant factor

$$C = \overline{\hat{\Psi}(a\Phi'(b))} = \overline{\hat{\Psi}(\omega^*)} \tag{27}$$

This part discusses the oscillation of nonlinear systems with several degrees of freedom, which in the general case can be considered as a set of single-frequency components with slowly varying $A_j(t)$ and $\Phi'_j(t)$

$$f(t) = \sum_{j=1}^{M} A_j(t) \cos \Phi_j(t) \tag{28}$$

The corresponding wavelet transform, being a linear support, can be written as

$$Wf(a,b) = \frac{1}{2} \sum_{j=1}^{M} A_j(b) \cos \Phi_j(b) \overline{\hat{\Psi}(a\Phi'_j(b))} + r(a,b) \quad , \tag{29}$$

Where

$$r(a,b) \sim \mathcal{O}\left(\frac{|A'_j|}{|A_j|}, \frac{|\Phi_j \Phi''_j|}{\Phi'^2_j} \right). \tag{30}$$

If the signal contains several components whose frequencies are quite different from each other, then each individual component can be processed using the wavelet transform ridges. For closely located ridges or frequencies, analysis, and reconstruction of the variant of

λ-frequency shift $f(t)$, it is recommended to use “step by step” reconstruction in order to obtain a better frequency resolution [88].

2.3 Summary of the findings and implications for current research

Methods have their own specific limits, advantages, and disadvantages. A number of factors are connected with their capabilities for certain inspection applications. The following summary reflects the main features:

- Visual inspection is the main method for the operational in-service inspection of composite structures. “It is capable of detecting relevant impact damages and other surface irregularities” [62]. It is a cheap, fast and simple technique, but its quality highly depends on the performer. The additional tools as the automated tap test equipment can help to solve this problem. By its means, the performer can observe small areas in details where impact damage is suspected by visual inspection, where the human factor prevails.
- Mechanical impedance analysis (“BondMaster™” as an example) is a fast and low-cost technique. It can be used without coupling agent or additional equipment. However, the big disadvantage of this method is poor detection capabilities regarding in-service defects.
- Ultrasonic inspection is the most acceptable non-destructive method for in-service inspection of composite structures in the case when the detection by simple visual inspection can’t show any results. It is very useful for the detection of location, size and depth of the defect. However, there are limitations connected to ultrasound penetration depth and possible reflections of ultrasonic waves inside the structure. That is why highly experienced personnel is needed. Although this type of inspection does not waste a lot of time to execute the procedure, it requires additional equipment and the use of couplant between the sensor and surface of the test object.
- Ultrasonic phased array inspection can be divided from general ultrasonic inspection as separated technique with good properties for in-service inspection. As an example, the “RapidScan™” showed good results in tests when it was using multi-axis scanning arm. Additional information can be found in [102;103].
- Shearography and thermography are easy for in-service implementation for nonheavy maintenance forms as an example. The time consumption is the lowest, compared with other non-contact methods that require coupling and additional equipment or methods, that are not applicable for complex scanning. These types are good for detecting impact damages, but

their detectability of porosity (disbands and delaminations) is poor in comparison with the ultrasonic technique. The size of the defect that can be detected by shearography and thermography decreases with the increase of the defect depth. They are also not suitable for assessing the depth of the defect. Specifically, shearography is good for inspecting honeycomb sandwich structures and thermography for testing water penetration and its location in composite structures.

But due to the fact that the use of honeycomb sandwich structures is less common now, the prospect for shearography and thermography application become more doubtful. Additional information could be found in [104;105;106].

- Low-frequency vibration method is potentially the most promising method with a large area for its implementation. Such a method provides reliable sensing of significant damage but has difficulty for the determination of its location or its detailed characterization. This method is the most useful tool for the detection of gradual changes that take a long time to detect and when it is not clear, which area has high-stress concentration. The main disadvantage is the large instrumental and operating expense for high accuracy results for the monitoring of advanced composite materials. There is still a need for a fast, low-cost technique that can be easily implemented in operation.

Fourier transform is good for the decomposition of a signal into simple infinite length functions like sines and cosines. However, this technique effectively loses all time-localization information of the signal. The CWT's functions are scaled and shifted versions of the time-localized mother wavelet. This is a very good tool for the construction of a time-frequency representation of a signal, for mapping the changing properties of non-stationary signals, that offers an accurate explanation of its time and frequency localization. The contemporary combination of Fourier and Wavelet transforms as tools for searching deviations in vibration signals of different types of not fully studied composite materials is also an area of novelty in the present research. The Fourier transform will be used for spectrum analysis and search of a certain frequency ranges where the difference of amplitudes can reflect the condition of the construction. The continuous wavelet transforms will help to show the deviations of the transformed signal linked to the time domain including analysis of frequency bands detected by Fourier. Another main difference of this approach from other works in various areas (107-111) is the direct simple systematic principle of its implementation to modern hardware and software systems, using Fourier transforms and CWT with a selection of the appropriate function of the mother wavelet for non-stationary signals. All this can be done in one algorithm with approbation on a variety of composites, including the promising not fully researched ones.

- In the modern realities of aircraft operation, an important role is played by the efficiency of detecting technical failures. It is extremely unprofitable to subject composite structures to urgent repairs under conditions of untimely operations. It is much more profitable to conduct a quick check of the structure during light operational technical maintenance forms in order to timely identify the pre-failure condition and to perform subsequent replacement of the structure. The determination of the defect location and its size becomes a secondary issue. As a result, ideally monitoring in operation realities should come down to control (level 1) and a possible prediction of the technical condition (level 5) if we are considering autonomous systems.

The priority goal of this research, which is mostly dictated by the needs of the aerospace industry, is an integral estimation of the residual resource (lifetime) of the object under control. Analysis of deviations of the vibroacoustic picture, including the use of wavelet transforms in combination with the Fourier transforms, can help to determine the condition of the structure in time, as well as highlight deviations by which the current state of the structure can be estimated. The application of this method contains both operational evaluation by the means of Fourier transforms, data acquisition by the means of simple state-of-the-art hardware and software instruments, signal processing by Fourier and Wavelet transforms. The failure related features can be extracted by an engineer or a technician in case of not autonomous systems or by the software that may be additionally programmed on the required damage levels for autonomous systems. The statistical pattern processing can be potentially achieved by long term collecting and analyzing large amounts of data during the operation of composite structures on modern aircrafts.

Regarding technical levels in this research specifically, we are aiming to achieve levels 1,2,3,4 and to give suggestions on level 5. The damage existence will be reflected in the deviations of the vibration signal, which gives us an opportunity for its detection (level 1). However, since research is focused on the integral estimation of the structure, level 2 (localization) and level 3 (classification) become secondary issues. These levels can be estimated with high accuracy by additional means (NDT methods as an example). Quantification of damage extent (level 4) and estimation of residual life of the structure (level 5) can be achieved by practical experiments and by the use of complex parameters for assessing the technical condition which is presented further. The criterion for assessing the status of the testing object will be the chosen parameters that could be within or exceed the maximum permissible values.

Potentially, the method can be extended in terms of level 2-5 by multisensor systems with a classical sensor triangulation methodology, different “smart” sensors, and classifier algorithms with the use of neural networks.

Chapter 3: Experimental Methodology, Analysis and Preliminary Results

3.1 Introduction

From a mathematical point of view, a signal is a function, i.e. dependence of one quantity on another. Basically, it is an information function that carries a message about the physical properties, state or behaviour of any physical system, object, or environment. The purpose of signal processing can be regarded as the extraction of certain information that is displayed in these signals (briefly, useful or target information) and conversion of this information into a form that is convenient for perception and further use.

By signal analysis, we mean not only their purely mathematical transformations but also drawing conclusions on the basis of these transformations about the specific features of the corresponding processes and objects. The signal analysis objectives are usually:

- Determination or evaluation of numerical parameters of signals (energy, average power, average square value, etc.).
- The decomposition of signals into elementary components to compare the properties of various signals.
- Comparison of "similarity", "relatedness" degree of various signals, including with certain quantitative estimates.

The mathematical apparatus of signal analysis is very extensive and is widely used in practice in all areas of science and technology without exception.

The term signal registration is inextricably linked with the concept of a signal, the use of which is as broad and ambiguous as the term signal itself. In the most general sense, this term can be understood as the operation of extracting a signal and converting it into a form suitable for further use. So, when obtaining information about the physical properties of any objects, signal registration is understood as the process of measuring the physical properties of an object and transferring measurement results to a material carrier of a signal or direct energy conversion of any object properties into informational parameters of a material carrier of a signal. But signal registration term is also widely used for the processes of extracting already formed signals carrying certain information from the sum of other signals (radio communication, telemetry, etc.), and for the processes of recording signals on long-term memory media, and for many other processes related with signal processing. This chapter presents the development of an experimental methodology. The investigation is connected with vibration methods, their features, and mathematical apparatus technique. It also covers vibration characteristics as frequencies damping properties, some details of the test setup, equipment, and devices, preparation for the test, and the techniques used to conduct tests and initial results of the experiments.

3.2 Features of building information systems for non-destructive testing tasks.

The problem of developing general principles for constructing efficient information systems is relevant to most areas of application programming. Under the effectiveness of the information system, in this case, we can take:

- Ability to adequately respond to user requests;
- Ensuring work using the concepts and mechanisms adopted in the industry;
- Minimization of maintenance costs.

Unfortunately, the fundamental differences in the requirements make it impossible to create universal principles for the development of such systems. However, for information systems of non-destructive testing, it is possible to identify several features that allow combining them into a single class of tasks.

Information systems in non-destructive testing, in general, serve to obtain primary information, it's preliminary processing, and storage (with the possibility of information support), and final processing and presentation of the result in the required form. Such a system can be implemented as an independent device with complete functionality, made on the basis of a standard computing complex, or be divided between several independent functional components with the ability to exchange information between them.

Depending on the implementation, it is often possible to select several stages of user interaction with the system. The development of these interface stages must be conducted considering the intended qualifications of the user working with it. At the same time, it is important to take into account both their qualifications as a user to the system and their qualifications in matters of non-destructive testing itself. Dependant on this, the form of providing information can be approximated both to the type of the measurement result of the initial physical quantity, and the abstract indicator that reflects the result of the control operation.

A number of features are caused by the specifics of the software development process itself for non-destructive testing systems. Extremely high demands are made on the interface of such systems, their sustainability, and their reliability. At the same time, developing the system part of the project substantially costs less than consumer programs or large business systems. This is due to the focus of the main efforts of programmers on the development of mathematical algorithms for information processing and hardware interfaces. In addition, it should be noted that there are almost no standards for interfaces, processing techniques, and data formats used in non-destructive testing systems. As a result, there is an inability to use libraries of standard solutions. Since software for non-destructive testing systems should be attributed to systems of medium complexity, the use of modern high-performance programming methods in the development of the system part of the project is the best option.

Non-destructive testing systems very often use complex methods of information processing, which sometimes form the basis of a complex. For this part of the program, portability is one of the most important factors. It also implies the possibility of transferring processing algorithms between different parts of the complex, the hardware implementation of which may be fundamentally different. And if the task of porting a good software code in a high-level language can be solved by standard methods, then for code written in assembler, it is likely to result in a complete rewriting of the project. Therefore, the task of transferring the user interface still cannot be satisfactorily solved by standard means at all.

At the moment, the use of machine-independent programming systems at all stages of work looks promising [112]. Until recently, this was hampered by the lack of efficient high-level programming systems for microcontrollers widely used in hardware complexes. The modern level of development of specialized hardware-oriented towards the use of such systems allows us to hope to achieve almost complete integration of various parts of the information system.

The use of modern programming systems also allows solving the problem of fully portable interfaces, which will greatly facilitate the mastery of the system as a whole and allow the use of a wide range of computing platforms.

It should be mentioned that there is a problem of supporting and maintenance of information systems. Non-destructive testing systems have a long life, this period may exceed ten years and more. Throughout this period, there may be a question of adapting the old system to new hardware platforms or replacing obsolete components. It may also be necessary to transfer the consumer's practices from the old system to the new one. This question is particularly relevant in the development of large complexes, where this aspect can sometimes play a decisive role in the choice of the system architecture.

As in all areas of human activity, in non-destructive testing, computerization influences both the means of non-destructive testing and the general methodology of work in this industry. Computer, microprocessor, microcontroller are the means of information processing. When considering the task of NDE as an information process and abstraction from the used physical methods of non-destructive testing, the following three characteristic parts of this process can be identified:

- obtaining primary measurement information using transducers and bringing it into a form convenient for further processing;
- information processing and presentation of processing results in the form suitable for analysis and further interpretation;
- analysis of the information received and the formation of a decision on the state of the controlled object, the possibility of its normal functioning or forecasting its residual resource.

These factors are explained in more details as follows:

3.2.1 Obtaining primary measurement information using transducers and bringing it into a form convenient for further processing.

Transducers can include any device of both active and passive principles of operation that ensures the interconnection of the monitored physical parameter (or several parameters) with the registerable output parameter of the transducer (response). In a number of NDE methods, the response can be recorded in the form of an image that can be directly analyzed (such as optical methods). In other NDE methods, the response is in the form of an electrical signal that is the most convenient one for recording and further processing. Primary information is usually recorded as a spatial-temporal distribution of responses. Further processing of information can be carried out in both analog and digital forms, depending on the complexity of the algorithm and price expediency. Currently, the prevailing trend is the use of digital information processing with a number of advantages.

Methods and devices for obtaining primary information in relation to the task of NDE are now quite developed in both technical and scientific terms.

3.2.2 Information processing and presentation of processing results in a form suitable for analysis and further interpretation.

Depending on the applied control method, the algorithms for processing primary information may differ. In the limit, the end result most suitable from the point of view of human perception is the image of the object being monitored (in the plan, schematic or in the form of a three-dimensional projection) to which there is the distribution of the physical quantity (for example, defect list and their physical parameters). It is assumed that the values of the desired parameter are reconstructed fairly accurately on the basis of the obtained primary information. In addition to the visual presentation, it is necessary to have quantitative values of the parameters of defects that are necessary for further strength and resource calculations, which simultaneously can solve the defectometry problem.

With all the variety of applied control methods used, types of monitored parameters and defects, the number of algorithms for obtaining the final result is not so great. It boils down mainly to various types of complex transformations, solutions of systems of equations, and methods of reverse reconstruction. It should be noted that it is possible to obtain an over-total effect when using several NDE methods and comparing the results obtained.

Currently, the implementation of almost any algorithms can be carried out using modern means of computing and microprocessor technology, both based on standard computing tools and in the form of specialized autonomous small-sized devices with the required performance of work. The choice of implementation options is determined by the available material resources to solve the problem of NDE and the categories of its feasibility.

3.2.3 Analysis of the information received and the formation of a decision according to the state of the controlled object and the possibility of its normal functioning or forecasting its residual resource.

The ultimate goal of NDE is not only to obtain information about the presence of defects and their physical parameters but also to formulate a decision on the state of the object being monitored, the possibility of its normal functioning, or forecasting its residual resource. For a number of objects, it is possible to carry out strength calculations and draw conclusions based on them. For similar objects, methodological recommendations were developed that formalize the decision-making process. In other cases, a heuristic approach or the use of associative decisions made on the basis of selective tests and destructive tests are required. Often, the decision is made by a person subjectively, based on accumulated empirical experience.

This part of the information process is the least amenable to formalization and algorithmization. This is due to the large variety of controlled objects and their physical properties. But in some cases, where there are proven guidelines, it is advisable to implement them in the form of software that directly uses the results of previous information processing and automatically generates a conclusion about the state of the test object. Self-learning structures based on neural processors can be used for this purpose. In case of feedback that confirms or refutes the correctness of the decision (based on further destructive tests of the replaced structures), it can increase the accuracy of decision making at the final stage of NDE. Moreover, with spatial separation of the places for receiving primary information, its processing, and decision making, the connecting element is the big database, which should evolve in relation to this problem from the medium of information transfer to the distributed knowledge base.

Based on the above, we can draw the following conclusions about the current state and prospects for the use of computer technology in the fields of NDE.

From the above, it can be seen that the hardware implementations of various methods of NDE tend to converge and reduced to a structure including the following main parts:

- physical quantity converter into an electrical signal;
- electrical signal converter;
- universal block of information processing and its presentation in graphical form.

The development of NDT methods, along with the existing directions, should cover the issues of automated decision making on the compliance of this object with the required conditions or its suitability for further operation.

To solve the problem of formalizing a decision on the state of a controlled object based on the results of surveys, organizational measures are needed. These are the formation of a unified methodological center for the systematization of existing methods, including worldwide ones, the accumulation of statistical information, the identification of trends, and the development of new methodological recommendations. The creation of such database center is possible based on a powerful international organization dealing with the problems of NDE and having great scientific potential and practical experience in such matters.

3.3 Methodology

According to earlier research analysis works, there could be three main approaches that may be selected for defects detection and their characterization in operation. The choice of the approach depends on the type of structure being inspected, ease of access and the area to be covered by the inspection [69;113].

- Traditional 'point inspection' or 'local-area' NDT, which assesses a small area of a test component. When coupled to an encoded scanning system, the probe or inspection device may be raster-scanned across the surface so that a 2D image ('C-scan') of the probe response at each point can be built up. This permits a more intuitive and comprehensive presentation of the results;
- 'Wide-area' or 'full-field' techniques cover greater areas (e.g. 400 mm × 400 mm or higher) in a single measurement, allowing rapid coverage of large components. A number of more modern NDT techniques fall into this category. The ability for rapid inspection tends to come with a trade-off in sensitivity or penetration, though, coupled with a point-inspection technique, can form a useful part of a two-stage NDT process;
- Structural health monitoring (SHM) in which a large number of sensors are permanently mounted to the test structure, in order to monitor pointers to failure (e.g. surface-strain levels), or to detect the gradual accumulation of damage.

Taken from [69;113].

In our case, we choose exactly “wide area” or “full-field technique” because the goal is integral monitoring of structure condition in time.

There are 5 main steps included in this research methodology:

- Creating a diagnostic model of an aircraft composite element, reflecting the effects of damage on the vibration characteristics;
- Theoretical and experimental studies of the influence of structural damage of composite materials on their vibration characteristics;
- The selection of the Vibration diagnostic parameters and detecting the signs of damage of the structures made of composite materials;
- Experimental evaluation of the sensitivity size parameter of damage;

Developing of the operating diagnostics technique for the damage monitoring of aircraft structures made of composite materials.

After combining the information obtained during each step we finally can present an algorithm. The proposed algorithm is presented further (Figure 20). The data obtained during experiments were compared with data from a Polytec PSV-400 scanning Vibrometer to ensure the results. The method of the procedure contains several iterations combining direct Fourier transformation and CWT (Figure 20).

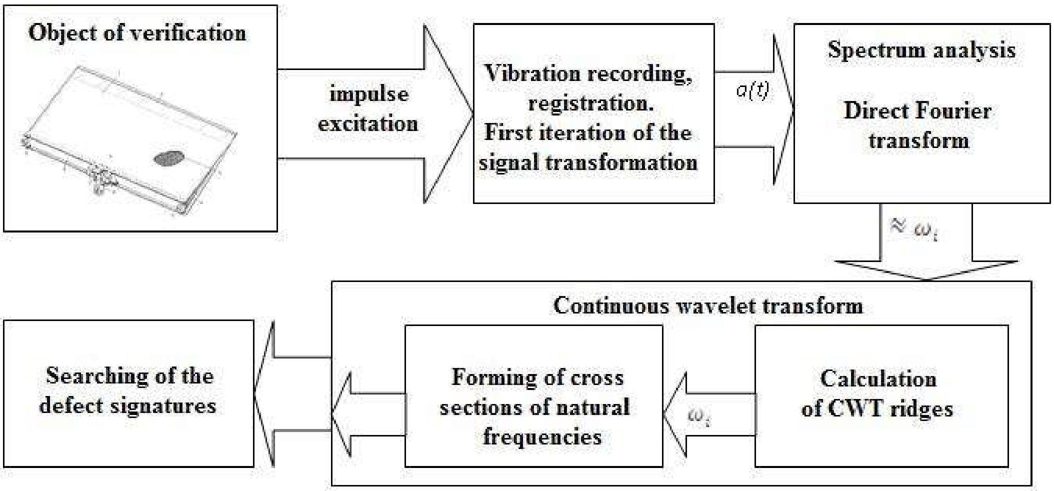


Figure 20.The main steps of the procedure (Algorithm) [114].

3.3.1 Chosen methods

- Alterations will be investigated in an integral state of aircraft structures made of composite materials.
- Using wavelet transforms (Mother wavelets, reverse, shift, multiply and integrate technique called convolution) for the construction of the 3d finite function specter.
- Determination of the modal parameters of free oscillations.
- Using Short Time Fourier Transform for vibration spectrum construction.
- Using scanning Doppler Vibrometer, vibration generator, and additional equipment to ensure the results, which will be obtained on the prototype.
- Using Labview (Laboratory Virtual Instrumentation Engineering Workbench) like a platform for the “National Instruments” equipment and its basic programming language for program writing for the system prototype.
- Investigating deformation characteristics using a mathematical model and computer simulation.

The methodology is approved by experimental testing on “National Instruments” equipment. The algorithm is implemented in LabView block-diagram as a platform for the “National Instruments” equipment using “G” programming language and is checked during the tests. In addition, the accuracy of the obtained data during the tests is monitored and the block-diagram, its interface and “toolkits” are updated. A number of LabView program versions for different equipment is developed.

3.3.2 Base Equipment

Hardware and software

Initially, as a software and hardware complex for the experimental development of the methodology, portable “National Instruments” PXI standard units were chosen. LCD monitor and keyboard accessory NI PMA-1115 (Figure 21), and VK-310 vibration sensors were used at the beginning for simulation, recording, and signal processing. Also, software products attached to PXI units were used, in particular:

NI Signal Express (for test signal simulation and registration), NI Sound and Vibration Assistant (for calibration, recording and initial signal processing), LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) as a development environment and platform for executing a program created in the graphical programming language "G".

To confirm and compare the obtained experimental data, a Doppler scanning vibrometers PSV-400-3D (Figure 26) and portable PDV-100 (

Figure 23) were used both as main and auxiliary means during almost each experiment procedure. After optimization work, there was no need for a massive NI PMA-1115 block.

Instead, the NI USB-4431 portable device and medium power laptop were implemented in tests. The USB-4431 (Figure 22) is designed exactly for sound and vibration measurements.

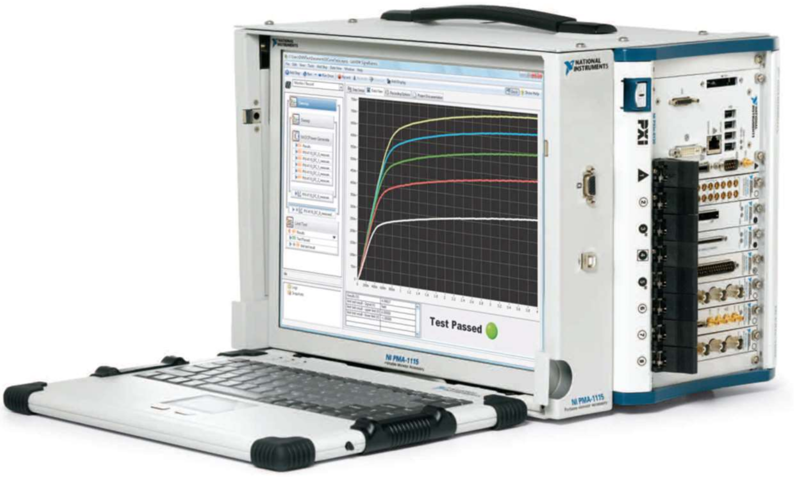


Figure 21. NI PMA-1115 block

Figure 22. NI USB-4431 block.

Input channels incorporate integrated electronic piezoelectric (IEPE) signal conditioning for accelerometers and microphones. The four USB-4431 input channels can simultaneously digitize input signals. Based on the method proposed earlier in Methodology (3.4), a technique was developed for diagnosing of honeycomb construction and after that was approved on real objects in the laboratory. Further information is presented in (3.4) “interpretation of obtained data” section. A large amount of additional equipment and systems which are not presented in detail here also used during this research. These elements are amplifiers, vibration generators, portable laser heads, computers, resin systems, calorimeters, ovens, vaporizers, specially designed frames and shafts for the samples, equipment for flexible sample fixing, sound diffusers, noise insulation elements, special paints, glue systems, vibration sensors, ultrasound infrared optical systems, thermal imagers, different tooling equipment, etc.

Figure 23. Portable Doppler scanning vibrometer PDV-100.

After the selection of equipment and registration, multiscale analysis of the vibration signal is performed in the LabVIEW software environment. For this purpose, an executing program was created in LabView software. Figure 24 shows the simple block diagram of the written program.

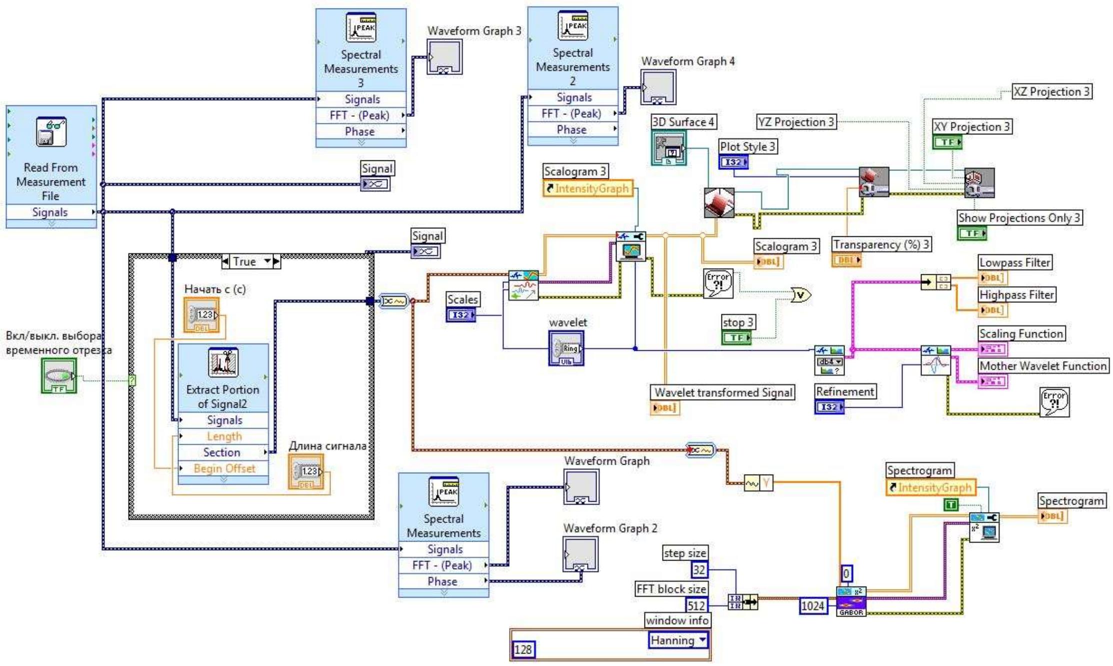


Figure 24. Block diagram “Final (one block) 3”.

After analysis based on the found values of the natural frequency and damping coefficient, the diagnostic parameter *K* can be calculated. After that, the value obtained during the experiment is compared with the allowable value of the diagnostic parameter [K], which corresponds to the maximum value in operation. The calculated value of the diagnostic parameter can be entered into the database to form a time series and conduct a statistical analysis of the state change of the monitored object. If the permissible value is exceeded by the diagnostic parameter, the object is removed from service and sent for repair to clarify the size and location of the detachment. If the obtained value of the diagnostic parameter is in the zone of allowable values, the normal operation of the tested unit continues and a forecast is made about the technical condition until the next check.

Like it was mentioned before in theoretical basis of wavelet transforms, in simple terms 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 the harmonics with the given frequency in a given time. There are two main features that make continuous wavelet transform (CWT) particularly attractive. First, the vibration modes are automatically separated in most cases, providing the natural frequencies, so that 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 (high amplitude areas of the CWT figure). It was noted that for the right choice of the corresponding "mother", CWT wavelets can serve as a filter for separation of free oscillations.

A good illustration of physics for the proposed method can also be found in work made by Haase M, and Widjajakusuma J [101]. In this work, we can see analyzation of a simple case of a linear system with two degrees of freedom (Figure 25). This can show the principle for obtaining instantaneous frequency and damping parameters through the use of CWT (calculated only for ridges).

