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D3.1 Mid-term progress report on pilot projects in aerostructures

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PU	Public	**X**
PP	Restricted to other program participants (including the EC Services)	
RE	Restricted to a group specified by the consortium (including the EC Services)	
CO	Confidential, only for members of the consortium (including the EC)	

The overall aim of the AERO-UA project is to stimulate aviation research collaboration between the EU and Ukraine through strategic and targeted support. AERO-UA is focused solely on Ukraine, because the country has a huge aerospace potential but a low level of aviation research collaboration with the EU. Ukraine's aerospace sector spans the full spectrum of systems and components development and production with OEMs, Tier 1 and 2 suppliers, aeroengine manufacturers, control systems manufacturers, R&D institutions, aeronautic universities, and SMEs. This is also reflected in the sector's important contributor to the country's economy (e.g. aircraft production of €1,9 billion in 2011).

Ukrainian aerospace organisations possess unique know-how that can help Europe address the challenges identified in the ACARE SRIA / Flightpath 2050 Report. Furthermore, following the signing of the Agreement for the Association of Ukraine to Horizon 2020 in March 2015, Ukrainian organisations are eligible to participate in Clean Sky 2 and H2020 Transport on the same funding terms as those from EU member states. Equally, genuine commercial opportunities exist for European aviation organisations to help modernise Ukraine's aerospace sector.

The AERO-UA project will achieve its overall aim via four high-level objectives:

1. Identifying the barriers to increased EU-UA aviation research collaboration;
2. Providing strategic support to EU-UA aviation research collaboration;
3. Supporting EU-UA aviation research knowledge transfer pilot projects; and
4. Organising awareness-raising and networking between EU-UA stakeholders.

The AERO-UA consortium is comprised of key EU and UA aviation organisations that will implement WPs closely mapped to the high-level objectives. The consortium will be supported by an Advisory Board involving Airbus, DLR, Min. Education and Science of Ukraine, Ukrainian State Air Traffic Services Enterprise and retired Director of EADS Jean-Pierre Barthélemy.

Table of Contents

1. Introduction

The task relating to the pilot projects between EU-UA partners in the field of aerostructures (Task 3.1) was part of WP3, "EU-UA aviation research knowledge transfer pilot projects" of the AERO-UA "Strategic and Targeted Support for Europe-Ukraine Collaboration in Aviation Research" project.

This work package provides targeted support for EU-UA collaboration in aviation research in the form of knowledge transfer pilot projects to be implemented by the AERO-UA partners. The pilot projects are structured around three key areas relevant to the challenges of ACARE SRIA / Flightpath 2050: **Aerostructures**, Aeroengines and Aerospace Manufacturing.

The task includes the organisation of short-term visits between the EU and UA partners, in order to exchange knowledge, receive training and/or conduct feasibility studies. Where possible, these visits are combined with project meetings and events.

Based on the results of the pilot projects, such as the feasibility studies prepared, it is expected the AERO-UA partners will continue to cooperate either by applying for larger scale research projects or preparing joint publications or presentations.

2. Pilot Project 3.1a: Advanced design of aerospace composite structures

According to the AERO-UA Grant Agreement (description of action), the main goal of this pilot project is to exchange knowledge and training between the EU and UA partners concerning:

- Advanced mechanics of composite materials and structures on micro- and macro-level
- Analytical design and FEM simulation approaches applicable for integral composite structures

UoM's relevant expertise includes FEM-based failure, fatigue and damage tolerance analysis of composite structures, and design of light weight multifunctional structures. Meanwhile, the UA partners – in particular KhAI and NASU - have experience of analytical-based optimization of composite structures strength, stiffness and buckling performances at early design stages, design of hybrid metal-to-composite joints using micro-fasteners concept and thin-wall airframe structures repair using CFRP composite patches of optimal geometry.

The knowledge exchange is expected to involve:

- Composite material and composite structure mechanics (micro- and macro-scale)
- Fast and accurate design and simulation methods applied for composites
- Failure, fatigue and damage tolerance analysis of composite structures
- Innovative experimental methods for micro-scale and macro-scale analysis
- Composite design for future components and structures
- Joining of composite structures (conventional mechanical joints, hybrid joints)
- Stress-strain state, failure initiation and propagation in joints
- FEM modelling of aerospace composite structures
- Virtual design of airframe structures for the entire life cycle

The training is expected to cover:

- Modelling of fatigue behaviour, damage initiation and crack propagations in composite structures
- Multi-scale modelling of composite materials and composite structures
- Design allowables and numerical modelling of airframe structures and joints
- Design of components, tools and facilities for efficient and economic production"

Project consortium members participating in pilot project 3.1a:

- **University of Manchester, Aerospace Research Institute (UoM)**
  - Structural design analysis and optimisation
- **National Aerospace University – Kharkiv Aviation Institute (KhAI)**
  - Multifunctionality (Mechanical and electrical behaviour) of composites
- **Public Joint Stock Company FED (FED)**
  - Multifunctionality (Mechanical and electrical behaviour) of composites
- **National Academy of Sciences of Ukraine, Frantsevich Institute for Problems of Material Science & Pisarenko Institute for Problems of Strength (NASU)**
  - Multifunctionality (Mechanical and electrical behaviour) of composites
- **Technology Partners Foundation (TECPAR) / Air Force Institute of Technology (ITWL)**
  - Test case and validation

Milestones achieved until M18:

- Identification of test case
- Preliminary model
- Final selection of analysis types to be performed
- Multifunctional testing
- Modelling of electrical conductivity

- Full model analysis of the provided test case
- Optimisation leading to design changes
- Implementing SHM results for design changes

Milestones planned M19 - M36:
- Publishing the results

2.1 Background to the pilot project

A key purpose of Pilot Project 3.1a is to perform Finite Element (FE) design analysis of aerospace composite structures to accelerate product innovation. In this regard, carefully selected case studies were performed / conducted to analyse the design parameters at various (micro and macro) scales for multifunctional composites and improved airframe light weight structures which can be incorporated into pilot projects 3.1b and 3.3b.

Within the pilot project two topics are being investigated, both involving the use of Finite Element Method (FEM).

Topic 1: Polymers reinforced by complex fibre architectures for multifunctionality – electrical conductivity and strength ("PLATFORM")

One selected topic of the pilot project is to develop and validate strategies for Finite Element Model (FEM) simulation of Multifunctional Composites (MFCs). This topic investigated achieving multifunctionality in composite materials by designing complex fibre architectures (woven, weft-knitted, etc.) with novel combinations of reinforcement fibre materials and strategies for simulating the multifunctional composite. In multi-functionality, a combination of mechanical characteristics and electric and thermal conductivity was the main consideration. Combined microstructure and structural simulation were performed by KhAI on complex fibre architecture reinforced polymer composites, provided by NASU (Frantsevich Institute for Problems of Material Science), and tested by NASU (Pisarenko Institute for Problems of Strength).

Polymer composite materials based on carbon fabrics of various weaving schemes have found wide application in the aerospace industry. In terms of specific strength and stiffness, carbon composites are significantly superior to metals, but they have a significantly lower electrical conductivity, which must be taken into account in designing structural elements subjected to direct and indirect effects of lightning strike. At present, there are many ways to increase the electrical conductivity of composite materials and structures made of them, such as the use of carbon fibres with increased electrical conductivity, the introduction of conductive layers in the form of metal nets into the composite structure, modification of the matrix material using conductive nanoparticles, and others. The use of these methods makes it possible to create multifunctional composite materials possessing the necessary combination of mechanical and electrical characteristics.

Carbon fabrics with 3D knitting architecture have some advantages over traditional reinforcement materials, such as high manufacturability, high resistance to out-of-plane loading and also increased transversal electrical conductivity, which allow for effective dissipation and transfer of electrical charge caused by lightning strike. This type of reinforcement materials is more suitable for providing multifunctional properties of structure by selecting appropriate fabric architecture, filament type and modification of matrix material to increase their conductive properties.

The development of such materials requires the availability of reliable methods for determining their mechanical, thermal and electrical properties. At present, the determination of the electrical characteristics of composites is based mainly on the use of experimental methods that provide reliable results but at the same time are not effective for choosing the optimum architecture of material when a large number of variants are required. Obviously, the availability of reliable simulation methods will allow for solving the problem of creating multifunctional composite materials more effectively.

Pilot project 3.1a is focused on the development of methods of design and producing of multifunctional composite materials based on the use of carbon fabrics with 3D architecture and conductive polymer matrix. The first stage of work concerned development of a reliable method for prediction of mechanical and electrical properties of composites with 3D reinforcement, enabling the selection of the knitting scheme with the optimal combination of material properties.

Pilot Project 3.1a has assumed the working name of 'PLATFORM' (Polymers reinforced by complex fibre architectures for multifunctionality).

Topic 2: Simulation informed by Structural Health Monitoring (SHM) acquired data ("SINDBAD")

This topic investigates designing composite structures, i.e. a UAV model by FEM simulation techniques that are enhanced by in-situ measured strain of data acquired through SHM technologies (principally continuous fibre optic strain measurement).

It has been decided that Pilot Project 3.1b [composites SHM] could be used as the case study for this topic and the SINDBAD topic will be incorporated in Pilot Project 3.1b.

2.2 Knowledge exchanged

The following is a list of significant meetings and visits that have progressed Pilot Project 3.1a (composites design):

- Kick-off meeting (11th & 12th October 2016), Hamburg
- Meeting between KhAI and UoM (10th December 2016), as part of British Council in Ukraine funded visit of KhAI to UoM, Manchester
- Teleconference (27th March 2017)
- Consortium Meeting and tour of Antonov (19th & 20th April 2017), Kyiv
- UoM representative visits to NASU institutes: Frantsevich Institute for Problems of Materials Science, Pisarenko Institute for Problems of Strength, Paton Electric Welding Institute (21st April 2017), Kyiv
- Teleconference (6th June 2017)
- Working meeting hosted at UoM (3rd & 4th July 2017), Manchester

The majority of the effort under Pilot Project 3.1a [composites design] has been devoted to identifying specific skills and interests of each partner as well as a challenging project to come to a consensus between project partners as to a specific topic, scope of work, and work share which will yield sufficient research output to generate at least one journal publication and one conference attendance.

Topic 1: Polymers reinforced by complex fibre architectures for multifunctionality – electrical conductivity and strength ("PLATFORM")

Samples of two types of carbon fabric were produced by the Frantsevich Institute for Problems of Material Science at NASU and provided to KhAI for the manufacture of samples for mechanical testing and electrical measurements. Specimens for tensile tests in the weft direction and specimens for electrical conductivity measurement in both warp and weft directions were fabricated with the vacuum infusion method (Fig. 1).

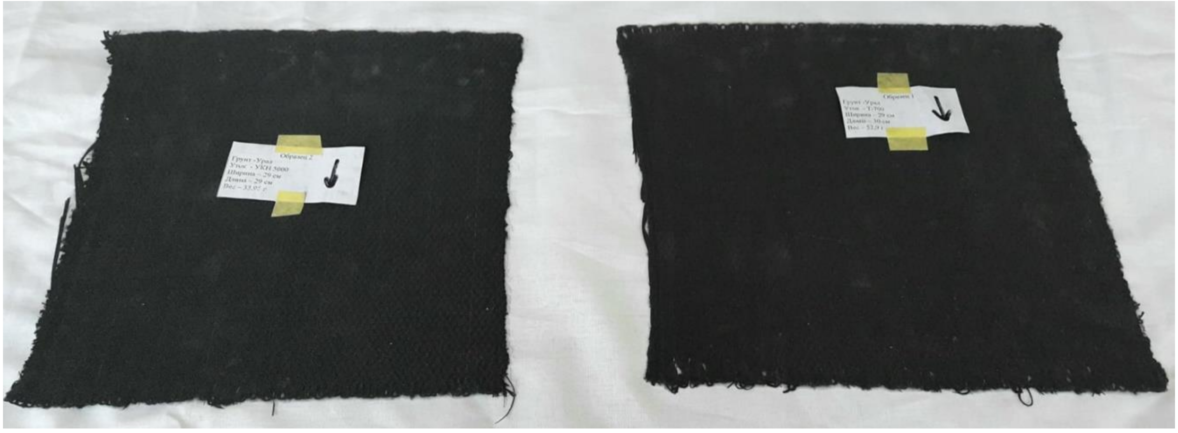


Figure 1. Produced plate made of carbon 3d-fabric

Pilot project 2: Simulation informed by Structural Health Monitoring (SHM) acquired data

UoM has received a model of airframe structure for investigation from TECPAR / ITWL and the model will be used for design analysis.

2.3 Training provided

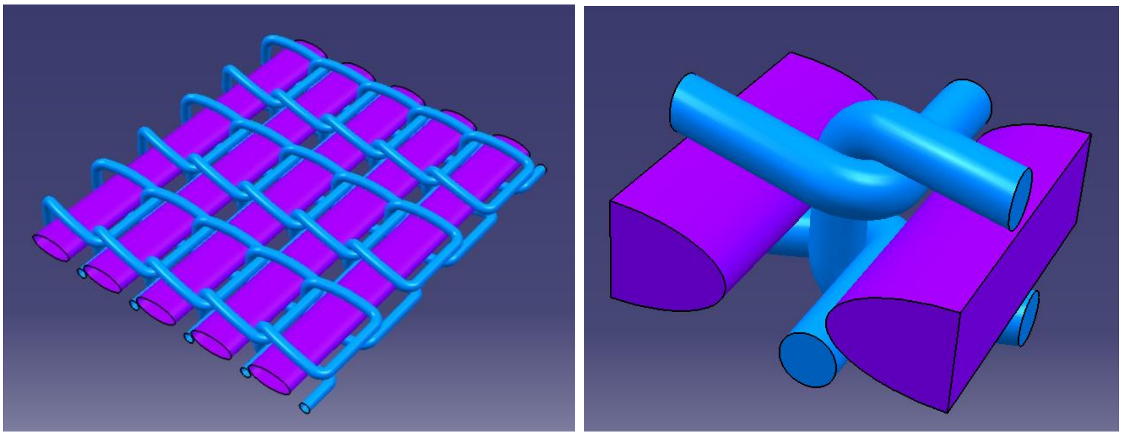
The participants of the AERO-UA Pilot Projects 3.1a, 3.1b, and 3.3b working meeting on July 34 2017 at the University of Manchester or in Warsaw were:

No.	*Name*	*Organisation*
1	Prof Mojtaba Moatamedi	Aerospace Research Institute (UoM)
2	Dr Adam Joesbury	Aerospace Research Institute (UoM)
3	Dr Matthieu Gresil	i-Composites Lab (UoM)
4	Prof Prasad Potluri	Northwest Composites Centre (UoM)
5	Prof Constantinos Soutis	Aerospace Research Institute (UoM)
6	Dr Lina Smovziuk	National Aerospace University (KhAI)
7	Dr Fedir Gagauz	National Aerospace University (KhAI)
8	Dr Valeriy Fadeyev	Public Joint Stock Company (FED)
9	Dr Krzysztof Dragan	Technology Partners Foundation (TECPAR) / Air Force Institute of Technology (ITWL)
10	Dr Michal Dziendzikowski	Technology Partners Foundation (TECPAR) / Air Force Institute of Technology (ITWL)
11	Dr Iryna Bilan *(via Skype)*	Frantsevich Institute for Problems of Material Science (NASU)

2.4 Scientific results

Topic 1: Polymers reinforced by complex fibre architectures for multifunctionality – electrical conductivity and strength ("PLATFORM")

For simulation of mechanical and electrical behaviour of 3D reinforced plastics a CAD-model of fabric was built using passport data about knitting scheme (see Fig. 2). Filaments of "background" and weft were modelled as solid bodies with average cross-section size.

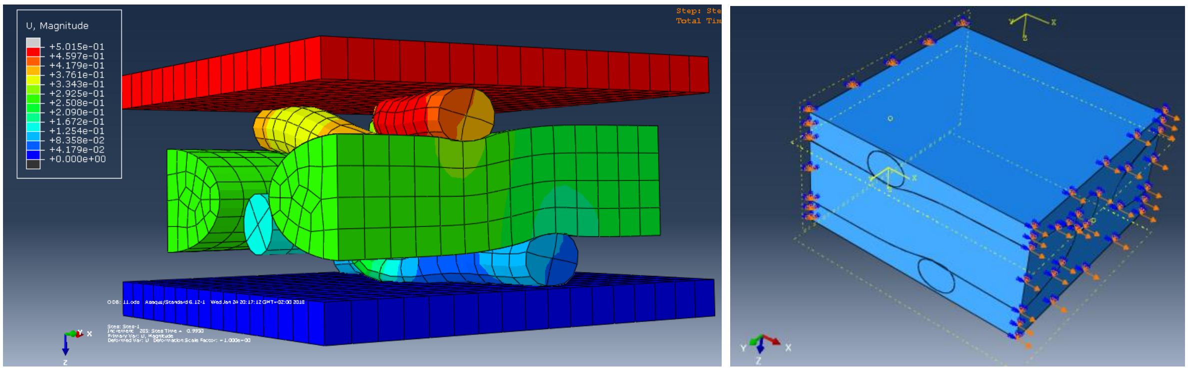


(a) (b)

Figure 2. CAD model of 3d-fabric (a) and representative element (b)

For further simulation of mechanical and electrical behaviour of 3D reinforced composites it was necessary to take into account deformation of fabric during processing that causes a change of material thickness from about 1,53 to 0,98 mm. In order to solve this problem, the process of deformation of the fabric under vacuum pressure was simulated using FEM (fig.3). The filaments of the fabric were modelled as elastic bodies with transverse and shear moduli of elasticity tending to zero. After simulation deformed mesh was imported in CAD system to create CAD-models of deformed materials.

The obtained CAD-models of 3D reinforced plastic representative elements were used for simulation of the material's mechanical properties and electrical conductivity using unit-cell approach with FEM in Abaqus system.



(a) (b)

Figure 3. Simulation of 3D fabric deformation under vacuum pressure (a) and resulting CAD-model for simulation (b)

For determination of filaments mechanical and electrical properties in all directions with account of local fibre volume fraction, known relations of micromechanics of composite materials and percolation theory were used. As a result, numerical values of elasticity moduli and failure stresses in warp and weft directions, Poisson ratios, and also electrical resistivity of 3D reinforced plastics were obtained.

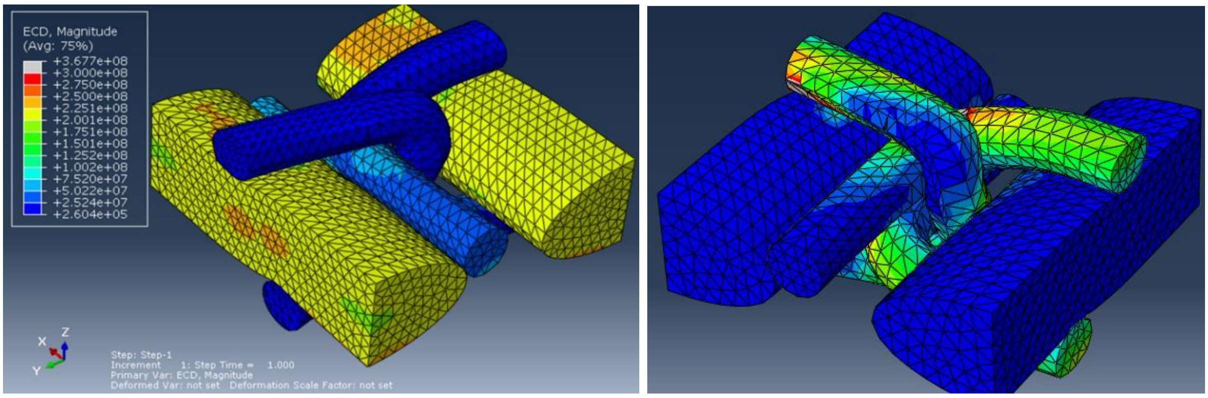


Figure 4. Electric current density in weft and warp direction of 3D fabric cell

Mechanical tensile tests were performed using a universal tensile machine. A video extensometer system Mercury-RT was used for determination of specimen strains during loading (Fig. 5). As a result of testing, elasticity moduli and failure stresses of materials made of two types of 3D fabrics were obtained.

Figure 5. Mechanical testing of specimens

Electrical resistivity of materials was measured with an RLC-meter under current frequency 1 kHz. Ends of specimens were clamped between brass bushes to achieve better electrical contact (Fig. 6). Electrical resistivity of materials made of two types of 3D fabrics was obtained during the experiment.

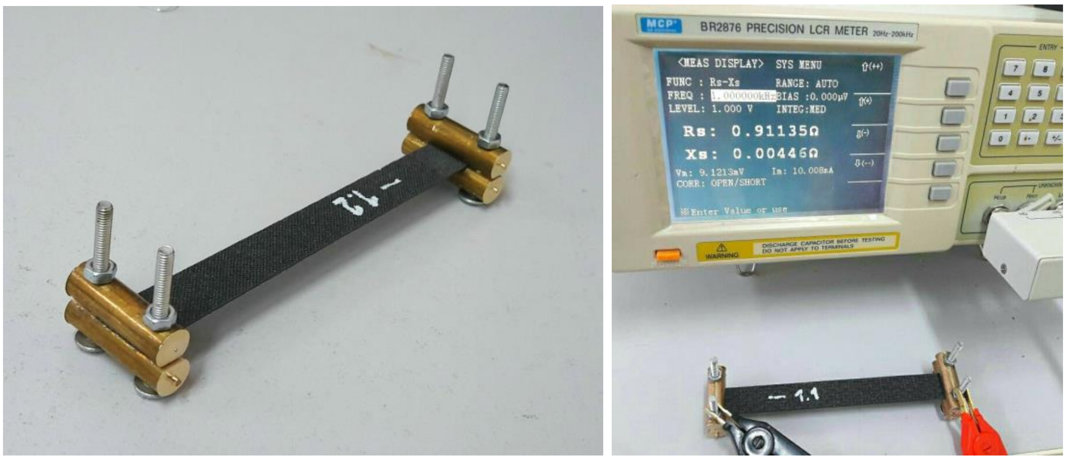


Figure 6. Electrical resistivity measurement

During analysis of the obtained results, the reliability of the proposed method for predicting the properties of materials reinforced with 3D fabrics was evaluated. The mechanism of material failure was analysed and this analysis forms the basis of the recommendations for modifying the fabric parameters to increase the strength of the material given.

Topic 2: Simulation informed by Structural Health Monitoring (SHM) acquired data ("SINDBAD")

The airframe structure model provided by TECPAR / ITWL is still under investigation by both UoM and TECPAR / ITWL.

3. Pilot Project 3.1b: Aerospace composite structural health monitoring system

According to the AERO-UA Grant Agreement (description of action), the main goal of this pilot project is to conduct a feasibility study for an aerospace composite structural health monitoring system using a network of embedded sensors – developed by TECPAR / ITWL – for application in Ukrainian aircraft. The project will examine issues such as: composite structure manufacturing, determination of failure mode detection and optimisation of technology for embedding sensors in the composite materials structure at TRL 5 and higher.

