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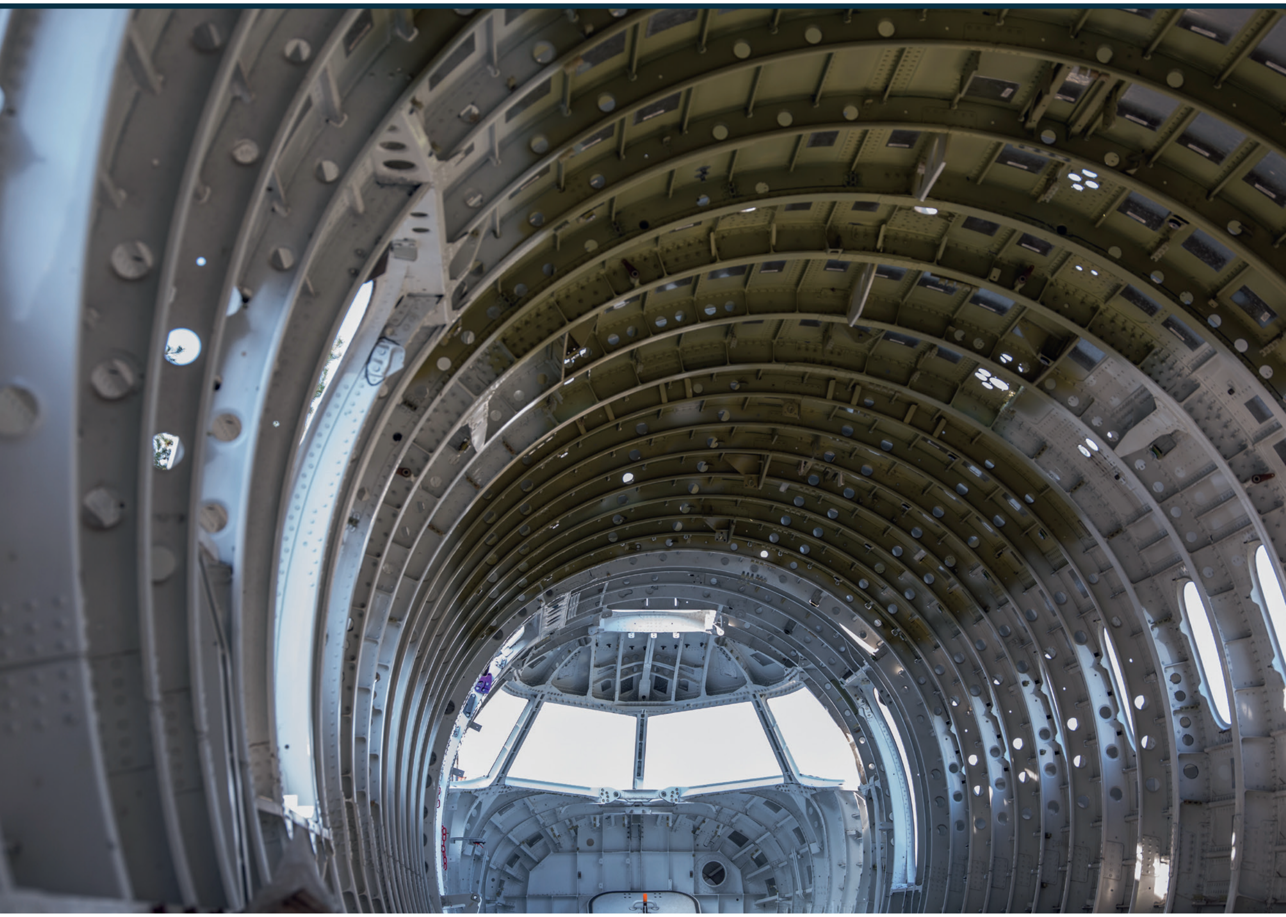
RIGA TECHNICAL UNIVERSITY

Pavithra Nagaraj

STUDY OF FATIGUE DAMAGE DETECTION BY CURRENT INFORMATION OF MEASUREMENT SYSTEM

Doctoral Thesis



RTU Press
Riga 2023

RIGA TECHNICAL UNIVERSITY
Faculty of Mechanical Engineering, Transport and Aeronautics
Institute of Aeronautics

PAVITHRA NAGARAJ
Doctoral Student of the Study Program "Transport, Aviation Engineering"