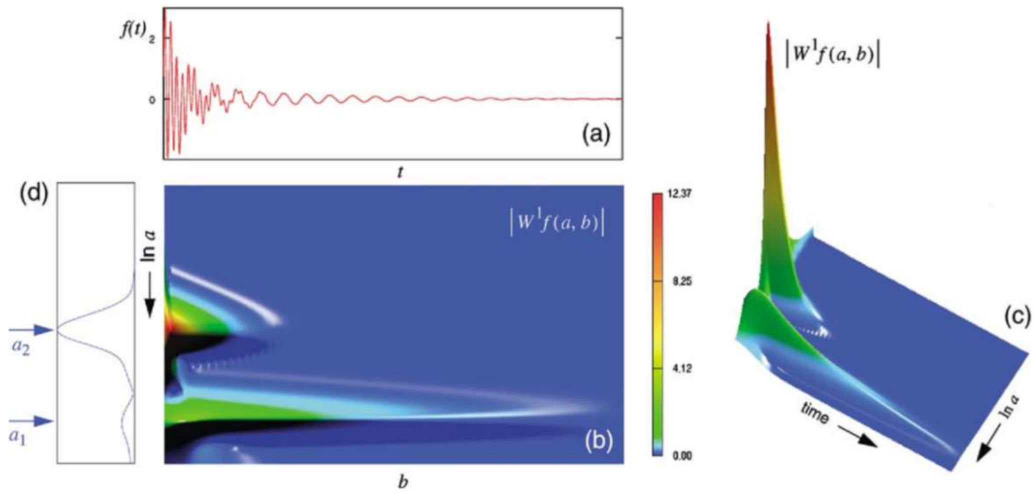


Figure 25. Linear system with two degrees of freedom. (a) plot of the function; (b,c) wavelet transform module; (d) Free oscillations frequency determination [101].

$$f(t) = \sum_{j=1}^{2} A_j(t) \cos\Phi_j(t), \tag{31}$$

where $A_j(t) = \alpha_j e^{-\zeta_j \omega_j t}$ and $\Phi_j(t) = \sqrt{1-\zeta_j^2}\omega_j t + \varphi_j$; are the natural oscillation frequencies; with ζ_j - coefficient of damping; α_j - initial amplitude $(t = 0)$; φ_j is the phase shift of the jth mode (α_1= 0,5; α_2= 3,0; ζ_1= 0,03; ζ_2= 0,045; ω_1= 40π = 125,66; ω_2= 156π = 490,09; φ_1= φ_2= $\frac{\pi}{2}$). Figure 25(a) shows a plot of the reaction on the impulse excitation on the time interval ($0 \leq t \leq 1$). The first-order derivative for the CWT wavelet analysis was selected to be equal to

$$\psi_1(t) = (-t + i\omega_0)e^{\frac{-t^2}{2}}e^{-i\omega_0 t}, \tag{32}$$

with $\omega_0 = 5$. Figure 25(b) and (c) show two CWT modules, from which we can see that CWT divides the modes of oscillation, however, the proposed method does not need a complete calculation of the CWT. It is only necessary to perform the calculation for a fixed time b_0 Figure 25(d) and evaluate the scales $a_{1,}$ a_2 for the maximum deformation: a_1 = $4{,}159\text{x}10^{-4}$; a_2=$1{,}046\text{x}10^{-2}$. The relevant frequencies, ω_j, and damping parameters, ζ_j, can be determined by the following formula [101].

$$\alpha_j\sqrt{1-\zeta_j^2}\omega_j = \omega^*,\ \zeta_j\omega_j = -m_j. \qquad \text{..............................(33)}$$

Based on the principles presented, the obtained data from each test was compared with data from a Polytec PSV-400 scanning vibrometer (Figure 26) to ensure the results. As stated, the method of the procedure contains several iterations combining direct Fourier transformation and CWT.

Figure 26. Polytec PSV-400 Scanning Vibrometer during a test of a composite aircraft blade.

3.3.3 *Preliminary methodology approbation. The first interpretation of obtained data and explanation of further experiments logic regarding wavelet transforms.*

The following figures (Figure 27, Figure 28, Figure 29) schematically describe the features of the CWT before and after the appearance of the artificially created defect. Such results were obtained during the experiments with aviation honeycomb constructions. This information gives a visual basis for the understanding of CWT use in methodology. As we can see, there is a clear difference between the statement of the object before and after the signs of the defect appears in the reference honeycomb structure according to the CWT 3d pictures. The differences which are marked by a yellow colour show the changes in certain areas. A comparison of these pictures helps to better understand the process of how the appearance of the defect changes the whole CWT picture step by step.

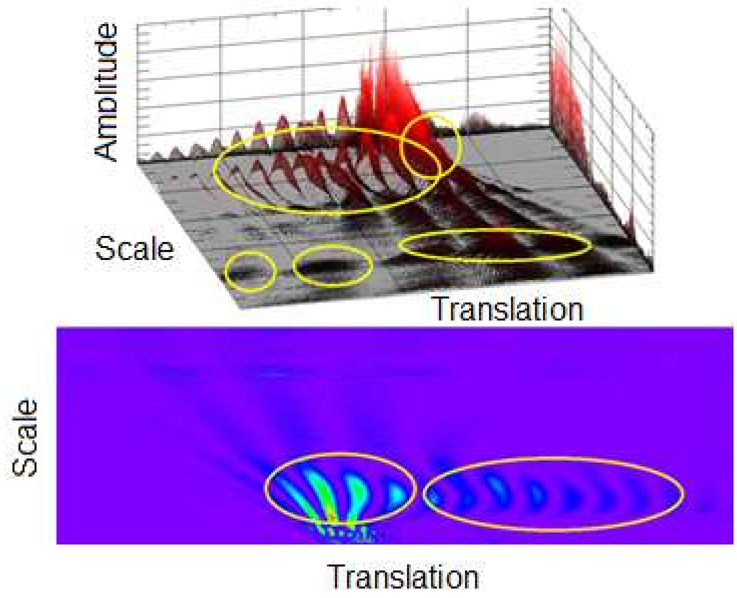


Figure 27. CWT 3d and scalogram without the defect.

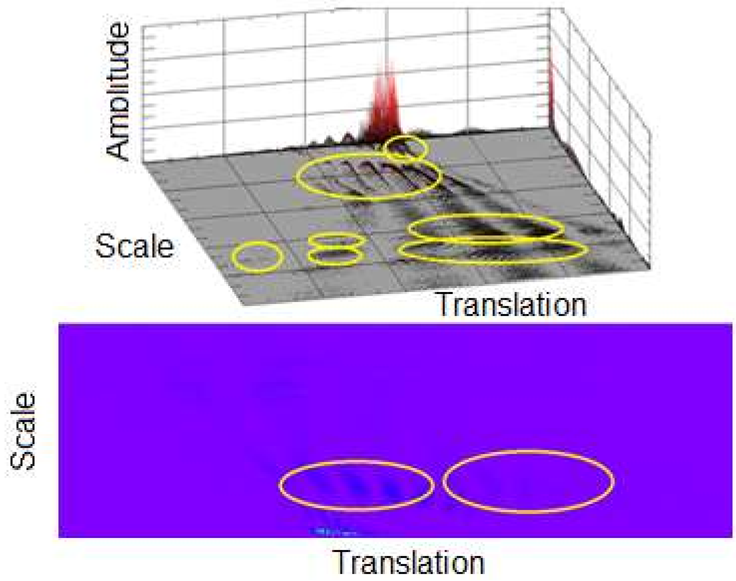


Figure 28. CWT 3d and scalogram with an artificially created defect.

The area of the defect in reference honeycomb construction was gradually increased, approximately from 1% to 5% of the internal honeycomb construction space. It was conducted by means of injected water, which was frozen after injection to make the delamination between the honeycomb core and the layers. After that, the water was vaporized, and the sample was weighted to ensure that there is no more water in the reference honeycomb construction.

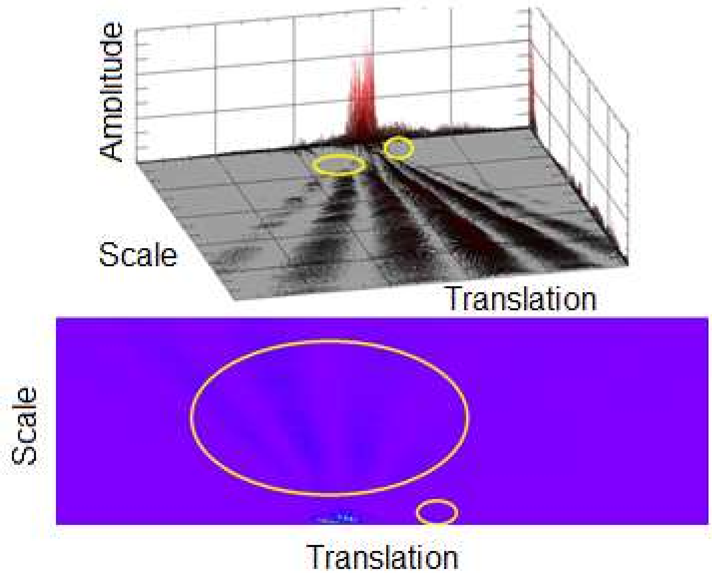
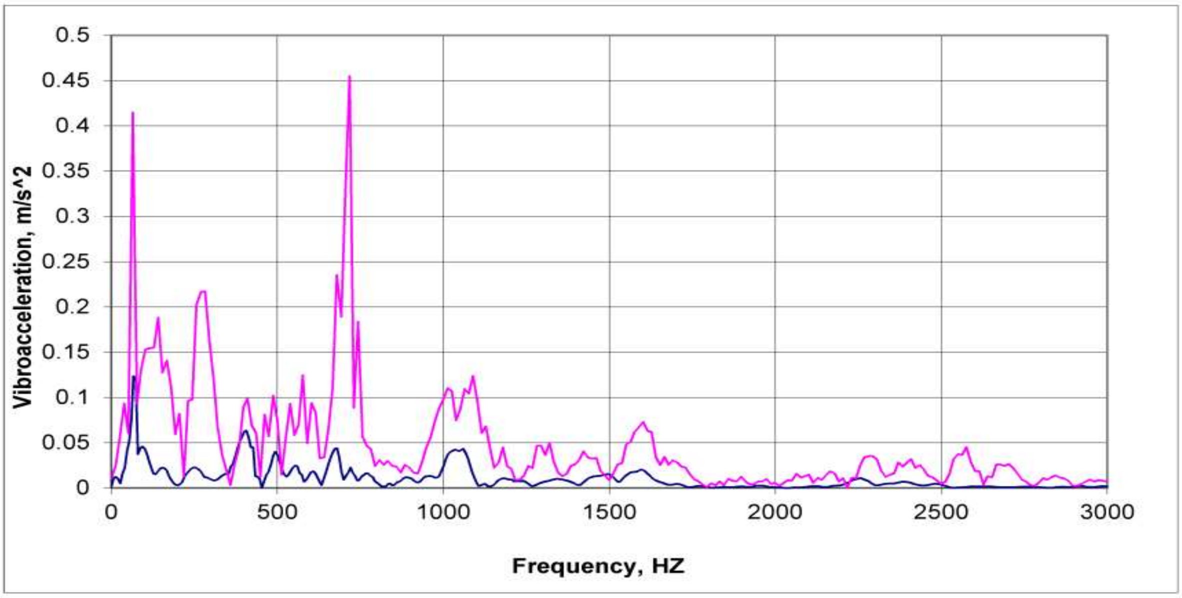
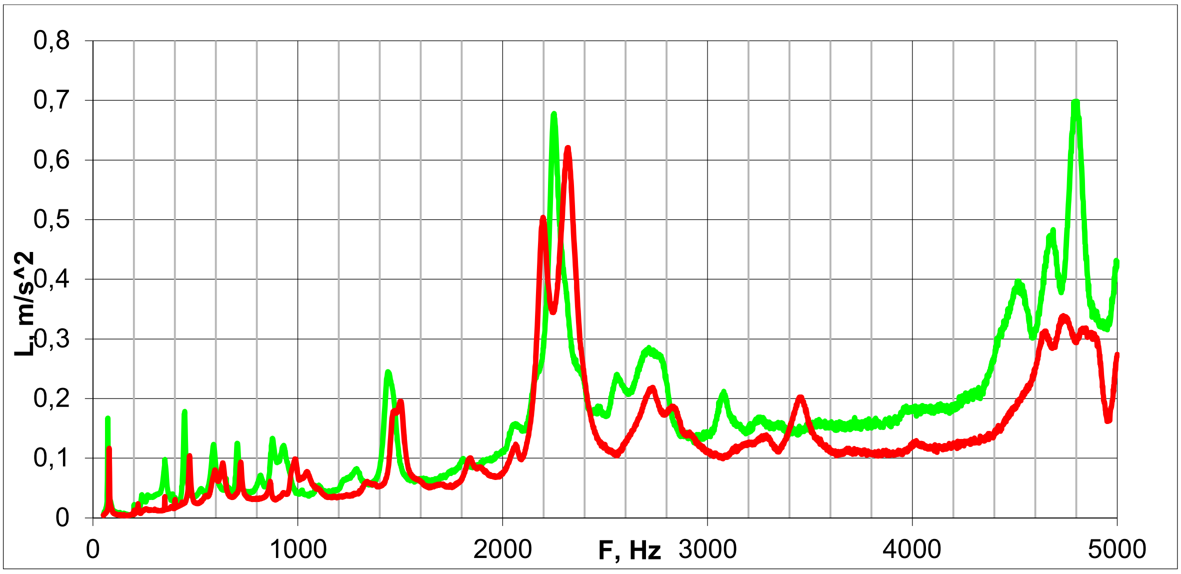


Figure 29. CWT 3d and scalogram with increased defect area.

With the increase of the bundle area, the CWT picture changes rapidly. This allows us to make the first conclusion about typical signs that can be occurred from 3d scalograms. It is obvious that for each object the picture will be different, but some alterations can be marked during the aircraft life-cycle to set the points in operation for maintenance checks. If the data can be collected statistically by means of many iterations (vibration tests) during operation and such deviations in connection with other parameters like resonance frequencies, potentially we can talk about improving aircraft maintenance performance and safety. The dependence of the vibratory acceleration on the frequency, using a direct Fourier transform – first iteration using vibration sensor with one-layered honeycomb structure (a) and Doppler scanning vibrometer with multi-layered honeycomb structure (b) (Figure 30), indicates frequency damping with the appearance of a defect.



(a)



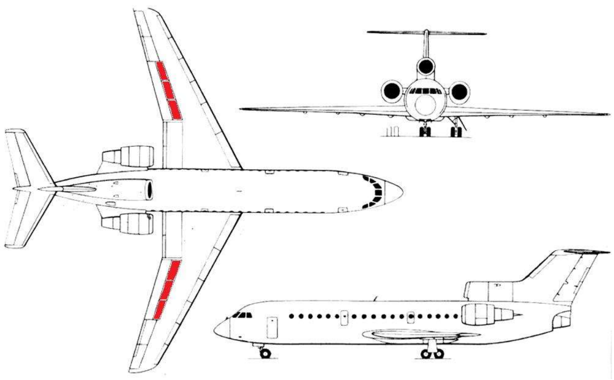
(b)

Figure 30. Graph of vibratory acceleration of one-layered honeycomb structure, with the defect (blue) and without a defect (pink) (a). A hard attached one channel sensor was used.

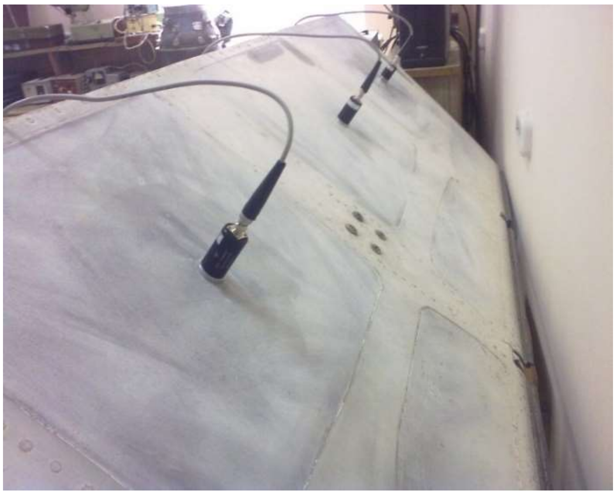
Graph of the average vector of vibratory acceleration for a multi-layered honeycomb structure, with the defect (red), without a defect (green) (b). A doppler scanning multichannel vibrometer was used.

The raw results of the testing in a large scale of the experimental procedure on the reference honeycomb structures showed a reduction of natural frequencies and an increase in damping at the resonant (natural) frequencies as a result of the presence of damage. Visual features of 3d and scalograms indicate changes in the overall vibration picture of the signal, those changes (which were accepted as a part of the original thesis) interpolated in time and compared can describe the integral damage condition of the object itself.

The described technique was tested on Yak-42 aircraft spoilers, which were made of three-layer reinforced honeycomb construction. To diagnose the surface of the spoiler, as shown in Figure 31, the vibration sensors VK-310A were fixed with glue. The NI PMA-1115 unit is switched to the recording mode of the vibration acceleration signal. In the registration process, a signal of vibration acceleration is recorded in the frequency range from 0 Hz to 10,000 Hz. Then the controlled spoiler is rejected to the released position by the standard spoiler control system of the Yak-42 aircraft. When setting the spoiler to the thrust of the released position, a strike on construction is created to excite the free vibrations necessary for further analysis. The measurement results are stored in the signal processing and storage unit in the TDMS format. Spoilers were tested in the lab and then on the training airfield on real aircraft. Summarized information can be found in an earlier published article: “Damage monitoring of aircraft structures made of composite materials using wavelet transforms” [114].



(a)



(b)

Figure 31. Yak-42 passenger jet (spoilers marked red) (a). Spoilers in the Samara university lab during the testing (b).

3.3.4 *Selection of diagnostic parameters for detecting damage of aircraft structures*

Rational choice of diagnostic features, i.e. appropriately presented characteristics of oscillatory processes sensitive to changes in the technical state of the testing object, is the main feature that can determine the success of diagnosis. The selection of diagnostic signs is preceded by a procedure for evaluating the properties of signals that reflect a change in the technical state of an object.

Specific requirements for the analysis of vibroacoustic processes properties are made during the diagnostic of incipient defects. The signal parameters containing information about incipient defects have low power consumption and require the use of a mathematical apparatus for analyzing the properties of non-stationary processes under conditions of weak noise immunity of useful information.

As an example in early research of identification of complex crack damage for honeycomb sandwich plate using wavelet analysis and neural networks [115] with the appearance of delaminations in honeycomb structures, the damping coefficient ζ_{i} will increase, and the natural frequency of oscillation ω_i - will decrease. Therefore, it is advisable to use a complex parameter for assessing the technical condition, which can be written in the form

$$K = \sum_{i=1}^{n} \frac{\zeta_i}{\omega_i} \qquad (34),$$

where *i=1, 2, 3, …* – mode number of natural oscillations. The criterion for assessing the status of the testing object will be that this parameter exceeds the maximum permissible value:

$$K < [K],$$

where $[K]$ - maximum permissible value of a complex parameter.

The advantage of this parameter is in the possibility to achieve the required sensitivity of by varying the set of modes used in the calculation.

Definition of maximum lines and wavelet transform ridges.

One of the most valuable characteristics of wavelet transforms is the ability to get an accurate analysis of the signal regularity. Even for a discrete function given by $\{f_1, f_2, \dots, f_n\}$ we can accurately determine the location of those points where the signal or some derivative of it, has drastic changes. This is possible when analyzing the behaviour of changes in scale, along with so-called specific lines or maximum lines, where the CWT module is localized.

Another important characteristic of wavelet transforms is their ability to decompose vibrational signals into natural components in accordance with their own frequencies [101;102]. If Fourier transform of the analyzed progressive wavelet $\psi(t)$ is concentrated near the fixed frequency ω^*, then the CWT module is concentrated next to a series of curves called ridges.

Usually, calculations of the maxims and ridges lines are made during the initial estimation of the CWT, which is done, using the fast Fourier transform. Therefore, CWT is received for a discrete grid of points (a_i, b_j). Local maxima are then determined either by the scale parameter a_i, or by the time parameter b_j for the lines of maxima and ridges, respectively. Further, an additional link is needed to identify linking lines, which can be difficult in the case of split lines.

Further, such lines will not be considered, but instead, a method is proposed for calculating CWT only along the characteristic lines, thus unnecessary calculations and complex algorithms are not performed. The special properties of the Gaus and Morlet families' wavelets allow setting the differentiation of a system of homogeneous differential equations for the parametric-written lines $a(s)$ и $b(s)$, which can be integrated numerically. This technique is effective only if the calculation of CWT can be performed separately for each point (a, b) of the time domain, which are possible for a discrete sampling function. This method gives another advantage over the conventional scheme when the wavelet transform is calculated in Fourier space, which is based on the assumption that the signal is periodic. The CWT advantage is that the spurious cyclic effect can be eliminated [101].

According to Haase and Widjajakusuma, damping parameters can be determined using ridges (Figure 32). As can be seen from Table 1, the proposed method for the determination of damping parameters using the maxima and ridges of the wavelet transform has sufficient accuracy.

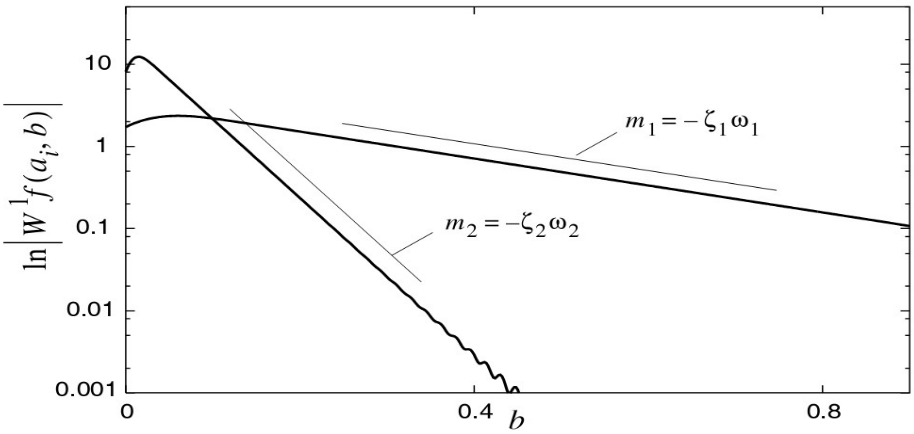


Figure 32. Determination of CWT damping parameters using ridges [101].

Table 1. Evaluation of the accuracy determining the parameters of damping, when using wavelet transform.

Parameter	Value	Value obtained using the wavelet transform	Deviation, %
ω_1, Hz	125.66	124.91	0,6
ω_2, Hz	490.09	496.88	1,39
ζ_1	0.03	0.0301	0,33
ζ_2	0.045	0.0429	4,67

3.4 Summary

Significant part of analysis work was done. According to research aims, for the development of vibration diagnostic method, the main types of analysis of vibration signals and their applications were discussed in detail. The optimal method for the selection of diagnostic parameters was chosen. As a result, the method based on wavelet transforms combination became an entering wedge for further research. The theoretical basis of wavelet transforms was presented. After the development of a method for damage monitoring based on vibration characteristics using wavelet transforms, the conclusions on whole analysis were derived.

Features of building information systems for non-destructive testing tasks including primary measurement information for further processing and presentation of processing results in a form suitable for analysis and further interpretation were discussed. Analysis of the information received and the formation of a decision according to the state of the controlled object and the possibility of its normal functioning or forecasting its residual resource was derived. The methodology part contains accurate information about chosen methods, equipment, and its use in research. Interpretation of obtained data after preliminary results showed that the selection of diagnostic parameters can be made by the means of chosen facilities.

Chapter 4. Experimental Results and Discussion

4.1 Introduction

This chapter contains information on practical experiments with different composite structures and their parts. The first part is connected with integral state monitoring of aircraft blades, and their discussion. The second part gives information about experimental results with CNT/Polymer applications and conclusions on tests with confirmation of the information from available sources. The third part is dedicated to the research of the vibration properties of advanced metal-polymer-metal composite materials. It contains detailed information about objects of study and their production. Processing of the proposed methodology and results of experimental modal analysis allocated in a separate part.

The conclusions from the results from the previous chapter are that it is possible to control and forecast the condition of the object with the proposed method. The relation of diagnostic parameters is discussed for each test condition. Structural analysis for each test type is detailed with failure patterns and behaviour.

To better understand the behaviour of research objects, testing and characterization approaches are used that also investigate the effects of behaviour. When a composite part is involved in the operation, its condition definitely differs from the original state. During the production or in operation, micro-cracks, flaws, interlaminar separations, and other defects may occur. As it was stated in chapters 2 and 3, the vibration method could be most appropriate for this research. The monitoring of vibration characteristics allows us to monitor the integral condition of the composite element through the lifecycle.

This chapter presents results and discussion of the implementation of an experimental methodology for different advanced composite materials.

In the current research, four sets of experiments were used (Table 2). All experiments' goal is vibration control and diagnostic of different composite material objects. The first set was used for the approbation of the proposed methodology with the artificially created defects on reference surface with simple excitation by the means of a controlled strike. In the second experiment, different kinds of real operational objects (aircraft spoilers, aircraft blades with different operation time) were tested with hard attached vibration generator using different approaches. The third type of experiments was used for approbation on potentially new CNT polymer applications with the addition of highly conductive particles. After all probationary tests, the main experiment set was used for new metal-polymer-metal sandwich samples with an imitation of operation loads. Imitation of operation loads was executed by means of zero-to-tension stress cycle at the servo-hydraulic test machine. FEA analysis was used to verify the data obtained experimentally, as well as to estimate the possible errors introduced into the study during experiments (instability of the experimental conditions due to possible events as interference, noise, etc.). Lock-in thermography testing of MPM samples was used to check the condition before and after cycle loading, due to the inability of using simple visual inspection procedures for the composites of this kind.

Table 2. Classification of experiments.

1. Preliminary experiment section			
Set №	Objects of study	Essence and composition of experiment	Goals
1.	Honeycomb constructions	Excitation of eigenmodes (natural modes) by the means of a controlled strike.	Approbation of the proposed methodology with the artificially created defects on reference one layered honeycomb construction sample.

	(one layered and multi-layered)		
2.	Aircraft spoilers (multi-layered honeycomb constructions with aluminum frame).	Test of operational objects with hard attached vibration generator using different approaches.	1. Approbation of the proposed methodology on real objects. 2. The search of most appropriate technique of excitation (use of strike excitation, periodic chirp, and white noise sounds) 3. Approbation of contact and non-contact techniques of signal acquiring. 4. Approbation of three dimensional and single laser techniques with the proposed methodology.
2. The main experiment section			
Set №	Objects of study	Essence and composition of experiment	Goals
1.	Aircraft blades with different operation times.	Test of operational objects with hard attached vibration generator using different approaches.	1. Study of natural frequencies and modal shapes 2. Approbation of the proposed methodology on real objects (using a combination of wavelet and Fourie techniques). 3. Approbation of three dimensional and single laser techniques with the proposed methodology. 4. The search of simple diagnostic indicators of possible defects and proposition of fast light and cheap SHM system.

2.	Carbon nanotubes polymer applications. (Epoxy resin with MWNTs table 4).	Excitation of eigenmodes (natural modes) by the means of direct periodic chirp and white noise sound pressure.	Approbation of the proposed methodology on epoxy resins. Investigation of acoustic properties of epoxy resins with the addition of CNTs.
3.	MPMs sandwich composite samples	1. Excitation of eigenmodes (natural modes) by the means of direct periodic chirp and white noise sound pressure by a non-contact method with imitation of operation loads. 2. Finite element analysis (FEA) 3. Scanning of MPM samples by lock-in thermography testing at different frequencies (0.1, 0.3, and 0.5 Hz)	1. Approbation of the proposed methodology on MPMs samples. 2. Acoustic behavior modeling, calculation of modal characteristics (natural frequencies and vibration modes) and comparison with real conditions under imitation of the rising operational loads. 3. Verification of experimentally obtained data by FEA. 4. Estimation of the possible errors introduced into the study during experiments by FEA. 5. Checking condition of two samples by Lock-in thermography testing, before and after cyclic loading.

Each experiment set has its own features, from special additional rigging (designed diffuser, frames, and additional parts) to equipment (designed sound generator, thermal camera, different type lasers, Doppler vibrometer, computer sets, etc.).

4.2 Experimental results and discussion of integral state monitoring of aircraft blades made of composite materials using multiparameter analysis including wavelet transforms.

Technical condition monitoring of aircraft structures, including those which are made of composite materials, shows the prospect of methods for dynamic control of aircraft components based on the analysis of trends in the vibration characteristics. Such methods include a method of free oscillations.

It is known that mechanical testing of the product allows us to find only facts of its output parameters for the tolerance limit and do not provide information about the upcoming behaviour of an object, especially in the context of dynamic effects, when there can be a failure and even sudden avalanche breakdown of structure.

The method essence is that during object lifecycle (in regular time periods) dynamic effects are simulated in control points and that allows us to get feedback from construction. This feedback gives a field to judge the occurrence of a “close to critical condition” point in aircraft operation.

According to the fact that composite materials, under the action of harmonic excitations in a certain frequency range, have an accumulation of damage during operation ("disbonds" zones, etc.), there is a change in stiffness characteristics. In addition, there is a clear “drift” in resonance frequencies, which was captured by sensors. This together with the use of wavelet transform for analyzing of results allows to create response evaluation criteria of the critical state of the object and make a forecast for the period of operation until the next inspection. For evaluation of technical status base amplitudes and resonance frequencies can be used successfully to calculate values and store them for each object before it can be put into operation. The calculated values can be obtained with the use of the model, built with the help of vibration theory and also with the finite element model. At the same time based on the information about the object, it is possible to extrapolate its behaviour in the future and to establish the optimal time for regular maintenance checks or decommissioning of the facility.

The method is based on the analysis of free and forced oscillations, which can be excited (one of the options) by a mechanical strike at the control points of an object. Then the echo from strikes is recorded and transformed into an operational unit. To eliminate random errors, a series of measurements are produced. After that, from the received signal by using a fast Fourier transform, we obtain the approximate values of the natural oscillation frequencies. Next, by using a continuous wavelet transform the sufficiently accurate visual values of natural frequency modal parameters are determined. At the final stage, in obtained data, we look for the characteristic signs of defects, mark them and make a conclusion about the present state of the control object. This obtained data is compared with data from a Polytec PSV-400 scanning Vibrometer to ensure the results.

A comprehensive methodology for integral monitoring that can overcome the disadvantages and take advantages of various methods is one of the main issues. In the low and mid-frequency range, modal parameters are usually less sensitive to localized defects, but often reflect global changes from overall damage. A permanent monitoring of the engineering structure can be possible by the means of (SHM) and (NDE) methods. Innovations in this kind of market have increased after the development of advanced portable X-ray radiation-shielded equipment such as microfocus X-ray tools or integrated X-ray equipment, etc. Among the most prospective and accurate techniques, there are some like phased array ultrasonic testing, computed tomography testing, and data management systems.