Embedding sensors in a composite structure can increase the reliability of its operation. However, it may adversely affect the structural properties of the composite. An additional challenge will be linked to the use of sensors for monitoring repairs of composite patches bonded to metal structures. The project will address these issues by developing manufacturing technology guidelines for smart composite structures with self-diagnostic capabilities. Furthermore, the feasibility of preparing a technology demonstrator will be considered e.g. a Ukrainian aerospace composite structure containing an embedded sensor network for structural health monitoring.

Project consortium members participating in pilot project 3.1b:

- **Technology Partners Foundation (TECPAR) / Air Force Institute of Technology (ITWL)**
  - Coordination, development of the PZT guided waves, passive SHM system development
- **University of Manchester, Aerospace Research Institute (UoM)**
  - SHM of composites monitoring based on FBG sensors
- **National Aerospace University – Kharkiv Aviation Institute (KhAI)**
  - FOS and Sensors integration with composite structure
- **National Academy of Sciences of Ukraine, Paton Electric Welding Institute PEWI (NASU)**
  - Acoustic Emission for damage detection, active system development

Milestones achieved until M18:

- Definition of the project participants' list
- Formulation and agreement between the contributing partners of the tasks to be performed within the feasibility study
- Partners' agreement to prepare the State of the Art portion of the feasibility study in selected areas
- Preparation of partners' input for the project meeting held in Kiev (April 19-20, 2017)
- Preparation of involved partners' input for a working meeting of Task 3.1 pilot projects, which was held at the University of Manchester (July 3-4, 2017); during the meeting objectives for the SHM study for composites structures were defined (facility tour included a short presentation of the SHM capabilities)
- Preparation and delivery of the State of the Art
- Contribution of the Merging Partner's to the State of the Art description, discussion and agreement on the final version of the document
- Preparation of the partners' input for the project meeting held in Kharkiv (May 30 – June 1, 2018)

Milestones planned M19 - M36:

- Discussion on the common case study to be followed by the involved Partners
- Preparation of specimens for the study
- Experiments on the specimens using guided waves
- Experiments on the specimens using Acoustic Emission
- Preparation of the summary of the results and conclusions from the Pilot study

3.1 Background to the pilot project

One of the **basic technical challenges** of our time is ensuring a high **safety level with minimal costs** of operation of machines and the civil infrastructure. This is particularly important in the case of transportation, especially in the aerospace industry, as well as in many other industries, e.g. in the energy sector, where the loss of structural integrity can cause severe injuries or death of many people or high material losses.

Currently, in order to prevent the development of damage to critical level, especially in the case of aircraft or critical infrastructure in the power, petrochemical or mining industry, various non-destructive testing (NDT) methods are used. Besides methods based on visual assessment of the surface of the inspected structure, e.g. with use of liquid penetrants or magnetic powders indicating surface discontinuities, the most commonly used NDT techniques are: ultrasonic testing (UT), eddy current testing (ET) and thermographic testing (TT). UT and TT methods can be used in particular for the detection and evaluation of subsurface damage, e.g. debonding or delamination of composite structures.

Non-destructive inspections are crucial for the current system of ensuring the safety and reliability of aircraft and industrial infrastructure [1,2]. However, their use is associated with some limitations, e.g. the inspected object needs to be removed from service for the time of the inspection. Furthermore, most advanced NDT methods are time consuming which contributes significantly to operational costs, especially for the inspection of components of complex geometry or hard to access hot-spots. In some cases, their use causes a danger to the health of persons performing the inspection, e.g. for inspections of wind turbine blades, other power or petrochemical infrastructure.

In order to reduce operating costs, as well as to increase safety, extensive research has been carried worldwide on the development of Structural Health Monitoring (SHM) systems. SHM systems are supposed to work autonomously and provide continuous assessment of the structural integrity. A variety of sensors and measurement methods have been applied for SHM thus far [38]. Changing the philosophy – from periodic NDT inspections to continuous structural integrity monitoring – would greatly improve the safety, especially for hard-to-access critical hot-spots or elements subjected to high loads or operated in an aggressive environment. Ultimately, SHM systems will become components of the so-called Health and Usage Monitoring Systems (HUMS) which will allow to assess the remaining lifespan of a structure, taking into account its individual operating conditions, e.g. loads spectrum of wind turbine blades and structural components of aircraft, as well as their current condition. This could reduce the number of unscheduled inspections and overhauls, which increase the maintenance costs.

There is no single, universal method allowing for detection and assessment of damage of any kind [1, 39]. Therefore, SHM systems are developed based on different kind of transducers and signal analysis methods, in order to enhance their efficiency in detection of damage of a given type. Within the Aero-UA project, different SHM technologies are involved, based on expertise and capabilities of the project partners.

3.2 Knowledge exchanged

The following knowledge was shared among the partners by the mid-point of the project:

Partner	***Knowledge shared***
Paton Electric Welding Institute at NASU (UA)	*Acoustic Emission (AE) based SHM*
TECPAR / ITWL (PL)	*PZT sensors for SHM applications*
KhAI (UA)	*Technology of FBG sensors integration with composite structures*

3.2.1 Acoustic Emission for evaluation of structural state – new generation equipment for AE based SHM – contributor: E. O. Paton Electric Welding Institute at NASU (UA)

Background of SHM introduction in Ukrainian industry

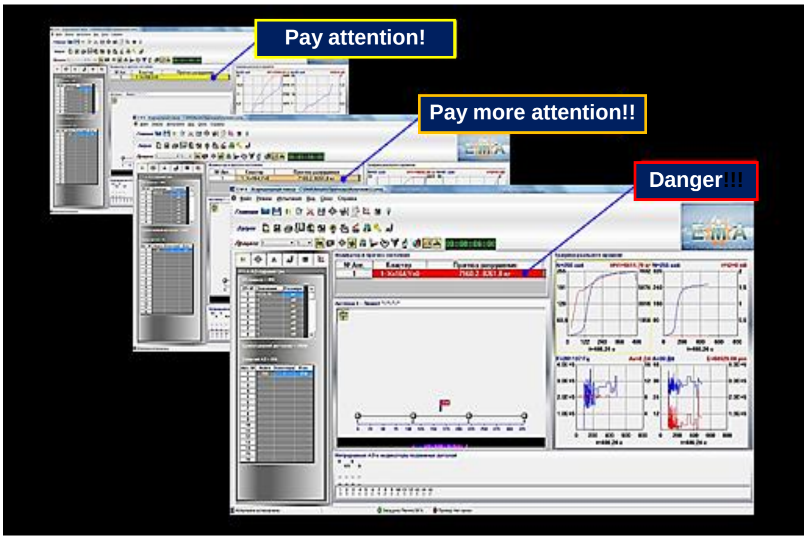
The idea of development and introduction of systems of continuous monitoring of technical state of chemical production facilities of the OJSC Odessa Port Plant (OPP) emerged as far back as in 1990. By this time, construction and mastering of design capacities of all the plant facilities was completed. The main purpose of the plant is manufacture and export reloading of chemical products of its own production and products of other chemical enterprises in Ukraine and Russia. At the same time, the plant was successfully operating two large-capacity ammonia production units, and later, in connection with the need for expansion of production volume due to favourable world chemical products market and the plant's good geographical location, three such units, two units for carbamide production, and complexes for ammonia, carbamide and methanol reloading were built. The ammonia reloading complex included four large-capacity storage tanks with a total design storage capacity of 120,000 tons of liquid ammonia. These were exactly the structures where development and introduction of systems of continuous monitoring of technical state of OPP objects began in 2001 to ensure their safe operation took place.

By the end of the 1980s, social pressure appeared to fundamentally improve the ecological condition of the regions by closing potentially hazardous chemical enterprises. Odessa held a referendum on closing such productions in OPP. Considering that this was already after the accidents at Chernobyl NPP and Jonava "Azot, Ltd." (Lithuania) with destruction of isothermal liquid ammonia storage tanks with a capacity of 10,000 tons, the OPP issue became even more serious. Even though the safety and reliability of plant operation was ensured by application of modern equipment and technologies, strict observation of technological modes of operation of the main production units and reloading complexes, timely performance of overhauling and scheduled maintenance, compliance with labour protection standards and requirements, in the referendum it was decided to close the hazardous productions at OPP.

The plant's management managed to reach a compromise variant: the plant was not closed, but the frequency of filling the liquid ammonia tanks storage had to be reduced twofold compared to the design value, which drastically affected the rhythm of reloading complex operation, leading to disruption of operation of the liquid ammonia suppliers, and to downtime of ammonia-carriers waiting for loading. However, even with reduced storage capacity, it remained Europe's largest liquid ammonia storage facility, located 18 km from the of Odessa with its 1 mln inhabitants and 8 km from the city of Yuzhnii. This fact, as well as continuous traffic of transport ships with liquid ammonia in Black Sea waters, required a closer consideration of the issue of ensuring OPP safe operation.

It became necessary to develop and introduce such a system of monitoring the technical condition of technological equipment, and, primarily, large-capacity isothermal liquid ammonia storages, which would enable application of instrumental methods of continuous monitoring for absence of propagating defects in the material and welds of equipment, detection of initiating defects, monitoring their propagation, as well as simultaneous calculation of safe residual operating life of facilities for ammonia production and storage.

Figure 7. Indication on monitoring equipment screen with presentation of the main parameters, characterizing the



a

Readings of indicator in display upper left corner	Personnel actions
Green band	**Standard operation mode**
Yellow band	**First warning** Attention! At appearance of predicted breaking pressure and it exceeding the working pressure by more than 50% - continue operation
Orange band	**Second warning** At predicted breaking pressure exceeding the working pressure by more than 50% and less – stop operation
Red band	**Emergency situation** Stop operation! After appearance of prolonged intermittent sound signal – urgent load relief

b

storage material state (a), and personnel actions at different readings of hazard indicator (b)

For this purpose, the experience of enterprises and organizations from Ukraine, Russia, Germany, Italy, Finland, USA and Japan on application of methods of non-destructive testing and diagnostics at critical industrial facilities was studied. The approaches to ensuring reliable and safe service of operating structures and constructions were developed in the most comprehensive manner by domestic scientists led by the E. O. Paton Electric Welding Institute of the NAS of Ukraine in a new scientific direction: real-time diagnostics and prediction of structure failure. It was necessary to conduct the required retrofitting and introduce the developed technology at OPP.

The solution to the problem became possible with development of the Acoustic Emission method and instrumentation and modern advances in the field of electronics, computer engineering and information technologies. So, EMA-3 diagnostic system was developed at the E. O. Paton Electric Welding Institute together with Hungarian specialists, realized an algorithm, allowing determination of breaking load of structure materials already at insignificant level of the current load. Depending on material grade, this level can be equal to 20% of breaking load level. Moreover, analysing the material state and having in the data base information on the initial level of this state, the system assesses the structure's residual life.

Fig. 7(a) shows three images of EMA-3 system monitor screen, formed during structure operation. It is interesting to note the presence of rectangular signal indicators, changing their colour successively from green to red, located in the screen upper left corner, and informing the operator about the stages of fracture development and their criticality for the monitored structure (Fig. 2(b)). Signal indicators in "Fracture prediction" line give the ranges of anticipated breaking loads, calculated already at the first stages of structure loading and at each next warning. Continued application of load allows the system to acquire a sufficient scope of information so as to precise the breaking load magnitude and calculate the material residual life. For greater clarity, warnings about the hazard of further loading of structures in keeping with the Table are displayed on the monitor screen (Fig. 7(b)).

Thus, the EMA-3 system can answer the main questions of interest:

1. At what load the structure will fail.
2. For how long the structure will preserve its serviceability with the defects found at the moment of monitoring.

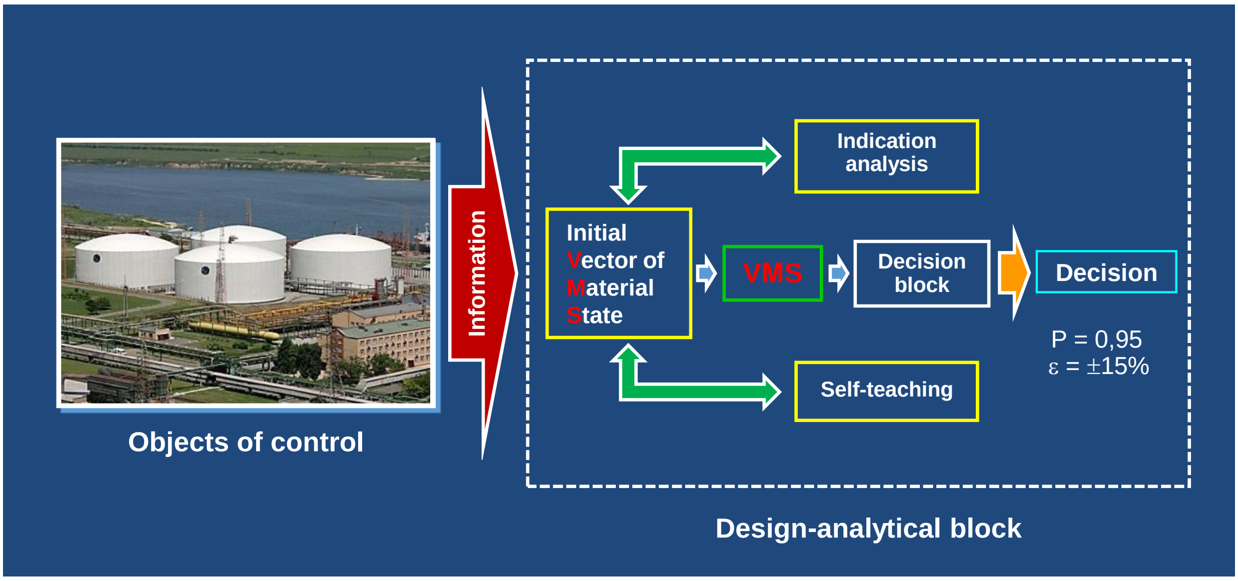


Figure 8. Block-diagram of adaptive image recognition system at structure state assessment

Operation of software and respective program packages (SW and PP) of this kind of systems is based on the principles of the theory of image recognition, when the indications of fracture processes running in materials are formed into the vector of material state (VMS) (Fig. 8). Its further comparison with the training vector and correction of both of them when entering additional data into decision module, allows for generating a system decision on structure material state and predicting this state for the period of time for which the structure will preserve its serviceability. Simple schematic of material state recognition contains two main blocks – transducer and classifier.

Instruments and programs realizing AE technology

In order to implement the technology presented above, instrumentation and special software have been developed, which provide the information, required for further analysis and applying on its basis the theory of structure state recognition at the present moment and its prediction for a certain time interval. Application of modern measuring instrumentation and powerful computer equipment allows realization, with application of this software, of an advanced information AE technology and ensuring its efficient operation. We will consider these subjects in greater detail.

Review materials on software for AE diagnostic systems EMA were first published in 2005 [20]. In particular, basic capabilities of the software for prediction of breaking loads and residual life were described. By that time, technical parameters of monitoring hardware and software, including the prediction, had been confirmed by Ukrmetrteststandard service (former TsSM of Gosstandart of Ukraine). Since then, upgrades and expansion of software capabilities have been successively performed, based on experience of practical application of the systems, interaction with users and taking into account the world experience.

With the development of new programs, expansion of the capabilities of current software version, cardinal change of basic capabilities and their visual presentation in the program, the version number has changed. Publications [21, 22, 33] deal with the most important features of EMA program version 3.9 and concurrent supplementary programs used at periodical inspection and continuous monitoring of industrial facilities.

Note that, similarly to previous versions, the EMA-3.9 program was developed in Microsoft Visual Studio 6 environment to the requirements of Windows SDK which ensures its performance on the basis of all the currently available 32-bit Microsoft operating systems for PC, starting with Windows 95 and ending with Windows 10, as well as 64-bit ones. The program is device-independent and supports application of AE measuring systems of different manufacturers. Also envisaged is the so-called batch data processing mode that allows analysing any format-compatible data derived with application of this or third-party software in AE systems of various types.

Numbering of Version 3.9 was selected proceeding from the fact that 4th generation equipment for AE diagnostics is currently at the stage of final modification and testing. After complete integration of software with the above-mentioned equipment, the upgraded program will receive a new number. Improvements and upgrades made after EMA-3.5 presentation in 2005 make this a fundamentally new software product, as many of the most important internal data processing algorithms and their external visual presentation have changed.

Development of the Internet enabled solving the problem of remote control of monitoring systems, remote assessment of the state of operating structures and prompt decision-making in emergencies. More than 10 years of experience of operation of diagnostic systems with such capabilities, showed that they can form the basis for initiating the next stage of work in the field of ensuring structure safety, the stage of controlling their service parameters. The primary step in the sequence of stages to ensure the reliability of structures and equipment in operation is their continuous monitoring, obtaining a continuous flow of information about their state.

Reference [22] sets out in detail the requirements of AE monitoring systems, which should be incorporated into the software and hardware system, controlling the operation of industrial facilities based on the data on their state obtained during monitoring. These requirements were used for development and current testing, in particular at OPP, of new fourth generation of EMA system instruments, developed, similarly to the previous one, together with Hungarian specialists, who possess substantial experience in this area, acquired over several decades.

New developments of AE instrumentation incorporate the most recent advances in the field of electronics and computer engineering. The instruments are smaller and lighter, support the most modern data transfer interfaces, and have a higher reliability due to absence of mobile components. The system flexibility, based on connecting several instruments, was increased. Earlier, the number of jointly operating measuring modules was not more than two, with the maximum total number of channels standing at no more than 64. Now two main types of instruments, having 4 and 16 AE channels, respectively (Fig. 9), can be connected in any sequence, the total number of simultaneously processed AE channels has been increased to 128, and the number of LF channels, transmitting process data, was increased similarly.

Figure 9. New generation instruments EMA-4 based on 4-channel and 16-channel modules AED-404, AED-416

EMA-3.9 system software was upgraded for interaction with new types of equipment. For this purpose, a program interface was implemented for network connection with instruments, obtaining diagnostic information from them, and issuing control commands. As EMA programs were initially designed for processing data from not more than 64 AE channels and 16 LF channels, changes of the inner processed data structure and file format used were required, with parallel optimization of memory, taken up by the transmitted and stored information blocks.

The user interface was also modified with a view to the possibility of displaying data from each AE and LF channel, selecting them in primary or additional processing algorithms, adjusting and configuring simultaneous operation of channels in complex location antennas.

Thus, a fundamental upgrading of EMA-3.9 program was performed after its presentation in 2013. The new software product was called EMA-3.91.

Given below are the main features of the EMA-3.9 and EMA-3.91 programs, providing new capabilities in processing diagnostic information and transition to controlling the operation of industrial facilities. The EMA-3.9 program combines the interfaces of adjustment of the processes of AE data clustering and filtering. The developed clustering algorithm allows selection of any combination of the following indications characterizing the AE signal: coordinate, amplitude, rise time, duration, oscillation number, velocity, frequency, energy and noise level. This enabled a more detailed classification of detected defects and analysis of AE information as a whole. The obtained AE events can be filtered by the same indicators by which their clustering is performed.

Parameter filtering criteria are set by minimum and maximum values. Simultaneous application of several filtering bands and clustering by the required parameters provides more effective filtering out of process noise and detailed analysis of information. The program enables selection between input parameter filtering, with cutting off of unnecessary information, and filtering performed after event occurrence. Application of these algorithms in practice showed that both the capabilities are useful, but the first should be preferred, as the scope of stored and processed data is reduced, sometimes quite significantly.

Location based on delay matrix enables error minimization and prevention of event coordinates falling into an inadmissible region. The matrix is created on the basis of the pre-determined velocity of sound propagation in the material; at the change of specified velocity automatic recalculation of the matrix is performed, which is then used as the basis for subsequent determination of AE event coordinates.

EMA-3.91 program settings windows contain a new interface with the common table of parameter entering for clustering and filtering (Fig. 10). Changes can be made in real time – both during adjustment and during full-scale testing or continuous AE monitoring.

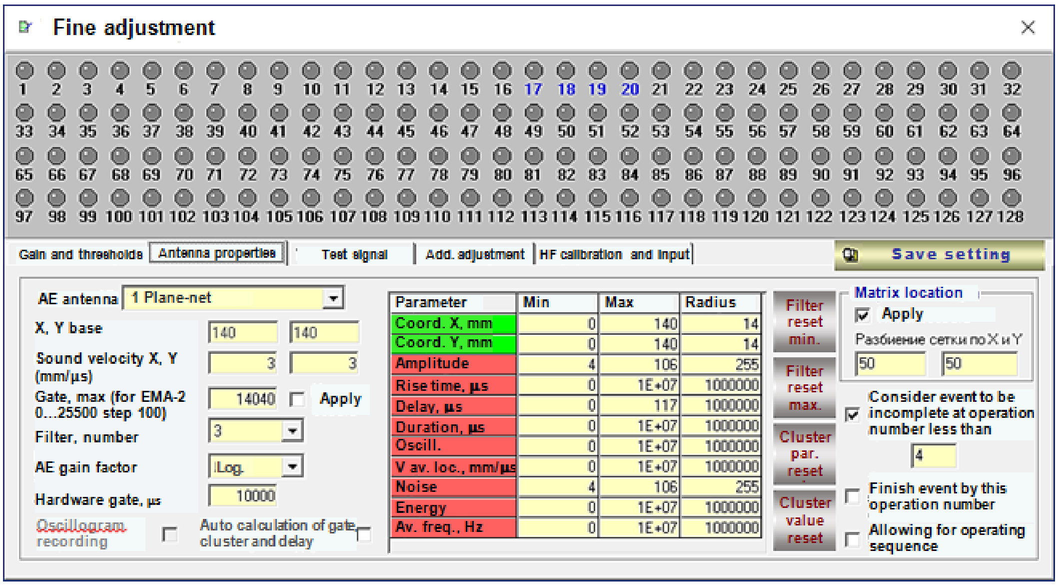


Figure 10. Setting antenna properties in fine adjustment window of EMA-3.9 program: in central part of the window – table with set filtering and clustering parameters, in the upper part – AE activity indicators in 128 AE channels

The "Antenna properties" insert allows for establishing bandpass digital filters for such AE event parameters as duration, oscillation number, time of signal rise to maximum, AE amplitude, average signal frequency, etc. Upper and lower band limits are set. If AE location antenna supports matrix location mode (for linear, planar or cylindrical antennas), matrix parameters in the window can be changed in real time.

One of the features of EMA system software is working not only with acoustic, but also with process information, which is entered into the system in the form of LF parameters: load, pressure, deformation and temperature, etc. Capability of adjustment of the coefficients and calibration functions directly during measurement is implemented. Changes are displayed on real-time graphs, which enables quick selection of the required kind of calibration. In addition, manual entering and extrapolation of LF are provided in the case entering any of the LF parameters into the system by electric or program means is impossible. A possibility of entering current value of LF parameters and their reverse extrapolation during measurement was added. This allows obtaining an LF parameter variation curve of, for instance, current pressure which is either stepped or represented by inclined sections.

There is also the possibility to automatically correct established thresholds of amplitude discrimination after a pre-set time passes (Fig. 11). The above modification is extremely important for the system's autonomous operation during monitoring, as it enables reacting on time to changes of acoustic background without operator intervention.