NDE and SHM both can detect and locate problems before they become serious. The effectiveness of NDE depends on facts - how often monitoring or inspection is performed, equipment sensitivity and the ability of the operator to perform and interpret the results. Ultimately, it comes down to speed, cost, and reliability of the NDE methods used (and the consequences of failure or poor performance). In order to close the gaps between NDE and SHM then, any of these variables need to be improved. That makes NDE faster (or more regular), less expensive and more reliable (or failsafe). Probably, the solution of the problem can be found in the combination of simple NDE and SHM systems. NDE should be like an easy to handle additional technique to SHM onboard system. It is noted, that apparent distinction between NDE and SHM is difficult since many ideas and techniques are certainly applicable to both NDE and SHM.

The choice for wavelet transforms as a tool for implementation in such techniques was made for several reasons. The opposite of harmonic basis functions are pulse basis functions. Such functions as the pulse Kronecker function is extremely localized in the time domain and "blurred" over the entire frequency range. Wavelets localization in two views can be seen as functions, occupying an intermediate position between the harmonic and pulse functions [97;98]. They must be localized both in time and frequency domain. The establishment of such functions is set again a principle similar to the Heisenberg uncertainty principle, which links the effective duration of the functions and values of their spectrum width. The more accurate we will localize the position of temporary functions, the greater will become the spectrum. A feature of wavelet analysis is that it is possible to use a large number of basic wavelet functions that implement the various embodiments of the relation between the frequency and localization signal under analysis. Therefore, during the study, there is a choice between the families of wavelet functions and flexible application of those specific tasks.

Like it was mentioned before, as a result of significant growth in the use of composite materials in aviation structural components, there is a strong need for an increased capability for the operational monitoring and inspection of such components. The main possible impact of this research may affect the future operation of aircraft composite materials. The data, which was received, can help to develop a universal non-destructive testing method and as a result to improve aviation safety. Condition monitoring of modern passenger aircraft with complex composite material elements as well as the state prediction of such elements can 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 integral control of a composite structural aircraft element during the operational inspection. Wavelets can be combined, by the means of reverse, shift, multiply and integration technique called convolution. This allows using portions of a known signal to extract information from the unknown signal. The research represents a “shift” technique with the use of the variable list of the “mother” wavelets such as Morlet wavelet (or Gabor wavelet), db4, db9 [96].

As mentioned earlier, discontinuities in CM structure may lead to the dramatic growth of binder fractures, causing the possible crash of the aircraft. Therefore, it is important to evaluate the integrity of the critical aircraft CM parts in a timely manner during the flight. However, existing methods of CM inspection make it possible to only diagnose units in an airfield laboratory. As a result, the development of an express-test, low-cost, reliable device for monitoring of aircraft CM in operation is an important task.

In order to implement the diagnostic device system on aircraft, it is required to solve two major problems. First of all, a parameter measurement system, which could indicate the defect manifestation, has to be developed. One of the possible solutions is a system of sensors, integrated into the structure. The simple installation of piezo-electric or microstrip resonators is unacceptable because it reduces the unit strength by an average of 27% [116;117].

This is why it is stated, that the carbon nanotubes, arranged between the layers of fibers in the manufacturing process could be used for the measurement of material properties. The same use of ferroelectric ceramic composites in the polymer matrix was depicted in the article [26]. Second, it is necessary to define the construction properties that could cause the defect to appear. Finally, the parameters corresponding to the said properties must be measurable in flight.

4.2.1 Objects of the study

Fully composite blades with Aluminum alloy ring in the attachment point can be the perfect example of a modern composite structure. The blades were made of fiberglass prepregs with different types of epoxy resin (monomer-free, accelerated dicyanamide, vinyl hybrid resins). Molding of blades was carried at high pressure and temperature in a metal matrix mould, followed by continuous polymerization. Blade hubs are made of duralumin D-16T. The ends of the blades are brass ferrules. The life-cycle of each blade according to product passport data on average is no more than 600 flight hours. The geometry of the propeller was adjusted to the optimum during flights, tested almost all gearboxes provided with ROTAX engines. All blades were made from the same matrix, they all had the same geometry and very similar top layer surface conditions. These blades are commonly used in small civil aviation aircrafts, especially in hydro-airplanes, trikes, trainer aircraft. Commonly they are used now in airplanes like the "Hawk", "A-27», «NG-4". The life-cycle of each blade according to passport data on average is 550 – 600 flight hours. During the operation, test pilots had mentioned the increase in vibration at different service life periods. It should be mentioned, that there were even cases of explosive fracture during the flight. These facts only proved the necessity of further investigation. The life of the composite blade for small aircraft can be less than 300 hours.

Apparently, blade replacement takes place from seven to twenty times during aircraft life. Moreover, the probability of airplane accidents will rise sharply with blade replacement time coming closer. Accidents may arise from time to time during airplane landing, taking off and climbing as well as high-speed and high-angle-of-attack maneuvering when the level-flight lift is not sufficient for gliding. Therefore, the blades of a small-engine propeller aircraft were chosen to study the changes in the modal parameters that are caused by composite material cracking and delamination.

The probability of CM components failure is increased dramatically by the end of the working period. The fatigue life of a light aircraft airframe ranges within 2000 and 6000 h, whereas the blade life is less than 300 h. Apparently blade replacement takes place from seven to twenty times during aircraft life. Moreover, the probability of airplane accidents will rise sharply with blade replacement time coming closer. Accidents may arise from time to time during airplane landing, taking off and climbing as well as high-speed and high-angle-of-attack maneuvering when the level-flight lift is not sufficient for gliding. Therefore, the blades of a small-engine propeller aircraft were chosen to study the changes in the modal parameters that are caused by composite material cracking and delamination. Table 3 represents the main characteristics of the first batch of the blades under study [118].

Table 3. General parameter values of the blades [118].

Main particulars	Value
Blade length L, (mm)	800
Blade chord at radius R = 0.9 L, (mm)	64
Blade thickness ratio at radius R = 0.9 L	0.125
Hub-to-diameter ratio	0.086
Blade section	Clark Y
Mass	Value
Reference blade (**Figure 33** a), (kg)	0.973

Defected blade (**Figure 33** b), (kg)	0.925
Defected blade (**Figure 33** c), (kg)	0.924
Defected blade (**Figure 33** d), (kg)	0.969

4.2.2 Methodology and results of experiments

The new blade, which never was in operation, was used as a reference unit (Figure 33a). The blades (Figure 33b-d) that exceeded suggested running time (more than 1.4 times the assigned resource) were examined for the visible defects. In manufacturing composite blades, their weight tolerance can exceed 50 g. This is due to the technological features of manufacturing composite items. The difference in blade mass can lead to blade natural frequency variation up to 2 Hz.

a b c d

Figure 33. Blades used during testing [118].

The study of natural frequencies and modal shapes was carried out using a rigid console-term blade support in the holding device with the mass of 28 kg (Figure 34a). The holding device was fixing the blade hub with clamps, as shown in (Figure 34b). The support was excited by means of vibration in nonparallel and non-perpendicular direction to a plane of the blade hub.

a b

Figure 34. Rigid console-term blade support. (a) View of supported blade. (b) Holding device for the vibration analysis [118].

This kind of excitation is used to transmit the input vibration to the tested blade and to initiate as many blade modes as possible. This allowed simulating the real ‘‘full-mounting hub situation”. Determination of blades modal parameters was performed through analysis of their response to the vibratory excitation of variable frequency. The periodic ‘‘Pseudo Random” signal was used, where the amplitude was constant at all excited frequencies, and the phase was subject to the normal law of distribution. This type of signal was chosen due to its fair accuracy of structure vibration response identification, maximum use of the vibration power at the investigated frequency, and reduced leakage effects for the waveform spectral analysis [114].

During the measurement process, the quality of the excitation signal was checked by two indicators. The first point was the stability of exciting force modulus dependency on frequency. In order to obtain adequate results, it was necessary to ensure that the vibration strength amplitude would remain almost constant at any frequency. The second indicator was the coherence between the measured signal and the excitation signal:

$$COH = 1 - \left(\frac{N_R^2}{A\overline{P}_{RR}} + \frac{N_V^2}{A\overline{P}_{VV}} \right), \qquad (35)$$

where N_R^2 stands for the noise power of input signal, N_V^2 is the noise power of output signal, $A\overline{P}$ is average autocorrelation function, indices V , and R corresponds to the measured signal on the surface of the blade and the reference signal accordingly.

Figure 35 gives a schematic representation of the experiment. An electrodynamic exciter (Modal shop, 2025 E model, with the fundamental resonance greater than 6 kHz, the suspension stiffness equal to 2.6 N/mm and the armature weight equal to 0.159 kg with the peak pushing force of 58 N) was used as a vibration source. The general practice shows that the first natural bending frequency of metal fan blades lies in the range of up to 200 Hz. However, the first modal frequency of composite blades is slightly lower. According to [119], the first flap and the lead lag modes of the turboprop composite propeller blade are in the frequency range of up to 150 Hz. Another turboprop propeller was investigated in [120].

The experimental study and numerical simulation showed that the first bending modal frequency is equal to 45 Hz. Thus, taking into account the dimensions of the blades in this part of the study, experiments were conducted in the range of 30 to 60 Hz, which ensured the capture of the blade first natural frequency. The vibration excitation response was analyzed from the average value of the blade surface vibration, which was measured using a three-dimensional scanning laser vibrometer (Figure 35).

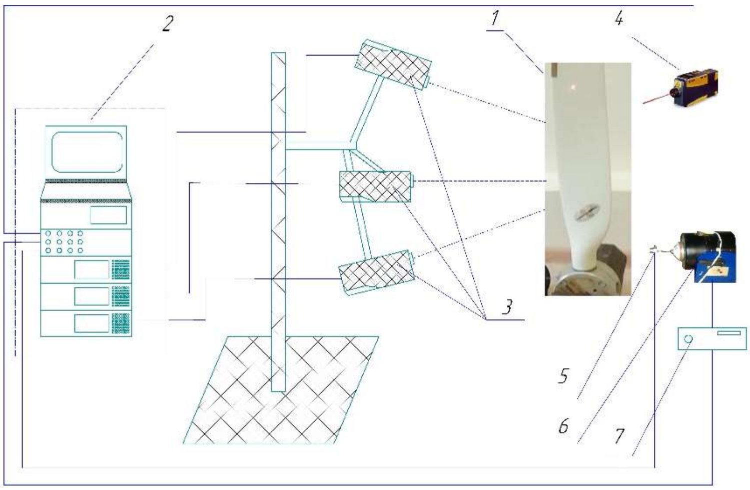


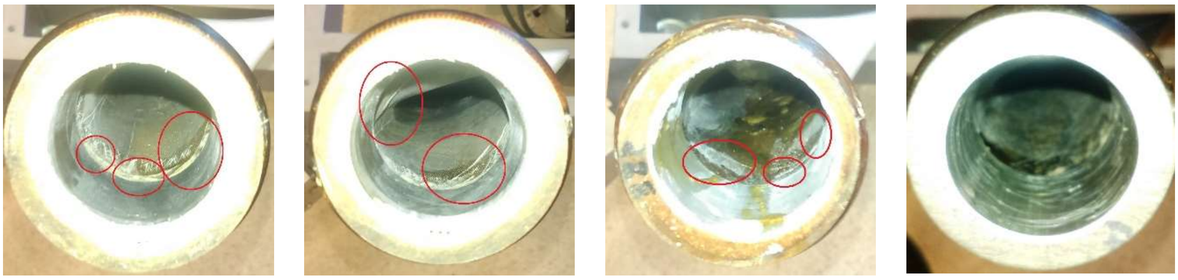
Figure 35**.** Experimental set-up. (1) Blade. (2) Scanning vibrometer control module. (3) Scanning head (PSV-400-3D). (4) Laser vibrometer (PDV – 100). (5) Force sensor. (6) Shaker. (7) Amplifier.

The vibrometer (Polytec PSV-400-3D model) allowed acquiring the vibration data in the frequency range from 30 Hz to 1 kHz with the maximum value of 100 mm/s and the resolution of 0.01 mm/s. During the experiment, the results of FFT (Fast Fourier Transform) analysis of scanned vibration were recorded and processed by frequency resolution of 0.625 Hz, Hanning window, and 100 averaging. The use of signal indications as a reference and auxiliary laser vibration sensor (Figure 36), made it possible to determine the natural frequency shape of the blade. For this purpose, the Polytec PDV-100 laser Doppler vibrometer with vibration resolution 0.02 μm/c was employed.

Figure 36. Additional laser vibrometer.

Experimental results

Due to high transient torque force acting on the surface of the blade in flight conditions the blade inner layer flakes off the outer layer. Figure 37 depicts the optical examination of the blades inner surfaces. The pilot study suggests that the defected blades have a clearly expressed swelling of the inner layer, while the inner surface of the reference blade does not have any swelling. However, this technique gives only a qualitative representation of the defect. The surface swelling has a great variety of forms and sizes.



a b c d

Figure 37**.** Optical revision of blades inner surface. (a-c) Defected blades.

(d) Reference blade. Red line circled swelling of the inner layer [118].

Therefore, it is impossible to answer the question of what kind of swelling may lead to blade malfunctioning in the next flight. Another disadvantage of the optical technique is very long implementation time. After each flight, first, the propeller and then the blades should be removed from the engine, and only after that, the blades can be examined. Moreover, the optical technique (like the others) can only be used in laboratory conditions, thus the blade cannot be tested in a fight.

Then the proposed modal analysis of the blades was applied. The quality evaluation of the excitation signal (Figure 38 and Figure 39) demonstrated a satisfactory value. The deviation of the exciting force modulus from the average value in the frequency range of 30 Hz to 60 Hz was measured with an acceptable value of less than 14%.

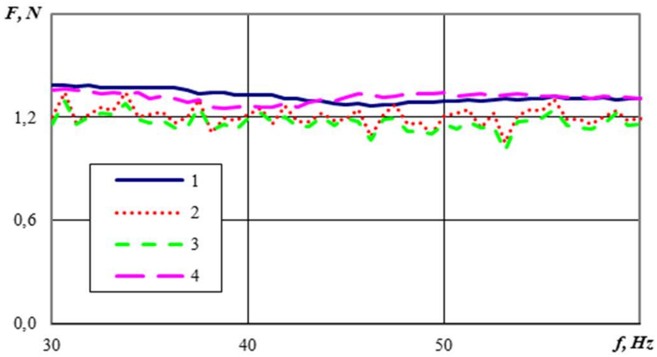


Figure 38. Exciting force modulus. 1, 2, 3 – life-expired blades, 4 – reference blade

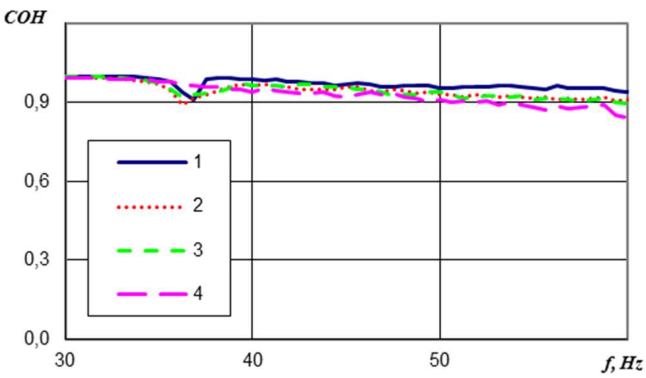


Figure 39. Coherence function of measured signal and excitation signal. 1, 2, 3 – life-expired blades, 4 – reference blade

This fact means that during the study of each blade, the excitation signal had approximately the same level. Therefore, it can be inferred that the experiments were conducted under the same conditions. Furthermore, a small deviation value of the exciting force modulus demonstrates a uniform distribution of the excitation signal energy in the frequency range in question. This finding suggests that blade resonance identification is of high quality [86].

The value of coherence function calculated according to Equation (35) was another indicator used for excitation signal quality evaluation. The minimum value of the coherence function measured is 0.84, while the average value of 0.93 indicated a low degree of extraneous noise influencing the desired signal definition. Thus it is possible to claim that the peak of the blade amplitude-frequency characteristics within the frequency of 37 Hz (Figure 40) corresponds to the resonance frequency.

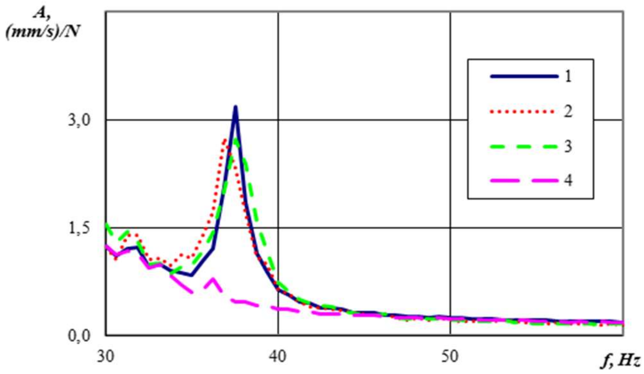


Figure 40. Amplitude-frequency curves of the test blades. (1, 2, 3) Life-expired blades. (4) Reference blade.

This is the dependency of the average vibration velocity amplitude at the blade surface on the amplitude of the exciting vibration force produced by the vibration generator. Figure 41 depicts the blade mode shape according to the phase of the oscillation (φ) at the frequency of 37 Hz. As can be seen, the obtained mode shape has only one node of oscillation which is near the support and only one antinode which is on the blade tip. The analysis of the discussed mode shape makes it possible to identify it as the first bending mode of the blade.

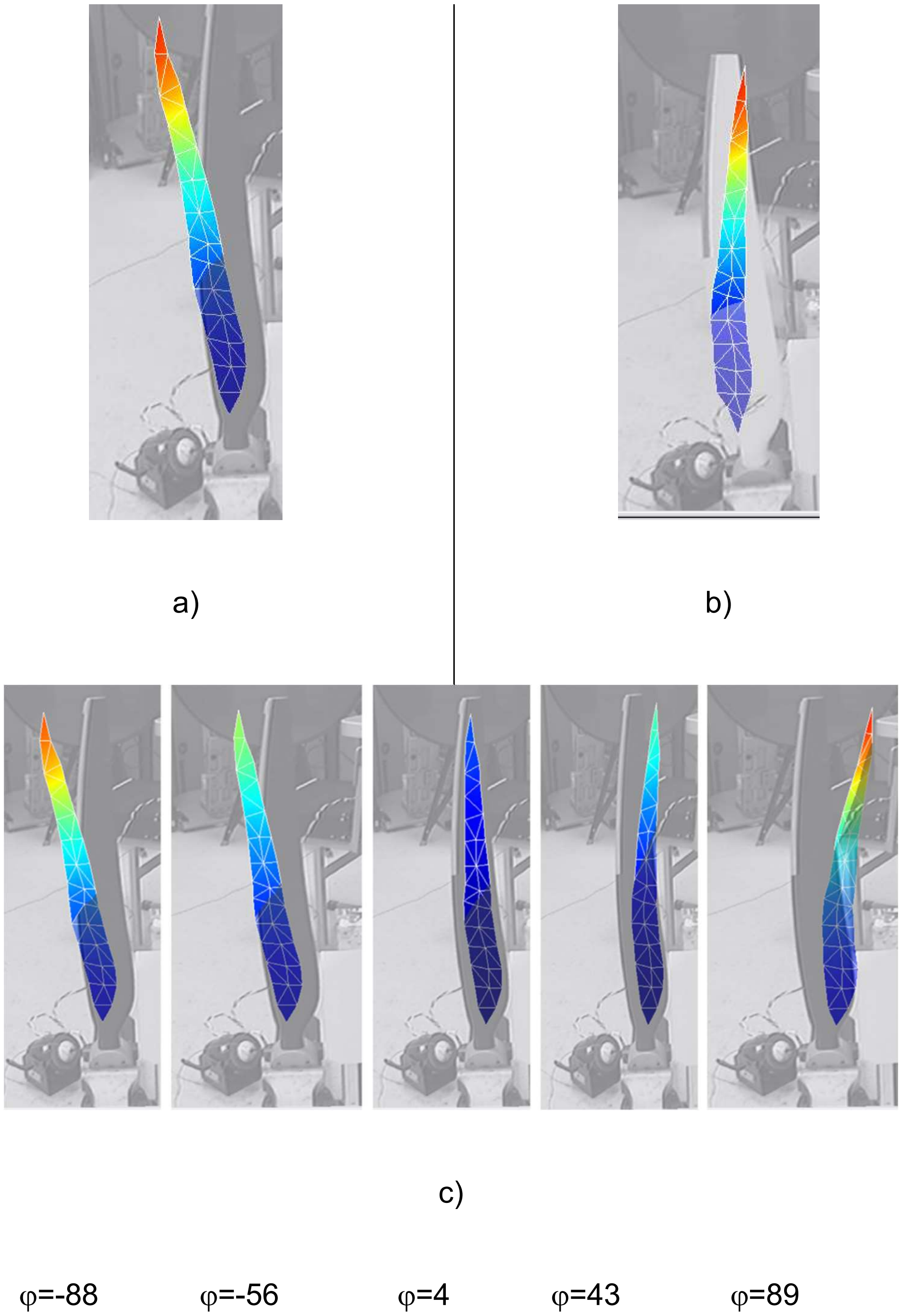


Figure 41. Blades mode shapes a) master blade b) blade after 500-600 flight hours at the same phase of the oscillation c) The first bending mode of the blade after 500-600 flight hours.

The analysis of the frequency amplitude characteristics showed that the first modal bending frequencies of the blades, which were in operation, and the reference blades are in the range of 36.25 to 37.5 Hz. However, the resonant vibration amplitude of the used blades is more than four times higher than the reference blades vibration amplitude. This led to the conclusion that such defects, as fiber bundle and crack formation in the material during the blade operation on small aircraft, lead to the amplitude increase in resonance oscillations at the first bending frequency. The increase of resonant bending vibrations during the operation can serve as a diagnostic indicator of possible defects in blades, made of composite material [118]. The situation with the amplitude at resonant frequencies is another control factor for the blades following an operating time of 500-600 hours in comparison with the reference sample with zero operating time. There is an increase of the amplitude at low frequencies of approximately 30%, and a sharp increase in the amplitude at frequencies above 500 Hz that is equal to 100% (of the master blade amplitude at the same frequency).

The second part regarding composite blades is connected with experiments using wavelet transforms. Based on the data from experiments with honeycomb structures and information above, further research was executed with aircraft composite blades with different operation time.

The excitation of oscillations was also executed in two different ways (by the means of):

1) Weak strike on construction (in certain points).

2) Insertion of an object from its equilibrium position. Mechanically and by the means of active sound from the active sound speaker and vibration generator (as shown in figure 35). The goal of this segment is to ensure the workability, repeatability, and functioning of the chosen wavelet transforms method for composite blades with different operation time.

Due to the different minor factors (like surface conditions, different geometric shape, and size) the new samples were divided into three different groups:

1) Samples 444,184,135. (a,b,c from Figure 37)
2) Samples 8979 41 (118),805228 (106), 876748 (152)
3) Samples (3) 926 65, (1) 926 65.

The results were combined and listed below in the following table. All sample numbers were taken from manufacturing product passports. They present blade batch numbers according to the certain time of manufacture. Samples with only three numbers in the batch had just a little less flight operation hours. It is also because of the fact, that the manufacturer decided to set a batch count to zero again. The first group results (Samples 444,184,135) are presented below. The first, second, and third samples with batch numbers 444, 184,135 were produced in June, July, and August 2014.

All the samples are composite blades made of many layers of fiberglass and epoxy resin. Blades are reinforced by the aluminum ring in the coupling screw connection point. The leading edge of each blade is reinforced by a small width aluminum alloy plate, it occupies 1/3 part of the leading edge. The construction is the same as described in the first segment of the experiments.

During the comparison of sample 135 with others in the group, obvious little damping of high frequencies was detected, low frequencies occurred in the middle level (on the average scale), amplitude increase was determined at a small scale (Figure 42, Figure 43):

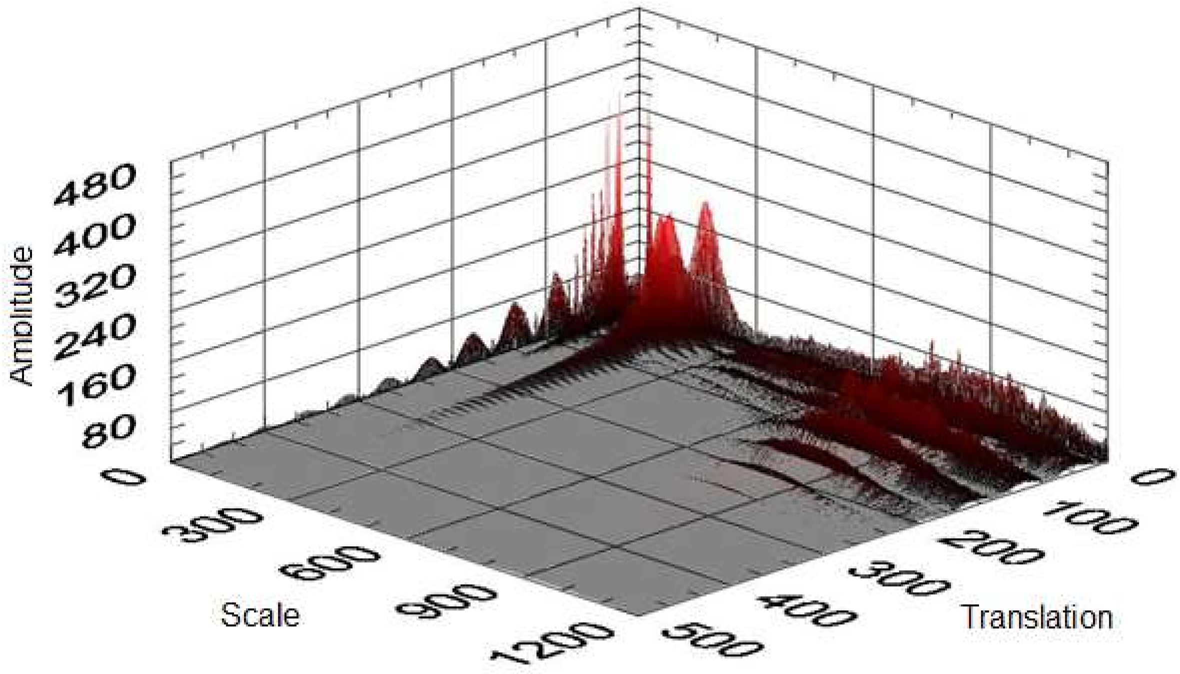


Figure 42. Sample 444 CWT result.

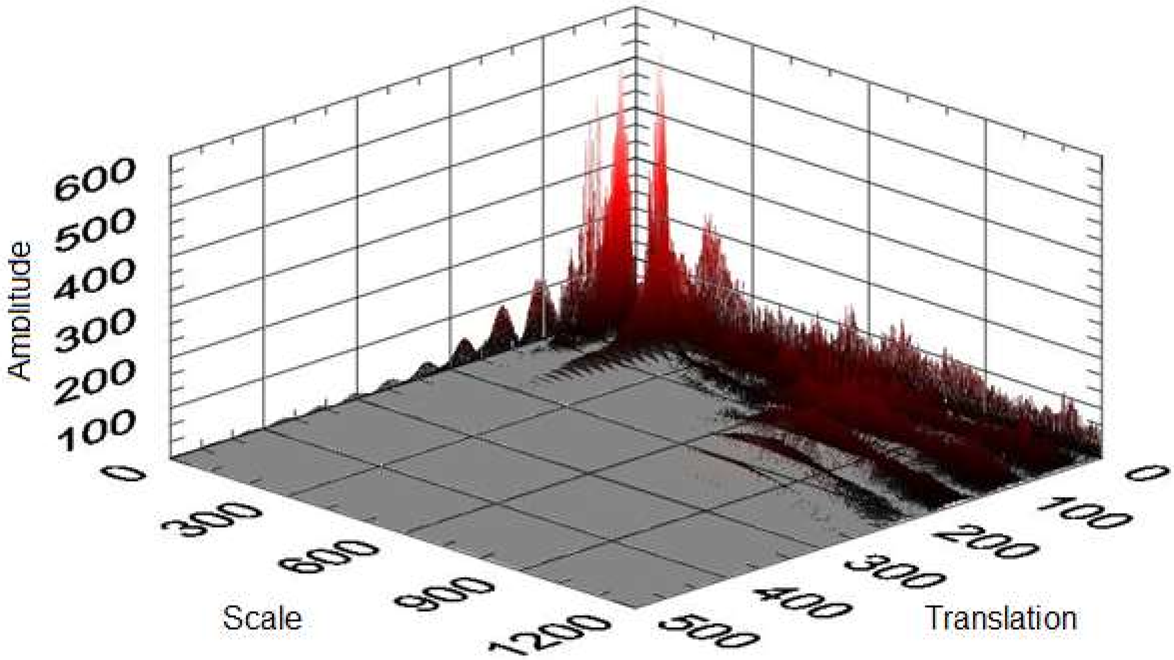


Figure 43. Sample 135 CWT result.

By reviewing sample 184, we can observe even greater damping of high frequency and amplitude increase on a small scale (Figure 44). Data shows that the middle part of CWT decreased and it has led to an increase in the first ridge. Amplitude is the biggest in the group. The shift of the resonance component to a low scale is also obvious.

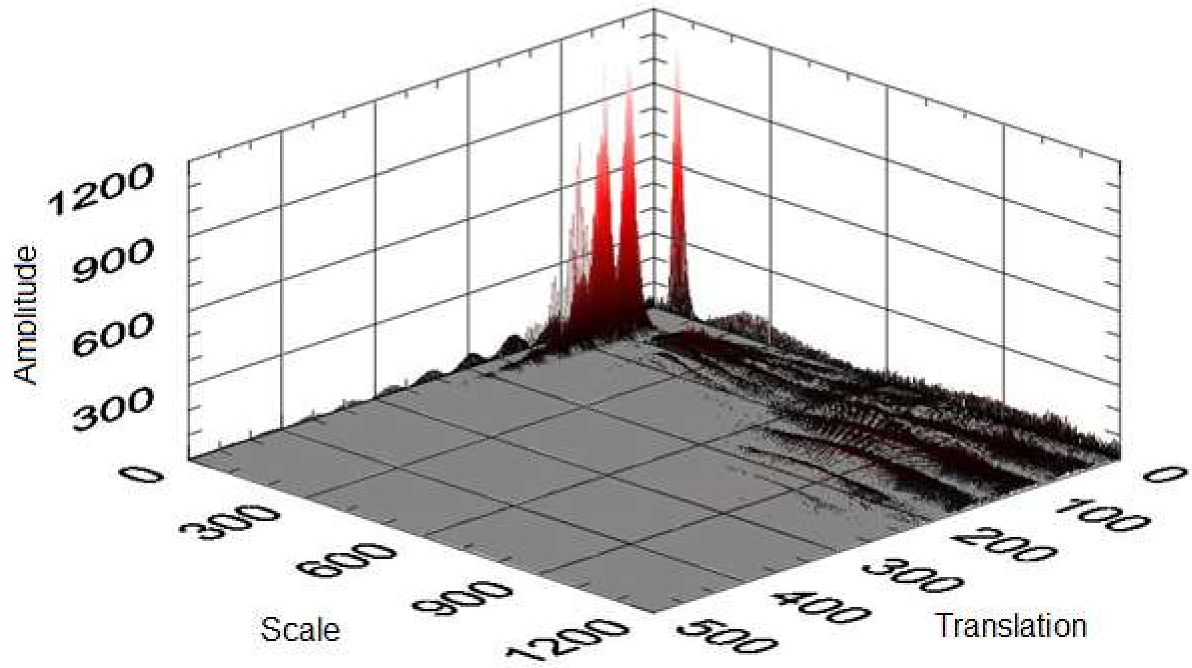
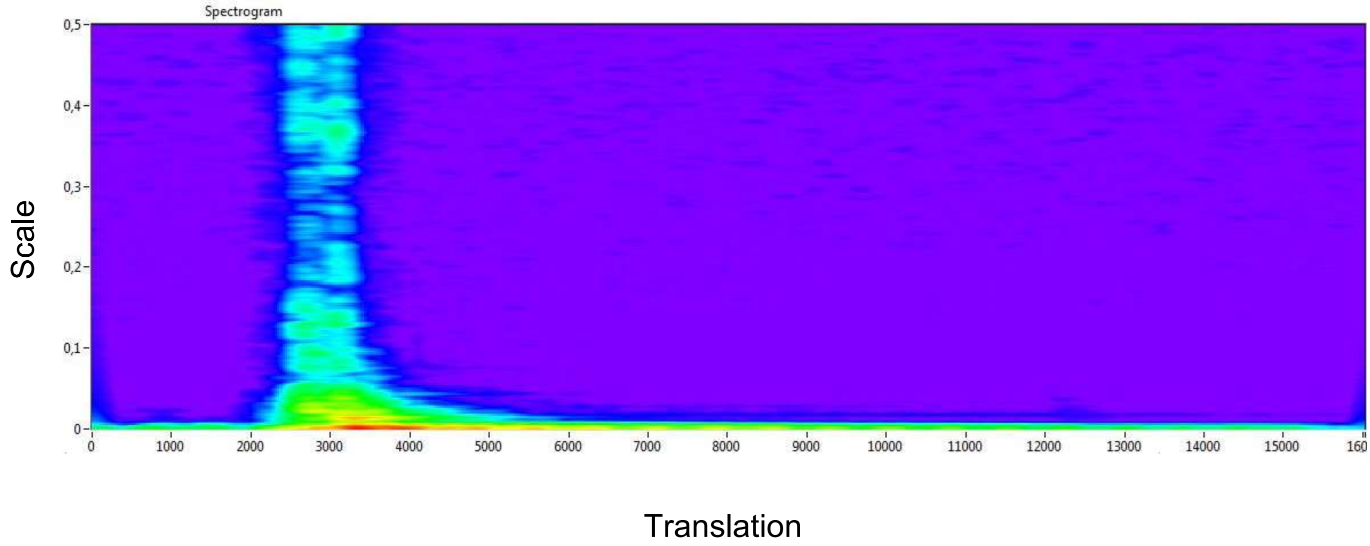


Figure 44. Sample 184 CWT result.

Second group results: This group contains one hardly damaged blade and two other blades with the different operation time. Scalogram of the sample 8979 41 (118) with hardly damaged blade outer surface with visible cracks is shown next (Figure 45; Figure 46).



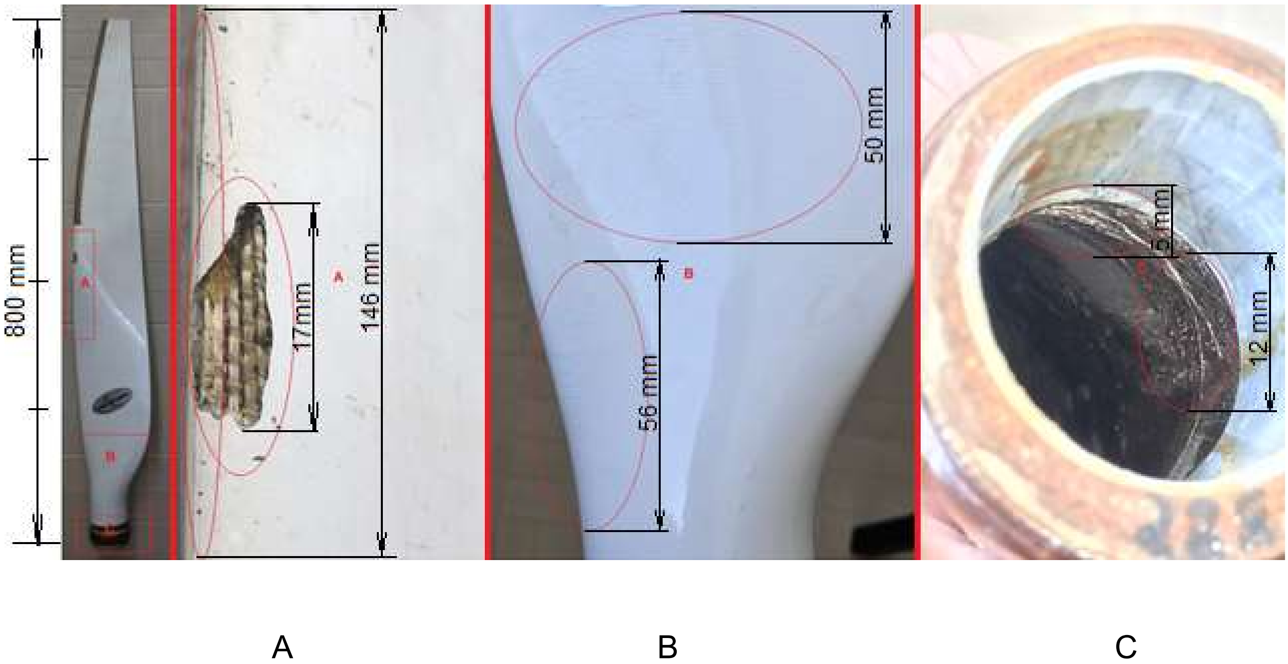


Figure 45. Scalogram of sample 8979 41 (118) and visually detectable defects in areas A, B, C of this sample (hardly damaged blade).

Spectral analysis (using the Fourier transform) shows a discontinuous pattern spectrum, low density, the occurrence of "noise", etc. The difference can be easily observed, the normal spectrogram contains an indissoluble picture of the signal, while there is a clear non-uniform component in this picture. Spectrogram of the undamaged blade is presented on the next page after the CWT result of the damaged blade Figure 46.

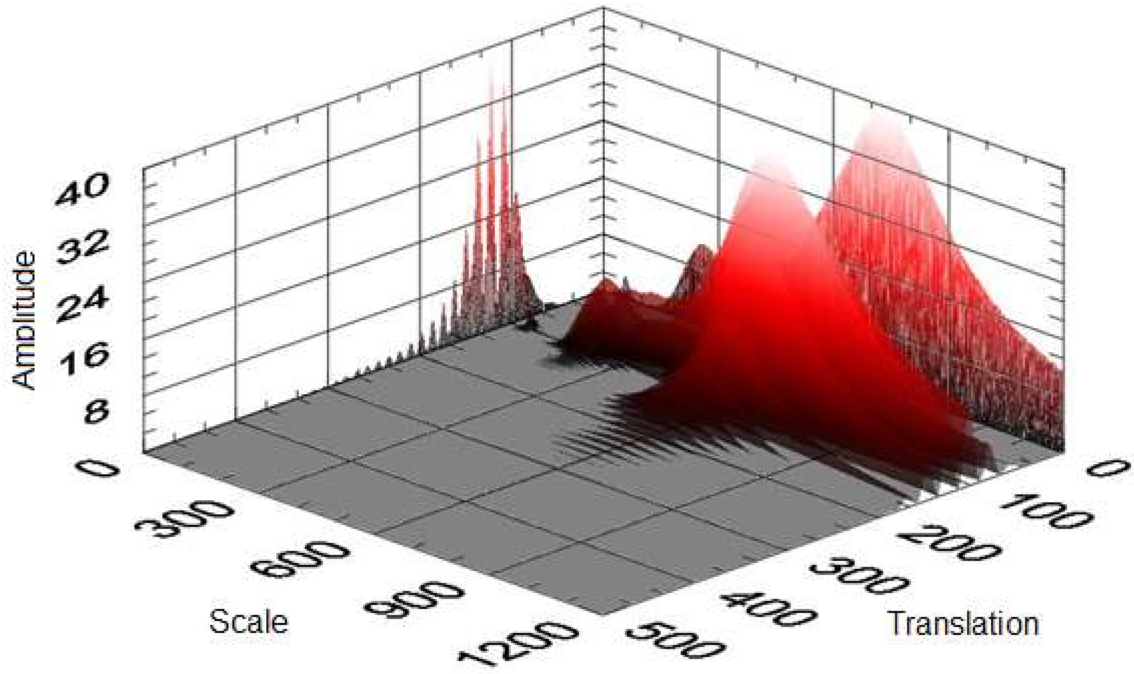


Figure 46. Sample 8979 41 (118) CWT result.

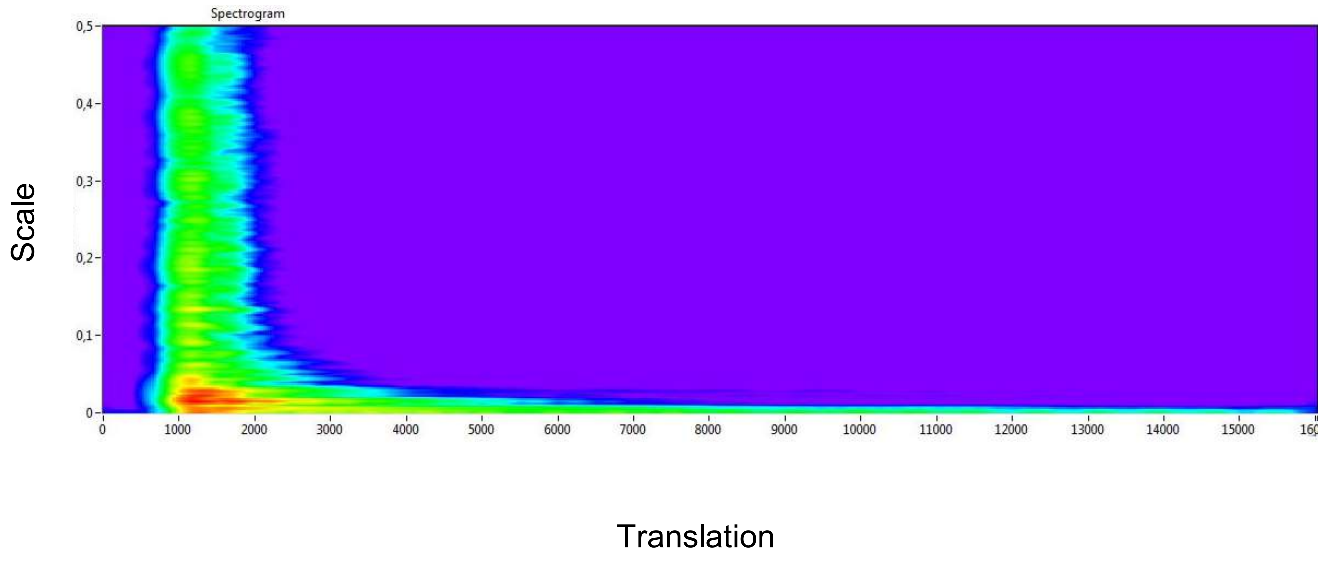
As it was predicted the CWT result (for 8979 41 (118) sample) consisted of the following features, the results of CWT as expected were:

1) Almost complete damping of high frequencies component (high frequencies were not generated)

2) The shift of the CWT maximum towards larger scale (toward lower frequencies)

3) Low amplitude

Sample 805228 (106) is presented next (Figure 47;Figure 48). Scalogram of Sample 805228 (106) was presented below to show the visual difference between the two signals.



A B C

Figure 47. Scalogram of sample 805228 (106) and visual representation of the same areas A, B, C of this sample (undamaged blade).

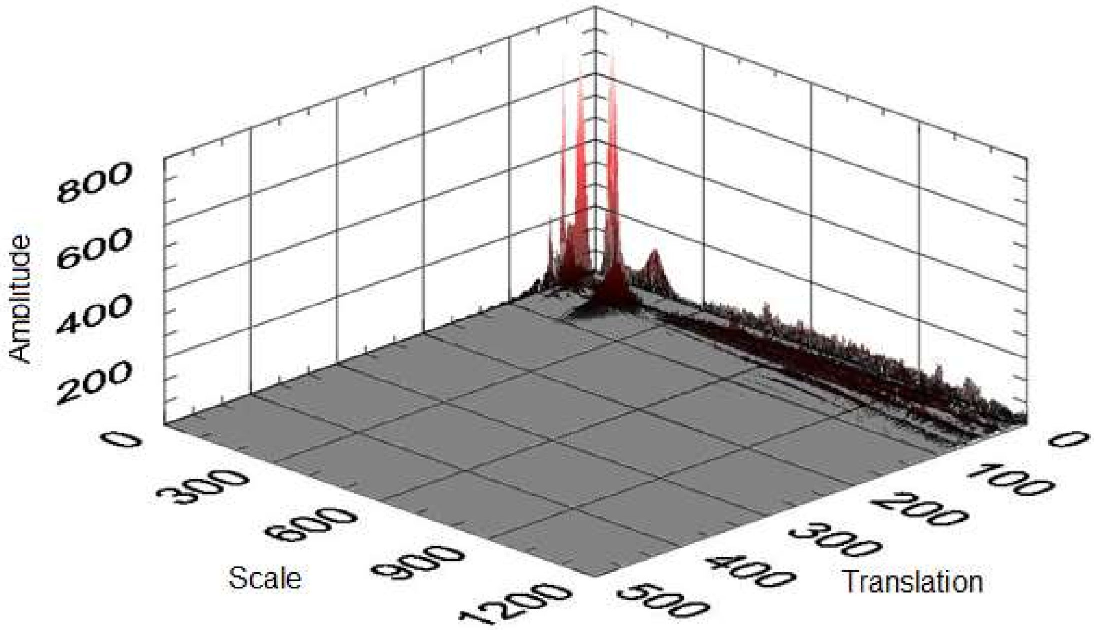


Figure 48. Sample 805228 (106) CWT result.

There is the damping of low frequencies and such called "drift", that can be seen in the beginning. Amplitude is the same on a small scale. Despreading spectrum was also noticed. This can be interpreted as a transition state when the object is still in a good statement, but some changes have already existed. Sample 876748 (152) is shown next (Figure 49).

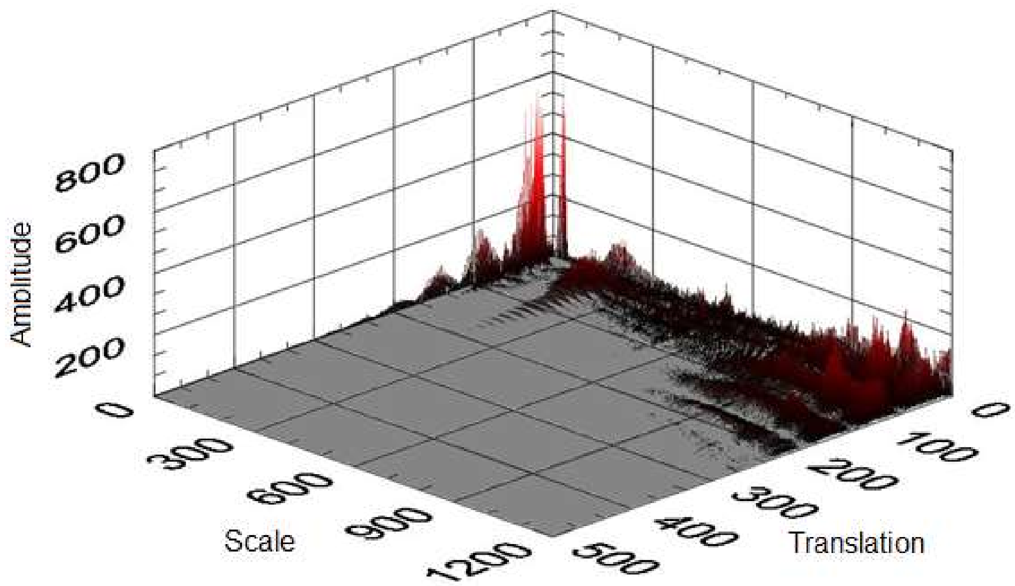


Figure 49. Sample 876748 (152) CWT result.

There is obvious damping of low frequencies and the presence of a small dispersion in the spectrogram. The velocity tends to have a reasonably uniform response over a wide range of construction frequencies and for that reason with a connection to low frequencies it is the universal measure of evaluation of construction integrity in relation to balance, tightness, alignment, and the like. Acceleration increases relative to amplitude with increasing frequency and it is the logical choice for monitoring those components that generate high-frequency vibration. For example, the use of SHM systems for our case is a more complicated task, because of the presence of other vibration from units like bearings, gearing box, etc. NDT technique is a better way for operational maintenance procedures. The third group of results is presented next. The Sample (3) 926 65 CWT graph is presented first in figure (Figure 50).

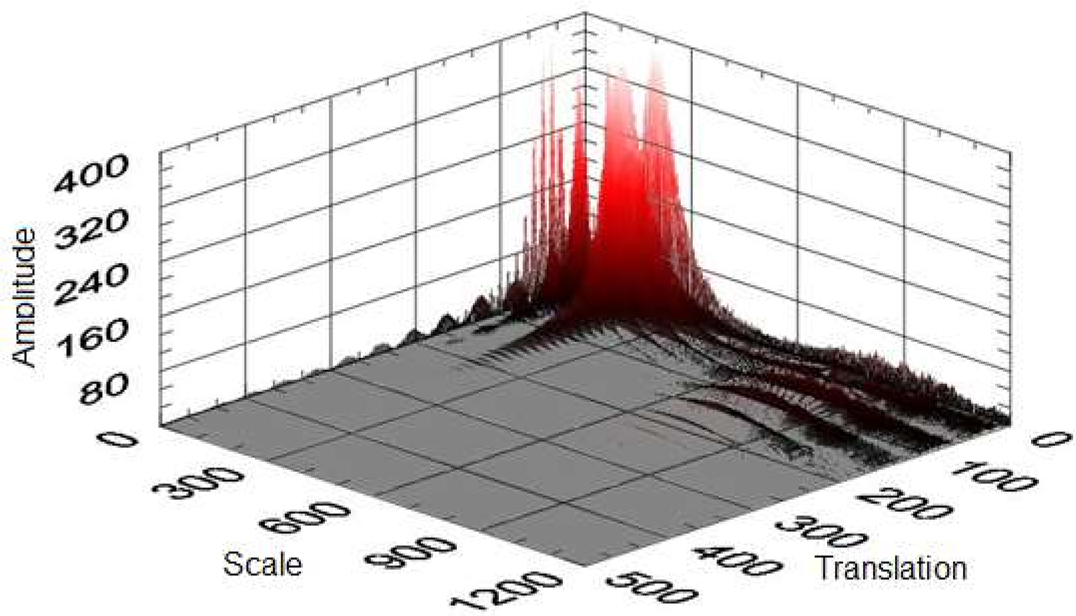


Figure 50. Sample (3) 926 65 CWT result.

A smooth transition from high to low frequencies was detected. There was an absence of high frequencies damping. Many splashes on the spectrogram and scalogram were registered. Obvious, there was the presence of three main ridges on 3d CWT and no high amplitude at a low scale.

Middle ridge is wider than the ridge at a low scale. A combination of obtained data tells us that an integral statement of the blade is in normal conditions, however, the value of amplitude which presents low frequencies is less in comparison for example with results for Sample 184.

It can be suggested that this (3) 926 65 sample can be still available for operation. According to information from earlier tests, due to high transient torque force acting on the surface of the blade in flight conditions the blade inner layer flakes off the outer layer. The study suggests that the defected blades have a clearly expressed swelling of the inner layer, while the inner surface of the reference blade does not have any swelling.

The quality evaluation of the excitation signal again demonstrated a satisfactory value. This means that during the study of each blade, the excitation signal had approximately the same level. This fact gives us the right to judge that the experiments were conducted under the same conditions. Furthermore, a small deviation value of the exciting force modulus demonstrates a uniform distribution of the excitation signal energy in the same frequency range. This finding suggests that blade resonance identification is of high quality [86]. The result of CWT for the sample (1) 926 65 is shown next (Figure 51).

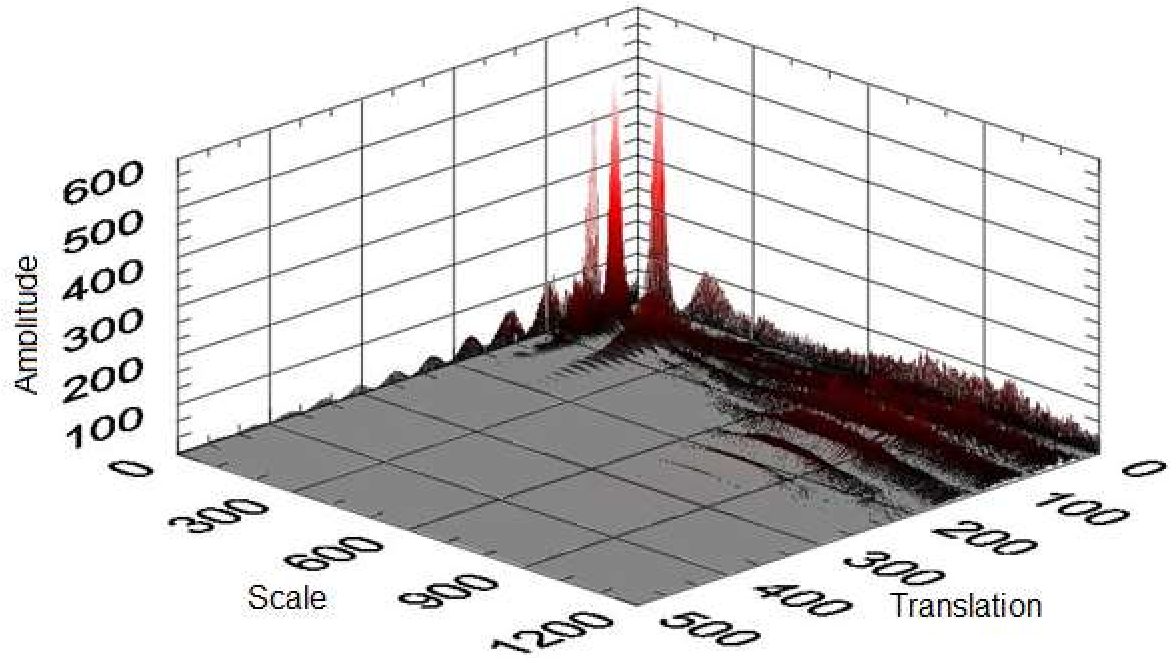


Figure 51. Sample (1) 926 65 CWT result.

This time, there was an increase in amplitude on a small scale of the wavelet transformed function. The presence of high-frequency damping was detected. Signs of deterioration of the structure were: natural frequency decline, damping of high frequencies, amplitude increase on a small scale, an increase in intensity at low frequencies, relevant frequencies "drift", shift of the CWT maximum towards larger scale (toward lower frequencies), low amplitude, absence of high frequencies (high frequencies could not be generated). Interpretation of results for 3d CWT spectrograms may be connected with features shown in table 4.

Table 4. Interpretation of obtained results for aircraft composite blades.

Object Groups	Sample №	Features interpretation in acquired data	The characteristic features that show the deterioration of the structure (defect signs)		
			Natural frequency decline	Low frequencies damping	Increasing the intensity at low frequencies
1st	444	The highest value of the amplitude in the group. (Just a few splashes in all	Occur	Absent	Absent
	184	The value of the maximum amplitude is higher at low frequencies.	Occur	Occur	Absent
	135	Many splashes. Large amplitude at low frequencies.	Absent	Occur	Occur
2nd	897941 (118)	Avalanche drop in amplitude, with no repeats. Intermittent picture of the	Occur	Occur	Occur
	805228 (106)	"Drift" in the beginning. Amplitude saved on a small scale. Despreading spectrum.	Absent	Occur	Occur
3rd	876748 (152)	The presence of small "dispersion" on the spectrogram.	Absent	Occur	Absent
	(1) 926 65	The highest amplitude value in the group	Absent	Occur	Absent

	(3) 926 65	A lot of visual splashes on 3d scalogram	Absent	Absent	Absent

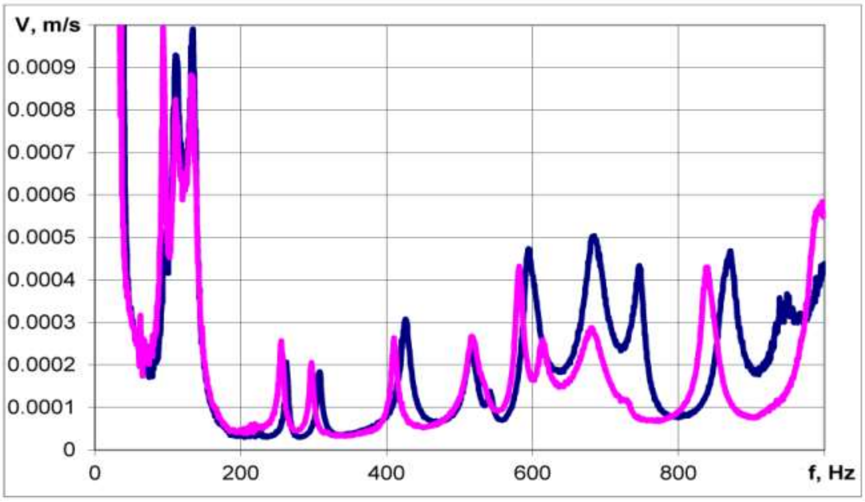
Results of this experimental segment could be presented in a few statements:

- The parameters of wavelet convolution signals of life-expired blades with different operational time were compared. Based on the results the suggestions of their status were given for each blade
- The used blades demonstrated the same typical deviations (defects signs) as described in 3.4.3 for honeycomb construction
- The signs could be used as diagnostic factors of emerging defects.

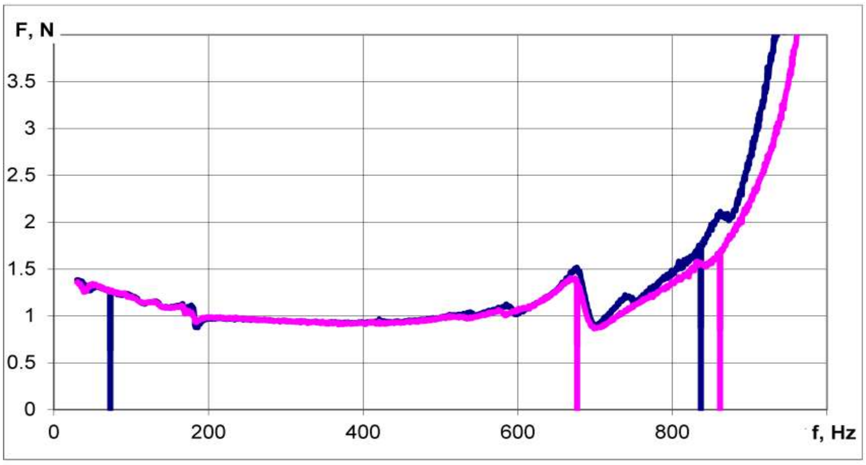
Overall visual features of 3d and scalogram indicate changes in the overall vibration picture of the signal, which can describe the integral damage condition of the object itself. The components for which this research would be most applicable include spoilers, propeller blades, and different types of honeycomb constructions. For the blades, 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.