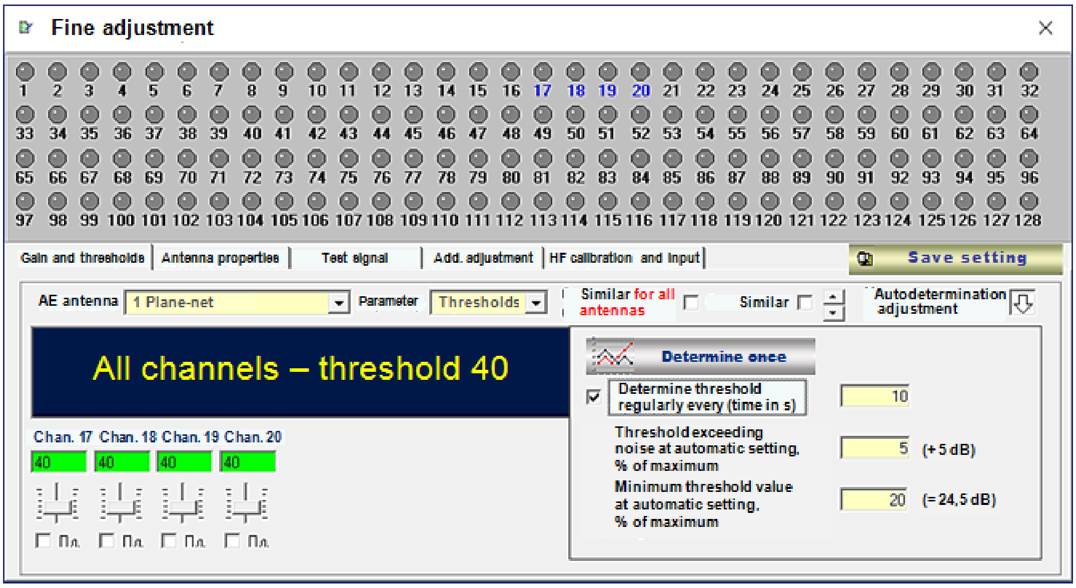


Figure 11. Setting the parameters of automatic determination of thresholds in fine adjustment window of EMA-3.9 program (bottom right)

The information window (Fig. 12) contains a graph showing table data from the information window list. When different content of the list is selected, the graph is automatically updated. Each of the parameters included on the list can be shown on the graph or switched off. The graph type can be point, bar, line, or stepped. Graph position and size are adjustable.

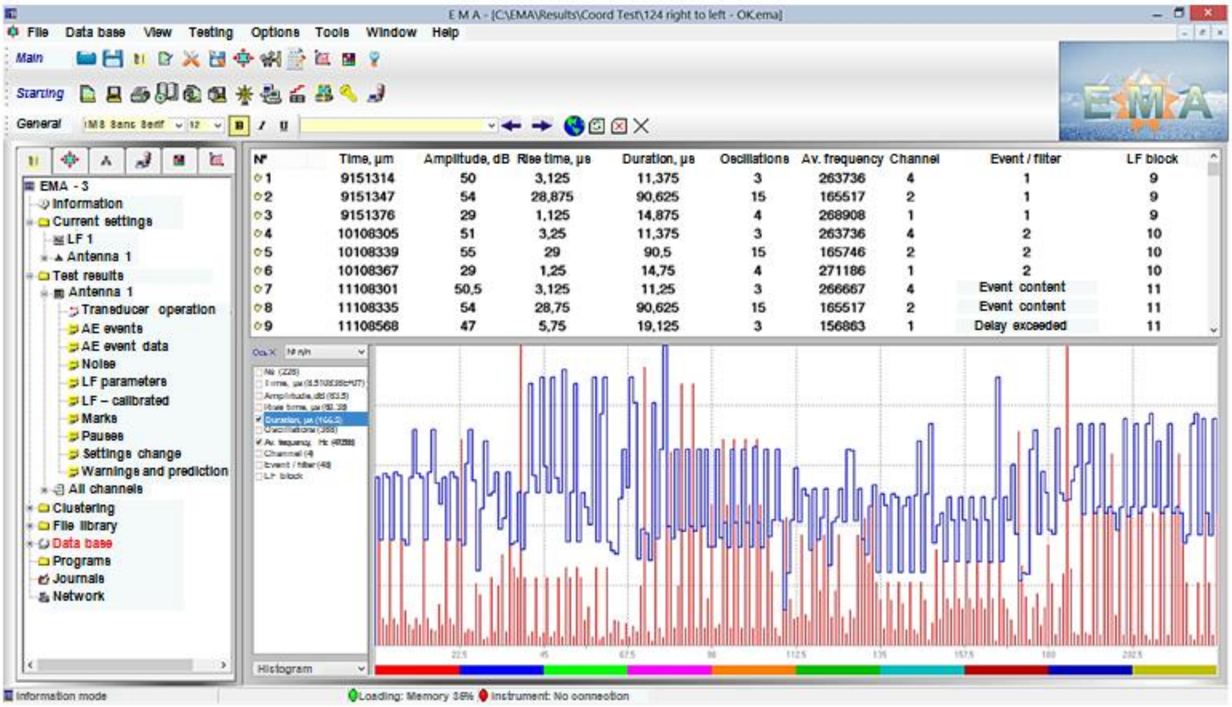


Figure 12. EMA-3.9 program information window with data on transducer operation: in window lower part – the graph, where response time and average frequency are selected as displayed parameters

At table analysis each transducer operation contains information on the AE events to which it referred (if the operation did not refer to any events, the reason for rejection is specified). In the case of rejection of events, the criteria based on which it was performed are indicated in the appropriate table. Considered possibilities allow an essential expansion of system informativeness and performance of complex comprehensive analysis of obtained data. Moreover, errors made by the operator when setting up the system can be easily detected and corrected.

The location screen (Fig. 13) displays both all the location antennas used during AE monitoring simultaneously, and the required antenna, as desired by the user. To improve visibility, a flash appears in AE generation points.

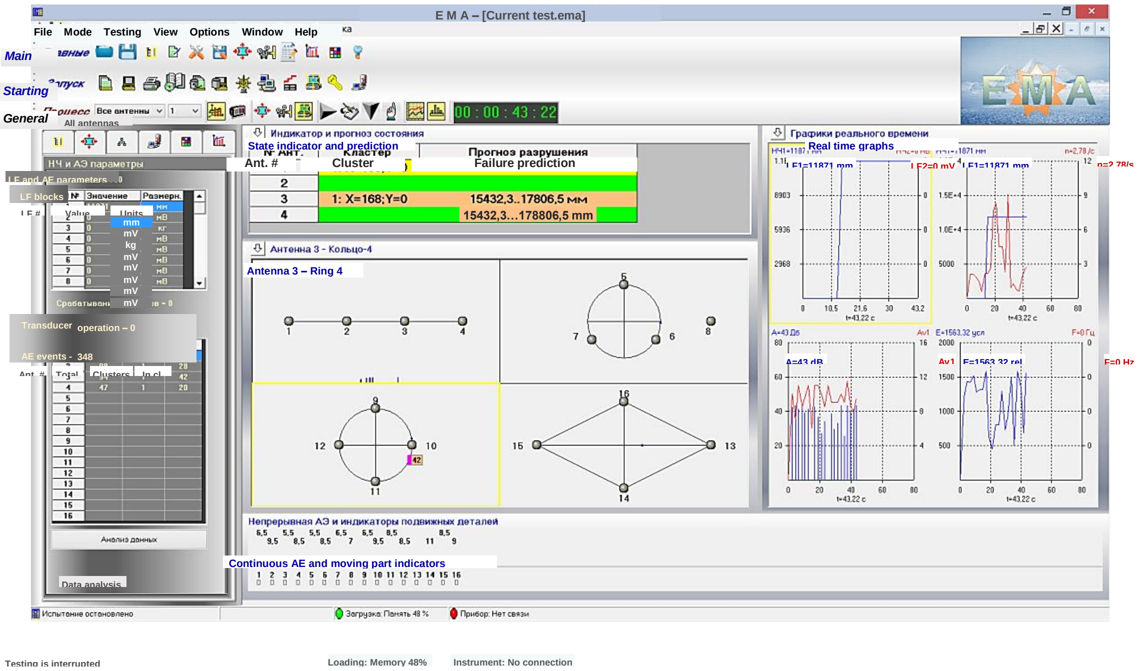


Figure 13. EMA-3.9 program testing window with displaying of 4 location antennas (Screen 1): above location screen – fracture prediction area, left – tables of AE and LF data, right – real-time graphs; below location screen – continuous emission value

The program applies additional methods of data analysis in the graphic form: distribution of AE parameter values by channels and correlation between channels. The data analysis window (Fig. 14, 15) is designed for viewing and additional analysis of obtained AE data, in particular with the capability of automatic real-time updating. Screen 1 (Fig. 13) contains data by clusters and is largely similar to the data in the information window; it enables viewing AE event data by selected antenna clusters and transducer operations associated with them. Screen 2 (Fig. 14) allows for selection and comparison of data in individual AE channels in the form of parameter distribution.

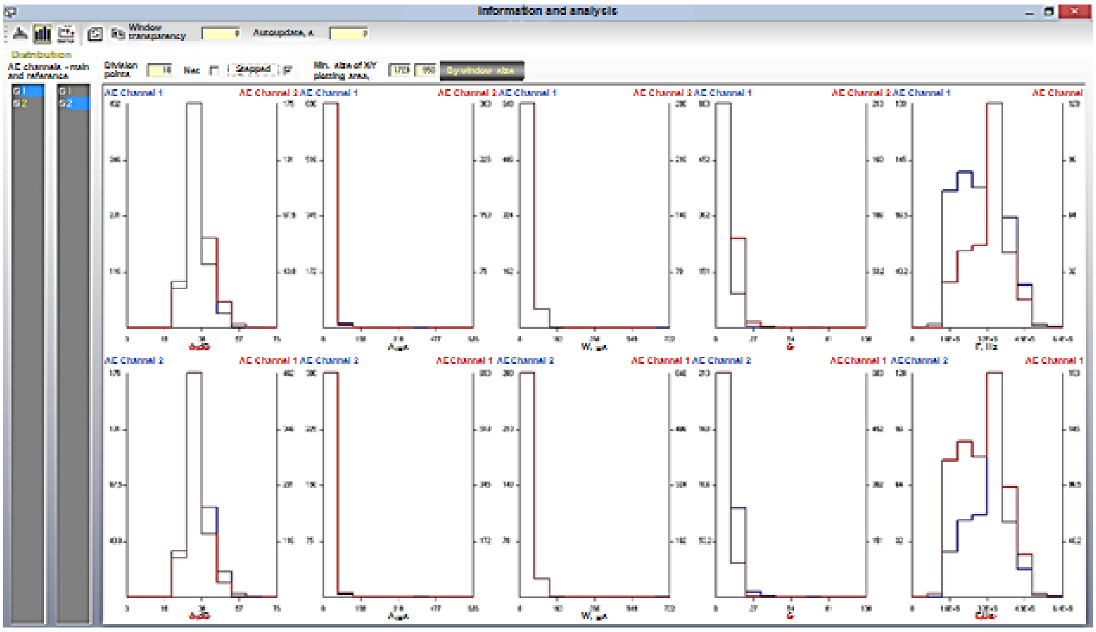


Figure 14. Window of EMA-3.9 program data analysis with graphs of AE data distribution by channels (Screen 2)

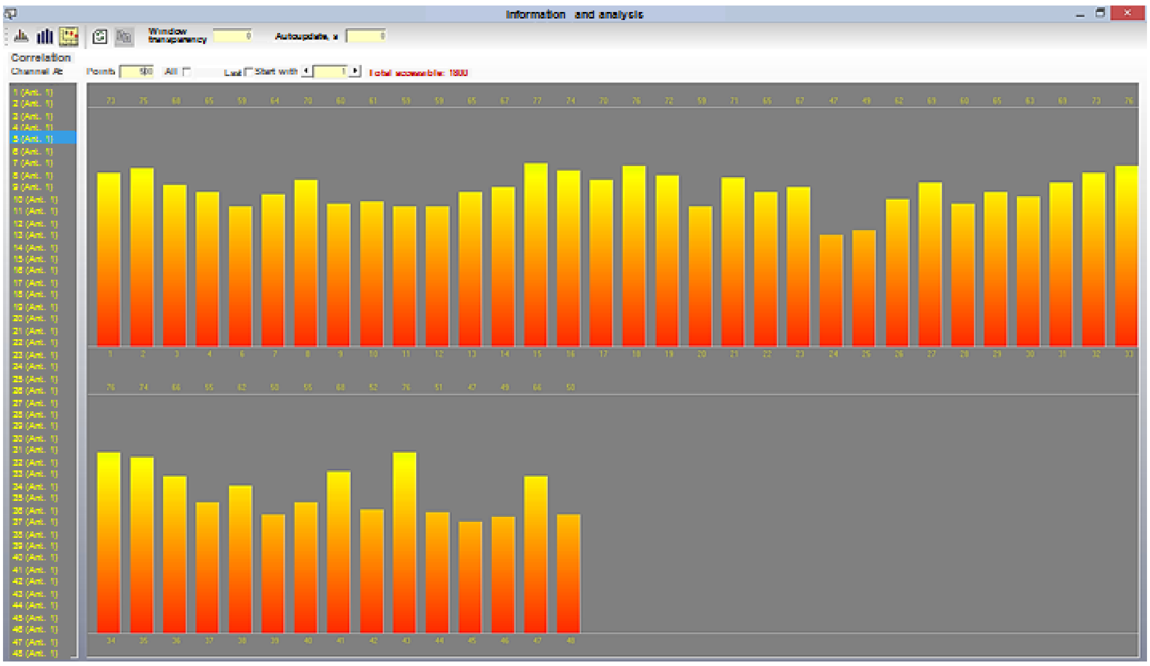


Figure 15. Window of EMA-3.9 program data analysis with graphs of AE noise correlation by channels (Screen 3)

Graph type selection (bar or stepped) and net displaying/hiding are provided.

Screen 3 (Fig. 15) displays a bar graph of the correlation of a specified number of continuous AE data for a selected channel with the other channels.

Experience of EMA system operation in production, in particular, in continuous monitoring mode, showed that automation of repeated and labour-consuming operations is one of the most important objectives. A number of software tools presented above solve some specific automation problems. Unfortunately, it is not always clear in advance what exactly the operations which will have to be automated are, due to the diversity of objects of control, their operating conditions and suggestions made by the staff operating the systems.

For this reason, EMA program Version 3.9 is fitted with built-in system of programming in VBScript language (Fig. 16), which corresponds to the Microsoft specification.

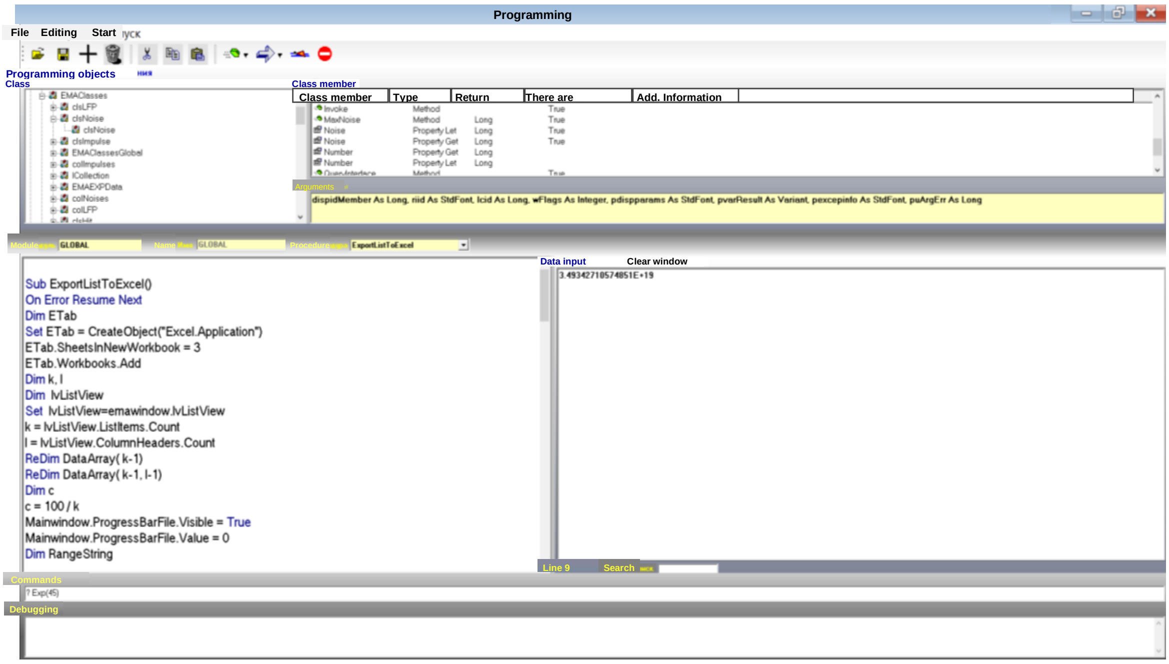


Figure 16. EMA-3.9 programming window: top – object browser; left – code editor; right – output window; bottom – command line and adjustment window

The possibility of further analysis of processed data or of their completely alternative processing is implemented. In particular, it is possible to completely change the algorithm of event formation, their coordinate calculation, displaying features, tabulated and graphic presentation of data, etc. This not only enhances program functionality, but also enables experimenting with data processing, extending the scientific and practical experience gained which will undoubtedly be useful in development of subsequent software versions.

It is noteworthy that a number of the above-mentioned developments and upgrades are the result of close interaction of developers of AE control and monitoring systems of different modifications with their users, performance of joint investigations and analysis of arising comments and suggestions.

Analysis and optimization of methods and algorithms for AE source coordinate location were performed in 2015 with application of new capabilities [22]. Transition to control of complex-geometry objects, particularly with random arrangement of AE transducers, required fast and operative assessment of possible errors at locating AE sources. Previously such assessment was performed experimentally, directly on the object after transducer arrangement, with application of pulsed sounding from a special generator or by Hsu-Nielsen method, based on graphite rod breaking. In EMA system software, verification is performed using automated program virtual testing of location errors for pre-set location antenna configurations (Fig. 17). An undoubted advantage of this checking method is the fact that it can be performed very quickly, and before the start of physical placing of transducers on the object. This way an optimum transducer layout and the most suitable algorithm for AE source coordinate calculation are selected.

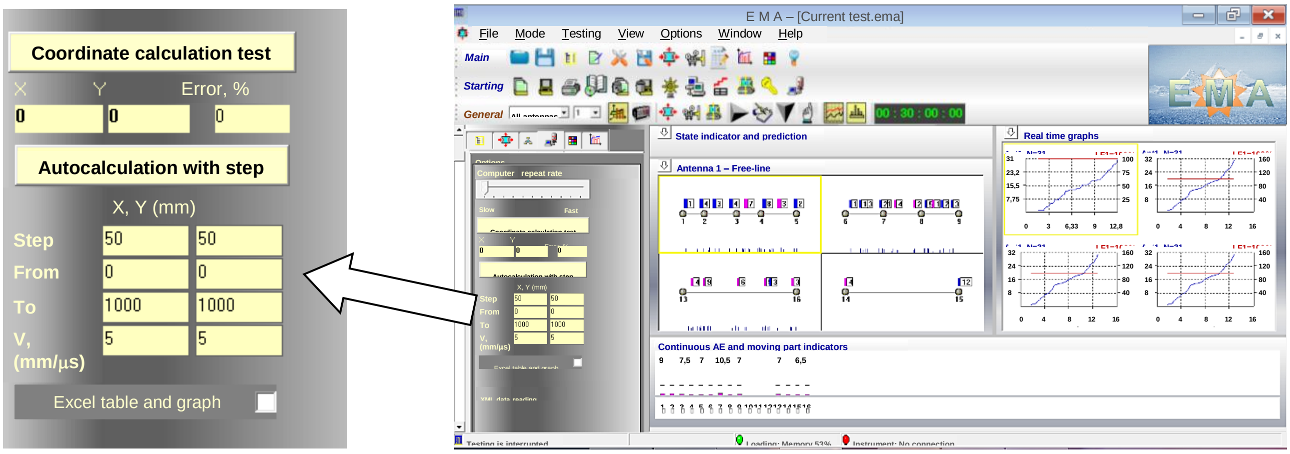


Figure 17. EMA-3.9 program testing window with elements of control of virtual testing of coordinate determination error

The developed system of testing AE source location accuracy allowed for considerable simplification and shortening of the process of AE testing setting up, as well as advance assessment of the reliability of location of AE sources detected during real measurements in certain areas of the object of control. The developed program allows assessment of the range of sound wave velocities for selection of the optimum variant to be used during location that qualitatively improves its accuracy.

Virtual testing allows for quickly checking the currently available or newly created algorithms of AE source location for accuracy and promptly correcting them. It should be noted that the results of such a check were used for correction or complete replacement of location algorithms developed for EMA systems, in cases when virtual testing demonstrated their insufficient accuracy.

The hardware and software tools developed allow for obtaining all the required information from the object of control as initial data for operation of the algorithm of assessment of structure material state at specified conditions of probability of assessment and error. As already mentioned, the following AE parameters can be obtained in real time: signal amplitudes, number of operations and events, event energy, time of signal rise up to maximum, normalized event duration, number of oscillations in the signal and event, frequency characteristics of AE arising in the material; in VMS – also monitored material temperature, stressed state of monitored components and some derivatives of the above parameters, required for completing the full vector.

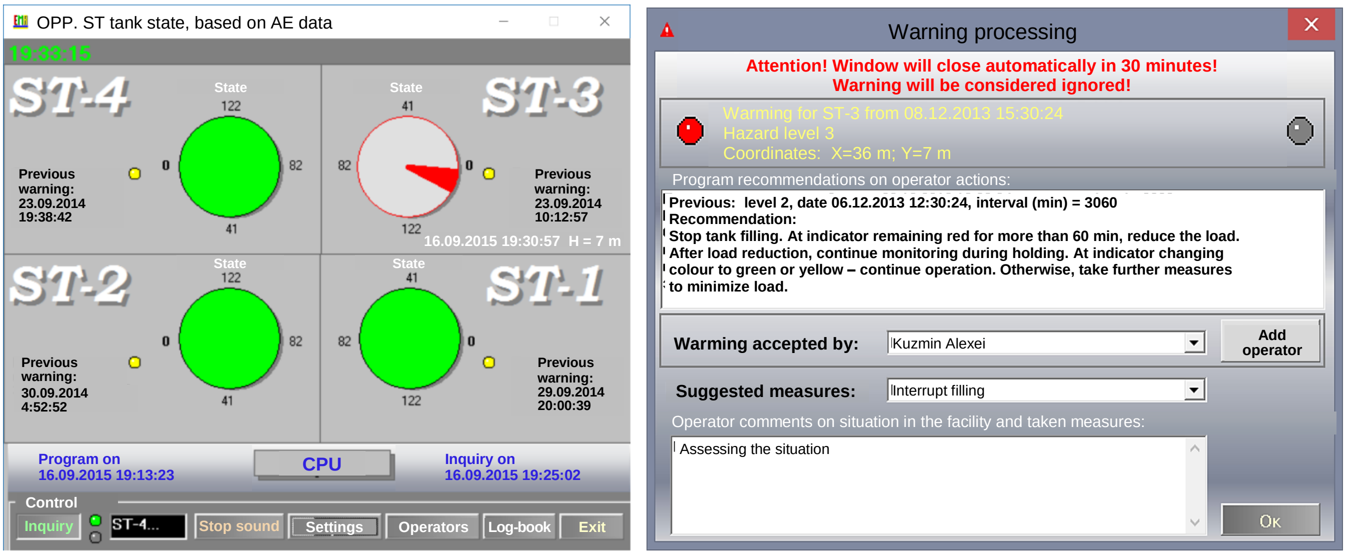
The above additional analytical tools enable complementing the prediction derived with VMS application, by expanded data on specific processes of damage and fracture propagation in structures. Note that fourth-generation EMA systems also allow performing real-time analysis of AE signal oscillograms.