This research indicates that wavelet-based NDE analysis with Fourier could provide a basis for determining damage levels in structural composite aerospace components, and thus a means to decide whether a component is still operational. It is worth mentioning that the transformed signal reflects the overall picture of registered vibration in the time domain. Based on the proposed algorithm Fourier transforms separately used for the determination of certain frequencies and resonance picture evaluation. The only combination of these techniques can give affordable information for interpretation of obtained results.

The used blades demonstrated a fourfold increase in the amplitude of resonant vibration in the first bending mode. The amplitude growth of the first bending mode resonant vibration can be used as an individual diagnostic sign of emerging defects. The ease of amplitude and frequency analysis of a blade resonant vibration in flight conditions can allow researchers to develop an express-control device for technical condition analysis of composite material blades while in the air. Vibration speed and vibratory displacement of two blades (reference blade and blade with big operational time more than 650 hours) presented in Figure 52. This figure shows the overall deviations of vibration speed and displacement at the frequency range up to 900 Hz. As can be seen on the graph with the increase of operational time the signal function of vibration speed that characterized the total vibration energy shifts to higher frequencies. The intensity of deviations and the appearance of new peaks are also more relevant for higher frequencies.



(a)



(b)

Figure 52. Vibration speed graph a) and vibratory displacement graph b). Comparison of the checked master blade (pink) with zero operating time and blade with big operating time more than 650 hours (blue).

Repeated tests with aircraft blades (Figure 53; Figure 54) in the third part of experiments showed the constant behaviour, which is completely enough for the attempt to determine the transitional state of an object before failure conditions. These figures showed the dependency of the average vibration velocity amplitude at the blade surface on the amplitude of the exciting vibration force produced by the vibration generator. Presence of factors like natural frequency decline, low frequencies damping, increasing of the intensity at low frequencies also allows making a decision about excluding these objects from its operation.

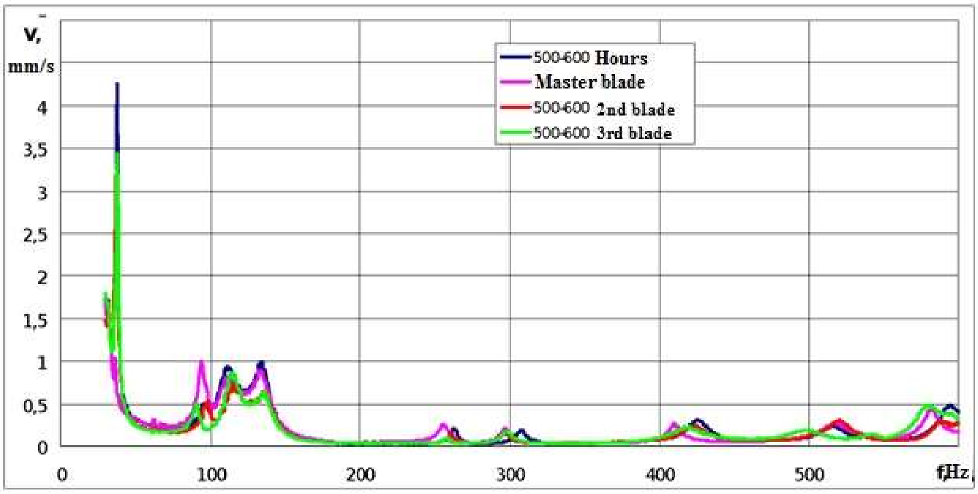


Figure 53. Vibration speed of four blades. Master blade and blades with 500-600 operational hours.

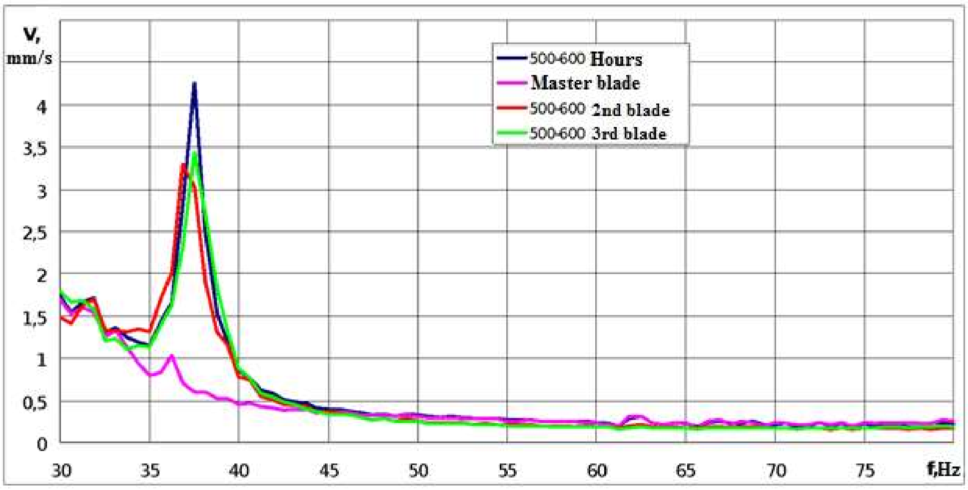


Figure 54. Vibration speed of the same blades at lower frequencies (from 30 to 80 Hz).

4.2.3 Conclusion for aircraft blades

Experimental studies of modal frequencies and shapes changes during the operation of composite blades in light-engine aircraft revealed the growth of resonant bending oscillations at the first natural frequency. The resonant frequency response function value of defected blades exceeded the corresponding value of the reference blade by more than four times. In this regard, the amount of the bending vibrations resonance amplitude growth can be used as a separate diagnostic sign of the defect appearance in composite materials units. A fairly simple set of equipment will be required to determine the blade amplitude and frequency at the first bending resonance, a low-frequency vibration sensor and data processing equipment. It is worth noting that in this investigation the Doppler laser scanning vibration technique was used to determine the detailed vibration field on the surface of the blade and to avoid the influence of additional mass on the blades modal characteristics. These precise sensors are used to determine the diagnostic sign. However, in field conditions, there is no need to have a laser sensor. In order to measure the blade first bending resonance, it is sufficient to have a more economical contact sensor installed on the stationary part of the propeller connecting unit. Therefore, the price of the controller which acquires the sensor data and makes the operational modal analysis at a low-frequency range would also be lower. Finally, it is necessary to have a fault indicator light on a pilot's instrumentation panel. Altogether, the full price of the solution will not exceed $ 300 which makes up 0.2 % of the light aircraft cost. Therefore, the main advantage of the proposed method is the possibility of an easy composite material state analysis and simple measurement in flight conditions. Moreover, the introduction of the proposed method will lead to a risk reduction of flight accidents. The second part results connected with experiments using wavelet transforms showed features of 3d and scalograms that can indicate changes in the overall vibration picture of the signal. In combination with each other, these features can describe the integral damage condition of the object. The repeatability was proved in the third section of experiments for composite blades.

4.3 Experimental results with CNT/Polymer system.

In combination with the existing algorithm, it is very important to implement and try the procedure with other advanced composite materials too. As it was mentioned in the beginning, the analysis shows that there are some main directions for future industry needs now. The main advanced composite materials area covers ceramic matrix composites, fiber-reinforced laminate, and sandwich composites, metal matrix composites, nanocomposites, etc. According to Ron Mertens: "Since 2014, Ford Motor Company and its partners have tested graphene-reinforced foam covers for noisy components. The graphene was mixed with foam constituents, and the resulting parts are said to be 17% quieter, 20% stronger, and 30% more heat-resistant" [121]. Feasible argument is the overall passive damping increase in carbon nanotube-epoxy reinforced composites [122;123]. These factors make CNT/Polymer applications a very interesting area for the present research.

The alternative to traditional composites, a nanocomposite, contains pre-dispersed reinforcing elements in its matrix. Glass or carbon fiber reinforced composites have typical diameters of conventional fiber more than 10 μm. They can be prepared by using a complex molding process, where a prepreg of aligned fibers is infiltrated with the matrix material, often a thermosetting polymer. Epoxy matrix with carbon fiber is still the most common combination of composite used for aerospace and other high-performance applications. There have been multiple investigations where CNTs were added into epoxy matrices [124;125;126]. According to Zhu et al.,"there is a 12% increase in the thermal conductivity of the nanocomposite containing functionalized CNTs compared to that containing pristine CNTs" [127]. The results in [128] demonstrate that the CNTs functionalization simultaneously facilitates the transfer of mechanical load and thermal energy across the matrix–filler interface. Carbon nanotubes have excellent mechanical properties, electrical and thermal properties, and can be used as a reinforcement [129]. Compared to a single material, the composite materials generally have better performance (as the lower weight with higher strength and more important for this research improved damping characteristics). Recently, "nanocomposites" aroused the majority interest [130;131]. They use reinforcing materials, such as carbon nanotubes [132].

Carbon nanotubes can be divided into multi-walled carbon nanotubes (MWNTs) and single-walled (SWNTs) and MWNTs is used in this study. Compared to SWNTs, MWNTs are easier to synthesize and to produce [131;132]. Following the results in [131], the use of CNT composites in the free vibration and forced vibration test showed that adding 5 wt % MWNTs in composites could increase the damping ratio to 700 % compared to a pure epoxy specimen. The following part of the research affects the vibration properties of dispersed CNT epoxy resin.

4.3.1 Objects of the study

Part of practical experimental (sample preparation) work was carried out at Advanced Composite Training and Development Centre, Hawarden (Wales, UK) all other experiments were carried out in Samara University. Oven cured samples have been prepared with and without the addition of highly conductive particles (CNTs) (Figure 55).

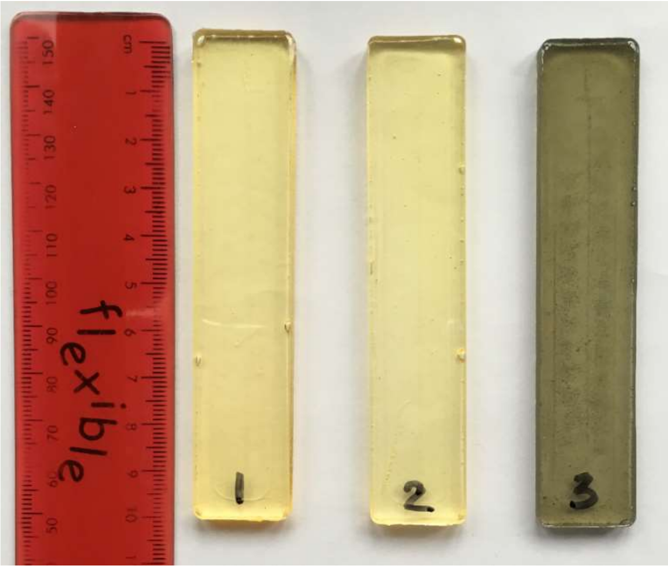


Figure 55. Cured epoxy resin samples, (1) and (2) are pure epoxy resin (Araldite/Aradur), (3) is the type 2 sample with 0.01 Wt % CNTs.

CNTs were synthesized by the chemical vapour deposition (CDV) method. Multi-walled CNTs were obtained from Electrovac, Austria (95% as per TGA (thermal gravimetric analysis), having traces of metal and metal oxide), density = 0.98 g/cm^3 specific surface area = 26 m^2/g, average length up to 2500 nm and average diameter = 50 nm (Figure 56).

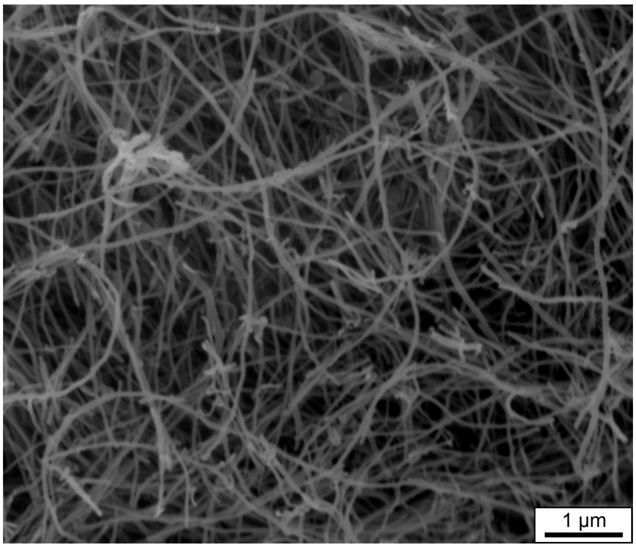


Figure 56. Multi-walled CNTs from Electrovac, Austria.

4.3.2 Processing of the CNT samples

A number of tests were performed in order to manufacture samples and disperse the particles. Samples were tested according to ASTM E756-05 [133]. Information about two types of samples and the cycle is presented in table 5.

Table 5. Samples used during the experiment.

№	Samples (mix ratio 100:38 for all)
1	**Type 1.** Epoxy resin (Araldite/Aradur). System Araldite® LY 5052 / Aradur® 5052 Degassing 1 h. Oven cured (1 h at 100 °C) (Dual formulations epoxy, divided into resin base and hardener)
2	**Type 2.** Epoxy resin (Araldite/Aradur) + 0.01 wt % CNTs Sonication 1 h. Degassing 1 h. Oven cured (1 h at 100 °C) + 1 day at 23 C (room temperature) (Dual formulations epoxy, divided into resin base and hardener)
3	**Type 2.** Epoxy resin (Araldite/Aradur) + 0.01 wt % CNTs Sonication 1 h. in an ultrasonic bath. Degassing 1 h. Oven cured (1 h at 100 °C) + 1 day at 23 C (room tempretature)

4.3.3 Methodology and results of experiments

Two types of samples were installed in the center of a specially manufactured frame using four rubber strings for testing integrity, and the natural frequency of this fixation was less than 5 Hz. Due to the low weight of the samples, the non-contact method was chosen for vibration excitation. The use of a contact excitation method would change the characteristics of the samples under study. As a non-contact vibration excitation, the speaker, which reproduced a floating tone from 100 to 20000 Hz was used. As a result of the study, the vibration velocity spectrums of both (type and type 2) samples were obtained (Figure 57).

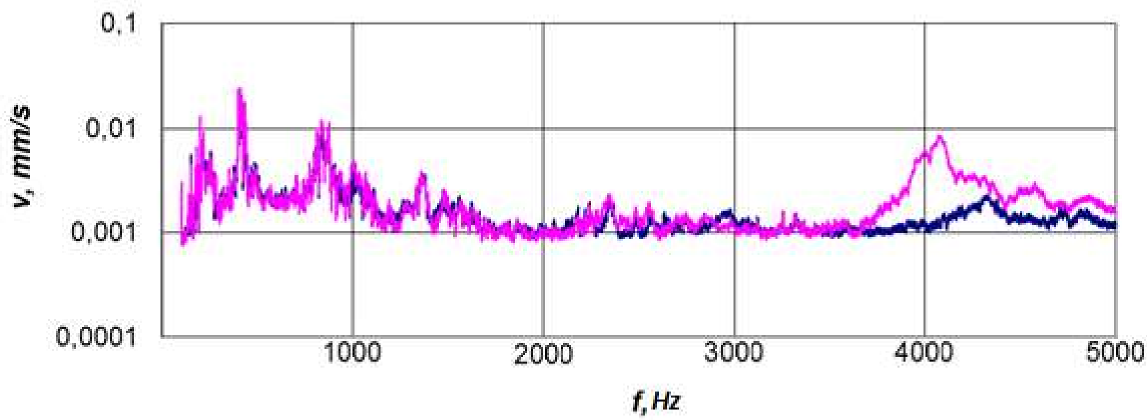


Figure 57. Vibration velocity spectrum of two types of epoxy resin samples. Pink – without CNT. Blue – with CNT.

The first graph contains information about two samples of vibration properties through the whole frequency range. These samples were made using the same procedure. They have identical geometry and surface conditions. The only difference is that the Sample № 2 was made with CNT (it is marked by blue colour on the graph). Before the test, samples were coloured by white paint (for better laser calibration) and were put in the suspended condition in a special frame. These actions allowed us to get clear experimental results. Scanning vibrometer PSV-400 3D and additional equipment were used in the experiment. Scanning vibrometer used 3 lasers and speaker which generated “peak sounds” on all frequency range. As can be seen, the vibration speed is the same from low frequencies to frequencies at approximately 2000 Hz (Figure 57). Amplitude and resonance frequencies are also the same at this range. The vibration modes at all resonance frequencies (at range from 50 to 2100 Hz) are completely the same. Modes are constant but there is a translocation of these modes from low to high frequencies in a sample without CNT, in case if we compare two samples. The next step was to test the samples with a system prototype at high frequencies. For this reason, a laser beam, sound speaker, 20Hz to 20kHz frequency soundtrack, the same frame, and samples were used. Results on vibratory acceleration are presented next (Figure 58).

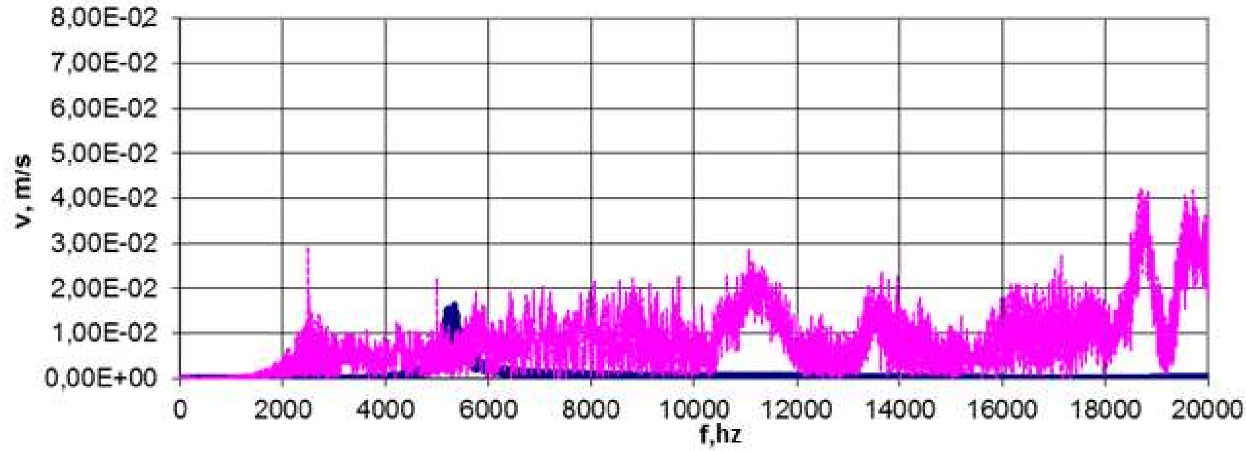


Figure 58. Vibratory acceleration of two epoxy resin samples. Pink – without CNT. Blue – with CNT.

As it is illustrated, there is an obvious difference in amplitude at the high-frequency domain. The suggestion is that the presence of CNT in the sample is the main reason for high frequencies damping. For the accuracy, the experiment was repeated three times and the results were the same. Data from experiments was put in the LabView program to get the pictures of Fourier and wavelet transforms. Figure 59, shows the spectrogram of the sample without CNT.

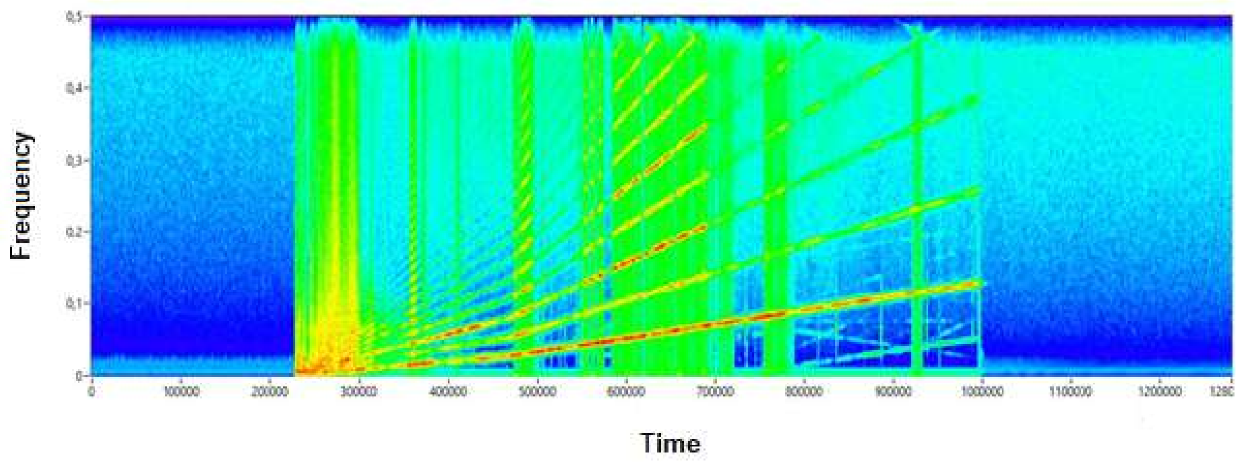


Figure 59. Fourier spectrogram of epoxy resin sample.

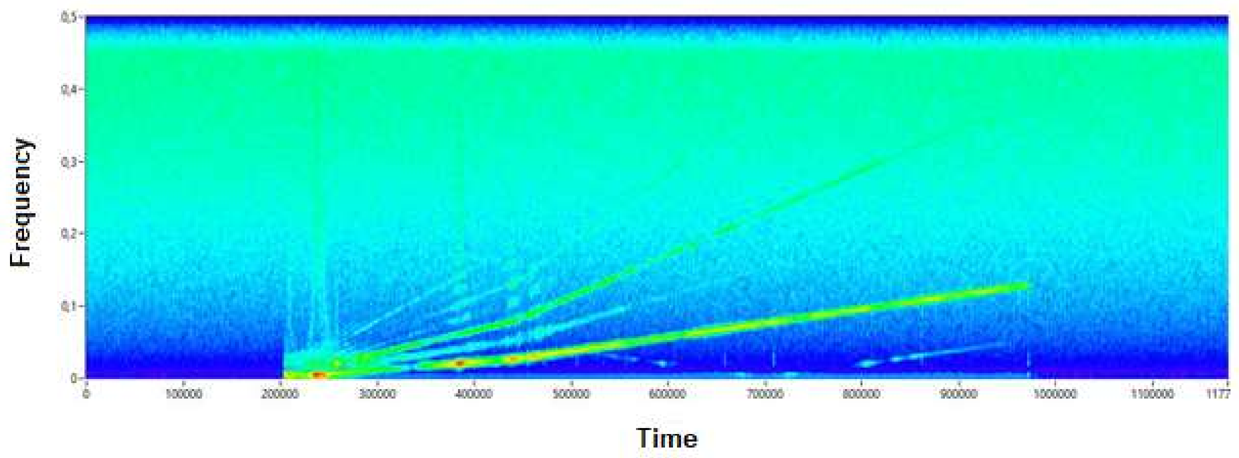


Figure 60. Fourier spectrogram of epoxy resin sample + 0.01 Wt % CNTs.

From the spectrums, it can be seen that a conventional sample (without CNTs) has higher values of vibration velocity than the second sample (with CNTs) (Figure 60). It is also evident from the spectrum that a conventional sample has a large number of natural frequencies and that its use in various applications can lead to its more rapid failure under high vibration. The second sample rather has only two natural frequencies: 5211 Hz and 5345 Hz, which is direct evidence that using this material will increase the strength of the substance and durability of the possible structure with CNT epoxy agent inside a composite under vibration conditions. Moreover, if those two natural frequencies can be minimized by a mechanical damper or by the geometry features of the construction it can affect the lifetime resource of the composite element itself. Morlet wavelet was also chosen as a mother wavelet for additional non-stationary signal analysis. 3D Scalograms are represented next (Figure 61;

Figure 62) can show the difference between signals from two samples.

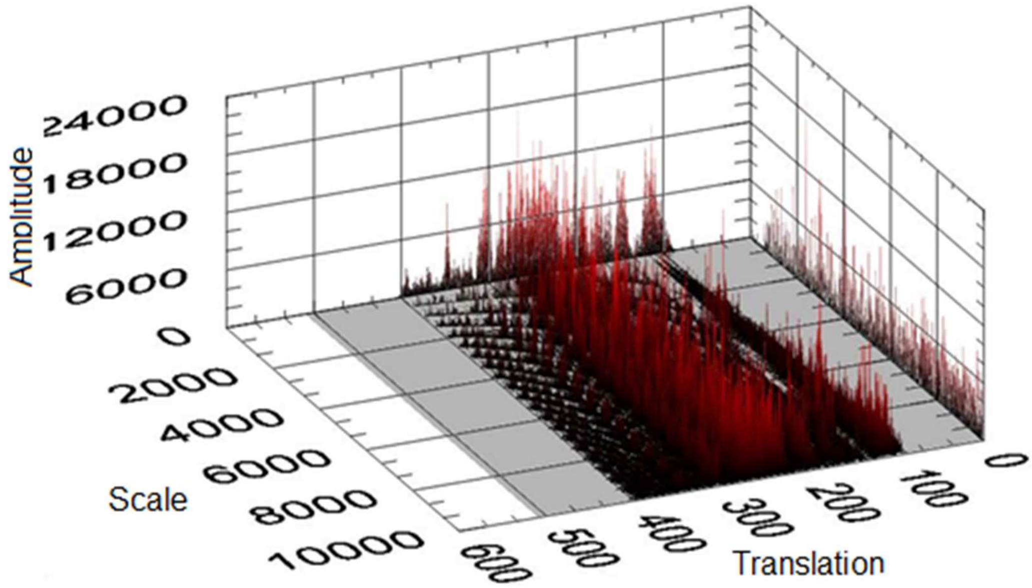


Figure 61. Morlet CWT with scale 10000 3D-spectrogram of epoxy resin sample.

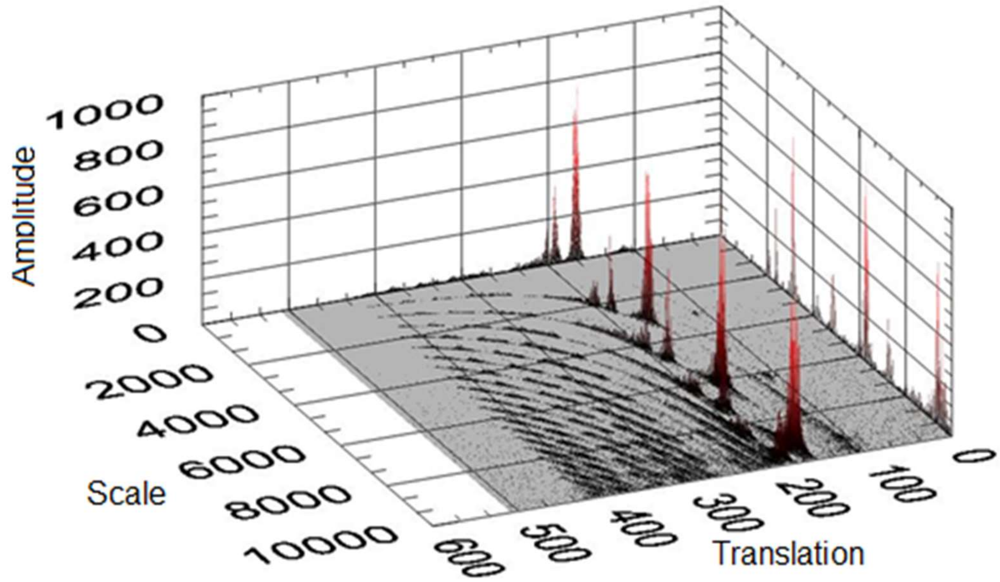


Figure 62. Morlet CWT with scale 10000 3D-spectrogram of epoxy resin sample + 0.01 Wt % CNTs.

4.3.4 Conclusion for CNT/Polymer Applications results

There is an obvious difference in amplitude and splashes spread when comparing two pictures (Figure 61 and

Figure 62). In other words, the sample with CNT has very good damping properties at the high-frequency domain. There is a presence of the same resonance frequencies, but they all have very small (close to zero) amplitude in the sample with CNT. The multivariable analysis which includes Window Fourier transform and Continuous Wavelet can be used for a better understanding of the integral statement of an object with CNT when using non-stationary signals. Using of Morlet wavelet (or Gabor wavelet) that is composed of a complex exponential multiplied by a Gaussian window can help for a better understanding of a signal picture deviation. Experiments with real objects which contain CNT in its surface coatings or in objects with epoxy or polyester resins that can be used as a binding agent in honeycomb constructions, laminates, etc. provide further information about CNT resin composites. Only after the test series with objects which have different operation time, we can talk about diagnostics of such elements and prediction of their future condition. Part of practical work was carried out at Advanced Composite Training and Development Centre, Hawarden (Wales, UK). Oven cured samples have been prepared with and without the addition of highly conductive particles (CNTs). A number of tests were performed in order to manufacture and disperse the particles.

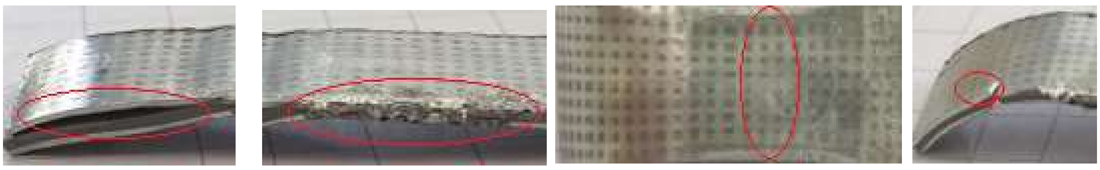
4.4. Experimental results with metal-polymer-metal sandwich composite samples. Research of vibration properties.

The following chapter is dedicated to the study of the vibration properties of metal-polymer-metal composite materials, and the application of the non-destructive testing method. The main vibration properties of the metal-polymer-metal composite material structures were researched. Multiple vibration parameter dependencies on the noise reduction factor were derived. The method of scanning laser vibrometry used for experimental determination of natural frequencies and modes of oscillations. For the numerical modal analysis, the finite element method was used. The material model was a layered composite with isotropic linearly elastic layers and metal layers. The task of identifying the material model was considered as the problem of minimizing the discrepancy between the calculated natural frequencies and the experimental ones. The developed method can be recommended for the determination of parameters of material models for calculating the modal characteristics of polymer-metal sandwich sheets and metallic mono-materials composite products. Methodology for identifying models of elastic behaviour of polymeric-metal composite materials, based on the results of the experimental modal analysis using the example of laminated metal-reinforced samples is presented.

Metal-polymer-metal (MPM) composites have been rapidly replacing metallic materials in the aerospace industry. They have many advantages over monolithic materials. Although in the past they were not so tough, more expensive, unreliable, and difficult to handle, modern applications from MPMs can become more and more valuable [134]. Possible applications made from these composites are interior parts, floor supports, fuselage parts and potentially even highly cyclically loaded surfaces as parts of rotor blades, fans etc.

One of the aims today in using advanced composite materials in aircraft construction is to provide strength in different conditions of vibrations, typical for aviation materials. At considerable amplitudes of oscillations, which can occur for example under resonance conditions, situations can lead to critical outcomes up to failure. To exclude resonance oscillations, it is necessary to calculate the modal characteristics in detail at the design stage: their own frequencies and forms of oscillations. In the case of products made of new composite materials, this calculation becomes more complicated due to the lack of reliable data on mechanical characteristics. The main problem (in comparison with isotropic materials) is a large number of parameters to be included in the material model, as well as the fact that these parameters depend on the material layers, changing with the layers orientation, bond-reinforcement, and technological factors. For example, an orthotropic elastic material contains nine parameters, which definition is a laborious task. Data on materials characteristics, given in the literature, are often contradictory and in carrying out reliable calculations require additional verification. For the computational analysis of the stress-strain state and modal analysis structures, the finite element method (FEM) can be effectively used [135-137]. Another big issue is the control and diagnostics of such structures during operation.

Practice showed that delamination, partial melting, cracking and necking are failure modes relevant to MPM sandwich composite type mostly during the bending conditions (Figure 63).



a) b) c) d)

Figure 63. Damage modes after bending the MPM sandwich sheets by electromagnetic forming.

Damage by delamination between the sandwich layers could occur in the bending region, Figure 63-a). This type of damage is more capable in the sandwich sheets with less ductile in aluminum. Low ductility is also the reason for cracking in the outer skin sheet, (Figure 63-d). The partial melting could be more relevant for the intermediate sample section (Figure 63-b). Melting could appear in these sections because of the concentrated induced currents, and high energies during the bending by electromagnetic forming as an example.

For bending and not bending conditions the necking (Figure 63-c) is not a rare event. It can happen during the local compression in the bending radius. Necking is more probable in the case of the annealed Al sheet, however, melting is more probable for the hard Al sheet. Moreover, forming with a higher free bend length less damage occurred. With increasing the energy level, the intensity of damage increased.

In our case, for the imitation of conditions which can occur during operation, cycle loading could be most appropriate. Tests proved the fact that when damage or stress is increasing, the load that can cause failure after cyclic iterations will be a decreasing function of these cycles. This could be the result of damage that has been already present in the structure or was created during cyclic loading. In composites, multiple types of damage may be present in the structure at the same time such as matrix cracks, fiber kinks, delamination, broken fibers, etc. Various types of damage can simultaneously affect the structure. Delamination, cracks in the matrix and layers, and other types can interact and transfer from one type to another and as a result, be responsible for serious structural failure [138]. Due to uncertainties and assumptions that are inevitable in the complex application, the correct FEM application requires verification and identification (adjustment) of finite element models according to experimental data. Under-identification of a finite element, the model should be taken a change in its parameters, which minimizes the differences between the calculated and experimental data.

This work has several main purposes. The first one is the approbation of developed methodology for identifying the parameters of the elastic behaviour based on the results of the experimental modal analysis by the example of the layered metal-polymer-metal composite. The second one is the use of data, acquired during the first part for evaluation of control and diagnostic method for this type of composite materials based on wavelet transforms. Additional tasks are also checking of the condition of two samples by lock-in thermography testing, before and after cyclic loading and simplification of the proposed vibration method in terms of reliability.

4.4.1 Objects of the study

Metal-based polyolefin (PP/PE) core composites were used for this research. This type of MPM composites with PP/PE core is highly deformable under room temperatures. The production cost of such composites is the same as the production of the same mono materials and approximately twice times cheaper than the production of the aluminum mono materials. High bending strength and a possibility to play with the type of energy absorption of the composite part show high potential for the implementation of such composites for industry needs (including driven and moving parts).

In order to enable investigating various parameters regarding the thickness ratio of the core and skin sheets of the sandwich materials as well as different mechanical properties, the following material combinations have been prepared for study. Objects of study are metal-polymer-metal sandwich composites and mono-materials. Detailed information about their properties (materials, thickness, grades, skins, cores) is presented in tables 6 and 7. Similar samples are recommended by the ASTM standards for the determination of composite materials' mechanical characteristics during tension and fatigue testing [138], and [139].

Samples with different thicknesses, mass, and compound materials were tested. As an example, detailed results only for samples RX5L and RD1 are further presented.

Table 6. Reference samples (sandwich sheets and metallic mono-materials)

Mono-materials				
Notation	Material	Thickness [mm]	Notation	Grade
St. 0.24	Steel	0.24	St. 0.24	TS245
St. 0.49		0.49	St. 0.49	TS245
St. 2		2.0	St. 2	NA
Sandwich				
	Thickness [mm]	Thickness [mm]	Skin	Core
RP	0.24/0.3/0.24	0.78	TS245	PP-PE
RH	0.49/0.3/0.49	1.28	TS245	
RF	0.49/0.6/0.49	1.58	TS245	
RD	0.49/2.0/0.49	2.80	TS245	
RW**	0.49/0.3/0.24	1.03	TS245	
RX***	0.49/0.3/0.24/0.3/0.24	1.57	TS245	
*: 3-layered sandwich with skin sheets of 0.5 mm thickness and a 0.6 mm core layer. **: 3-layered sandwich with different thicknesses of the steel (same grade) skin sheet. The thickness of each side is given.				
***: 5-layered sandwich. The thickness f the outer steel sheets is given. This one should be compared with the three-layered RF due to the same metallic contribution and thicknesses but a different distribution.				

Table 7. E-Moduli and Poisson values of the mono materials

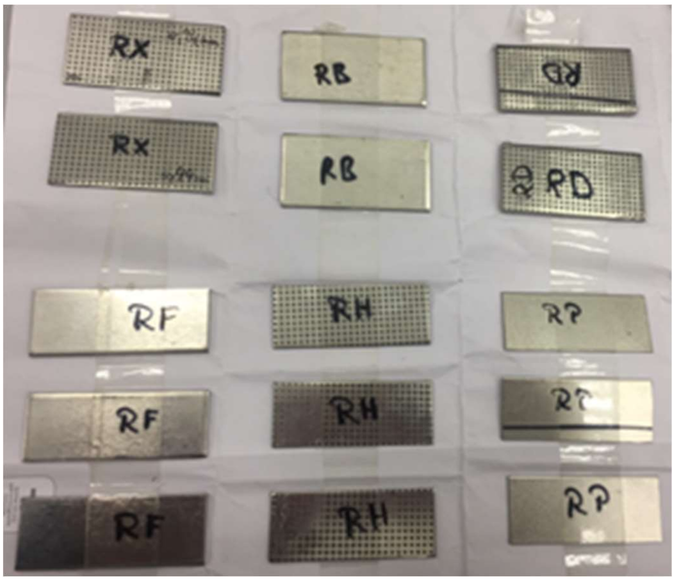
Mono material	Thickness [mm]	E-Modulus [GPa]	Poisson ratio [-]
PP-PE	0,2; 0,3; 0,6	1,45	0.45

TS 245	0,24	197	0.247
TS 245	0,49	191	0.276
TH 470	0,49	210	0.264

4.4.2 Processing of the metal-polymer-metal composite sandwiches

The Sn-coated metal sheets used were of deep drawing quality (Tinplate® TS 245 - EU 1.0372) with thicknesses of 0.24 and 0.49 mm. The polymer was a PP/PE foil with thicknesses of 0.2, 0.3 and 0.6 mm. PP/PE represents 80% of the copolymer, the rest was talc, rutile, and barite. To produce different sandwich types, processing by roll bonding was used. Firstly, the mono-materials were prepared by cleaning and activating (polymer) and afterward bonded together in a two-step process using the epoxy resin Köratac FL201. The procedure is described in more detail in [140;141]. For the five-layered sandwich, an additional step for preparing and activating the center metal sheet was necessary, performing the same procedure used for the outer layers. The faultless production and quality of bonding were controlled by thermography and shear tests.

The Poisson ratios of TS245 and TH470 were calculated by the width changes. Typical five-layered MPM sandwich composite among other samples is shown in (Figure 64).

a) 

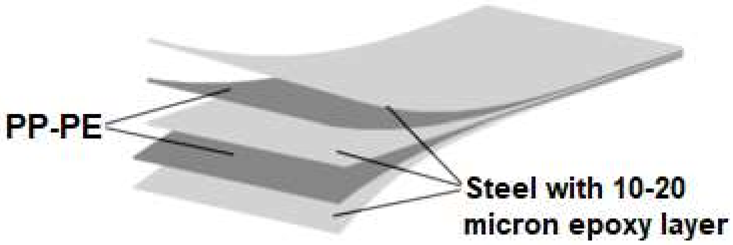
b) 

Figure 64. Sample - "RX5L" a) (5 layered metal-polymer-metal sandwich composite) left up corner, before tests on the servo-hydraulic testing machine, b) RX5L schematic structure of layers.

4.4.3 Methodology and results of the experiments

Experimental modal analysis

The experimental modal analysis (EMA) is performed to obtain data about the natural frequencies and modes of oscillation, necessary for the subsequent identification of the computational model. Modern EMA analysis, in particular, the method of scanning laser vibrometry was used in this work. This allows us not only to obtain high accuracy data on natural frequencies but also to determine forms of oscillations with high spatial resolution.

The EMA method is based on the representation of the object under study as a vibrational system with a finite number of freedom degrees ($\boldsymbol{n}$). The experimental determination of the natural frequencies of the system and the corresponding Eigenmodes (oscillations forms) is based on the analysis of the transfer function matrix $[\boldsymbol{H}]$, each element of which is the result of measurements of a separate frequency characteristic as a ratio:

$$\boldsymbol{H_{ij}(\omega)} = \frac{\boldsymbol{X_i(\omega)}}{\boldsymbol{Fj(\omega)}}, \boldsymbol{i, j = 1, \ldots\ldots, n,} \tag{36}$$

where $\boldsymbol{X_i(\omega)}$ - is a frequency response function in the form of speed or acceleration for the i-th degree of freedom (FD) to the effect Fj($\boldsymbol{\omega}$) corresponding to the j-th FD; $\boldsymbol{\omega}$ - is frequency. When using scanning laser vibrometry, to one FD of object $\boldsymbol{i}$, an external force is applied and the response in the form of vibration velocity is measured in the set of FD j = 1, ..., n when they are sequentially scanned [142-144]. After that, according to eq. (1), the components of the transfer function matrix Hij (ω) are determined.

The natural frequencies are determined from the peaks on the measured amplitude-frequency response (AFR) of Hij (ω). To determine their own form of oscillations, one of the degrees of freedom is taken as the reference and a series of measurements of the vibration velocity amplitudes for all FD is performed at the corresponding value of the modal frequency. The number of freedom degrees n for EMA is chosen to provide sufficient spatial resolution for a reliable representation of the vibration modes. Non-contact measurement of vibrations by the means of scanning laser vibrometry has many advantages. First and the main one is the high spatial resolution. The density of the measurement points of the response is limited only by the accuracy of the laser focusing.

The masses of equipment (laser heads, sensors, etc.) do not introduce any errors during the measurement procedure. Secondly, factors like cable stiffness do not affect the oscillation system (their impact is negligible). Due to the fact that this is also an NDT method, the object integrity remains untouched. There is no need for additional complex preparations to proceed with the test. The Polytec PSV400-3D three-component scanning vibrometer was used during this experimental modal analysis. This is the laser-digital measuring complex, based on the use of the Doppler effect for the measurement of vibration velocity. It consists of a geometry scanning module, three optical scanning laser heads, and a control system based on an industrial computer. Measurement of vibration velocity is based on the principle of the Doppler effect. The test sample was fixed on a rigid specially designed and manufactured metal frame in elastic suspensions (Figure 65).

Figure 65. Experimental setup: 1 - sample; 2 - three head laser Doppler vibrometer PSV-400; 3 - acoustic oscillator; 4 - acoustic diffuser; 5 - amplifier.

This scheme is usually used in the experimental modal analysis. It allows to maximally approximate the clamping conditions with the absence of any restrictions on movement ("free suspension"). The specially designed acoustic dynamic was used for excitation of vibrations (by the means of sound pressure). It generated a signal varying in time according to a harmonic law with a constant amplitude and a frequency (White Noise) and (Periodic Chirp) increasing to 6000 - 6400 Hz. For each sample, three experiments with different parameters of scanning net were executed.

To perform the theoretical modal analysis, the finite element method (FEM) was used. Finite element analysis FEA was performed to verify the data obtained experimentally, as well as to estimate the possible errors introduced into the study during experiments (instability of the experimental conditions (interference, noise, etc.)). If we assume, that the damping is neglected, the natural oscillations of the finite element model with (n) degrees of freedom can be described in matrix form by the equation

$$[M]\{\grave{u}\}+[K]\{u\} = 0, \quad (37)$$

where [K] and [M] are stiffness and mass matrices; {u} and {ù} are the displacement and acceleration vectors in the finite element (FE) model.

This equation has a real periodic solution $\{u\} = \{u_0\}\cos \omega t$, in case of condition

$$([K] - \omega^2[M]) \{u_0\}= 0. \quad (38)$$

In this way, the task of calculating the natural frequencies and modes of vibrations was reduced to the problem of ω_k eigenvalues and $\{u_0\}_k$ vectors, which null the determinant:

$$\det\left|[K] - \omega^2 [M]\right| = 0. \quad (39)$$

The problem was solved by the finite element method in the ANSYS Workbench software. It was assumed that the sample was free from restrictions on movement in a "free suspension" state.

The task of identifying a material model is considered as an optimization task with an objective function:

$$I = \sum_{i=1}^{n} a_i \left(\frac{f_{ip} - f_{ie}}{f_{ie}} \right)^2 \rightarrow min, \qquad (40)$$

Where f_{ip} and f_{ie} are calculated and experimental values of (i) natural frequency; and a_i - are weight coefficients.

The control parameters are material characteristics. The calculated and experimental values of the natural frequencies should correspond to the same own forms. In the present work, a comparison of the calculated and experimental eigen forms was carried out in the analysis of their visual representation. For the construction of the finite element model, the finite elements of a volumetric body (SOLID185) with the option of a layered body were used. It should be noted that these elements provide modeling bulk bodies and can be used to simulate real structures. In addition, the use of the layered body option allows simulating layered bodies, in particular, composite materials. In this case, a multilayer material consists of several different materials. Special commands written in the programming language APDL (Ansys Program Design Language), set the material properties and the thickness for each layer. The finite element model of the object of study is presented in the

Figure 66.

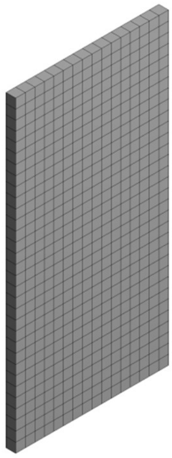


Figure 66. Finite-element model (SOLID185).

Scattering of experimental data was estimated by the values of the coefficient of variation, which lies in the range of 0.59 %, this shows that the natural frequencies were determined with high accuracy during the experiment.

Sample vibration properties were measured (every 100000 cycles) by means of 3-head scanning Doppler vibrometer until unstable conditions were detected. The vibration speed vector was calculated for a frequency range from 0 to 6400 Hz. Graphs were compared.

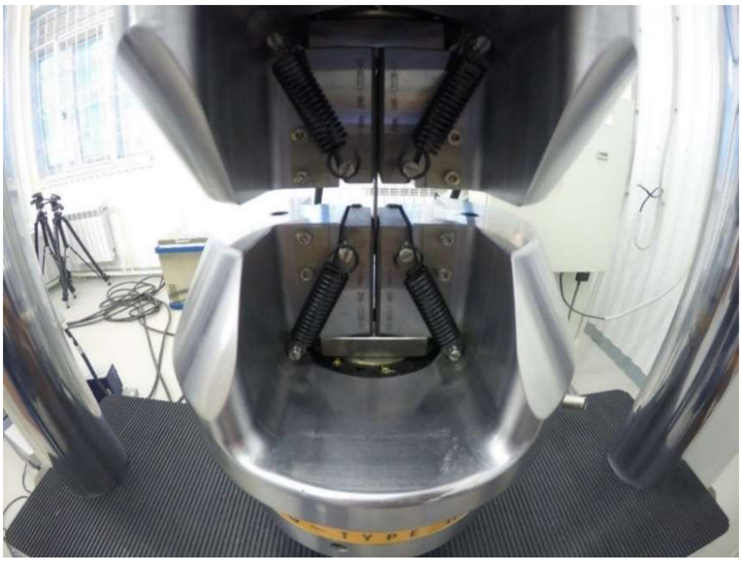


Figure 67. Servo-hydraulic testing machine with a sample.

Loading was executed by means of zero-to-tension stress cycle at the servo-hydraulic test machine SHIMADZU EHF-E (Figure 67), with the possibility of creating a wave of different shapes (sinus, triangle, straight, trapezium, 1/2 inversus, inclined plane, stepwise, arbitrary, sawtooth, oscillation, irregular) at frequencies from 10-5 Hz to 102 Hz. In our case, we used the zero-to-tension stress cycle.

Cycle loading characteristics for sample RX5L (each iteration): Frequency = 80 Hz; Force = 1.265 kN; Cycles count = 105. In order to avoid irreversible changes in the material (sample) associated with plastic deformations, the loading level was selected on the linear area of the material (stress-strain) diagram (Figure 68). Analyzing the corresponding diagrams, it was concluded to select the stress load at the level of 30 MPa for all samples.

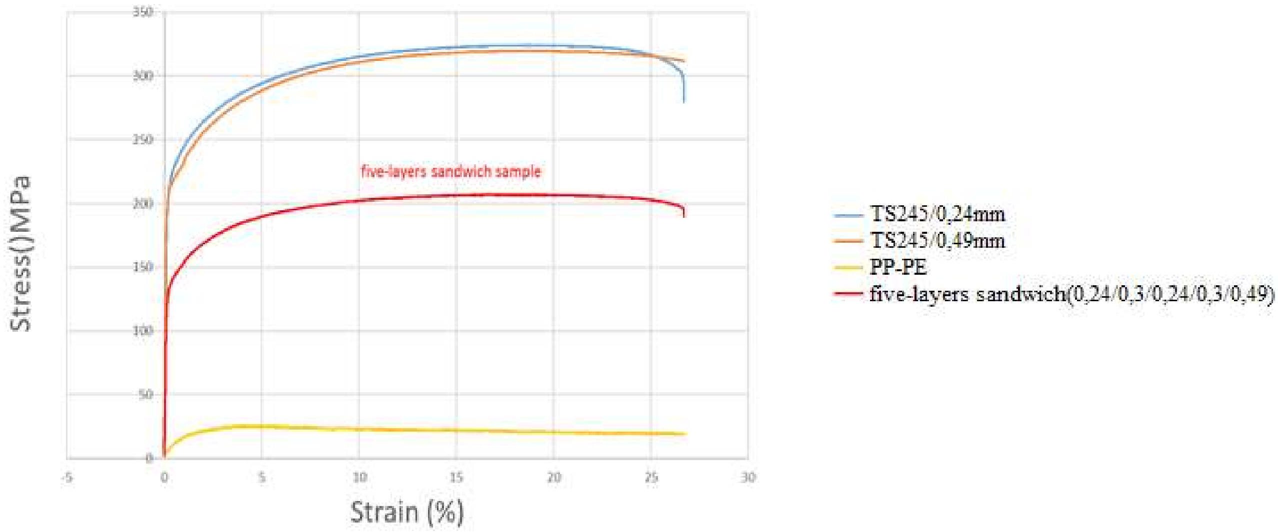
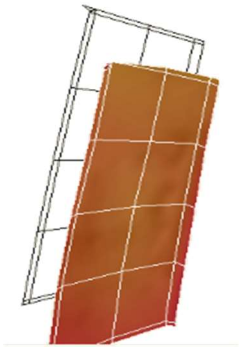
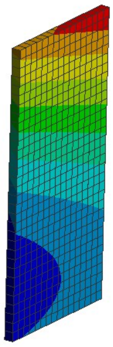
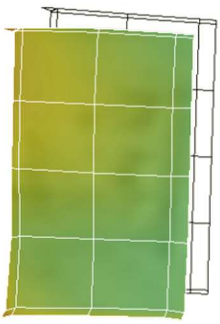
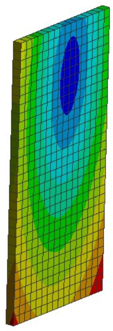
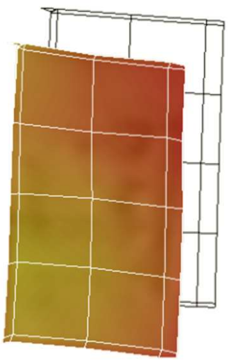
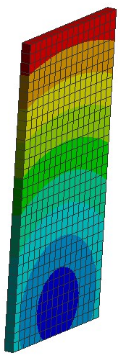
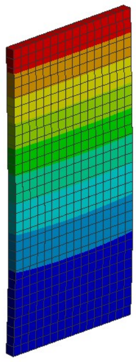
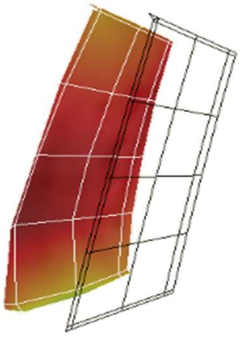
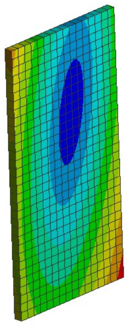
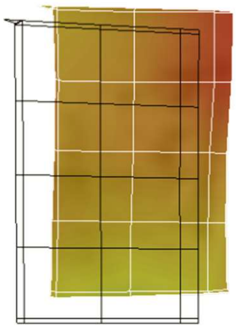
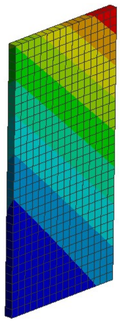
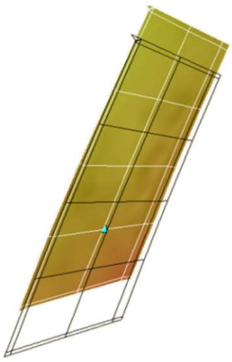
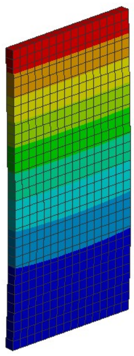


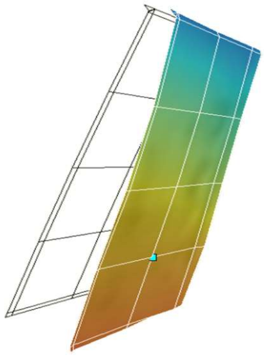
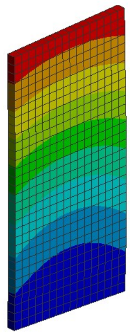
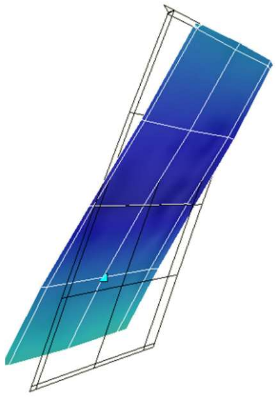
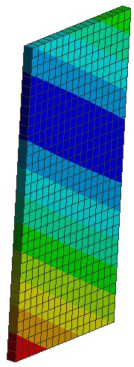
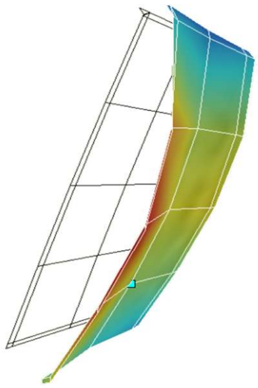
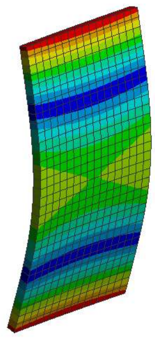
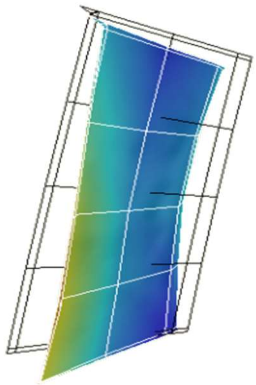
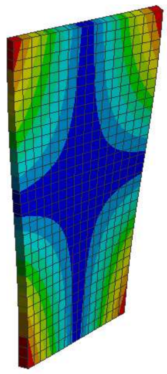
Figure 68. Stress-strain diagrams for materials of tested samples.

Table 8 presents the Eigenmodes (natural modes), results of experimental testing (vibration vector, 3 heads) and computer modeling results for the 5-layered sample “RX5L”.

Table 8. Test and finite element method calculation values of natural modes shapes and frequencies for sample “RX5L”.

RX5L					
№	Test value		FEM calculation		Deviation[%]
	Natural mode (eigenvibration)	Natural frequency [Hz]	Natural mode (eigenvibration)	Natural frequency [Hz]	
1st bending form		144		128	12,5
1st torsional form		163		177	7,90
2nd bending form		200		189	5,82

3rd bending form		469		416	12,74
4th bending form		700		798	12,28
2th torsional form		990.5		1113	11
5th bending form		1283		1441	10,96

6th bending form		1553		1480	4,93
3th torsional form		1811		1732	4,56
Membrane form		3070		3503	12,36
4th torsional form		4838		4365	10,83

Modal shapes of RX5L sample were very similar in connection with translocation on frequencies. This gives us the right to make a judgment that the experiment was quite clear. After 2nd and 3rd iteration at 300000 cycles, the graphs show small differences. After 4th iteration at 400000 cycles, there was an obvious translocation at high-frequency ranges. In terms of reliability and repeatability, the vibration properties of “RD1” (3-layered sandwich) sample also were measured (every 100000 cycles) by means of 3-head scanning Doppler vibrometer until unstable conditions were detected. The vibration speed vector was calculated for a frequency range from 0 to 8000 Hz. Cycle loading characteristics (for each iteration) were: Frequency = 80 Hz; Force = 2.25 kN; Cycles count = 100000. Results were completely the same as with 5-layered sample, specifically modal shapes were very similar in connection with translocation on frequencies, which also gave the confidence to judge that experiment was quite clear. As for RX5L sample after 2nd and 3rd iteration at 300000 cycles, the graphs for RD1 sample had small differences (in comparison with its original condition). There was also an obvious translocation at high-frequency ranges after 4th iteration at 400000 cycles.

Further experiments have proved the fact that the change of vibration speed picture became enough predictable for the future forecast. It was found that the reference mode shapes at resonance frequencies are practically the same as with samples after 100000 – 800000 cycles loading. Another situation is with the amplitude at resonance frequencies, for samples after cycle loading of 100000- 400000 cycles, in comparison to the reference sample. Vibration speed vector diagrams presented in (Figure 69), show the difference between the original and further conditions. There is an increase of the amplitude at low frequencies of approximately 30 % and a sharp increase in the amplitude at frequencies above 500 Hz (equal to an amount more than 100 % of the amplitudes of the original signal when the samples were not under cycle loading at the same frequencies).

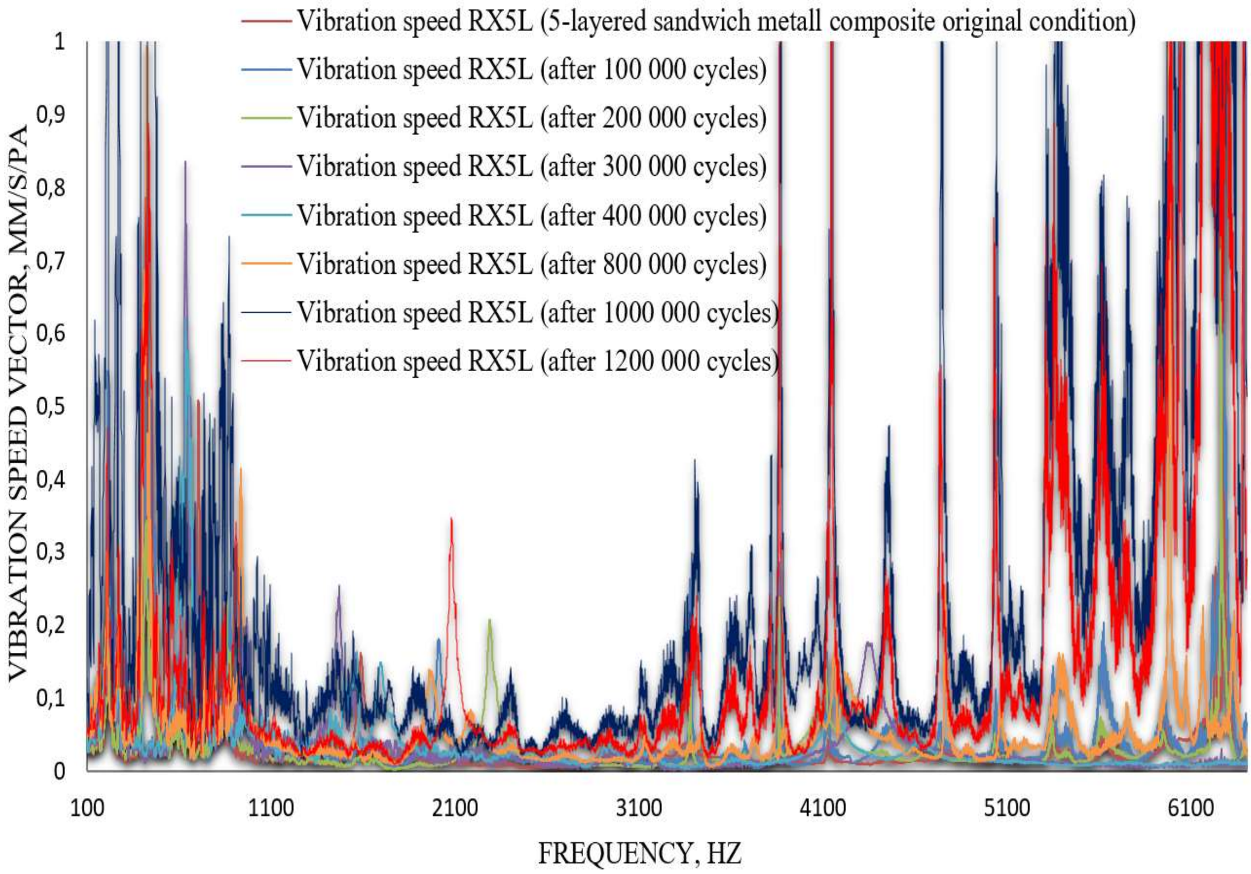


Figure 69. “RX5L” (5-layered sandwich) vibration speed vector – frequency diagram.