Safe operation management and normalized intelligent advice

The AE technology developed is incorporated as a component into the production process and the monitoring, integrated into the enterprise computer network, complements the currently available tools of following the current state of objects in production. At OPP, considering the company requirements, the management defined a new task: transition from statement of data obtained during monitoring to their application in controlling safe operation of ammonia reloading complex equipment. Instead of a simple indication of the degree of safety of the current state, automatic recommendations on responding to the hazard were provided. This means deeper integration of monitoring into the production structure with intelligent tools for formulating and making decisions on the possibility of further operation and recommended operating modes.

"Normalized intelligent advice" (NIA) is put into practical use in Reference [22]. In the context of production objectives such advice contains analysis of the situation in the object of control and clear instructions on object operation in this situation. In case of danger, such instructions envisage interrupting the structure loading or even its partial or complete unloading, if required; NIA is formulated automatically and in a short time (several seconds) after appearance of potential danger for the object. NIA issuing is accompanied by visual and sound warning about the danger, information about the degree of danger and specific section of the object of control which is in danger (Fig. 18).

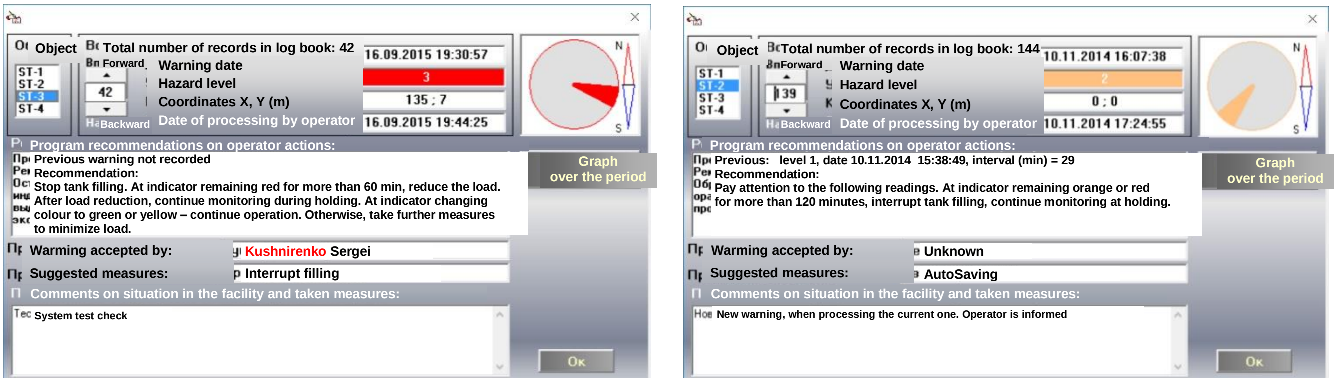
The advice is formulated in keeping with the Table (Fig. 7(b)), based on analysis of not only the current, but also previous data on the state of the object of control, and it is based on many years' experience of operation of this type of objects and their control by continuous AE monitoring systems. NIA is the base for subsequent realization of automated safety management. Its implementation required extensive practical experience in advanced computer technologies.



a *b*

Figure 18. User interface of indicator program for operators when monitoring the state of OPP liquid ammonia storages: a – window with state criticality indicator, right upper indicator shows 3rd level warning: "Danger" for one of the sectors of object of control; b – window for warning processing by operator, which includes "Normalized Intelligent Advice" recommendation

The program automatically keeps a log of accepted warnings (Fig. 19), which is filled in only when the "Demand operator reaction to warning" flag is set.



a *b*

Figure 19. Window of accepted warning log: a – after filling by the operator, b – in the case of autosaving of current warning, when receiving the next

When the log is opened, the window automatically displays the latest entry. To go through the other entries, scrolling through them using "Up" and "Down" arrows is recommended.

The other window elements are designed for displaying data on the warning and its processing. They show the time of the program receiving the warning and finishing its processing by the operator, data on the danger level and coordinates of acoustic activity centre, program recommendations for the situation and measures taken by the operator.

The dangerous sector is displayed in the right-hand upper part of the window with indication of the tank's location, with the button of starting the warning statistics graph for this tank located below it.

Considering that continuous monitoring systems operate for long periods of time, periodically generating warnings about the danger, studying the tendencies of dangerous situations arising is urgent. It enables comparison of generation of a certain warning or their group with technological processes, load parameters, climatic conditions, etc. Earlier it was not possible to perform this analysis automatically. Now acquisition of monitoring statistics is fully automated. Control elements allow selection of the time period during which warning statistics are required and plotting a graph in which the bar colour designates warning level.

Graph plotting is based on data, stored in special files (log-books). Information is processed and displayed in a window shown in Fig. 20. Users can change the period over which the statistics is required by selecting it from a list. The start date is selected by arrows, as well as when pressing a button, which allows automatic calculation of the reported period from the current calendar date. Graph data can be copied using a special button, into a clipboard for the purpose of its further use in, for instance, reporting documentation.

Data for several AE antennas can be stored in statistics files, so that the user can choose whether to display in one graph the data for all the antennas simultaneously or just for one.

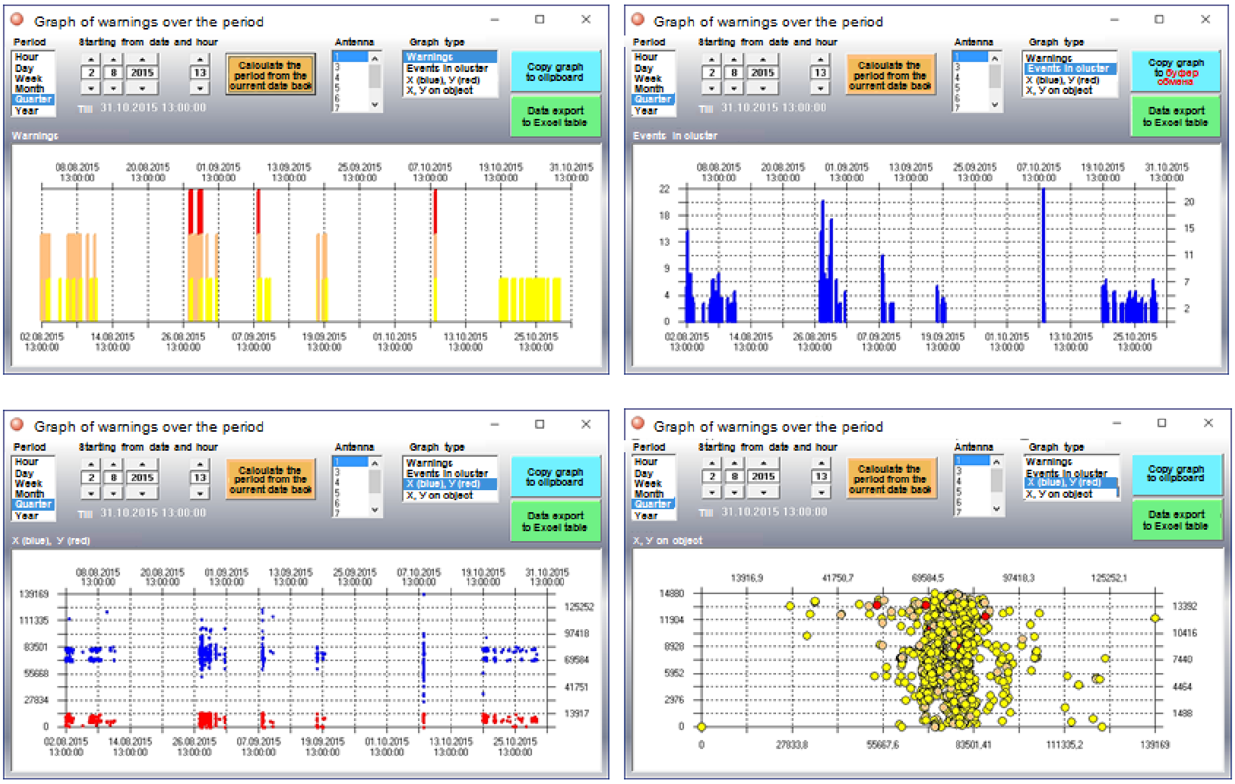


Figure 20. Window of warnings statistics of EMA-3.91 program with different graph types

Data can be presented in 4 different types of graphs.

The "Warning" graph indicates by colours and bar height the warning level at a given moment:

- 1st warning – yellow, bar height of 1/3 of the graph;
- 2nd warning – orange, bar height of 2/3 of the graph;
- 3rd warning – red, bar height takes up the full height of graph;
- 4th warning with greater danger – black, bar height takes up the full height of graph

The graph has no axis of ordinates.

The "Events in cluster" graph indicates by bar height the number of events in the cluster, when receiving the warning at a given moment.

The "X (blue), Y (red)" graph indicates cluster coordinates by points, when receiving the warning at a given moment. The scale along the ordinate axis corresponds to both the X and Y coordinates. For linear antennas just the X coordinates are shown in blue.

The "X, Y on object" graph shows cluster coordinates by circles, when receiving the warning at a given moment the X coordinate being traditionally shown along the abscissa axis and the Y along the ordinate axis. For linear antenna types this graph is shown by bars with the height of each bar representing the number of events in the cluster at the moment when the warning is received.

The warning statistics window is scalable and allows changing the graph proportions and dimensions.

Thus, an up-to-date information technology which allows for performing analysis of the state of structures over a prolonged period with its prediction for the future, determining with pre-set probability the load at which failure will occur, proceeding from accumulated warning statistics, assessing the potentially dangerous sections in the objects of control on the basis of AE monitoring data has now been developed and put into production.

Automation of monitoring and processing of incoming data leads to gradual elimination of the human factor, both from the process of adjustment and monitoring, and, recently, from the process of making decisions on the structure state and measures required to provide its safety. This, in its turn, will be the basis for introducing, in the near future, systems of fully automated safety management, in which the diagnostic data will be used not only for analysis of the state of the object of control, but also for controlling its operation.

In the case of potential danger of failure arising in such an "intelligent" structure, the software will select the optimum loading mode, issue commands to control mechanisms to ensure it, and will monitor its execution. Application of such a technology will allow an essential improvement of operational safety and, in most cases, prevention of failure and possible catastrophic consequences.

In conclusion, it should be noted that:

- prompt development of means of controlling structure material state, particularly with application of AE technology, and the attention given to this issue in many countries of the world, justify expectations of further extensive application of AE technology for development of intelligent structures and constructions that with specified accuracy and probability will themselves provide information about their state and suggest measures to overcome emergency situations;
- continuous monitoring systems, using integrated control methods and, in particular, the AE method, will be ever more widely used in monitoring first hazardous operating structures, and then also in ordinary industrial structures;
- widening of the network of specialized centres for monitoring of operating structures should be anticipated. Such centres will be fitted with highly qualified specialists, and up-to-date digital technologies and communication means will allow them performing remote monitoring and assessing the structure state, being at any distance from the object of control. Control, from labour-consuming and inconvenient, is gradually transforming into more convenient, office technique;

- global tendencies in information technologies allow anticipating further automation of all the available processes of structure state control, including AE monitoring. Priority will be given to technological solutions with application of the most advanced trends in IT development: distributed and cloud computing, use of inexpensive high-speed connection, miniaturization and unification of developed equipment, standardization of data description on the base of HTML and XML standards.

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3.2.2 PZT sensors for SHM applications – contributor: TECPAR / ITWL (PL)

Brief overview of SHM technologies

Studies to use measurements of characteristic features of objects, or to monitor critical areas to prevent catastrophic events have been carried out worldwide for many years now [1,2]. There is no 'one and only' effective method that enables detection or description of each and every damage to the structure. In accordance with the assumptions made by Ch. Farrar [3] there exist the following axioms for the SHM implementation:

1. *"All materials have inherent flaws or defects at some level;*
2. *The assessment of damage requires a comparison between two different system states;*

3. *Identifying the existence and location of damage can be done in an unsupervised learning mode, but identifying the type of damage present and the damage severity can only be done in a supervised learning mode;*
4. *A. Sensors cannot measure damage. Feature extraction though signal analysis and statistical classification are necessary to convert sensor data into damage information;*
   and:
   B. Without intelligent feature extraction, the more sensitive a measurement is to damage, the more sensitive it is to changing operational and environmental conditions.
5. *The length and time scales associated with damage initiation and evolution dictate the required properties of the SHM sensing system;*
6. *There is a trade-off between the sensitivity to damage of an algorithm and its noise rejection capability;*
7. *The size of damage that can be detected from changes in system dynamics is inversely proportional to the frequency range of excitation."*

Structural Health Monitoring is then simply the use of NDI principles associated with in-situ NDI testing of the structure-oriented applications. The main goal of the SHM is thus real time damage detection and from the cost point of view, a decrease of the time required for the inspection [4]. There also exist a few challenges associated with the implementation of the SHM technologies for the aerospace community.

These challenges are connected with:

- Costs of the sensor for potential technology;
- Ease of use and local vs global application;
- Need for validation (similar to NDI);
- Certification (reliability analysis, environmental impact etc.);
- Implementation to the maintenance.

If we move to the use of the SHM in the aerospace application few questions have to be addressed to the potential application of the SHM technologies [5]:

"Validation of the ISHM reliability/capability as a function of time/usage:

- *What damage type, size, and location will be reliably sensed?*
- *What is the expected rate of false-positive indications?*
- *What is the service life of the sensors?" e.g. Durability: 40% of strain gages failing within 15 years (Ware, et. al.) "*

There are exist several SHM technologies which are used for damage detection, loads monitoring, deviant analysis (e.g. vibration), corrosion monitoring. Application for that potential SHM technologies differ one to another from the following point of view:

- Technology readiness level (TRL);
- Maturity of the technology for the real case use (than laboratory application);
- Global vs local application;
- Signal analysis
- Reason for sensing.

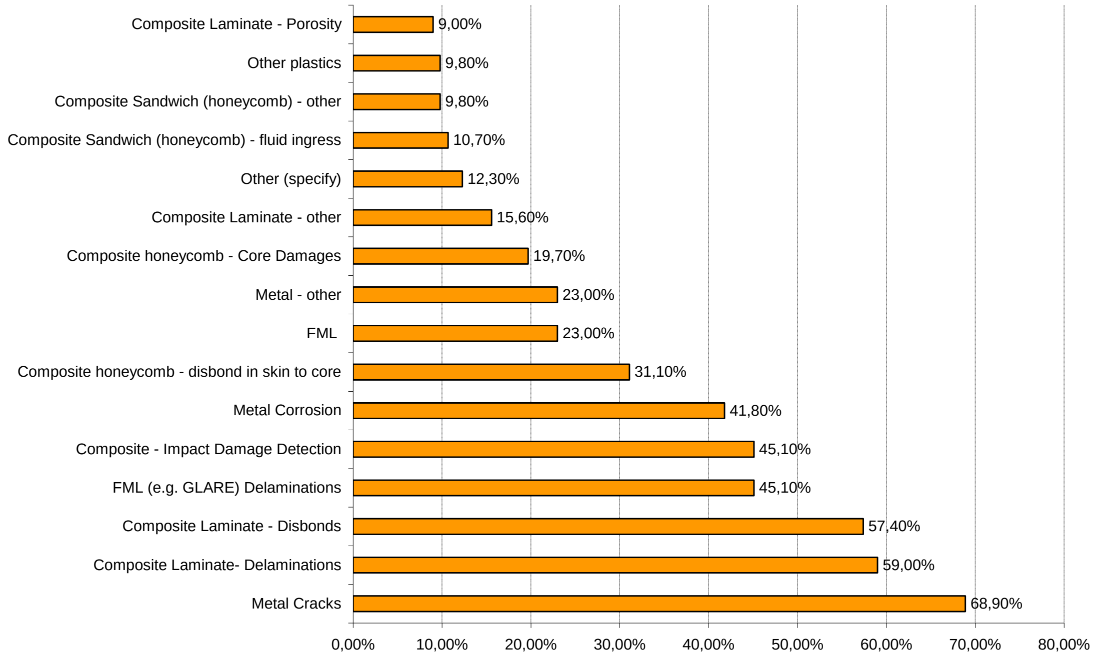

Figure 21. Potential use of the SHM technology

One of the interesting issues from the point of view SHM use in 'real aerospace applications' is to answer the key question – what the main goal for the application such technologies in aerospace components is. This answer is provided by the work done at SANDIA [6]. The Internet survey was addressed to key NDE/SHM personnel including: OEM, manufacturers, airlines, R&D centres, academia etc. Part of the results of the survey are presented in Fig. 21. One of the major applications of SHM is dedicated to fatigue crack detection in the aircraft structure. The consecutives are connected with the composites application what shows potential interest of the diagnostics community in the development of in situ diagnostic capabilities for composites.

The list of the potential SHM technologies for the aerospace application is presented below [7,8].

A. Electrical strain gauges

Sensors used for load monitoring. Well known and established technology for local stress distribution. An established and reliable technique where strain gauges are bonded into the structure of the aircraft.

They are relatively inexpensive, can achieve total accuracy of better than ± 0.10%, are available in a short gauge length, have high primary sensitivity, and have only moderate thermal sensitivity. Recently the new technologies of the printing sensors have emerged. That technology definitely has the best reputation and is the most commonly used in the aerospace community. Because of the large experience the use of that technology on the major problems identified is connected with low durability of the sensor.

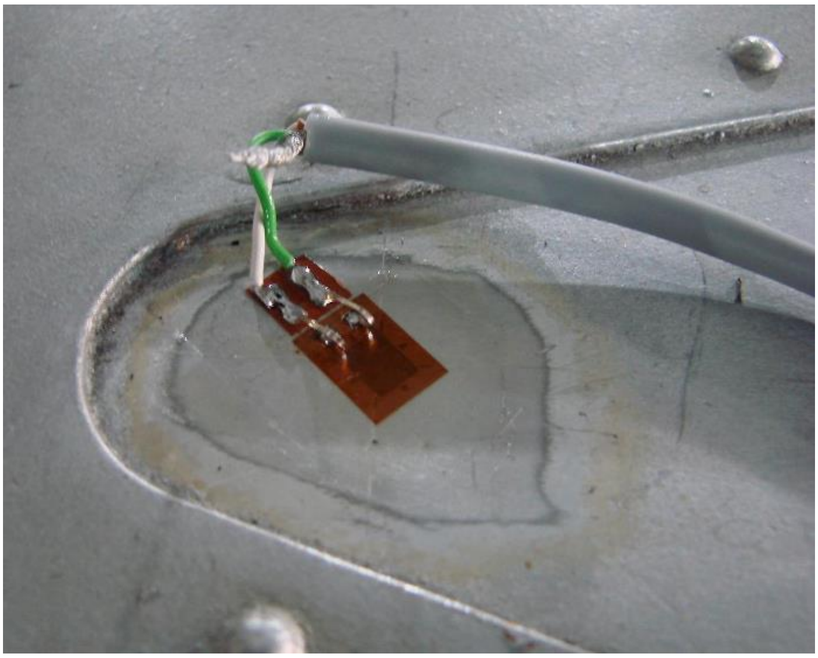

Figure 22. Strain gauge in the structure for load monitoring

Pros: validated and simple technology, low cost of the sensor;
Cons: cabling installation necessity and soldering, low durability of the sensors;
Type of monitoring: local area monitoring.

B. Electrical ladder sensors

Simple, reliable and low-cost technique that allows cracks of different size to be detected. Similar to the strain gauges, this technology involves the use of foil sensors bonded to the surface of the monitored location.

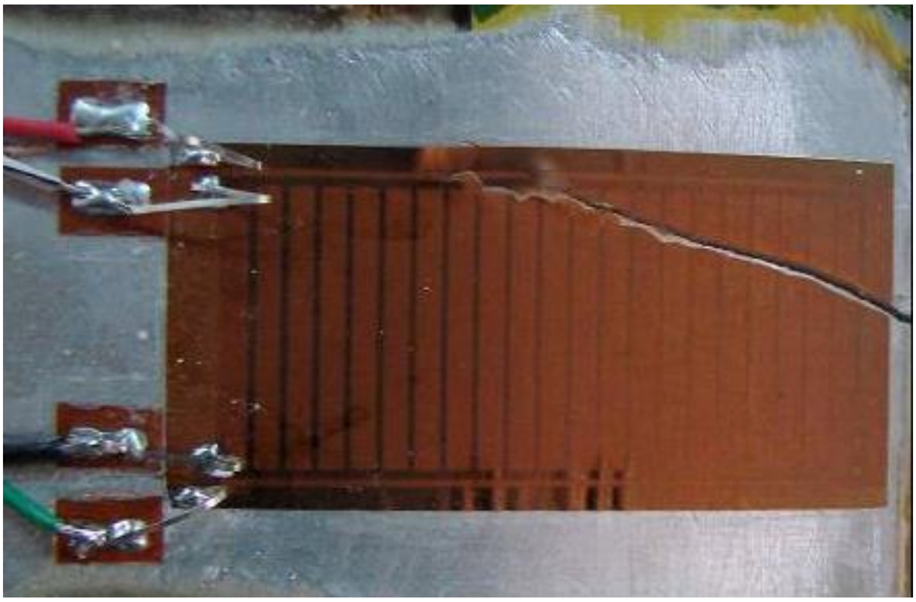

Figure 23. Resistive ladder sensor

The sensor needs to be permanently bonded to the structure in a hot-spot area. When a propagating crack appears under the sensor, it causes a local deformation and gradually tears the foil of the sensor.

Concurrently with the foil, permanent open out of conductive path occurs. Electrical resistance is measured between the sensor's two terminals, and any changes affect the output signal.

Pros: simple technology, low cost of the sensor, good detectability if the crack is under the sensor;

Cons: cabling installation necessity and soldering, low durability of the sensor;

Type of monitoring: local area monitoring.

C. Optical fibre Bragg grating (FBG)

Although foil resistive gauges currently dominate on the market, a high growth of commercially available fibre-optic solutions for strain measurement has occurred over the last few years. That is rather sensor than any type of monitoring technique18. FBG is to be applied to an optical fibre of 100 μm in diameter or less that can be integrated into a structure.

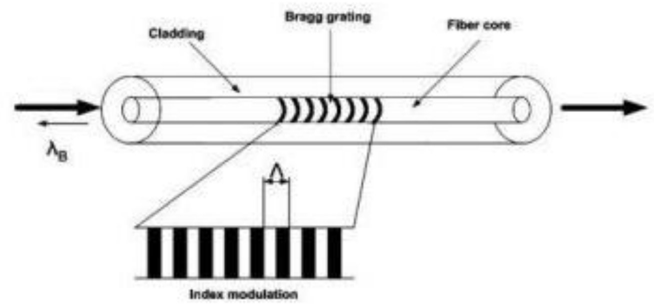

Figure 24. Fibre Bragg Grating Sensor

FBG's are structures made in core of the single mode optical fibre characterized by periodic changes in the value of the refraction index occurring along the axis of the optical fibre. As a result of these changes part of the optical wave transmitted by the optical fibre is reflected by the Bragg grating's structure, and the remainder is propagated along the optical fibre's core without any loss.