This research indicates that wavelet-based NDE analysis could provide a basis for determining damage levels in structural composite aerospace components, and decide whether a component is still operational. It is worth mentioning that the transformed signal reflects the overall picture of registered vibration.

Based on the proposed algorithm Fourier transformation separately used for the determination of certain frequencies and resonance picture evaluation. The combination of these techniques can give affordable information for the interpretation of the obtained results. The same behaviour of vibration speed vector functions can be seen with all tested samples. It also should be mentioned that stress-strain diagrams were checked during each iteration, see figures (Figure 70; Figure 71).

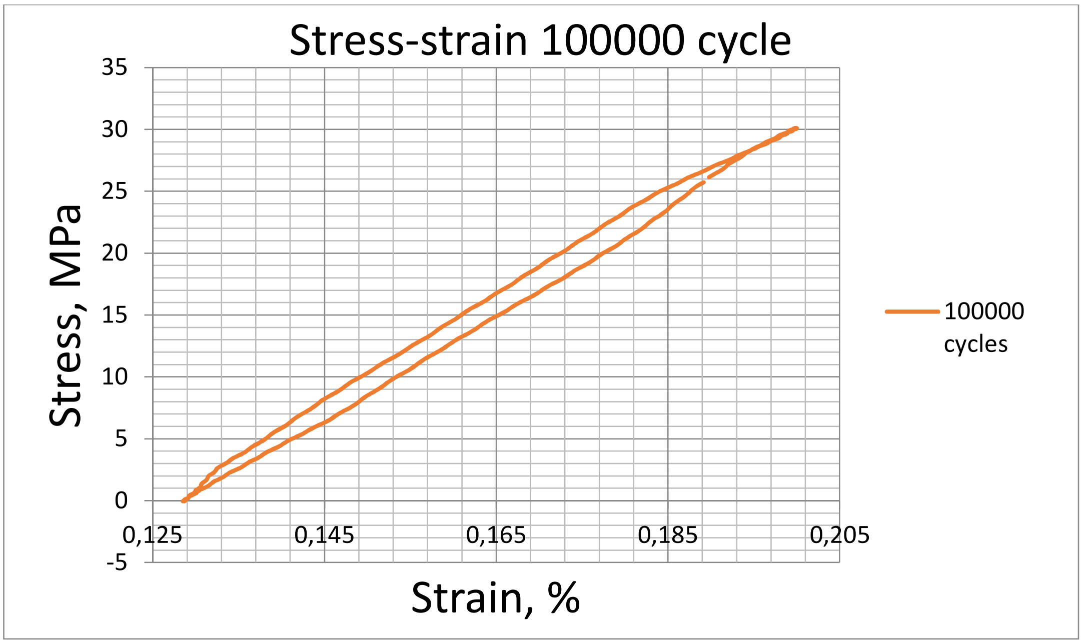


Figure 70. Stress-strain - 100000 cycles for sample “RX5L” (5-layered sandwich).

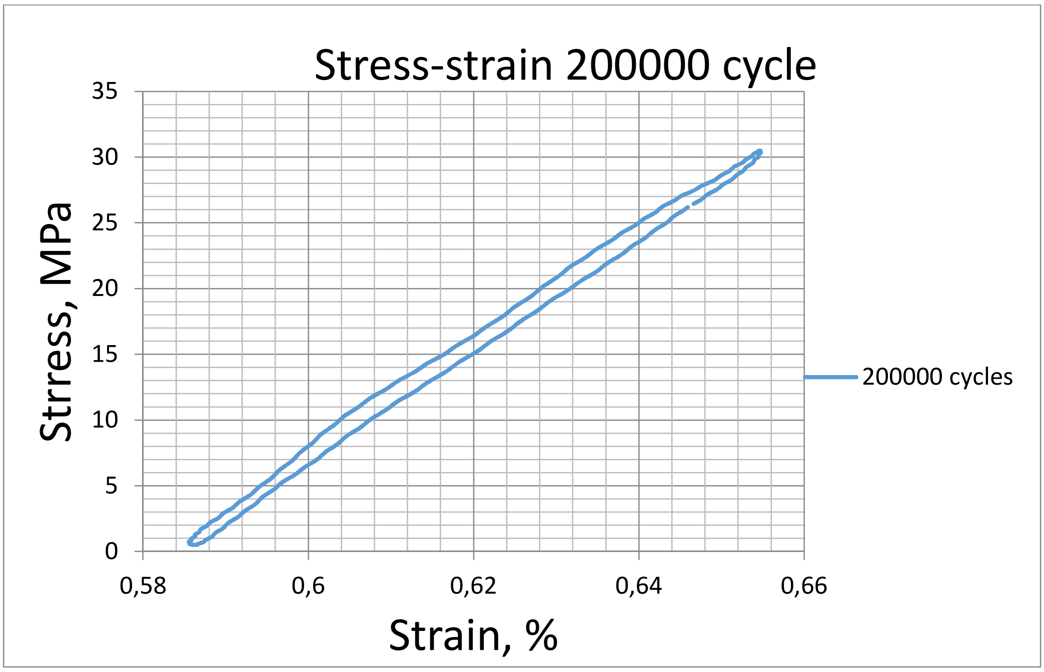


Figure 71. Stress-strain - 200000 cycles for a sample - “RX5L” (5-layered sandwich).

The presence of plastic (yield strain) deformation is the main cause of plastic hysteresis loops square area increase. The field bounded by the hysteresis loop is proportional to the energy absorbed by the material during the single loading cycle. Experiments were executed until critical conditions. As an example, the 5-layered sample was broken after 1263200 cycles. The stress-strain diagram at 63199 cycles (7 load iteration for RX5L sample) presented at (Figure 72). Under the conditions of soft loading of the hardening material (for our case), the hysteresis loop narrows with the increasing number of cycles. This can be seen in Figure 72.

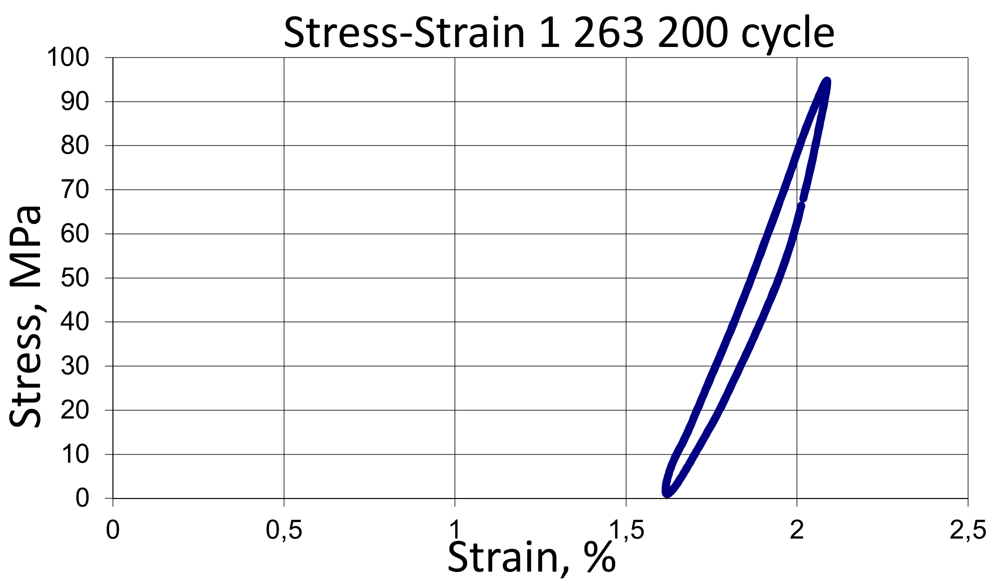


Figure 72. Stress-strain diagram for the sample - “RX5L” (5-layered sandwich), one cycle before the break.

By evaluating the area of the hysteresis loop, we can also estimate the accumulation of damage and the degree of development of defects. The area of the hysteresis loop shows the level of plastic deformation and the degree of possible damage accumulation. The larger the area of the hysteresis loop, the greater the effect of defects on the structure.

The conclusion is that stress-strain diagrams also can be separately used for integral monitoring needs, but this approach is expensive, time-consuming, and not appropriate for fast operational control (due to the inability for fast testing on the aircraft).

In our case, the MPM sandwich composites showed good visual stability for deformation after cyclic loading in a longitudinal direction. Nevertheless, the vibration characteristics are changing in time showing the deviations of the signal opposite to the absence of obvious visual defects that can be detected by visual inspection. To check the condition of two samples with various material ratios the thermography experimental facility was used as a fast alternative variant of NDT.

Lock-in thermography testing of MPM samples

For the Lock-in thermography (developed by the company Edevis GmbH) investigations, the test setup was used (Figure 73). The test sample was sprayed with a special black spray to ensure uniform emissivity. The distance between the IR camera and the sample was 50 cm. Two halogen lamps (each 1000 Watt with 100% amplitude) were used. Five periods of sine heatwaves were applied to pre-heat the sample, however, 15 – 30 other periods were applied afterward depending on the used frequency: with higher frequency, a higher number of periods is recommended. To enable detecting different defects along the thickness of the sandwich sheet, three frequencies (0.1, 0.3, and 0.5 Hz) were applied. Thermal waves can penetrate less depth with higher frequencies (the lower the frequency is, the deeper the heat waves can penetrate).

The maximum applicable Frequency (f) in our lock-in thermography analysis is 1 Hz. According to trials, in the range of f <= 0.5 Hz, the defects approximately at 0.5 mm metal thickness can be detected. This is the reason to apply different frequencies, where different depths can be reached, to detect the corresponding defects. Additionally, for very low frequency, the sample can be overheated, which is also not recommended. Temperatures up to 30 – 35 °C during the test are acceptable. The software version “Display 4.9” was used to analyze the thermal waves and to identify the existing defects (Table 9).

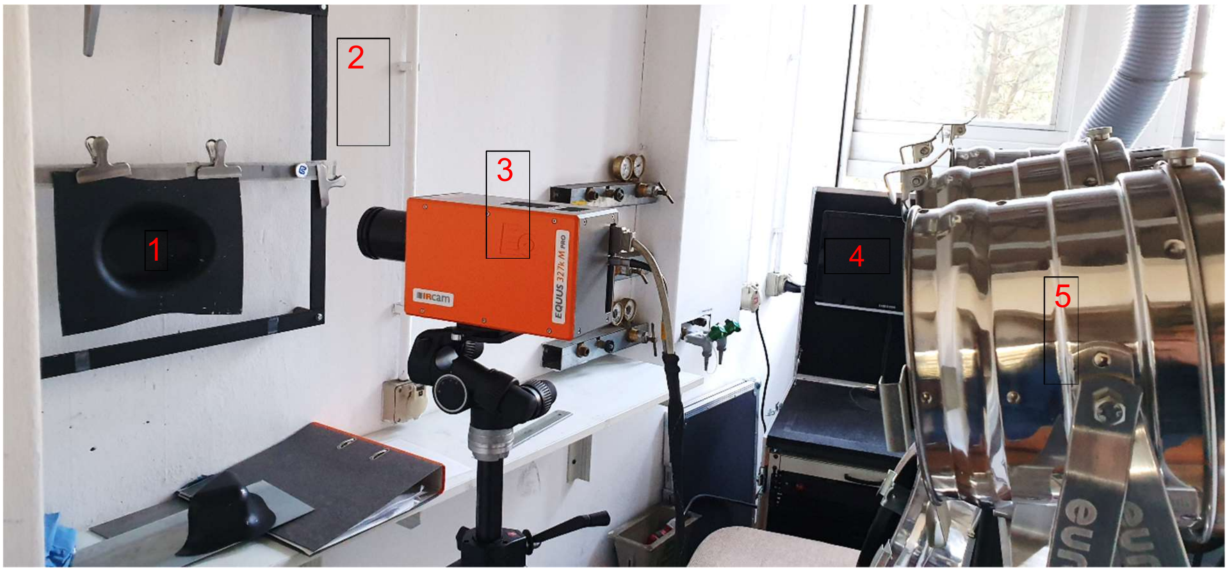
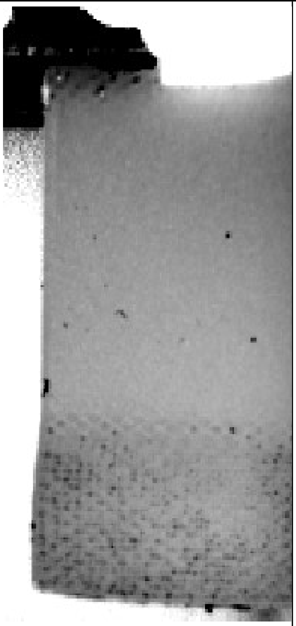
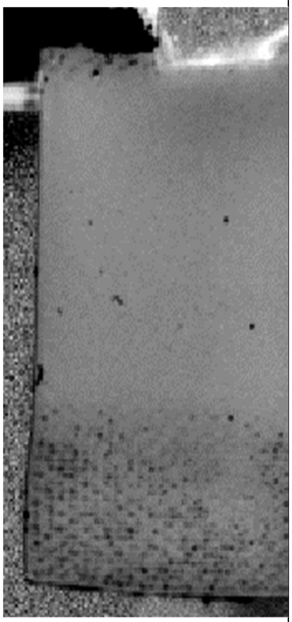
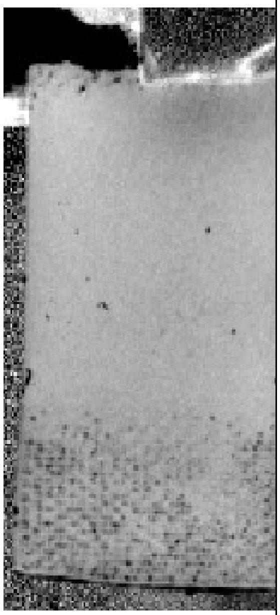
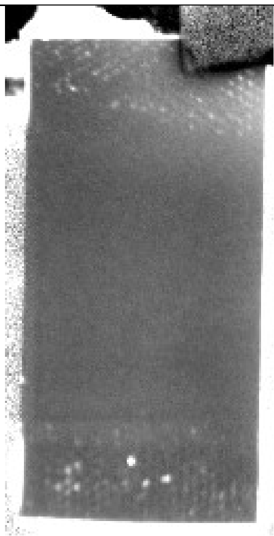
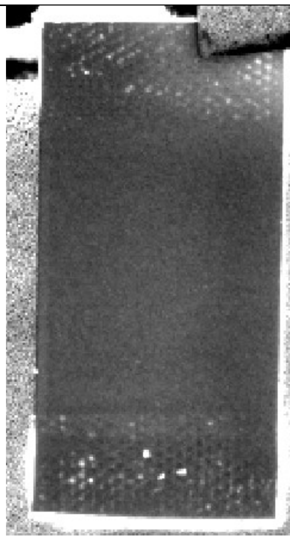
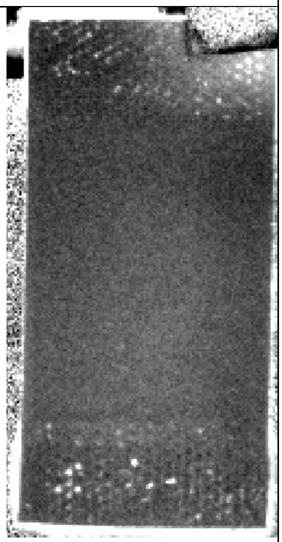


Figure 73. Thermography experimental facility. 1. Location of the test sample 2. Fixing frame 3. IR Camera 4. Computer 5. Heat source (Halogen lamps).

Two samples with the following composition were tested; 1) 0.49/0.6/0.49 and 2) 0.49/2.0/0.49 (Table 9). For the sandwich with the thicker core thickness (2.0 mm), no defects could be detected regardless of the used frequency. As can be observed, some defects (most probably surface ones) in the clamping regions could be detected. Testing results after cyclic loading are presented in Figure 74 with comments.

The 0.6 mm core sandwich showed some defects in the central part of the sample, which is most probably pores in the core layer. These defects can arise due to the melting of the core layer during the production step. However, these pores will not show a negative influence on the global behavior of the sandwich sheet.

Table 9. Lock-in thermography testing before long cyclic loading.

Samples	Real image after the black spray	Frequency		
		0.1Hz	**0.3Hz**	**0.5Hz**
RX5L 0.6 mm core 0.49/0.6/0.49				
RD1 2 mm core 0.49/2.0/0.49				

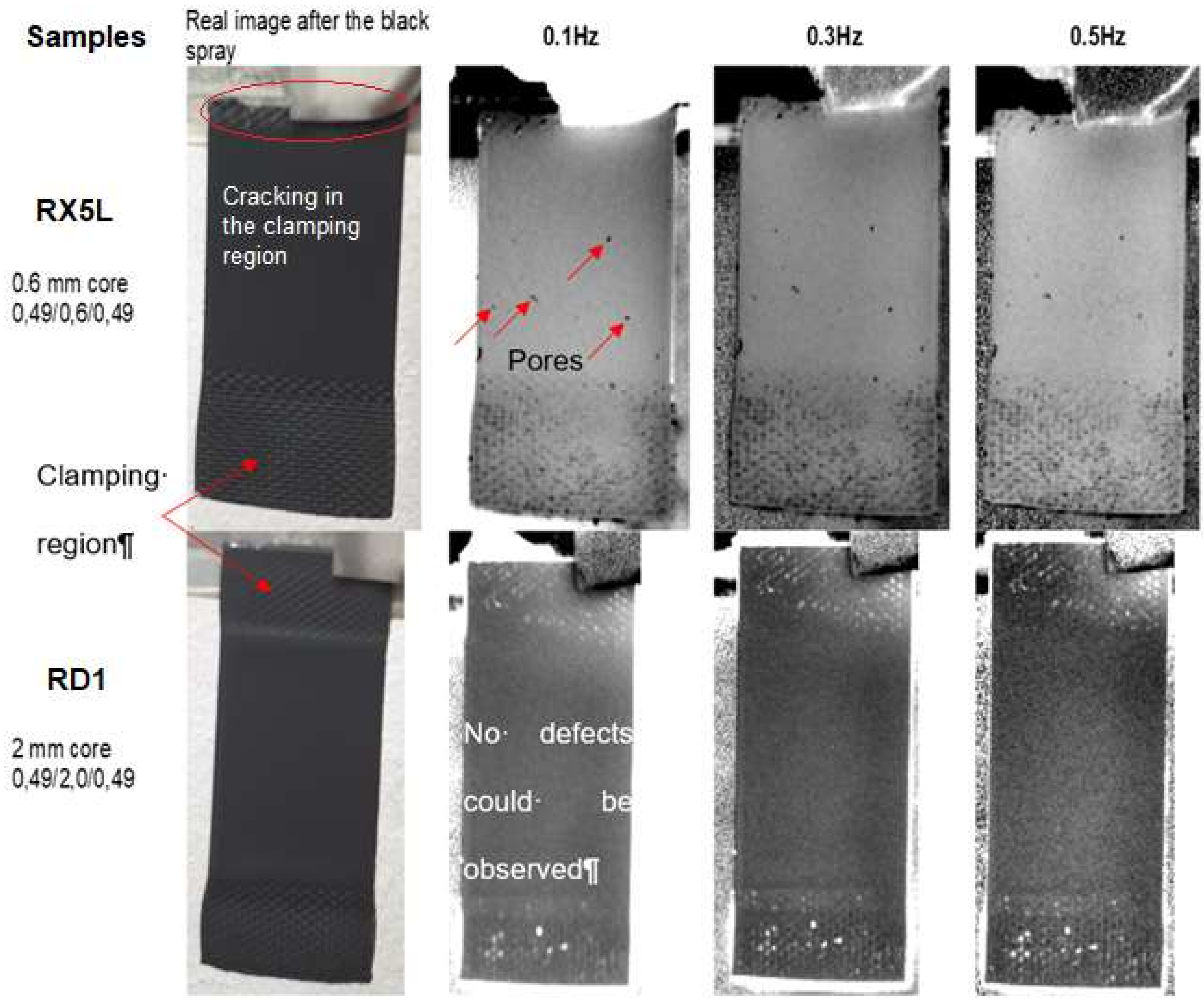


Figure 74. Lock-in thermography testing after long cyclic loading (1263200 cycles).

Possible failure modes for these composite are more relevant for other loading conditions. As was discussed at the beginning of this experimental section the bending by the means of electromagnetic forming (EMF) is more relevant for a variety of possible failures. In our case, due to the specific loading conditions, no obvious defects could be observed by visual inspection. Lock-in thermography fails to identify defects in MPM structures too. The logical assumption is that deviations in vibration characteristics are associated with the accumulation of micro damages (they cannot be detected by using simple non-destructive testing methods until they become large enough during cyclic loading). Another possible reason for deviations in vibration properties could be connected with the translocation of layers.

Simplified method of obtaining amplitude response in combination with using Fourier and wavelet transforms

The second part of the tests is devoted to the simplified method of obtaining amplitude response in combination with using Fourier and wavelet transforms. Additional basic information about the used method of wavelet transforms can be found in previous works [114;118];. The presented experimental setup contains almost the same equipment (Figure 75).

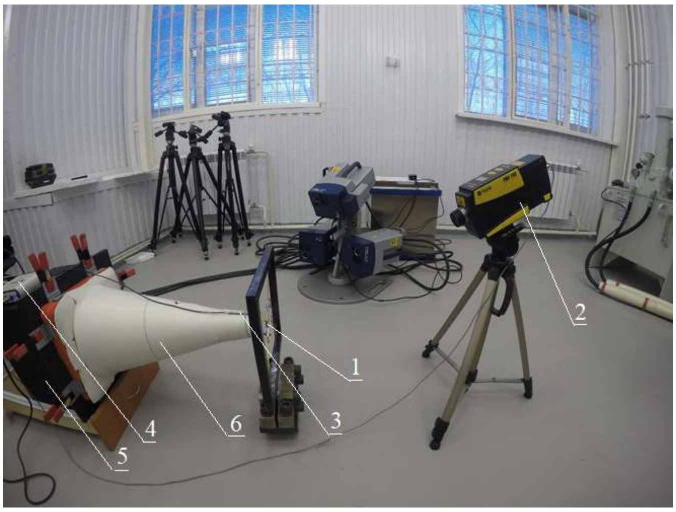


Figure 75. Experimental facility: 1 - sample; 2 - one head laser Doppler vibrometer PDV-100; 3 – microphone; 4 - NI- USB-4431; 5 - acoustic oscillator; 6 - acoustic diffuser.

The main difference is the use of a one-head laser Doppler vibrometer PDV-100, USB-4431 sound and vibration device, and average processing capacity notebook. USB-4431 (102.4 kS/s, 100 dB, 0.8 Hz AC/DC coupled, 4-Input/1-Output Sound and Vibration Device) designed for sound and vibration measurements. Input channels incorporate integrated electronic piezoelectric (IEPE) signal conditioning for accelerometers and microphones. The four USB-

4431 input channels simultaneously digitize input signals. The analog output (AO) channel is ideal for stimulus-response tests and can be synchronized to the AI channels.

After the measurement, recorded signals were put into written LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) program for calculation of Fourier spectrograms and wavelet transform convolutions. Another difference is the use of periodic chirp as generated sound in opposite to the white noise sound used in the first experimental part. Results for the RD1 sample as spectrograms and 3D-scalogram reflection after periodic chirp excitation (using one laser head) are presented in figures (Figure 76; Figure 77; Figure 78).

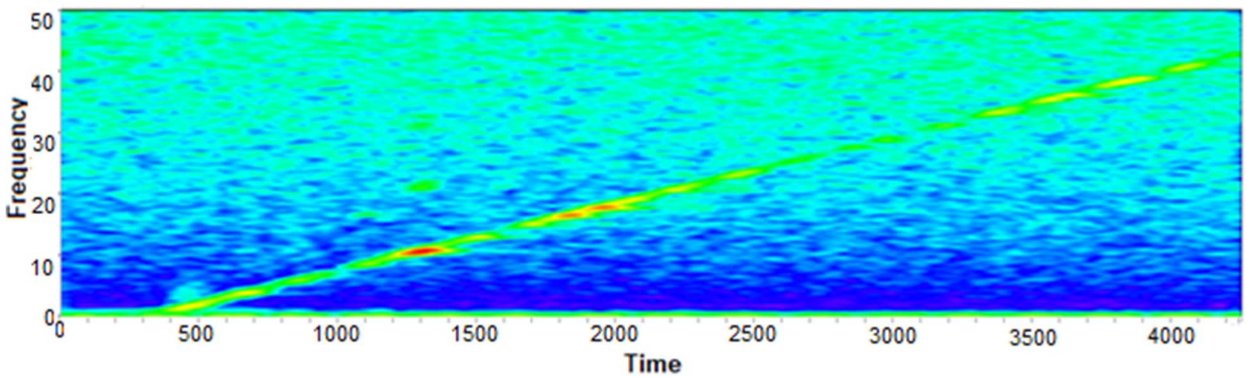


Figure 76. Spectrogram of the reference sample RD1.

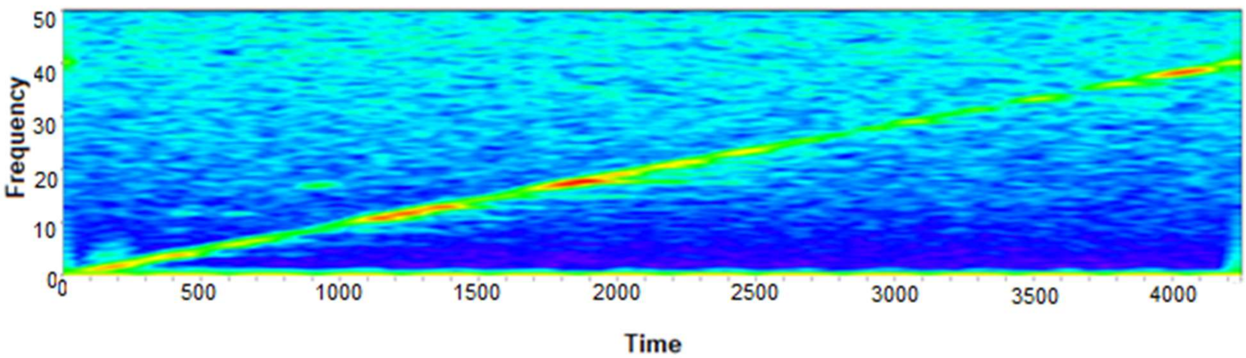


Figure 77. Spectrogram of the sample RD1 after 100000 cycles.

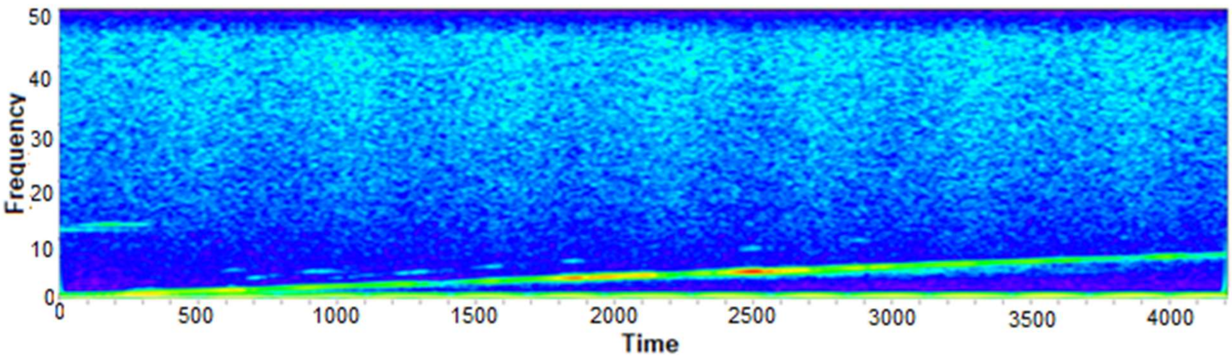


Figure 78. Spectrogram of the sample RD1 after 300000 cycles.