The sensor is able to monitor any kind of strain resulting from mechanical loads, pressure, temperature, acoustic vibrations or others. A major advantage of the sensor is that a large number of sensors (depending on sampling frequency) can be placed along a single fibre, which significantly reduces wiring complexity. Because it works on an optical basis the system is immune to any electromagnetic interference and makes it easy to compensate for the temperature effect. It has shown robustness with regard to in service application.

Pros: multiple sensors in one wire, electrical free connections, resistant to electromagnetic disturbances;

Cons: costs of the sensor and interrogation unit;

Type of monitoring: local area monitoring (global with the meaning of multiple sensors use).

D. Acoustic emission

Acoustic emission is a recognized NDT technique which enables 'listening' to damage (i.e. crack, delamination) progression developed during operation. AE testing uses changes in signal strength associated with the sudden release of energy emitted because of a changing stress field. That change of the stress field may be connected with the potential growth of the damage in the structure.

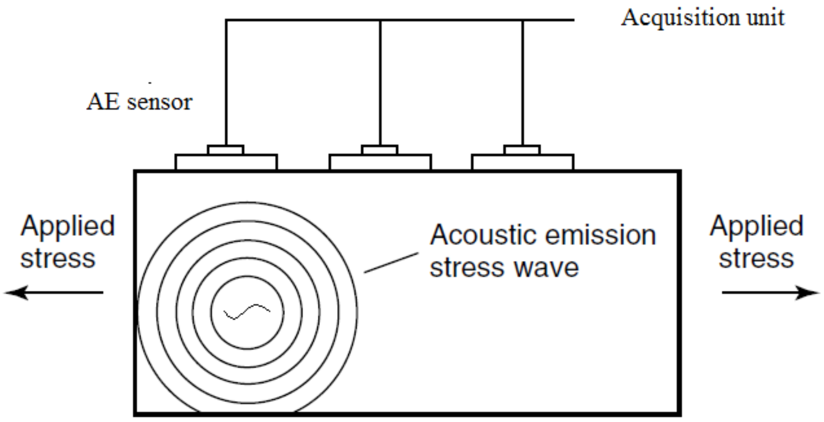

Figure 25. Acoustic emission method

This technique is potentially suitable for global monitoring. However, it needs to operate when the structure to be monitored is in operation. In that case signals are collected which may be affected by background noise which can complicate the situation for specific applications. The technique is passive, which means that external forces have to be applied to introduce the stresses in the object under investigation. There are several types of acoustic emission methods such as continuous emission and burst emission.

Pros: global monitoring, approved for some NDT applications, no requirements to hold sensor close to the damage;

Cons: does not give direct information about damage severity, complex signal analysis, cabling installation necessity;

Type of monitoring: global monitoring.

E. Nonlinear acoustics:

Traditional active acoustic/ultrasonic methods utilize the linear effects of the waves phenomena's and such as: reflection, scattering, transmission and attenuation of the elastic waves by structural inhomogenities to detect structural damages.

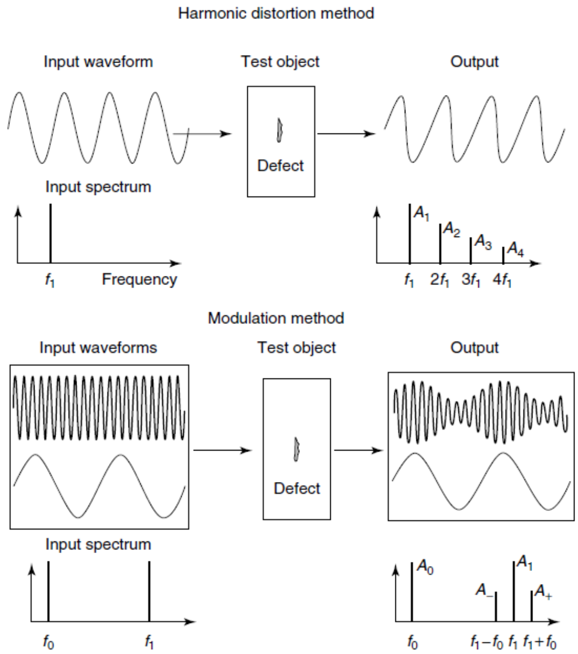

Figure 26. Concept for damage detection with the use of nonlinear acoustics

The use of nonlinear approach for damage sensing deals with the model of the elastic waves introducing stress between the edges of the damage and leading it to a bilinear (nonlinear) stress-strain relationship. Another type of material degradation associated with increased nonlinearity is micro- and mesoscopic fatigue damage accumulation. Here the stronger nonlinearity is due to dislocations, hysteresis, formation of slip planes, and microcrack development and clustering. Scheme for the method is presented in Fig. 20. A signal with a specific frequency is introduced to the tested article. Nonlinearity in the object (as the damage itself) introduce nonlinearities for the waveform so that the spectrum include additional harmonics. Analysing such spectrum components (especially in most cases of the second harmonics) leads to inference about damage presence. There are two primary methods of testing with the use of Non Linear Acoustic Methods: harmonic distortion and modulation. The first correlates the amplitude of the second harmonic (sometimes higher-order harmonics and even intermodulation and sub harmonics) with the presence and severity of the damage. The second one employ the nonlinear interaction of two signals: typically lower frequency modulating vibration and higher frequency probing ultrasound.

Pros: better damage resolution than in linear ultrasonic, use in more complex geometries than ultrasonic;

Cons: laboratory level for the application, requirement for the good baseline signal of the structure;

Type of monitoring: global monitoring.

F. Acoustic waves propagation:

Acoustic waves are elastic waves that propagate in the structure of the material being inspected. There are many techniques used for the assessment of the material with the use of that technology and such as: ultrasonics, guided waves including acousto-ultrasonics. For the purpose of the SHM the physics of the guided waves is used due to their robustness and possibility of long-range propagation (e.g. LRUT – Long Range Ultrasonic).

In the guided waves approach, their energy is guided by the boundaries of the structure. In guided-wave terminology, the structure is referred to as the waveguide, and guided waves include waves on free surfaces (Rayleigh waves), waves in plates (Lamb waves), waves in rods, waves in solid and multi-layered media, isotropic and anisotropic structures.

Guided wave phenomena exist over a wide frequency range from <1 Hz seismic waves generated by earthquakes to >100 MHz surface waves used in acoustic microscopes. Sensing capabilities are based on the linear acoustics principles and waves phenomena such as: reflection, absorption, refraction and mode conversion. There is wide range of approaches for the sensing capabilities including:

- single actuator – sensor;
- arrays (compact, linear, sparse);
- nodes (multiple sensors, single actuator).

There are also diverse solution for the actuators (mostly PZT used). In most cases PZT used are generating waves from the point of generation spherically (like source point of radiation). For many applications such approach is inconvenient due to the multiple reflection existence. To avoid that phenomena, unidirectional MFC piezo-composite transducers were elaborated to create one directional field of wave propagation [9]. This approach enables creation of specially designed arrays of transducers inspection of elements with a complicated shape (e.g. ribs, omega shape stiffeners etc.).

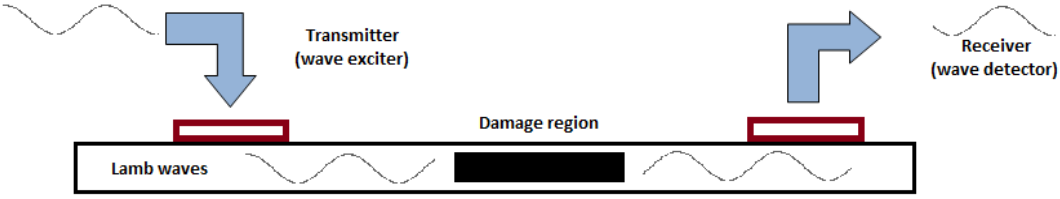

Figure 27. Use of guided waves approach principles

Figure 27 presents the principles of the use of guided waves for damage detection in plate-like structures. A variety of techniques is used in many applications for damage detection based on the Rayleigh-Lamb wave as well as the so-called acousto-ultrasonic technique. In that approach an actuator (usually a piezoelectric transducer) sends an acoustic signal into the structure to be monitored which is then recorded either by the same transducer (pulse-echo) or a different sensor (pitch-catch technique). Usually the network of the transducers is permanently bonded to the structure with the use of special adhesive. A reference signal (the so-called baseline) is taken for the undamaged condition and is compared to all readings from the measurements where the difference in signal is considered to be correlated to damage. In that method the most comprehensive techniques for signal analysis as well for inference about the damage are used.

Pros: high potential for the commercial application (highest assed TRL), ability for global monitoring, signal analysis enables damage recognition and damage size estimation, use of classifiers allows for automated inference about the damage presence;

Cons: cabling necessity, the use of baseline is required, need for consideration of the use special algorithms for stress and temperature compensation

Type of monitoring: global monitoring.

G. Laser vibrometry:

The principle of this technique is very similar to acousto-ultrasonics where the laser now takes over the sensor role by being able to scan a larger area. The advantage is the wide scanning area. A disadvantage is however the access to the component to be monitored which the laser requires.

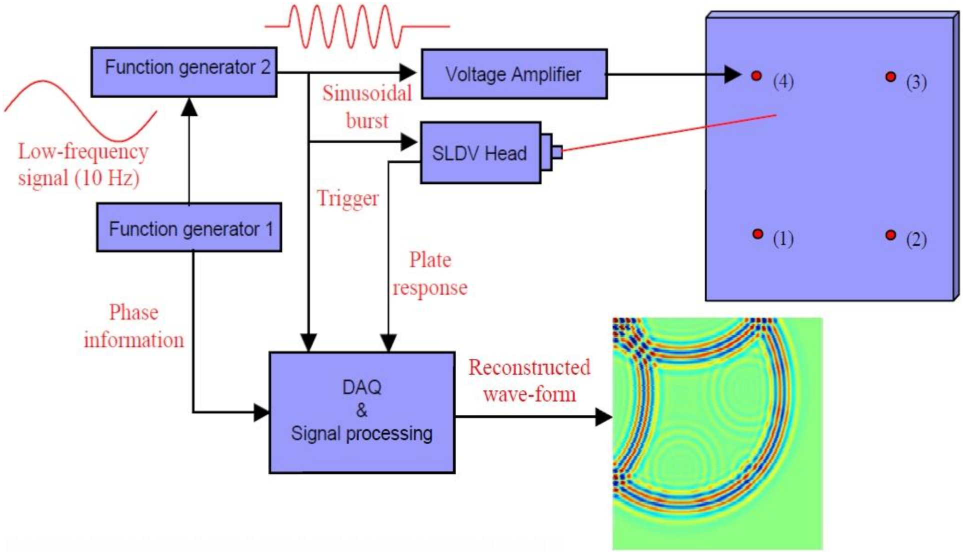

Figure 28. Scheme of the laser vibrometry unit

The way the laser vibrometer operates is similar to the laser interferometer. The main task of that unit is to measure the difference in the frequency (or phase) between the main beam which is the reference beam and the measurement beam reflected from the test article. As the beam source laser as well as laser diodes are used. Measurement beam is guided to the surface of the test article where the beam is reflected and compared with reference beam. Modulation of the measurement signal due to the displacements of the surface because of the wave propagation (the Doppler phenomenon is applied) is then used for the heterodyne process. The output signal which is the sum of the different frequencies from the heterodyne process is acquired and further processed in the system. The final output of the unit is a Frequency Modulated (FM) signal where the carrier frequency is modulated due to the Doppler frequency connected with vibration of the test article.

Pros: wide area of monitoring, fast and very reliable results directly visible in the acquired images;

Cons: direct access to monitored element (not efficient for the substructure), reflection problems, temperature affected;

Type of monitoring: global monitoring.

H. Electromechanical Impedance:

Electromechanical impedance is closely related to the mechanical impedance of a monitored structure. The electrical admittance of the PZT Y, which is the inverse of the electrical impedance Z, can be defined by the following equation [10]:

$$\underline{Y} = j\omega a\left[\underline{\varepsilon}_{33}^{T} - \frac{\underline{Z}_s}{\underline{Z}_s + \underline{Z}_a} d_{31}^{2}\underline{Y}_{11}^{E}\right]. \tag{1}$$

where: Z_s is the mechanical impedance of the monitored structure, Z_a is the mechanical impedance of the piezoelectric transducer, *a* is the geometrical constant of the piezoelectric transducer, d_{31} is the piezoelectric strain coefficient, $\underline{Y}_{11}^{E}$ is the complex Young's modulus, and ε_{33}^{T} is the complex dielectric constant of the PZT material evaluated at zero stress.

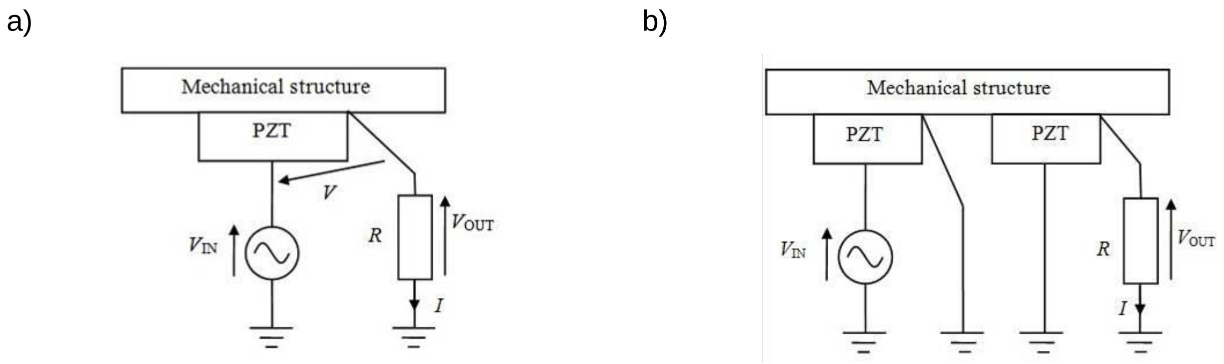

Figure 29. Methods for the measurement of the electromechanical impedance: point frequency response function (a), transfer frequency response function (b)

The two methods used to evaluate the electromechanical impedance are shown in Fig.29. The circuit presented in Fig.29(a) assumes the usage of only one PZT acting as both an actuator and a sensor. The diagram represents the method with a self-sensing actuation and allows to measure a point frequency response function (FRF) of the impedance. The circuit shown in Fig.29(b) corresponds to the second method which is used to evaluate a transfer FRF. The diagram includes two PZTs, an actuator and a sensor, which are mounted in different locations in a structure. In both cases the monitored structure is exposed to high frequency vibrations by applying alternating voltage V_{in} to one PZT.

The measured voltage V_{out} depends on the voltage V, which is generated in the PZT according to the direct piezoelectric effect. Eventually, the determined complex electrical impedance Z directly corresponds to the variation of the mechanical impedance resulting from any change of the mechanical properties of monitored structure when a damage appears. To qualitatively asses the changes of registered impedance plots, the necessary damage metrics such as Root Mead Square Deviation and Cross Correlation can be applied.

Pros: sensitive to gradual changes of the structural integrity (such as crack propagation), less than wave propagation dependent from the geometry;

Cons: necessity of bonding sensor close to the damage location, necessity to proper selection of damage index functions, more laboratory dedicated;

Type of monitoring: local monitoring.

I. Comparative vacuum monitoring (CVM):

This technique is provided by Structural Monitoring Systems (SMS) is based on a two-chamber system of very thin channels introduced into a silicon based sensor. The sensor is placed onto the location prone to cracking. One of the chambers is evacuated with vacuum to be held. Once a crack emerges under the evacuated chamber the pressure increases, which defines the presence of a crack. Detailed visual description of the way the system is operating is presented in the Fig. 30.

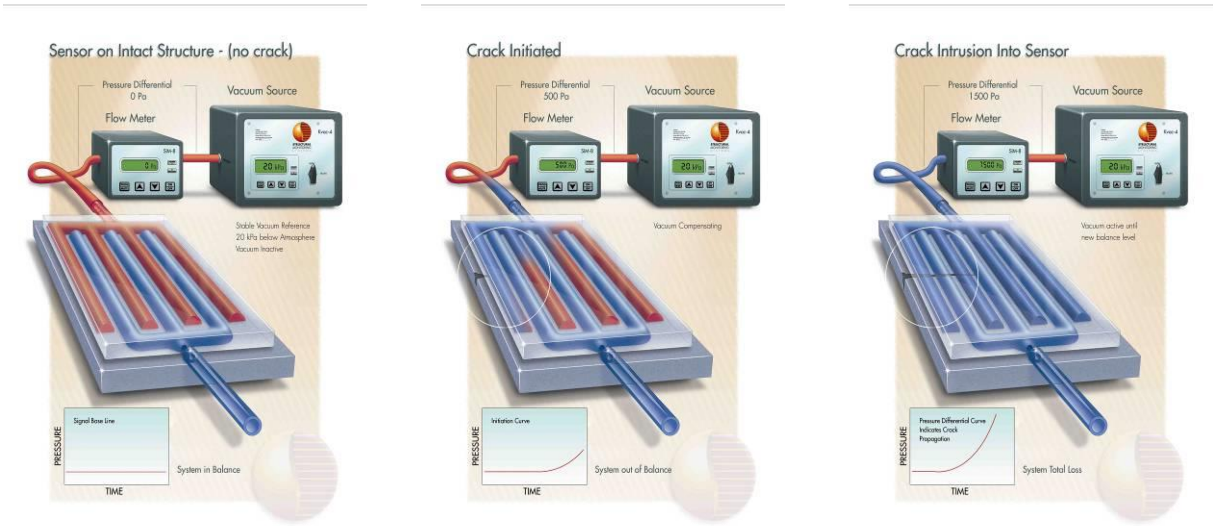

Figure 30. Principles of the system operation for the crack detection

The method works well for local monitoring where the location of cracking is well known. However, for global monitoring, the approach becomes rather complicated. The technique is currently widely explored and validated in various trials with aircraft manufacturers and operators.

Pros: sensitive to crack detection, possible to design any required shape of the sensor, electrical free, system was used on commercial aircrafts;

Cons: monitoring only for damages located under the sensor;

Type of monitoring: local monitoring.

J. Eddy current sensors (magnetic sensors):

Eddy-current testing (ET) is a non-destructive testing (NDT) technique that uses time-varying magnetic fields to induce eddy currents in a conducting material. ET is used to assess the material under test conditions or to detect flaws. The principle is the generation of electromagnetic fields in the way that is known from high frequency eddy current testing.

The presence of a flaw (e.g. crack) or a variation in a material condition (e.g. residual stress effects on magnetic permeability) is detected by the ET sensor in the region immediately under the sensor.

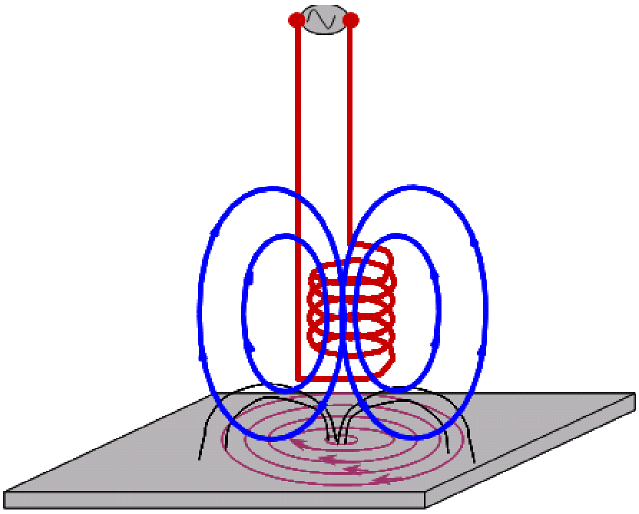

Figure 31. Eddy Current generation in the test article

Thus, ET is a local measurement. Eddy-current in situ sensors exists but the focus is on surface-mounted and embedded sensors for SHM, using onboard instrumentation or portable data-acquisition units. Using a portable data-acquisition system with onboard ET sensors is a direct replacement for conventional ET (NDT), but offers the advantage of allowing for the inspection of difficult-to-access locations without disassembly to gain access.

Pros: sensitive to crack detection, possible to design required shape of the sensor, possible to determine approximate depth of the defect, diverse application possible;

Cons: local monitoring, limitations to ferromagnetic elements as well as low conductivity articles;

Type of monitoring: local monitoring.

K. LPR sensors:

A Linear Polarization Resistor (LPR) corrosion sensor it is a device that corrodes at the same rate as the structure on which it is placed. The sensor is made up of two micromachined electrodes that are interdigitated at 150mm apart. The corrosion reaction – both oxidation and reduction – produces a corrosion current that can be pre-determined empirically for each sensor type, this I/V (Current/Voltage) form is called a Tafel plot [11].

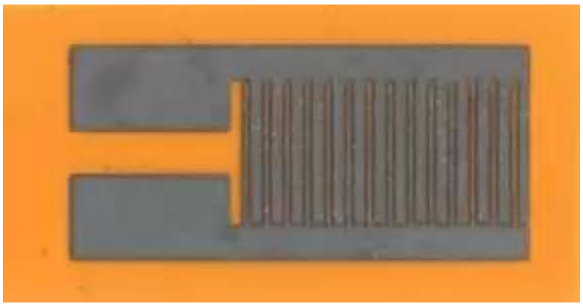

Figure 32. LPR sensor

The sensor itself is made from shim stock of the same material as the structure that is being monitored. The shim is usually 25mm thick (0.001") and is attached to a Kapton backing sheet of similar thickness. This gives the sensor a total thickness of ca 50mm, although a thickness of up to 200mm is possible if required. The shim is machined (pattered) using a photolithography technique, this allows for a varied design layout so that sensors can be fitted deep into tight structures such as bridge cables and lap joints. The sensor can be placed directly on the metal surface of the structure to be monitored. Painting and other surface preparations can be performed on top of the sensor with no damage to the sensor or coating. The sensors are unobtrusive in operation and require no maintenance or inspection.

Pros: sensitive to corrosion growth, corrosion growth rate determination possibility;

Cons: local monitoring, relatively clean aqueous electrolytic environments necessary for use;

Type of monitoring: local monitoring.