From the spectrums, it can be seen that a conventional sample spectrogram has higher values of vibration velocity than spectrograms after 100000 and 300000 cycles. Despite lower amplitude rise in time in comparison with the previous state, it can be seen the increasing sub-harmonic activity with cycle load after each iteration. That is a direct sign that during use a more rapid failure under high vibration conditions is possible.

Visual features of 3D scalograms indicate changes in the overall vibration picture of the signal, which can describe the integral damage condition of the object. The wavelet transformed the function of the reference sample is presented in Figure 79. Further results are presented in figures Figure 80,Figure 81, Figure 82 respectively.

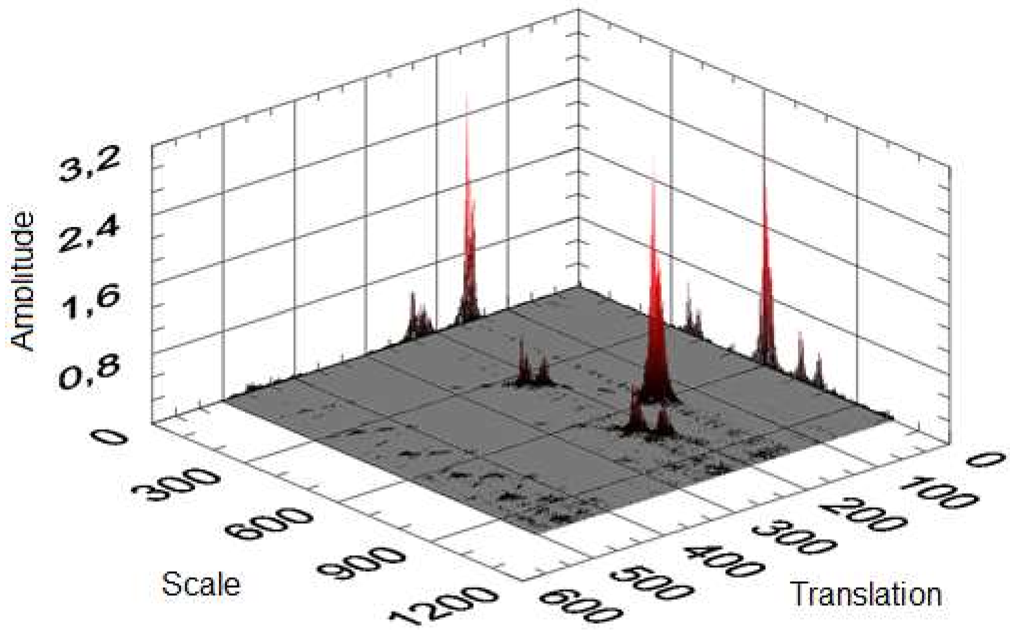


Figure 79. Signals of sample RD1 after wavelet convolution (mother wavelet db02; scale 1024).

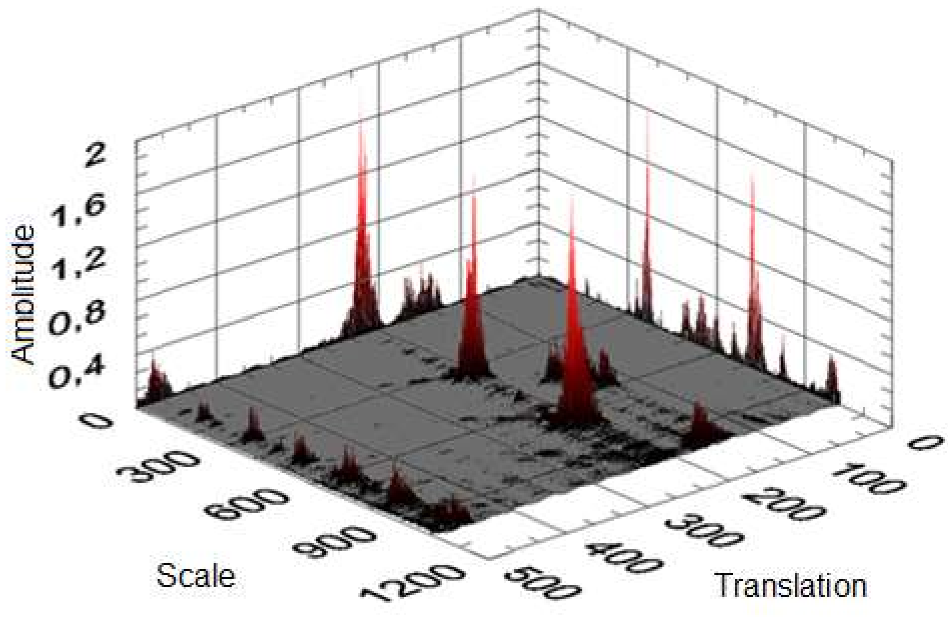


Figure 80. Signal after wavelet convolution (mother wavelet db02; scale 1024). Sample RD1 after 100000 cycles.

Signs of deterioration of the structure are: natural frequency decline, damping of high frequencies, amplitude increase on a small scale, an increase in intensity at low frequencies, relevant frequencies "Drift", shift of the CWT (continuous wavelet transform) maximum, overall low amplitude, absence of high frequencies (high frequencies could not be generated). With the increase of cycle loading after each iteration, the CWT picture changes strongly. This allows us to make a conclusion about typical signs occurring from 3D scalograms.

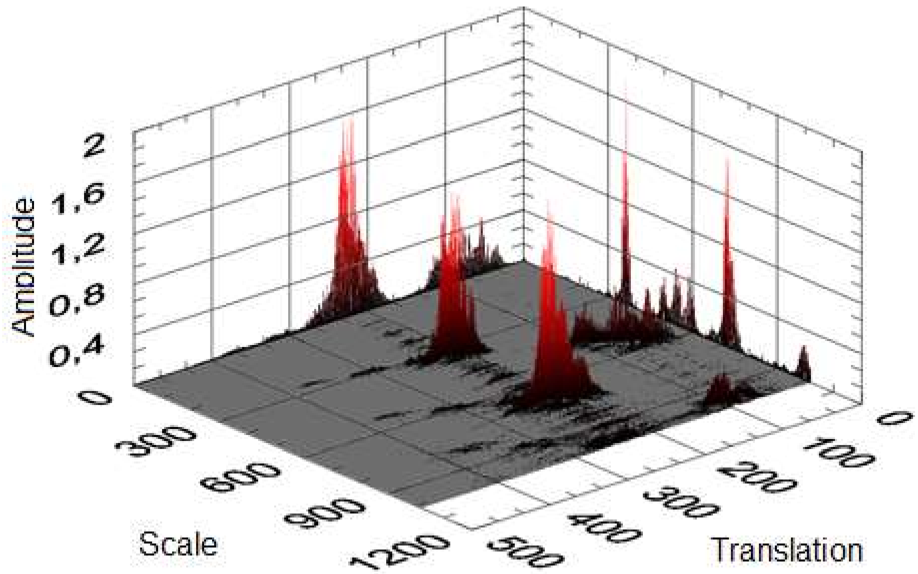


Figure 81. Signal after wavelet convolution (mother wavelet db02; scale 1024). Sample RD1 after 200000 cycles.

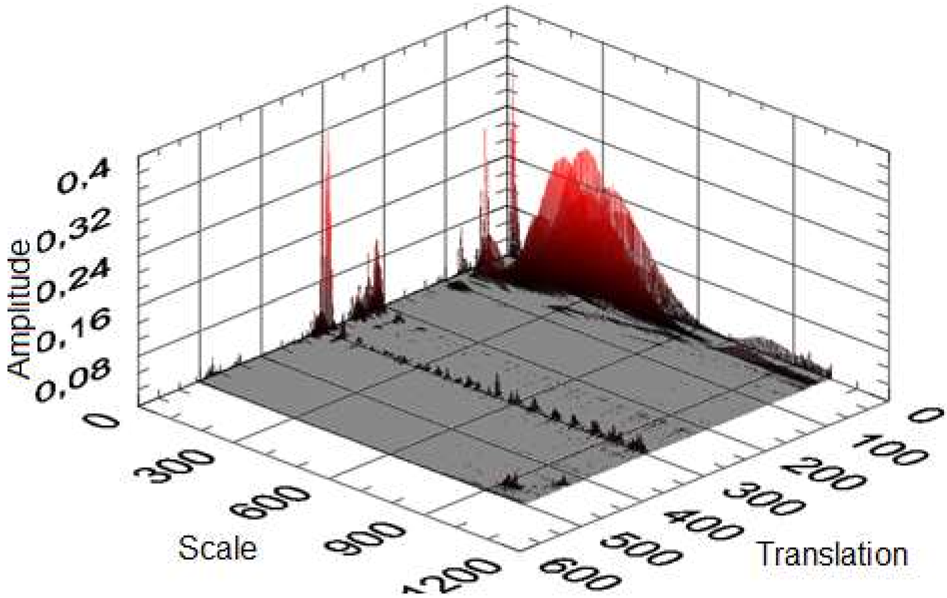


Figure 82. Signal after wavelet convolution (used mother wavelet db02; scale 1024). Sample RD1 after 300000 cycles.

It is obvious that for each object the picture will be different, but there are changes that can be marked during the life-cycle to set the points in operation for maintenance checks. If the data can be collected statistically by means of many iterations (vibration tests) during operation and such deviations in connection with other parameters like resonance frequencies, this could give a reliable data on condition picture of the object. Works [115] and [145] contain additional information about experimental investigations of defect sizing in composite materials and different inverse and direct measurement problems.

The amplitude-frequency diagram (Figure 83) contains a comparison of data in the initial condition and after 100000 and 300000 cycles for RD1. This diagram, which was acquired at more simple equipment (by the means of one laser) also shows the tendency, when amplitude on certain frequencies changes according to forecast. It should be mentioned, that the vibration speed at frequencies close to 20-80 Hz, was up to 0.06 mm/s (after 300000 cycles), and the fact that amplitude growth at this low-frequency range was connected with cyclic loading. In this case, we can see a rapid increase in amplitude at the range from 2100 to 2200 Hz.

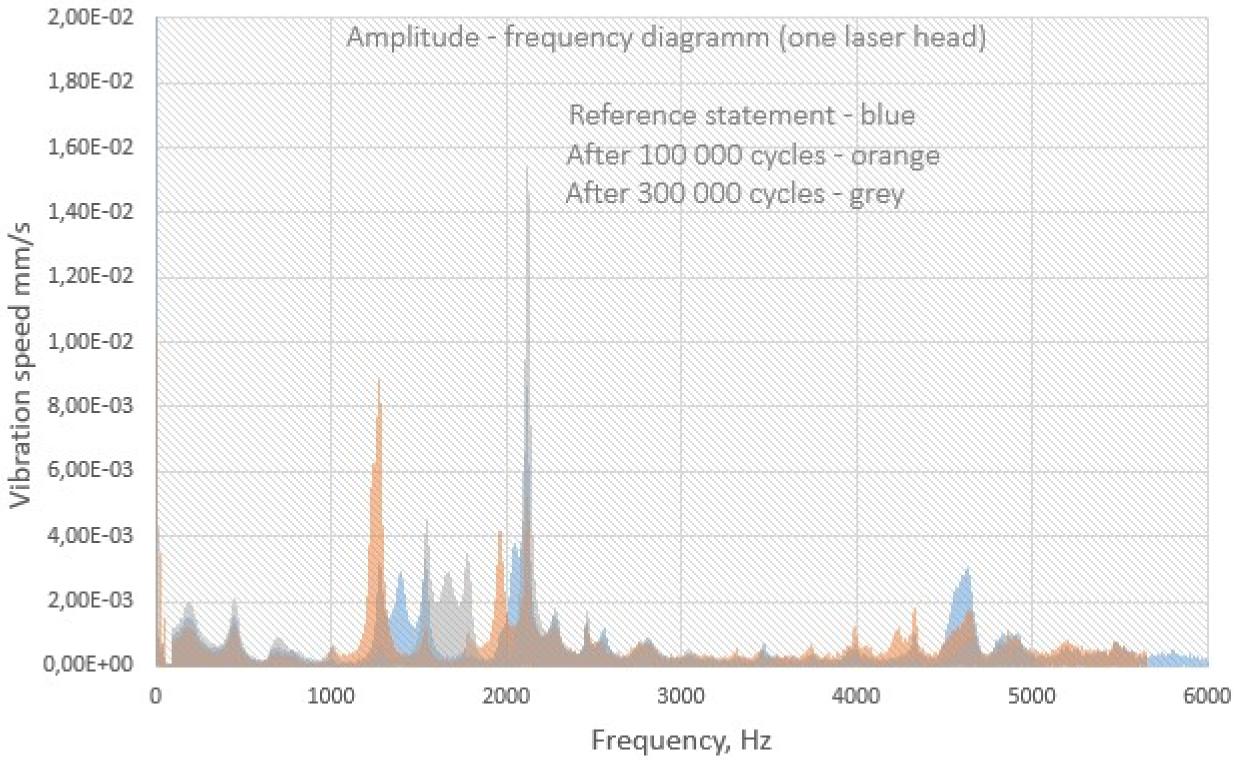


Figure 83. Amplitude-frequency diagram. RD1 sample reference statement and after, 100000 and 300000 cycles. (One head Doppler laser vibrometer).

4.4.4 Conclusion

During the calculation of modal characteristics (natural frequencies and vibration modes) of products made of metal-polymer-metal sandwich composites, it is necessary to exclude their resonance oscillations, which requires reliable data on the mechanical characteristics of the material. The problem is a large quantity of elasticity characteristics in comparison with isotropic materials, and also the fact that these parameters depend on a wide range of structural and technological factors.

One of these work purposes was to develop a methodology for identifying models of elastic behaviour of polymeric-metal composite materials, based on the results of the experimental modal analysis using the example of laminated metal-polymer-metal samples. The object of investigation was layered reinforced sandwich sheets and metallic mono-materials. Non-contact method of scanning laser vibrometry was used for experimental determination of natural frequencies and modes of oscillations. For the numerical modal analysis, the finite element method is used. The material model is a layered composite with isotropic linearly elastic layers and metal layers. The task of identifying the material model is considered as the problem of minimizing the discrepancy between the calculated natural frequencies and the experimental ones. To solve it, the quasi-random search method is used. The developed method can be recommended for the determination of parameters of material models for calculating modal characteristics of polymer-metal sandwich sheets and metallic mono-materials composite products.

For the experimental modal analysis, a three-scanning and optimized one-scanning laser vibrometer was used; with its help this work succeeded in obtaining semi-natural oscillation frequencies of samples, made from the metal composites in a frequency range up to 6000 Hz with very insignificant scattering (overall average within 0.59%), and own forms - with high space-resolution. Observation of the behaviour of five-layered samples under increasing of the load parameters led to simple conclusions: 1.) The percentage ratio of certain material dictates its behaviour. In other words, more percentage of the metal inside the construction shows more metal behaviour of the MPM composite as homogeneous substance. The opposite is true as well – more polymer shows more inhomogeneous behaviour. 2.) There is the significant amplitude increase at average frequency spectrum in combination with high damping of all other frequencies in the range from approximately 1180 up to 3050 Hz for this type of MPM composites. Based on the previous experience and according to results from tests with composite blades, it might give the possibility to use this data as a diagnostic sign of unstable operation condition of the structure. In the modern realities of operation, an important role is played by the efficiency of detecting technical failures. It is extremely unprofitable to subject composite structures to urgent repairs under conditions of untimely operations. It is much more profitable to conduct a quick check of the structure during light operational technical maintenance forms in order to timely identify the pre-failure condition and to perform subsequent replacement of the structure. The determination of the defect location and its size becomes a secondary issue. As a result, the best possible scenario is when monitoring comes down to control (level 1) and a possible prediction of the technical condition (level 5) if we are considering autonomous systems. According to the hierarchical pattern, the current technology level in this research for such systems is (level 1). Analysis of deviations of the vibroacoustic picture, including the use of wavelet transforms in combination with the Fourier transforms, can help to determine the condition of the structure in time, as well as highlight deviations by which the current state of the structure can be estimated. Potentially this data can help to achieve levels 2, 3, 4, and 5.

4.4.5 Summary

Like in previous works with different elements, made of composite material, obvious signs of alteration in CWTs were detected. The same features like virtually unchangeable mode shapes at resonant frequencies after long cycle loading, natural frequency declines, damping of frequencies, amplitude increase on a small scale, an increase in intensity at low frequencies, shift of the CWT maximum and overall low amplitude were detected.

According to tests and modeling procedures provided, MPM sandwich composites are not an exception in behaviour. This research also indicates that wavelet-based NDE analysis in combination with complex modal analysis could provide a basis for determining damage levels in structural composite components, and thus a means to decide whether a component is still operational. It should be concluded that in the case when statistical evidence on results is collected in the required degree and studied in detail there is a clear possibility of application of the proposed approach in industry needs.

Chapter 5: Conclusions and Future Recommendations

5.1 Conclusions

In the current research, the aims and objectives discussed in the introduction chapter have been achieved. The main objective of this research was to monitor advanced aircraft structures made of composite materials by proposed methodology and make a base for a fast, low-cost technique that can be easily implemented in operation. Composite structure failure analysis was carried out and for this reason, a set of experiments was designed.

From experimental results and simulation for validation of these results, the following hypothesis was proved:

- There are usable features of vibration characteristics that can reflect the effects of damage and integral changes in advanced composite structures. (Natural frequency decline, low frequencies damping, intensity increase at low frequencies). They show alterations in an integral picture of a signal. The importance of their detection and characterization lies in the practical use for control, estimation of the residual life, and forecast on their further operation.
- NDT vibration-based technique in combination with Fourier and mainly wavelet transforms is a useful, universal technique for composite element control and diagnostics in operation.
- A wide range of composite materials can be tested and monitored by the method which was proposed in the research.
- Experimental modal analysis can be useful for the determination of material models parameters for calculating the modal characteristics of polymer-metal sandwich sheets and metallic mono-materials composite products. As well as, solving the problem of

minimizing the discrepancy between the calculated natural frequencies and the experimental ones.

- The severity of the outcome depends on operating conditions as well as loading type.

During the research, the following conclusions and results were obtained:

- An analysis of modern damage monitoring methods for aircraft composite materials was done.
- Analysis of the statistics of failures and malfunctions showed that: with an increase of operating time, an increase in the number of defects is observed; most of the failures and malfunctions identified during maintenance, refer to the elements made of a range of composite structures; most often, failures and malfunctions occur due to the production and postproduction issues. As an example, poor quality of the adhesive bonding of the elements, resulting in the potential destruction of structural elements in flight.
- From the analysis of existing models, it was concluded that currently there are practically no universal models that are suitable for assessing the technical condition of products in service. The existing design models do not allow to obtain clear dependencies of the design parameters that allow evaluating its state.
- Diagnostic parameters and criteria for estimating the condition of the composite element have been selected.
- The existing methods of signal processing were analyzed and it was concluded that the most optimal method for analyzing free oscillations and vibration of variable composites is a continuous wavelet transform. A method developed for determining modal parameters of aircraft structures in particular with using wavelet analysis of vibration signals.
- A method for diagnosing aircraft cellular structures based on wavelet analysis of vibration signals was proposed.

- A method was developed to monitor different composite structures. An experimental evaluation of the stability of the diagnostic parameters was performed in the measurement of vibration signals at various points of different elements, as well as the sensitivity of the method was obtained.
- NDT vibration-based equipment set is proposed for the control and diagnostics of composite elements.
- The principle for an express-test device for aircraft composite materials based on the proposed methodology was developed.

After investigation of the acoustic properties of composite aircraft blades, it was found that the master blade mode shapes at resonant frequencies were practically the same in comparison with blades taken from their different stages of the lifecycle.

The used blades demonstrated a fourfold increase in the amplitude of resonant vibration in the first bending mode. The amplitude growth of the first bending mode resonant vibration can be used separately as an individual diagnostic sign of emerging defects. Technically the ease of amplitude and frequency analysis of a blade resonant vibration in flight conditions can allow developing a low-cost express-control device for technical condition analysis of composite material blades while in the air.

In detail, there is an increase of the amplitude at low frequencies of approximately 30%, and a sharp increase in the amplitude at frequencies above 500 Hz that is equal to 100% (of the master blade amplitude at the same frequency) and even higher (> 100%).

For diagnostic needs, the CWT was used in the methodology. Signs of deterioration of the structure for composite aircraft blades were the same as with reference honeycomb structures. These signs are natural frequency decline, damping of high frequencies, increase of amplitude on the small scale, an increase in intensity at low frequencies, relevant frequencies "drift", shift of the CWT maximum towards larger scale (toward lower frequencies), low overall amplitude of the signal, absence of high frequencies (the situation when high frequencies could not be generated). All these are the signs that can be used for the determination of the current object condition.

This research indicates that wavelet-based NDE 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 operational. It is worth mentioning that the transformed signal reflects the overall picture of registered vibration with its connection to time. Based on the proposed algorithm Fourier transforms separately used for the determination of certain frequencies and resonance picture evaluation. The combination of these techniques can give viable information for the interpretation of obtained results.

Tests with aircraft blades showed the constant behaviour, that allows to judge not only about the permanent condition but also to make a forecast about the transitional state of an object before failure conditions. Presence of the above-mentioned factors like natural frequency decline, low frequencies damping, increasing of the intensity at low frequencies allows making a decision about excluding of these objects from its operation.

Experiments with polymer applications with carbon nanotubes showed interesting results. According to vibratory acceleration data, epoxy resin samples with CNTs had only two natural frequencies. Due to the fact that vibration acceleration characterizes the force dynamic interaction of the elements inside the unit, which caused this vibration, this can be the direct evidence that the presence of CNT increases the damping characteristics at the high-frequency domain. It may be noted, that there will be an increase in strength of the cured CNT-epoxy resin system and durability of the possible structure with it inside a composite unit under vibration conditions. When using wavelet transforms we also see an obvious difference in amplitude and splashes spread during comparison of two CWT pictures. It is concluded that the wavelet transforms could be used for better understanding of the integral statement of an object with CNT when using stationary and non-stationary signals.

Lack of research on the specific type of metal-polymer-metal sandwich composite structures vibration characteristics, their failures, and life forecast provided the opportunity to investigate this in detail. Implementing the developed methodology in experiments with MPM sandwich samples showed the same tendency as for the previous objects of study.

The method of scanning laser vibrometry was used for the experimental determination of natural frequencies and modes of oscillations. For the numerical modal analysis, the finite element method is used. The material model is a layered composite with isotropic linearly elastic layers and metal layers. The task of identifying the material model is considered as the problem of minimizing the discrepancy between the calculated natural frequencies and the experimental ones. To solve it, the quasi-random search method was used. The developed method can be recommended for the determination of parameters of material models for calculating modal characteristics of polymer-metal sandwich sheets and metallic mono-materials composite products.

The experimental modal analysis (EMA) was performed to obtain data about the natural frequencies and modes of oscillation, necessary for the subsequent identification of the computational model. Modern EMA analysis allowed to obtain not only high accuracy data on natural frequencies but also to determine forms of oscillations with high spatial resolution. Calculated and experimental values of the natural frequencies were corresponding to the same own forms. In the present work, a comparison of the calculated and experimental eigen forms was carried out on the basis of an analysis of their animation representation.

For the construction of the finite element model, the finite elements of a volumetric body with the option of a layered body were used. It should be noted that these elements provide modeling bulk bodies and can be used to simulate real future structures. In addition, the use of the layered body option allows simulating layered bodies, in particular, composite materials. Imitation of possible operational loading was performed until unstable conditions were detected and further until the destruction of the object.

Modal shapes of five-layered metal-polymer-metal sandwich samples were very similar in connection with translocation on frequencies. This gives us the right to make a judgment that the experimental results were reliable. Further experiments have proved the fact that the change of vibration speed picture became enough predictable for the future forecast. The condition of two MPM samples with different composition was checked by lock-in thermography testing, before and after cyclic loading. The proposed vibration method was simplified in terms of reliability.

The simplified method of obtaining amplitude response in combination with using Fourier and wavelet transforms showed the possibility for minimizing the hardware and software requirements. As an example, from this simplified system, it was noted that a conventional three-layered sample spectrogram has higher values of vibration velocity than spectrograms after 100 000 and 300 000 cycles. In spite of lower amplitude rise in time in comparison with the previous state, it can be seen the increasing sub-harmonic activity with cycle load after each iteration. That is a direct sign that during use a more rapid failure under high vibration conditions is possible.

One of this work purposes was to develop a methodology for identifying models of elastic behaviour of polymeric-metal composite materials, based on the results of the experimental modal analysis using the example of laminated metal-reinforced samples. According to obtain results this aim was achieved.

Another overall conclusion for MPM sandwich composite structures is that the percentage ratio of certain material dictates its behaviour. In other words, more percentage of the metal inside the construction shows more metal behaviour of the MPM composite as homogeneous substance. The opposite is true as well – more polymer shows more inhomogeneous behaviour. There is a significant amplitude increase at the average frequency spectrum in combination with high damping of all other frequencies in the range from approximately 1180 up to 3050 Hz for this type of MPM composites. The data obtained from experiments with composite blades might give the possibility to use it as a diagnostic sign of unstable operation condition of the structure.

A part of up to date information about practical and theoretical areas of damage control monitoring of aircraft elements made of composite materials was combined elaborated and researched. Most parts of the practical and theoretical analysis of modern NDE and SHM methods for the aircraft composite material elements was done. Experiments with composite honeycomb structures helped to test the algorithm theory. Experimental data obtained on different composite structures also provided information for further research. The testing results of the experimental procedure on the reference honeycomb structures, as expected, were the reduction in amplitude of certain frequencies and damping increase at the resonant (natural) frequencies. Experiments with aircraft composite blades, CNT epoxy resin samples, and MPM sandwich composite samples provide information about its vibration properties and proved earlier presented statements.

It can be stated, that there is a possibility to identify the vibration parameters that determine further operational airworthiness. The acoustic properties of composite materials were researched to understand the integral picture of the object during the operation. It should be mentioned that hardware and software complex can be used to defect signatures searching, and composite structures control. Data which was received after the test series (using components with a different operating time) indicates that with a sufficiently frequent maintenance process, the damage growth with time is predictable enough to detect in advance failure conditions. The importance of the approved technique can be divided into two main parts: using the hardware and software complex for the detection of the state before failure condition state during the operational control and using hardware and software complex as a quality control complex during composite materials production.

High requirements for future advanced composite materials dictate strict regulations of such materials in operation. For safety reasons and to ensure the operational stability of an aircraft or vehicle or an element during the life-cycle the effects of damages were investigated by using a special approach and data processing technique. Experimental models and experimental data were used to investigate structural damages of modern composites (including composite materials with carbon nanotubes, and metal-polymer-metal composites). This will be helpful to predict their remaining capabilities. The research will also help to create new methods of vibration analysis for diagnostic of the aircraft operational elements, made of composite materials.

5.2 Future recommendations

Based on the findings in this research, where several techniques were used to investigate the behaviour of modern composite structures in the the postproduction period and operation, improvements could be made in future studies by considering the following recommendations.

1. The wavelet transforms in combination with Fourier in vibration analysis of modern composite structures can give viable information about their integral condition in operation. This kind of vibration testing can be used where individual properties are taken into account for aircraft composite element lifespan analysis.

2. Improved loading conditions can be used where both quasi-static and dynamic loading scenarios can be used to challenge composite material object mechanical integrity for experimental and post-impact analysis.

3. Mathematical modeling representing vibration properties (shapes, amplitudes, resonance frequencies) in combination with Fourier and Wavelet analysis can be used for further detailed investigation in this field.

Further research can be connected with the collection of statistical information, experiments with other objects made of composite materials (MMC, CMC, etc.) and optimization of equipment for future operational control and diagnostics. By today's standards, data collected during experiments can be used in neural network database systems with elements of artificial intelligence. In cases, when the system automatically makes a decision about the possibility of further operation of an element, according to data from global databases. It is expected that the results of the study can not only participate in the composite materials monitoring industry but also be involved in the practical use of future composite materials.

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Appendix A: Author's Publications

Makaryants G.M., Molchanov D.S., Safin A.I., (2017). Defect-caused alteration of a composite unit modal parameters // Measurement: Journal of the International Measurement Confederation. Vol. 95. Pp. 383-388. https://doi.org/10.1016/j.measurement.2016.10.011

D. Molchanov., A. Safin., N. Luhyna., (2016). Damage monitoring of aircraft structures made of composite materials using wavelet transforms. IOP Conference Series: Materials Science and Engineering. Volume 153, number 1. https://doi:10.1088/1757-899X/153/1/01.2016

Molchanov D.S., Safin A.I. Monitoring and diagnostics of composite blades for aircraft engines (2015). International Youth Forum "The Future of Aviation and Cosmonautics for young Russia". p. 38-44.

Author's publications under review (consideration)

Dmitrii S. Molchanov., Heinz Palkowski., Sergey Chernyakin., Panagiotis G. Karagiannidis (2020). Investigation of Metal-based Composites Vibration Properties Using Modal Analysis in Combination with Wavelet Transforms Under Imitation of Operational Loads. Materials and Geoenvironment. DOI: https://doi.org/10.2478/rmzmag-2020-0010.

Dmitriy S. Molchanov., Heinz Palkowski., Ahmed Elmarakbi., Sergei Chernyakin., Panagiotis Karagiannidis (2020). Investigation of MPM sandwich composites vibration properties using modal analysis in combination with wavelet transforms under imitation of operational loads. Measurement.

Molchanov D., Elmarakbi A., (2020). Integral state monitoring of composite aircraft blades using wavelet transforms analysis. Measurement.

Appendix B: Experiment data for five layered MPM composite sandwich.

1. <u>Rx 5l vibration vector comparison5</u>