L. Other solutions:

There are many other solutions which are being developed for the use potentially in the aerospace environment. There are: MEMS, wireless strain sensors, optical based sensors (DMI SR2), RFID sensors, Fibre Optic Sensors (FOS), techniques based on brittle coatings, magnetic sensors which utilize magnetostriction phenomena, chemical sensors which are also used in several lab trials in scientific test. Most of them still are at a low TRL level. The work presented only mentions potential technologies which are found in some aerospace applications (mainly laboratory). To identify clearly what the TRL is the following classification were used:

Mimics TRLs used by NASA & military - this classification system clearly defines benchmarks, direction and maturity of emerging Technologies:

- ***TRL 1*** *- Physical principles are postulated with reasoning;*
- ***TRL 2*** *- Application for physical principles identified but no results;*
- ***TRL 3*** *- Initial laboratory tests on general hardware configuration to support physical principles;*
- ***TRL 4*** *- Integration level showing systems function in lab tests;*
- ***TRL 5*** *- System testing to evaluate function in realistic environment;*
- ***TRL 6*** *- Evaluation of prototype system;*
- ***TRL 7*** *- Demonstration of complete system prototype in operating environment;*
- ***TRL 8*** *- Certification testing on final system in lab and/or field;*
- ***TRL 9*** *- Final adjustment of system through mission operations.*

So far, the highest ranked TRL in the aerospace for the SHM application of 8-9 is for electrical strain gauges and crack propagation sensors, FBG sensors as well as CVM. PZT applications have reached the level of 5-6. Therefore, to increase TRL and determine both diagnostic capabilities and limitations to be used then throughout the operational phase, it seems quite reasonable and of significance to carry out research on PZT applications and other abovementioned techniques.

PZT sensors

The most common way to actuate elastic waves is to use special electromechanical properties of piezoelectric ceramics. Piezoelectric ceramics have the property of developing an electric charge when mechanical stress is exerted on them. In these materials, an applied electric field produces a proportional strain. The electrical response to mechanical stimulation is called the direct piezoelectric effect, and the mechanical response to electrical stimulation is called the converse piezoelectric effect. Ceramics are inorganic non-metallic materials. Piezoelectric ceramics differ from piezoelectric crystals in that they must undergo a poling procedure for the piezoelectric phenomenon to occur.

For each material there is a characteristic Curie temperature. Above the Curie temperature electric dipoles inside the material exist in random orientations. When a strong electric field is applied they become aligned in the direction of the field and remain partially aligned after the field is removed, provided the material is first cooled well below its Curie temperature. In this state the ceramic is said to be poled. When the poled ceramic is subjected to a small electric field the dipoles respond collectively to produce a macroscopic expansion along the poling axis and contraction perpendicular to it [12-18].

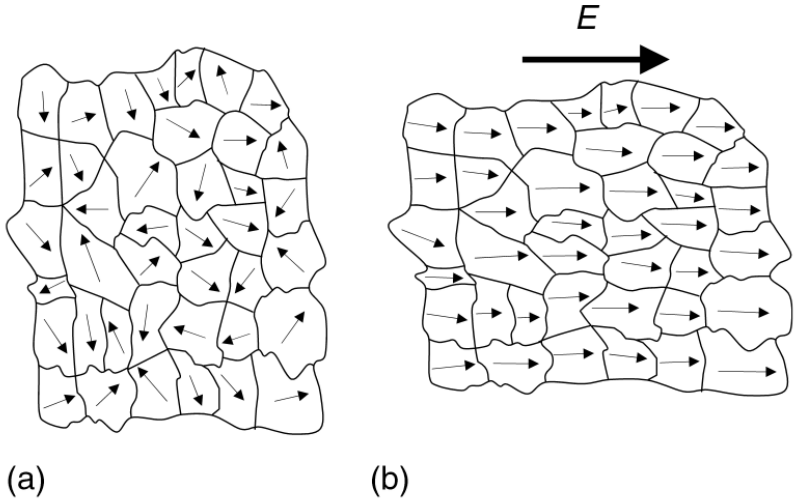

Figure 33. Polycrystalline perovskite ceramics: (a) not pooled and (b) after pooling [13]

The advantages of PZT ceramics are: simple technology and low manufacturing costs, easy machining which allows to obtain transducers of different shapes. Beside single layer transducers also multi-layered ones can be manufactured, by joining many layers of PZT ceramics with electrodes. This allows for obtaining a higher range of attainable displacements. In SHM systems also Interdigital Transducers – IDT are used [15], which allows for directional actuation of elastic waves. Their additional advantage is possibility to adjust the length of the wave, which is appropriate for detection of damage of given type. PZT ceramics are also mixed with epoxy resins, for production of the so-called Macro Fibre Composite MFC – transducers [15], characterized by their high elasticity. In this way, also highly integrated sensor patches are manufactured, e.g. SMART Layer® [15], which are ready to be integrated directly with the structure. Yet another way to obtain elastic piezoelectric transducers is to use polymer transducers, e.g. polyvinylidene PVDF [12,15], which additionally has very small thickness. The inertia of piezoelectric transducers is low, thus in SHM systems they are used as actuators and sensors of elastic waves of high frequencies, sensors of vibrations, strain gauges in fast processes, as well as accelerometers [12,13].

Structural damage, irrespectively of their type, cause local changes of material properties affecting elastic waves propagating through damaged area [13]. Therefore, PZT transducers can be widely applied for SHM. Applications of piezoelectrics in SHM systems include the so-called passive monitoring techniques, when they are used only as receivers of elastic waves actuated by an event leading to damage (e.g. impacts) or the waves emerge by releasing energy by developing damage – Acoustic Emission (AE). PZT networks can be used also as active elements – actuating in a monitored elements elastic waves.

Multilayer piezoelectric transducers are electromechanical devices for generating movements in the micrometre range. The conversion of electrical energy into mechanical motion takes place without the generation of any magnetic field or the need for moving electrical contacts. Piezoelectric devices are capable of response times in the microsecond range and can develop blocking forces up to several kN and their stroke varies approximately linearly with applied voltage.

Piezoelectric actuators possess unique and interesting properties. Dimensional changes proportional to the applied voltage can be adjusted with infinite resolution. They can be operated over billions of cycles without wear or deterioration. Speed of response is very high, limited only by the inertia of the object being moved and the output capability of the electronic driver. Virtually no power is consumed or heat generated to maintain a piezoelectric actuator in an energized state. Multilayer actuators may be fabricated from thin sheets of tape-cast ceramic [19].

During dynamic operation of a piezoelectric actuator, the PZT material will encounter a certain degree of aging, which will be observed as a small loss of displacement and blocking force, when comparing a virgin actuator with an actuator that has undergone a certain amount of actuation. The blocking force is defined as the force required for pushing back a fully energized actuator to zero displacement. The loss of performance is primarily encountered for the initial cycles, after which the aging becomes almost negligible. Aging is thus a logarithmic function of time [19]:

$$d(t) = d(t_0) + A\log\left(\frac{t}{t_0}\right),$$

where:

- A is the "aging rate" constant, specific to the composition, microstructure and the processing history of an element
- d is a constant representing the piezoelectric sensitivity by relating mechanical strain with the applied electric field, i.e. the ratio of strain to the electric field applied.

The below voltage-stroke diagram shows an example of a stacked actuator that has been measured for performance at four steps during an accelerated lifetime test [19]:

- in the virgin state
- after having undergone 10^7 cycles
- after having undergone $3x10^7$ cycles
- after having undergone 10^8 cycles.

The free stroke refers to the displacement achieved by the actuator at a given voltage level without the actuator working against any external load. The loss of performance is in the order of 10% after the first 10^7 cycles.

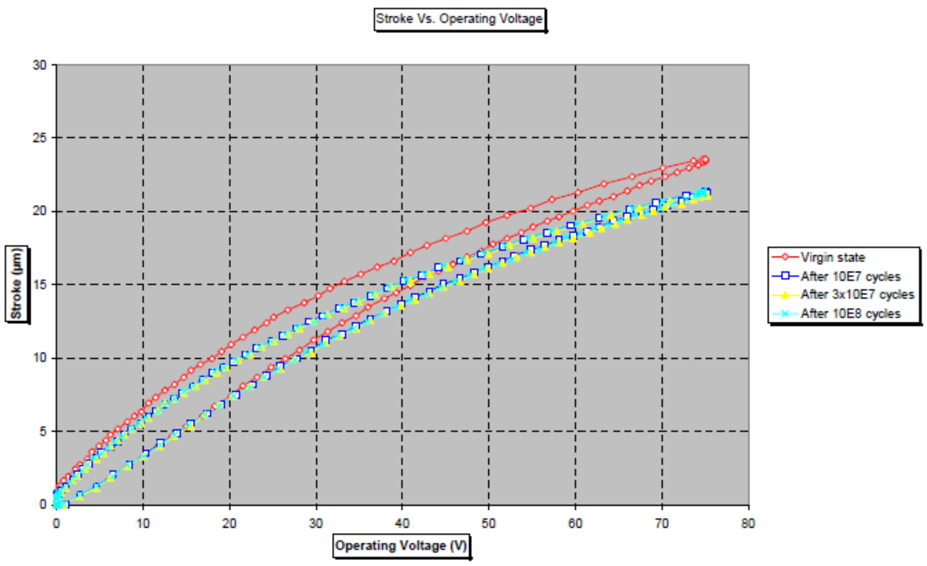

Figure 34. The voltage – stroke diagram showing aging performance loss of a PZT actuator [19].

Signal processing and damage detection algorithms I: damage indices

One of the major obstacle in direct application of Lamb waves in structure evaluation is the complexity of signals excited in real structures. Two examples of baseline signals obtained for structures of simple geometry and containing riveted joints and other wave reflectors are presented on the following figure (Fig. 35).

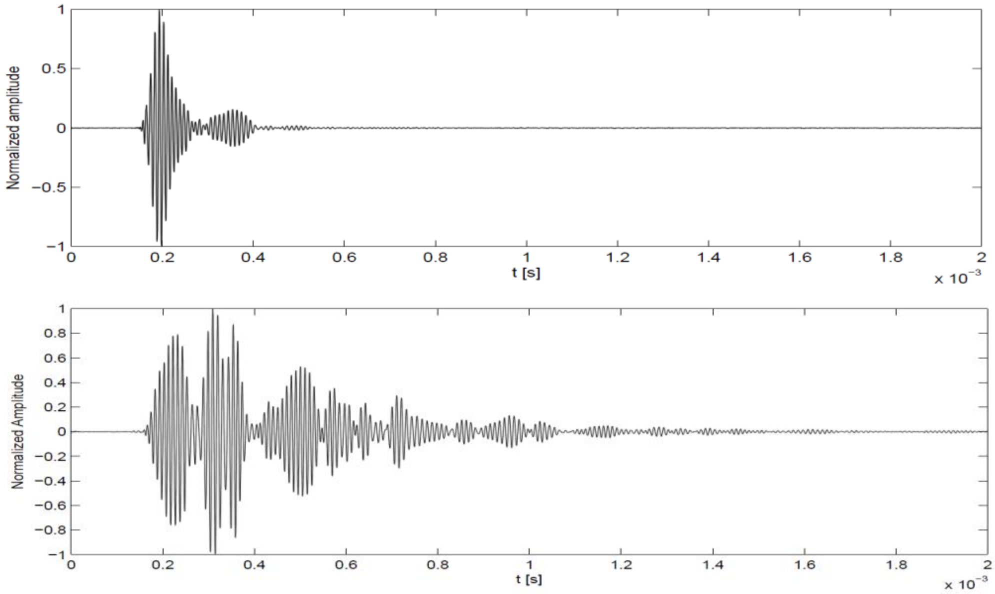

Figure 35. Examples of reference signals for structures of different type.

Reliable SHM systems should therefore provide different type of damage assessment which would allow for cross-validated evaluation of the structure:

- qualitative data - damage presence in a given network cell, its kind and the degree of criticality;
- quantitative data - exact location and size of a damage.

Basic information concerning the health of the structure can be provided by the so-called Damage Indices (DI's). Denoting as f_{gs} the signal generated in transducer g and received in sensor s and as $f_{gs,b}$ its baseline, i.e. the reference signal collected for the undamaged state of the structure, some basic DI's can be defined using the following simple signal characteristics [20]:

L^1 symmetric characteristic – $$DI_1(g,s) = \frac{\left| \int (|f_{gs}| - |f_{gs,b}|) dt \right|}{\int |f_{gs,b}| dt}, \qquad (1)$$

L^2 symmetric characteristic – $$DI_2(g,s) = \frac{\left| \int \left(f_{gs}\right)^2 - \left(f_{gs,b}\right)^2 dt \right|}{\int \left(f_{gs,b}\right)^2 dt},$$

correlation with the baseline – $$DI_3(g,s) = cor(g,s).$$

Similar DI's can be obtained using Fourier filtered signals, their envelopes or other signal transformations. These DI's are correlated with the total energy received by a given sensor therefore can capture the two main modes of guided wave interaction with a fatigue crack. Low information content carried by those DI's, makes them more persistent under varying sensor working conditions. This should improve the false calls ratio of the system.

There are remarkable examples of applications of analogous DI's to determine localization of a damage [21-23]. In these methods two stage algorithms are used. First for each sensing path $g \rightarrow s$, i.e. a signal received in sensor s originated from generator g, the structure is quantified into a damaged or undamaged state. This quantitative assessment can be performed using certain threshold level of one or multiple DI's. Then if the structure is considered as damaged a probability density of a damage localization in a given network cell is calculated. This density depends on DI's values and properly defined distance of a given point from a sensing path $g \to s$. Finally, joint probability for a damage localization is provided using probability maps obtained for all possible sensing paths in the network cell.

There are several limitations of the described SHM method. In particular in order to obtain accurate damage location probability map there is necessity to consider sensing paths for many transducers what influence on computational and system implementation costs. Furthermore, improper functioning of a single sensor in the network decrease number of reliable sensing paths which can disturb this probability density. Another obstacle in this approach is system sensitivity adjustment. In complex structures, which contain many wave reflectors, e.g. edges, joints, welds, rivets, etc. resulting map for sensitive algorithms can be noised [24], whereas weakening susceptibility of sensing paths cause risk of damage missing. However the main disadvantage of that method is the difficulty in estimating damage size. Since damage indices $DI_j(g,s)$ (Eqn. (1)) used for structure quantification in these algorithms depends strongly on damage localization with respect to given sensing path $g \to s$ it is very difficult to use regression or classification models in estimating size of a damage. In order to overcome the last issue the Averaged Damage Indices (ADI's) can be defined [25]:

$$ADI_j := \frac{1}{n(n-1)} \sum_{\substack{g,s: \\ g \neq s}} DI_j(g,s), \qquad (2)$$

where n is the number of transducers in a network measurement node. Averaged damage indices (ADI's) are less dependent on the damage localization which makes them better suited for damage size estimation, in particular they are invariant with respect to sensors permutation. These indices remain structure quantification possibility also in the case of improper functioning of several transducers of the network. The procedure of averaging (Eqn. (2)) is highly sensitive to outlying observations, emphasizing the importance of the sensor self-diagnostic component of the system. Relying on the ADI's defined above (Eqn. (2)) effective fatigue crack growth predictors can be obtained by means of statistical dimensional reduction methods, e.g. Principal Component Analysis (PCA) or Fisher's Linear Discriminant (FLD) [26].

PZT sensors for SHM applications: case studies

Laboratory test of aircraft specimens. In order to illustrate the proposed damage detection algorithms the results of fatigue test of an aircraft structure specimen are presented in this section [27]. Two independent piezoelectric transducers (PZT) networks, containing 4 sensors each were deployed on the structure (Fig. 36).

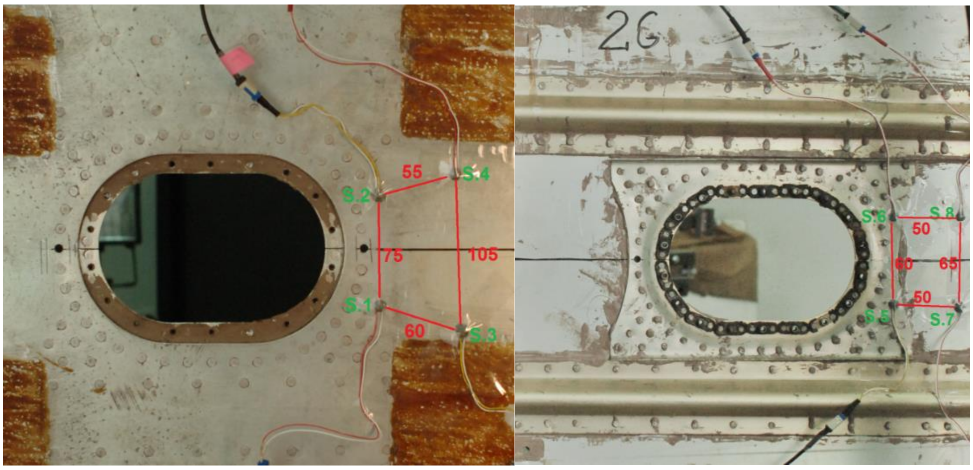

Figure 36: The specimen and the network deployed (network dimensions given in millimetres)

Signals were gathered under three different structure loads at each level of the damage development. The two chosen Principal Component Based efficient damage predictors (EDP's) with the best data separation properties as well as the first two Fishers' linear discriminant [26] EDP's are presented on the following plots (Fig. 37).

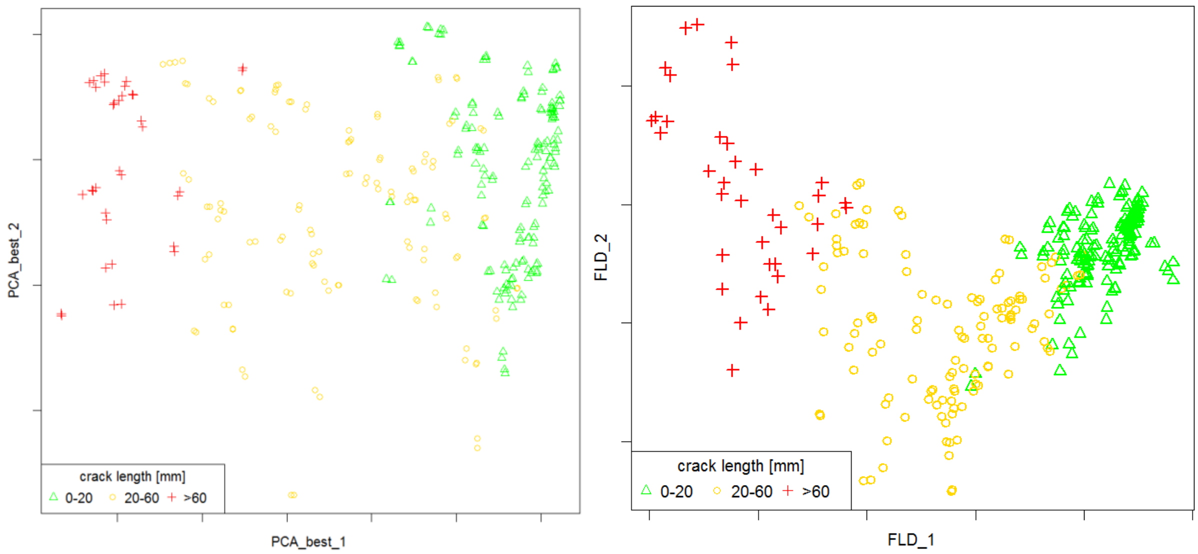

Figure 37. PCA (left) and FLD (right) based EDP's.

In the case of PCA method, only the first EDP distinguish data corresponding to different crack length, whereas in the case of Fishers' method both of the indices FLD_1, FLD_2 improve data separation. The data are well separated in both cases, with negligible overlaps, which may be caused by different stress distributions in the structure during measurements. Under high loads changes of Fisher's predictors LDA_1, LDA_2 for smaller cracks are comparable to those obtained for longer cracks under free end conditions. This yields misclassification probability between second (20-60 mm cracks) and third class (>60 mm cracks) of the damage severity.

Based on Fishers' efficient damage predictors FLD_1, FLD_2 nearest neighbour (NN) and LDA classification models were obtained. Their classification regions are presented on the following plot (Fig. 32).

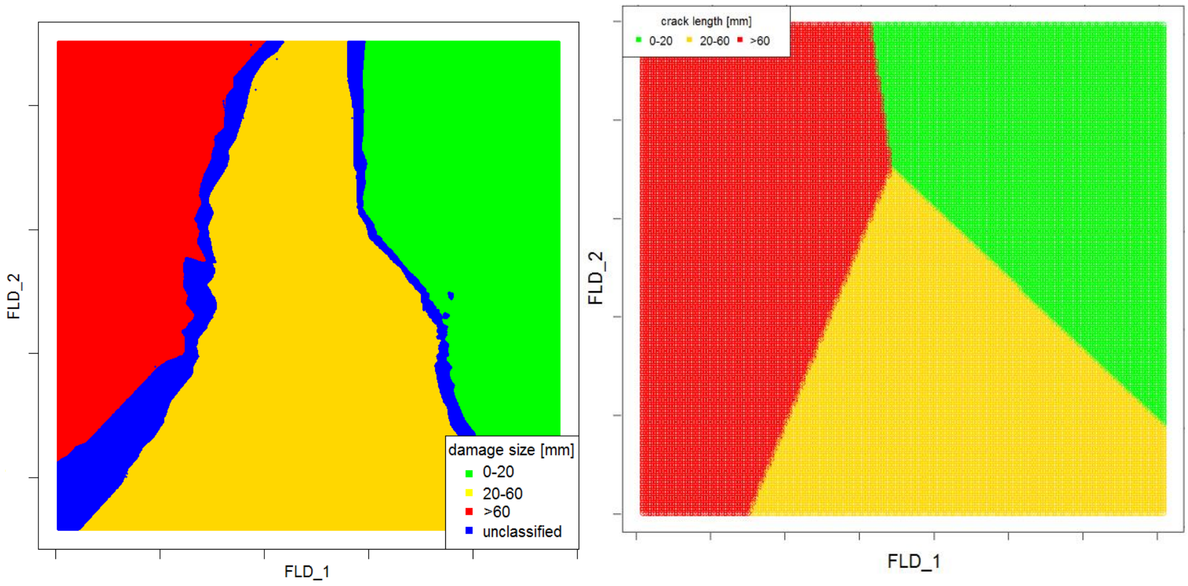

Figure 38. NN (left) and LDA (right) data classification domains.

The nearest neighbour model reproduces the gap between undamaged (0-20mm crack length) and severely damaged (>60 mm crack length), however classification regions of LDA model due to their regularity are more stable making the model better suitable for real applications.

PZT network application for fatigue crack growth monitoring during fatigue test of a helicopter tail boom

The fatigue test of a helicopter tail boom is a part of ASTYANAX (Aircraft fuselage crack monitoring sYstem And prognosis through on-boArd eXpert sensor network) project governed by European Defence Agency [28]. The platform used for the project is Mi-8/17 helicopter. The tail boom of the helicopter was equipped with FBG, PZT sensors as well as crack gauges. In Fig. 33 a PZT network and crack gauges installed near an introduced crack are presented.

Two kinds of PZT transducers were used: single- and multi-layered. The following parameters of PZT excitation were used:

- excitation frequency [kHz]: 100, 150, 200, 250, 300;
- duration: 3 or 8 periods;
- window type: Hanning.

The signal from PZT network is gathered under varying loads which can contribute to the DIs drift effect [20].

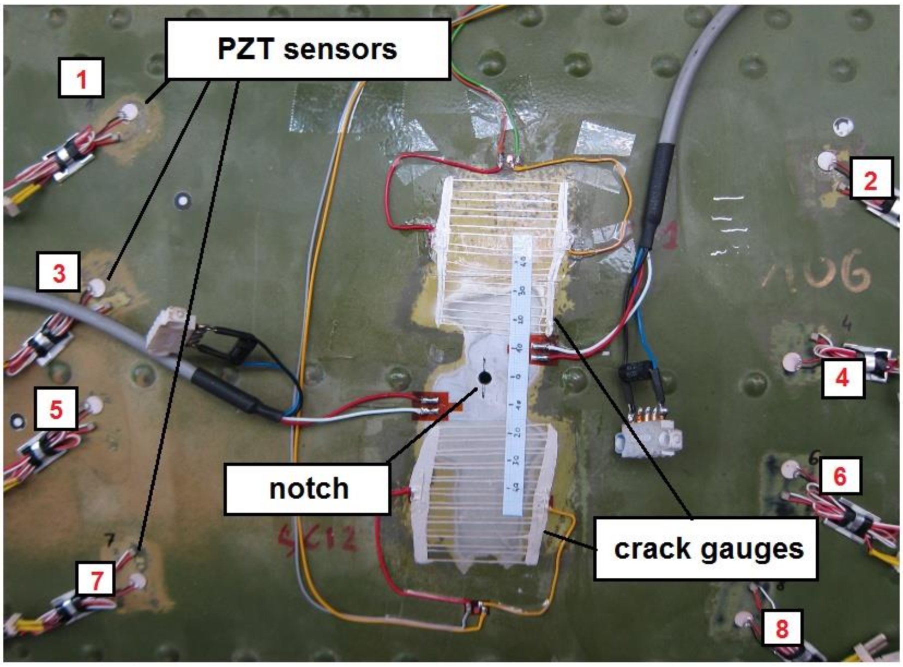

Figure 39. PZT sensors and crack gauges deployed on the helicopter structure with numeration of PZT network

In order to illustrate DIs change within a network a map:

$$I(x,y) = \max_{g,s} DI_1(g,s) R_{gs}(x,y), \qquad R_{gs}(x,y) = \left(\frac{l_{gs}}{l_{gp} + l_{gs}} \right)^{40}$$

is used, where l_{gp}, l_{gs} denoting the distance of the point *p* from the generator *g* or the sensor *s* respectively and l_{gs} is the distance between generator *g* and sensor *s*. The DI value on a given sensing path is weighted with a map R_{gs} representing the geometry of a given sensing path.

Fig. 40 shows the map before (Fig. 10(a)) and after (Fig. 10(b)) the compensation of the DI [20] for single layered transducers at the frequency 150 kHz. The change of compensated DI is the highest for sensing paths running in close proximity of the crack (Fig. 10(b)), whereas uncompensated DI can change also for paths for which signal should not be influenced by a damage (Fig. 10(a)), which can lead to a false indication of the system.

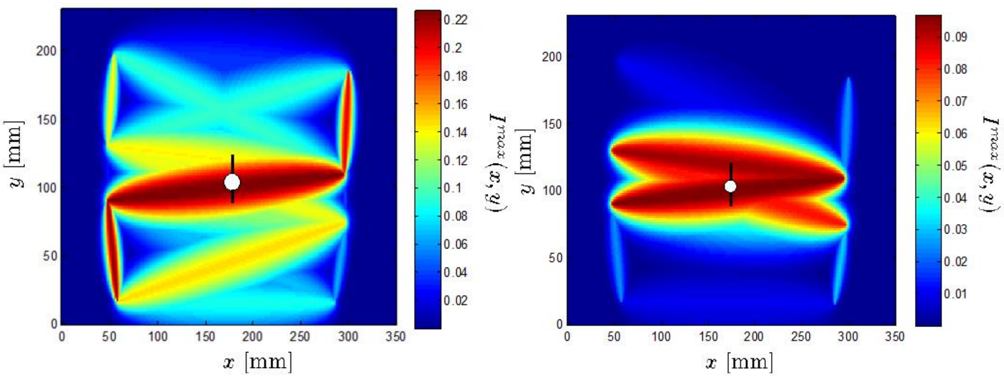

Figure 40. Visualisation of Damage Index change within the network using: (a) not compensated and (b) compensated DI.

PZT network application for fatigue crack growth monitoring during Full Scale Fatigue Test of PZL-130 ORLIK aircraft

Full Scale Fatigue Test of PZL-130 Orlik aircraft was performed due to structure modifications. That test opened an opportunity for a SHM system installation at selected aircraft hot spot locations (Fig. 35) monitoring as well as early damage detection as alternative approach which may support or in the future partially replace the scheduled NDI inspections [29].

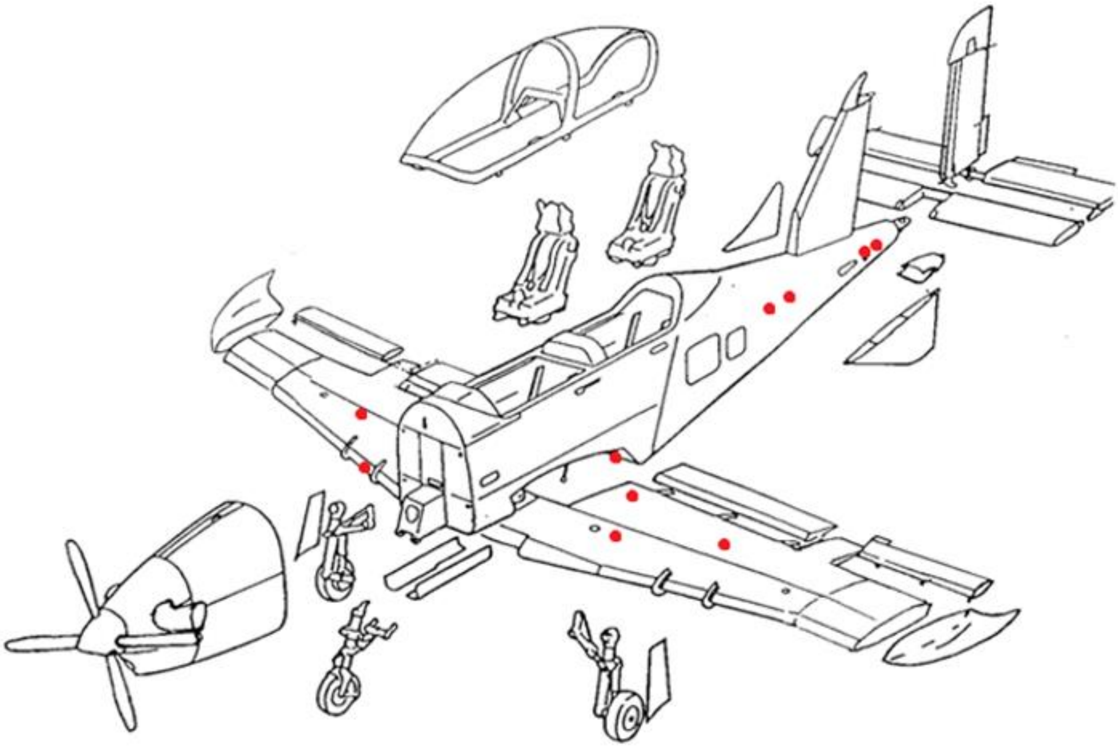

Figure 41. Selected aircraft hot-spots.

The SHM system building blocks are schematically presented on the figure (Fig. 41). These are:
- PZT network divided into several measuring nodes;
- Remote Monitoring Unit (RMU) – based on DSP architecture CPU;
- Data Storage Unit (DSU);
- Graphical User Interface (GUI).

The core of the RMU consists of four subsequent routines:
- signal collecting and its storage in DSU if indicated by sensor self-diagnostics component;
- signal processing based on several signal Damage Indices (DI's) correlated with the fatigue crack growth;
- sensor self-diagnostic component validating the PZT network, e.g. noise detection, sensors' surface coupling strength, significant sensor working conditions changes detection;
- data classification methods for damage growth assessment.

One of the key issues in applying of PZT-based monitoring systems to structures used in aerospace is to ensure sensor network durability in extremely varying environmental conditions. Thus, a network self-diagnostic tools allowing for signal decoherence tracking in time is a vital component for any such application. Furthermore, the most of data classification models are sensitive to outlying observations, therefore efficient sensor self-diagnostic prior to crack growth assessment is crucial for proper system working, e.g. misclassification avoidance.

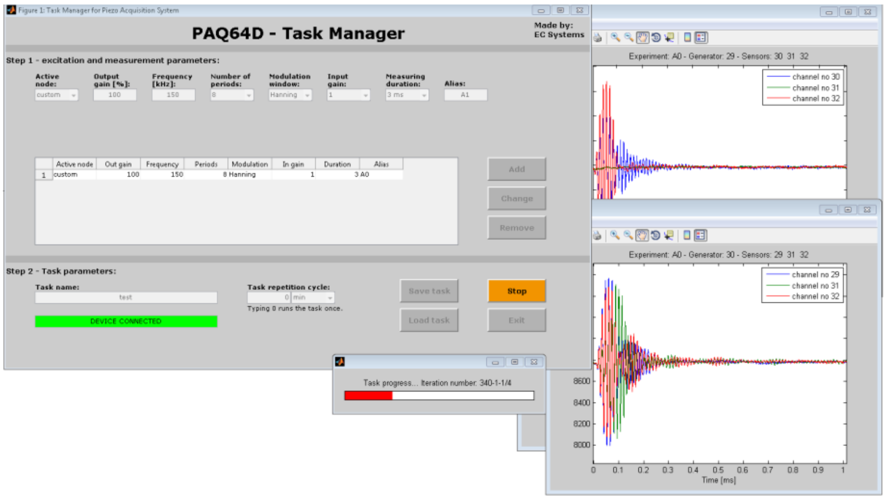

Figure 42. PZT sensor network remote monitoring unit control panel

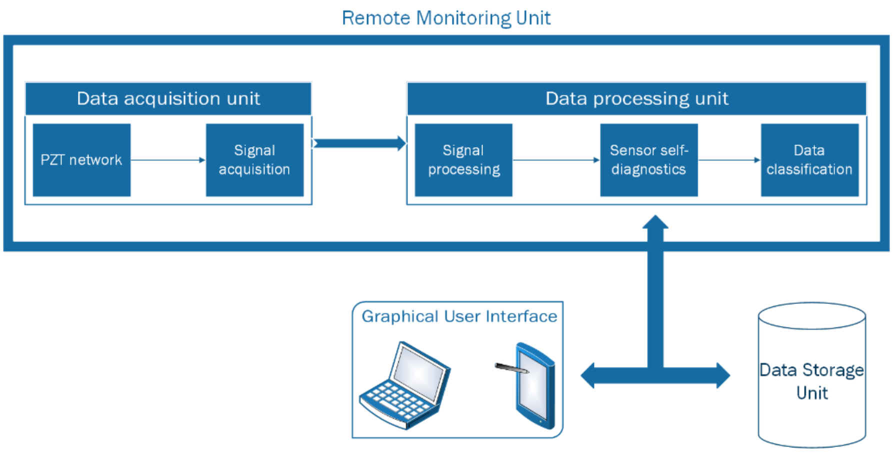

Figure 43. SHM system block diagram

In the proposed approach signals which do not pass the sensor integrity check are stored in DSU for further expert assessment as shown in Fig. 43.

Damage detection capabilities of the system are discussed based on two chosen monitored hot-spots (Fig. 44). In both of the locations Resistance Crack Gauges (RCG) adapted to the structure geometry were installed in order to verify the system indications. The crack was developing in the network shown in Fig. 44(b) and the other hot-spot (Fig. 44(a)) remained undamaged. One of the network nodes (Fig. 44(a)) was installed on a structure containing riveted joints and other wave reflectors, the other structure (Fig. 44(b)) was of relatively simple geometry. The Averaged Damage Indices for both of the nodes are presented in Fig. 45. It was noticed that the number of well separated groups of data, corresponding to different extent of the crack, agrees with the number of sensing paths crossed by the crack. The data corresponding to subsequent periods of the monitoring of the undamaged structure are not separated (Fig. 45).

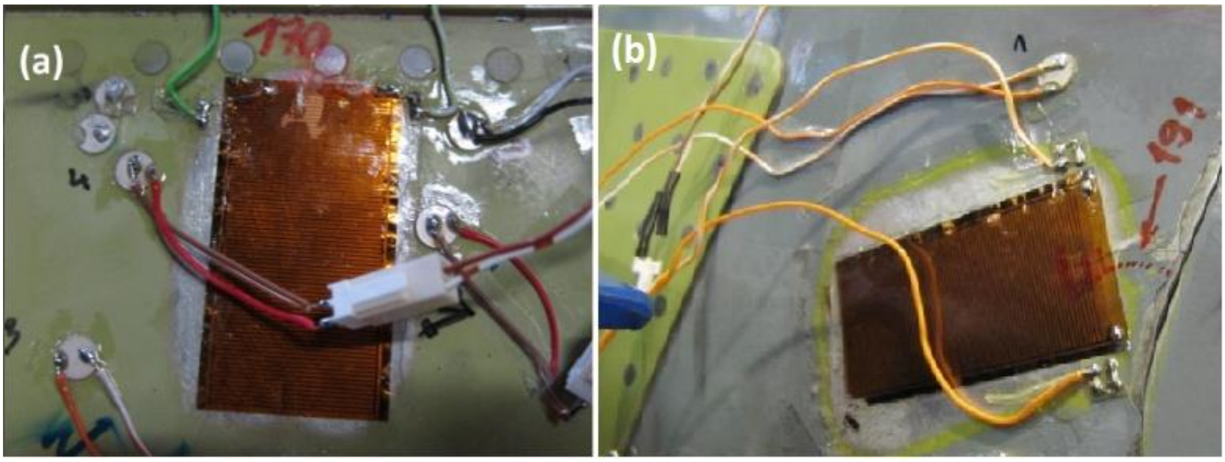

Figure 44. Example of monitored hot-spots

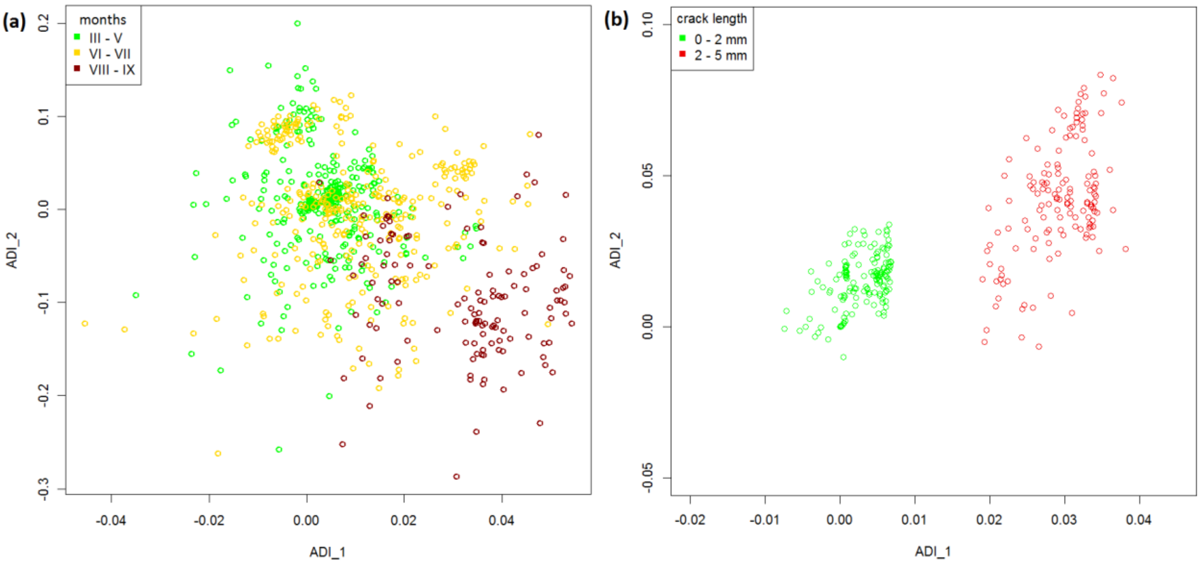

Figure 45. Averaged Damage Indices for the monitored hot spots

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3.2.3 Problems of the installation of FBG sensors in composite structures – contributor: KhAI (UA)

The installation of FBG sensors in composite structures for structural health monitoring requires measures and techniques to guarantee their reliability and durability. Embedding the FOBG sensors during manufacturing is a tedious task because it involves many difficulties such as the selection of ingress and egress points of the sensor data lines, the possible effect of the embedded sensors and ancillaries on the mechanical properties of the composite and the risk of sensor breakage during fabrication. Usually the sensors are surface-mounted or integrated into the composite structure.

Surface mounting is less challenging than embedding but also less suitable, due to the high fragility of the optical fibre. The literature contains extensive research regarding the strain transfer between surface-mounted FBG sensor and substrate. Due to the intense temperature/pressure conditions occurring during curing, the primary coating of the optical fibre was polyimide with a polyimide recoating on the grating location after inscription of the FOBGs to improve the mechanical performance. In this case, the adhesive layer thickness and mechanical properties play an important role in the transfer of strain to the fibre core.

The low resistance of fibre optic sensors against damage and the difficulties with fibre handling are important application problems. On the other hand, FOBG sensors embedded into the structure provide limited information on the buckling mode changes. Only the onset of buckling can be indicated. The subsequent development of the buckling waves and their changes are not generally indicated. This lack of sensitivity to these responses can be caused by the fact that the embedded FOBG sensors are placed into the structure very close to the neutral axis. Due to buckling, an additional bending originates in the structure. Both of these situations can result in the embedded sensors' lack of sensitivity to the local buckling.

Regarding final failure, the FOBG measurements do not provide a clear warning, possibly because final failure occurs suddenly. However, the ultimate tensile strength of the composites decreases to an extent due to the embedded FBG and optical fibres. Nevertheless, the wider acceptance of the use of these sensing systems is still hindered by issues regarding sensor performance, especially when embedded, detection capability, maintainability, size and weight of the available interrogation equipment, and the lack of a standardisation and certification framework.

Due to their small size and flexibility, optical fibres can be embedded in composite structures during the manufacturing process. The advantages are the enhanced protection of the fragile fibre sensor and the possibility of strain monitoring and damage detection in different locations inside the material. However, sensor integration in composites presents a number of issues and shortcomings that need to be addressed properly. Some of the most relevant among them will be discussed briefly in the following sections.

Mechanical Coupling

This embedment can give rise to additional issues, as standard sensors are usually too large in comparison with the thickness of the (resin-enriched) regions between the laminate where they can be deployed during the manufacturing stage. The local distortion of the microstructure has been shown to result into a shorter lifetime of these structures, due to the inception of small defects that can eventually coalesce to provide a failure mode on their own. It is necessary to avoid the SHM system being the source of damage, since it is something that the system is supposed to feel and prevent as much as possible.

Despite being very small, a standard telecom fibre has a size (125 µm) which is much larger than commonly used composite fibres (e.g. 5–10 µm for carbon fibres). As a result, resin-rich regions are created around the fibre, especially in the woven fabric. Figure 1 clearly shows the comparison between the sizes of the sensor and the host material for different types of fabrics. Even with the small-diameter (50 µm) fibres that have been developed for sensing purposes in aerospace structures, the difference is still an order of magnitude. However, it has been demonstrated that small-diameter fibres do not produce any significant modification of the mechanical properties in the host structure. Standard telecom fibres exhibit a similar minimally intrusive behaviour when embedded parallel to the reinforcing fibres.

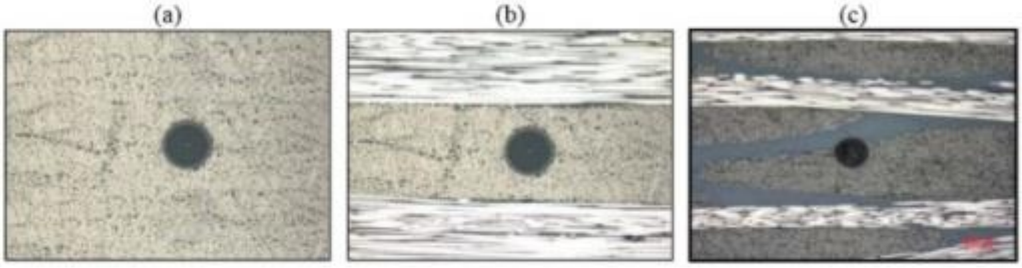

Figure 46. Optical fibre section in (a) unidirectional; (b) cross-ply and (c) woven fabric [5]

Fibre Protection at Ingress-Egress Points

Ingress and egress points of the fibre in the material are critical locations due to the sharp pressure gradient and therefore the severe bending experienced by the fibre. The concentrated stress acting during some manufacturing processes, such as the vacuum bag technique, and later under operating conditions, cause severe optical loss and may lead to fibre breakage. Different approaches have been reported in the literature to mitigate this problem. The simplest method consists in the use of small plastic tubes protecting the fibre along short sections inside and outside the material. The tubes are usually made of polytetrafluoroethylene material (PTFE, also-called Teflon) or polyvinylidene fluoride (PVDF) and may be reinforced by using a metal coil. Moreover, their openings must be sealed to avoid the ingress of the resin. In order to allow cutting and polishing of the surface after manufacturing, the fibre ingress and egress points should be located before the end section of the composite structure. In this case, care must be taken to avoid sharp curvature of the fibre and thus prevent high optical loss. However, when the fibre is embedded below several plies this method is not applicable.

Partially embedded (also-called “surface-mounted”) or embedded connectors offer another possible solution. In the first case, the connector can be positioned on one of the surfaces of the composite structure. When the fibre is embedded between internal plies, this solution is also difficult to implement. Embedded connectors are devices specially designed to overcome this problem; only the female part of the connector is embedded so that proper machining of the composite element surface is still possible. These connectors are often miniaturised to be less invasive. However, one potential source of decreased reliability is the deformation that the embedded connector might experience during the manufacturing process which may affect the alignment. In addition, the use of embedded or partially embedded connectors requires a careful assessment of the potential reduction in the strength of the composite.

Most of these problems can be avoided by using the so-called free-space coupling, which enables coupling of free-space light into and out of an embedded FBG sensor without the use of a physical connector. This result is obtained by splicing a multimode fibre to a single mode fibre Bragg grating, and using hand polishing to integrate 45° mirrors into the ingress and egress point of the fibre and the grating respectively. Although the estimated total loss is quite high (23 dB), this technique makes it possible to measure accurate strain values up to 2000 µm and increase system robustness and simplicity.

Finally, during composite part manufacturing it is important to protect the outer section of the fibre from excess resin that may escape from the layers pile.

Spectral Response in Embedding Process

The spectral sensitivity of an embedded fibre optic sensor can deviate from that of the non-embedded sensor for a number of reasons. During the heating phase of the manufacturing process, the fibre is subjected to the stress created at the boundary between the coating and the composite ply; however, during the cooling phase, this stress is only partially released. This results in residual strains acting inside the material and on the fibre. Consequently, the sensor spectral response is affected by the existence of transverse and often non-uniform strain fields.

In the literature, it was observed that the spectrum of two embedded FBG sensors was severely distorted after the manufacturing process. The Bragg wavelength peak split into two spectral components, due to the existence of transverse strain. This effect is attributed to birefringence of the optical fibre and the difference between the peak wavelengths may be used as a measure of the transverse strain. However, such a distortion of the FBG spectrum prevents measurement of the longitudinal strain based for example on the commonly available algorithms for Bragg wavelength detection, such as the Full Width Half Maximum (FWHM) method. Even if the algorithm used to track both peaks and FBG sensors were added for multi-axial measurements, it would be necessary to distinguish the two spectral components of regular shape. That is not always the case, as transverse strain or local strain gradients can cause severe distortion of the spectrum. The fibre coating plays, however, an important role in minimising the effect of transverse strain due to the manufacturing process. When an acrylate or polyimide coating are used, the Bragg wavelength is simply shifted due to longitudinal transverse strain, but the spectrum is not distorted. Even in this case though, the accurate measurement of pure longitudinal strain with a uniaxial FBG sensor may be undermined depending on the load amount, type and point of application. For all these reasons and considering also that the strain is transferred across the coating to the fibre core, accurate calibration of the embedded sensors after the manufacturing process and critical evaluation of the actual operating conditions are mandatory to ensure the reliability of the measured data.

When it comes to damage detection rather than simple strain monitoring, the information given by the distorted spectrum of bare embedded FBG can be quite useful. By relating the distortion to the specific defect and damaging mechanism, it is possible to detect cracks, delamination or debonding in various types of composite laminates. A similar method to detect impact damage can be used with distributed sensors. In those cases, the use of optoelectronic demodulators with full spectrum detection capability is needed. In addition, the fibre optic sensor must be in close proximity to the damage location, requiring an a-priori estimation or knowledge of the defect position.

Increasing of SHM reliability

The reliability of the Fibre Optic Ribbon Tape (FORT) concept is studied to measure and monitor the real-time strain induced in the composite materials under prolonged cyclic loading and also for accuracy and repeatability of real-time measurement. The FORTs are nothing but pre-assembled composite ribbon tapes, where the optical fibre is embedded in between the two composite lamina. The main advantage of the FORT assembly is easy mounting and handling of optical fibre and also protection from atmospheric degradation.

Multi agent systems seem very reliable and efficient for the larger composite laminates where different types of sensing elements are used for various damages. The most important advantage of multi agent systems is wide coverage for various modes of failure and damage, because it consists of different types of sensors for various damage types. Also, the uniformly distributed sensor and its network can deal and fuse various kind of information about the failure and damage induced in the composite’s structure.

The recently developed Micro Electro-Mechanical Sensors (MEMS) have been hailed as the SHM for composite materials because of their easy handling, tiny size and negligible weight. In the Micro Electro Mechanical Systems (MEMS), the mechanical and electrical sensing element is combined together in a single silicon chip at micro scales. After the invention of MEMS, considerable efforts have been made toward development and integration of MEMS into composite structures for health monitoring purposes. A local transmissibility vibration-based diagnostic algorithm based Structural health monitoring system for aircraft structures using smart wired piezoelectric arrays of accelerometers (MEMS) as sensor is proposed.

However, limited attention was devoted to the damage severity, location, and the residual strength of the damaged composites. To be a better Structural Health Monitoring system, it should provide not only real-time strain, but also degree of damage and residual strength of the damaged composites. Also, the SHM should provide information about the various modes of failure occurring in composites such as delamination, fibre pull-out, matrix failure, etc. Hence, the future research should focus more on the damage assessment, failure mode prediction and residual strength evaluation of the damaged composites, in order to fulfil the purpose of the SHM System for the polymer composites.

Conclusions

The problems of introducing sensors into a composite panel:

- damage to the sensors during of the panel manufacturing: fracture, connection to the connector - flowing of the binder, glue, machining of the panel - pruning is difficult
- determine the critical sensor location: there are zones where deformations or stresses change little (for example, setting in the middle, close to the neutral axis), then it is difficult to separate the real changes in the readings from the noise. Because of the heterogeneous structure, the readings of the sensors on the surface and on the layers differ
- sensors affect the mechanical properties of the panel: the introduction of foreign bodies, the formation of areas with excessive binder content - reduces the strength of the panel, can cause stratification due to low adhesion to the main material or the discrepancy between the ultimate deformations of the panel and the sensor.
- width of composite fracture forms
- the sensor dimensions are larger than the fracture zone and may further contribute to structural failure
- low maintainability of sensors embedded in the composite
- lack of regulatory issues of standardization and certification of such equipment
- aging, relaxation, creep of the composite in the process of exploitation - how to recognize this defect or the processes associated with changing the properties of the composite
- operation - providing approaches to sensor connectors to read information. The difficulty of providing an aerodynamic surface due to the large size of the connectors. To ensure the smoothness of the vertex, the connectors are removed to the back of the panels to which access is difficult to operate. If the exit to the aerodynamic surface, then it is necessary to ensure the protection of the connector in the process of explanation
- preference is given to sensors with smaller dimensions, but the probability of their damage increases
- apply polyimide to the sensor surface, increase the operating temperature of the sensor to 20 °C, improve adhesion to the composite, and compensate for residual technological stresses. The initial sensor noise is stable, but the sensitivity of the sensor decreases.
- increase reliability - Use tape sensors that duplicate the measurement. In case of damage to one, others work. Duplication of different types of sensors, piezo, opto, strain gauges.
- the formation of channels in the composite, and after the manufacture of the panel, the insertion of sensors into the channel
- apply a special tool for gluing the optical fibre and connector
- solve the problem of choosing the location of optical fibre sensors: directly, sinusoidally, with what amplitude of the sinusoid, inside - on the surface of the composite, how close to damage is the sensitivity evaluation of the sensor, depending on the current load, experimental evaluation methods or KEM.

How to solve the problem: It is necessary to answer 4 questions

- Where to put? Based on the model, conditions of loading and work, taking into account the manufacturing and installation technology, the map of setting the sensors is optimized
- What sensors to deliver? In the course of optimization, the limiting deformations occurring in the structure will be obtained, the sensors will be selected from the condition of the sensor panel, with the required measuring range and sensitivity
- How to deliver? Development of TP, equipment for the implementation of the entrance and exit of fibre, where the fibres are most often broken, the equipment for connecting to the connector which ensures that the binder does not leak. TP must provide reliability and stability.
- How to exploit? The design of the connector and panel design, taking into account their overlapping and at the same time providing a free approach during operation and external requirements, for example, smoothness of the contour. Improve the maintainability of such panels.

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3.3 Training provided

The participants of the AERO-UA Pilot Projects 3.2a, 3.2b, and 3.3b working meeting on July 34 2017 at the University of Manchester on in Warsaw were:

No.	***Name***	***Organisation***
1	Prof Mojtaba Moatamedi	Aerospace Research Institute (UoM)
2	Dr Adam Joesbury	Aerospace Research Institute (UoM)
3	Dr Matthieu Gresil	i-Composites Lab (UoM)
4	Prof Prasad Potluri	Northwest Composites Centre (UoM)
5	Prof Constantinos Soutis	Aerospace Research Institute (UoM)
6	Dr Lina Smovziuk	National Aerospace University (KhAI)
7	Dr Fedir Gagauz	National Aerospace University (KhAI)
8	Dr Valeriy Fadeyev	Public Joint Stock Company (FED)
9	Dr Krzysztof Dragan	Technology Partners Foundation (TECPAR) / Air Force Institute of Technology (ITWL)
10	Dr Michal Dziendzikowski	Technology Partners Foundation (TECPAR) / Air Force Institute of Technology (ITWL)
11	Dr Iryna Bilan *(via Skype)*	Frantsevich Institute for Problems of Material Science (NASU)

3.4 Scientific results

Transfer Impedance Approach to composite structures monitoring – contributor: TECPAR / ITWL (PL)

In the first half of the project a new method for composite structures monitoring by use of PZT sensors was investigated. In the so-called electromechanical impedance (EMI) approach, sinusoidal steady state voltage is applied to PZT actuator in a given frequency range. Then, for a single transducer, its impedance is measured in a given range [1], while for actuator-receiver PZT sensor pairs, the receiver voltage, i.e. the output voltage, can be measured for the structure state assessment [2].

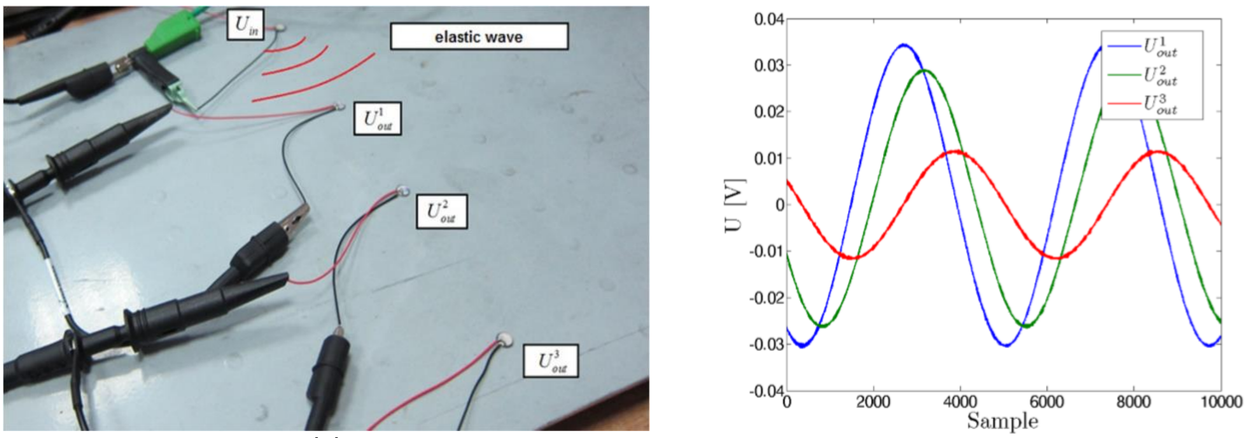
Figure 47 presents an example of a voltage obtained for three different PZT transducers, sensing distribution of elastic waves excited by a generator sourced with sinusoidal voltage. If one of the transducers of a PZT network integrated with a structure transmitting elastic waves, i.e. the generator - g - is powered with sinusoidal voltage U_{in} at frequency ω, then the voltage U_{out} obtained at any given receiver - s is also sinusoidal and has the same frequency, in accordance with Linear Time Invariant (LTI) systems theory. Therefore, the ratio, called the transmission function:

$$TF_{gs} = \frac{U_{out}}{U_{in}} \tag{1}$$

does not depend on time and can be written as a complex function:

$$TF_{gs}(\omega) = \frac{U_{out}}{U_{in}} = \frac{|U_{out}|\, e^{i\omega t + \varphi_{gs}(\omega)}}{|U_{in}|\, e^{i\omega t}} = |TF_{gs}(\omega)|\, e^{i\varphi_{gs}(\omega)}, \tag{2}$$

representing relative amplitude ratio $|TF_{gs}(\omega)|$ and phase difference $\varphi_{gs}(\omega)$ between output and input signals. Both parts of the transfer function depend on many factors, e.g. the geometry of the network, the technology of PZT transducers integration with the structure, but can be also influenced by a presence of damage near the sensing path *g*–*s*, i.e. the line which joins the generator *g* with the sensor *s*.



(**a**) (**b**)

Figure 47. Example of a sinusoidal steady state excitation of PZT sensors (a) PZT network; (b) Output voltages acquired on PZT sensors.

The dependence of the transmission function on the signal frequency can be quite complex, therefore its direct application is of limited usefulness. For structure assessment, some comparison of the baseline transmission function TF^0_{gs}, obtained for the initial state of the structure, with the actual transmission function TF_{gs} is needed.

This can be done by Damage Indices of the form:

$$DI_{gs}(\omega) = \frac{TF_{gs}(\omega)}{TF_{gs}^{0}(\omega)} = \frac{|TF_{gs}(\omega)|}{|TF_{gs}^{0}(\omega)|} e^{i(\varphi_{gs}(\omega)-\varphi_{gs}^{0}(\omega))} . \qquad (3)$$

Assuming that the voltage on the generator U_{in} is maintained the same, the modulus of DIs

$$|DI_{gs}(\omega)| = \frac{|U_{out}(\omega)|}{|U_{out}^{0}(\omega)|} \qquad (4)$$

describes the ratio between output voltage amplitudes on the sensor *s* at a given frequency for the actual and baseline measurements. Therefore, the DIs captures the information about output voltage amplitude as well as phase changes in a given frequency range. For undamaged structure, the DIs should be concentrated in the vicinity of the point *1+i0* in the complex plane (Fig. 48). If damage is present in the structure, its influence on the output voltage amplitude or the phase is expected, at least for some range frequencies, therefore DIs should exhibit some divergence from the origin, i.e. the point *1+i0* (Fig. 48).

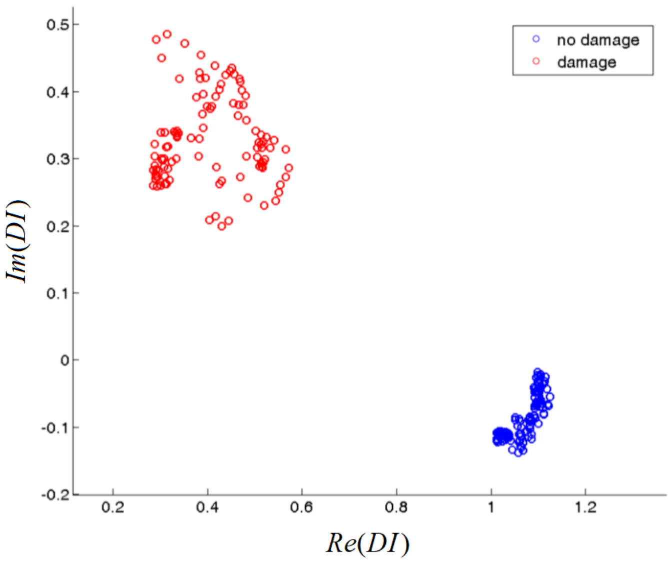


Figure 48. Example of DIs obtained for the pristine state of the structure and when a damage is present

It is worth noting that almost all of the information of the signal is carried by the DIs. Assuming the baseline transmission function TF_{gs}^{0} and input voltage U_{in} are known, $U_{out}(\omega)$ can be reconstructed from the DIs. The proposed method should therefore detect all damage types with an impact on the acquired signals in terms of the amplitude and the phase.

Design and Preparation of the Experiment

An experiment designed to verify basic properties of the Damage Indices proposed for structure monitoring was designed. The specimen under study was a GFRP panel made of 16 plies of HCS2401-015 – HEXCEL Fiberglass Prepreg. The stacking sequence of the layers was [0/45/0/45/0/45/0/45]s. In the symmetry plane of the specimen, a network of PZT discs SMD05T04R111 made by STEMINC Inc. was deployed. The diameter of PZT transducers is 5 mm and the thickness is 0.4 mm. After deployment of PZT transducers, the specimen was cured in the autoclave in accordance with the technical specification of the material being used.

Four PZT discs of the same type were deployed on the surface of the specimen, precisely above four selected transducers embedded in the specimen structure. Also, the orientation of the attached sensors was maintained the same as for the sensors underneath them. Fig. 49 presents the geometry of PZT networks. For both networks, for the network attached to the specimen surface as well as for the embedded network, one of PZT transducers was selected as the guided waves actuator whereas the remaining three sensors were used as sensors. Therefore, three sensing paths for each of the networks were considered in the study (Fig. 40):

- G-S1 of the length 167 mm;
- G-S2 of the length 213 mm;
- G-S3 of the length 90 mm.

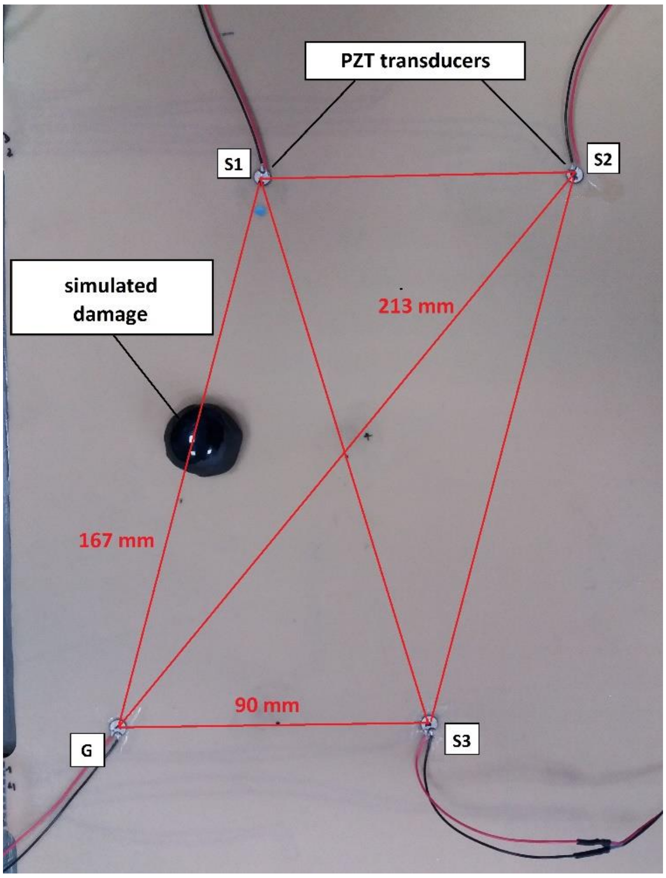


Figure 49. The geometry of the PZT network.

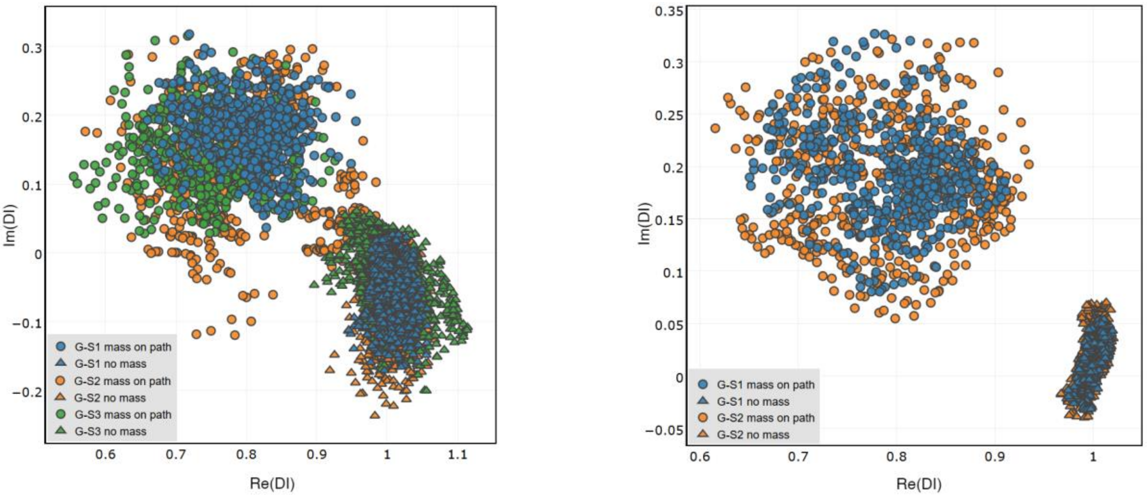
It is worth noting that not only the lengths of the networks sensing paths were different, but also their orientation with specimens' plies and respective orientation between actuator and sensor for a given sensing path.

For both PZT networks, the measurements were conducted according to the following scheme:

1. Measurement for the pristine state of the structure.
2. Measurement for simulated damage on sensing path G-S1.
3. Measurement for simulated damage on sensing path G-S2.
4. Measurement for simulated damage on sensing path G-S3.

The measurement scheme was repeated six times for each network. The damage was simulated by a mass element attached to the specimen by bitumen in the middle of a given sensing path. The bituminous mass used for the attachment was additionally attenuating elastic waves propagating between the sensors. The actuator G was powered by sinusoidal steady state voltage source in the frequency range of 240 – 350 kHz. The frequency increment step was 1 kHz, peak-to-peak amplitude was set to 88 V.

The figure below presents a comparison of DIs distribution for different sensing paths in the presence of simulated damage and for the pristine state of the structure. The data from all repetitions of measurements are merged for the purpose of comparison.



(**a**) (**b**)

Figure 50. Comparison of DIs obtained for the pristine state of the structure and for simulated damage presence: (a) Attached network; (b) Embedded network

Remarkably, for both networks the DIs obtained at certain conditions are confined in similar domain, irrespective of the sensing path being considered. It is worth noting that the material being studied exhibits mechanical anisotropies, as well as piezoelectric discs used for the study [1], i.e. the power of emitted or gained elastic waves usually depends on the direction of their incidence on a sensor. However, the results do not depend significantly either on the direction of the sensing paths or on respective orientation of generator and sensor. Also, the distance between sensors constituting a sensing path is not relevant for the domain where the data is concentrated. These properties are of particular importance for damage classification possibility. Stability of indications under similar conditions, e.g. presence of a given type of damage on a sensing path, allows for definition of domains in the DIs complex plane corresponding to different damage scenarios.

Further perspectives

Based on the provided experience of Aero-UA project partners, a joint study on the efficiency of different approaches to SHM of composite structures will be delivered. The method presented will be further developed by TECPAR / ITWL (PL). In cooperation with KhAI (UA) and E. O. Paton Electric Welding Institute at NASU (UA) composite specimens equipped with network of PZT sensors will be delivered by KhAI. The efficiency of the method proposed by TECPAR / ITWL will be tested towards detection of damage of composite structures, caused by low energy impacts. Further, fatigue or destructive (Compression After Impact) tests will be performed, in order to test Acoustic Emission system capabilities for continuous composite structure monitoring by E. O. Paton Electric Welding Institute at NASU.

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4. Progress with respect to WP3 performance indicators

Work Package (High-Level Objective)	Performance indicators	Amount achieved by project midpoint (M18)	Target by end of project (M36)
WP3. EU-UA aviation research knowledge transfer pilot projects ***(High-Level Objective 3)***	• No. of short term staff exchanges about advanced design of aerospace composite structures	3	> 8
	• No. of trainings on advanced design of aerospace composite structures	5	> 5
	• No. of short term staff exchanges about aerospace composite structural health monitoring system	3	> 8
	• Feasibility study on aerospace composite structural health monitoring system	*in progress*	1

4.1 Task 3.1: Pilot projects between EU-UA partners in the field of aerostructures - meetings

Completed visits:

- 11-12.10.2016, Hamburg - AERO-UA Project Kick-off Meeting
- 10.12.2016, Manchester - Meeting between KhAI and UoM, as part of a visit funded by the British Council in Ukraine
- 19-20.04.2017, Kyiv - AERO-UA Project Meeting, tour of Antonov
- 21.04.2017, Kyiv - UoM representative visited NASU institutes: Frantsevich Institute for Problems of Materials Science, Pisarenko Institute for Problems of Strength, Paton Electric Welding Institute
- 3-4.07.2017, Manchester - Working Meeting hosted by UoM
- 21-22.09.2017, Warsaw - AERO-UA Project Meeting, visit to ITWL, WZL-4, Warsaw University of Technology

Planned visits:

- 29.05-1.06.2018, Kharkiv - AERO-UA Project Meeting and visit to KhAI lab
- M24, Toulouse - AERO-UA Project Meeting
- M30, Zaporozhe - AERO-UA Project Meeting
- M36 Kiev, - AERO-UA Project Meeting