STUDY OF FATIGUE DAMAGE DETECTION BY CURRENT INFORMATION OF MEASUREMENT SYSTEM

Doctoral Thesis

Scientific Supervisor:

Professor Dr. habil. sc. ing.
VITĀLIJS PAVELKO

Official reviewers:
Dr. sc. ing. Sandris Ručevskis,
Riga Technical University

Ph. D. Wolfgang Grill
University of Leipzig, Germany

Dr. habil. sc. ing. Sergey Ignatovich
National Aviation University, Ukraine

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In memory of my late grandfather, who served as a pillar of support, both morally and emotionally, I want to express my deepest gratitude. His unwavering belief in my abilities and his constant encouragement have been a driving force behind my accomplishments. I am indebted to my family for their patience, understanding, and unwavering support throughout this journey. Their love, encouragement, and belief in my abilities have provided the foundation upon which I have built my academic achievements. Lastly, I would like to extend my heartfelt appreciation to all my well-wishers, family, and friends who have stood by me and provided encouragement and support during this challenging endeavor.

I am honored to have had the privilege of working with such exceptional individuals and being supported by a remarkable network of people. Without their contributions, this accomplishment would not have been possible. Thank you all for your unwavering support, guidance, and encouragement throughout my doctoral journey.

ANOTĀCIJA

SHM jomā ir daudz tehnoloģiju, kas ļauj noteikt noguruma bojājumus. Gidvainu tehnoloģija aviācijas nozarē ir pierādījusi plašu pielietojumu. Strukturālu bojājumu noteikšanas galvenā metode ir salīdzināt pašreizējo bojājumu indeksu ar tā vērtību intakta stāvoklī (atsauces vērtība). Dažādā pretējā gadījumā, atšķirībā no nelabojošas testēšanas, SHM sistēmas sastāvdaļas ir integrētas uzraudzītajās struktūrās un tām ir izturības un vides faktoru iedarbība, kas ir līdzvērtīga pamatkomponentu iedarbībai. Tas noved pie SHM jutīgo sastāvdaļu degradācijas procesiem, mērījumu precizitātes samazināšanās un dažreiz pilnīgas darbības zuduma. Lai sasniegtu pieņemamu novecošanas ātrumu un novērstu to pilnīgu iznīcināšanos paredzētajā kalpošanas laikā, jutīgo elementu aizsardzība vajadzētu nodrošināt SHM sistēmas projektēšanas stadijā un tās uzstādīšanas laikā uzraudzītajā komponentā. Tomēr degradācijas iemesli nekur neaiziet. Monitoringa rezultātu negatīvās ietekmes samazināšanai ir iespēja modificēt bojājumu noteikšanas procesu un salīdzināt monitoringa rezultātus divu alternatīvu struktūras stāvokļu gadījumā. Piezoelektrības koncepts nav jauns. Šajā autora pabeigtajā darbā tiek apskatītas tādas tēmas, kas cieši saistītas ar piezoelektrisko parādību un tās pielietojumiem: (a) sensoru pašu stiprības un izturības problēma; (b) plaisas atvēršanās/aizvēršanās ietekmes izpēte; (c) plaisas atvēršanās/aizvēršanās ietekme uz EMI un elastīgo viļņu izplatību; (d) bojājuma indikatoru EMI un vadīto viļņu izplatības problēmu izpēte; (e) plaisu atklāšanas problēma hermētiskās korpusa konstrukcijās; un (f) PZT izmantošanas slodzes un stresa monitoringā un prognozēšanas problēma. Patiesais fokuss darbā ir uz aktīvajām vadītajām viļņu tehnoloģijām SHM un-AE izmantošanu kā pasīvās ultraskaņas diagnostikas metodes.

Pabeigtā darba galvenais sasniegums ir šāds: (1) ir pabeigti īpašie projektēšanas procesi. Tika veikta taisnstūrveida formu PZT konkrēto analīzes stiprības problēmu izpēte un noteikta. Pēc pārbaudes tika noteikts, ka PZT lūzums, kas radies starp transduseri un līmējošo slāni robežas plaknē, tiek izraisīts statiskās vai cikliskās spriedzes iedarbības dēļ. Tika parādīts, ka stresa stāvokļa analīze var tikt veikta projektēšanas fāzē, lai palielinātu SHM sistēmas noturību un darbības laiku. (2) Jaunu EMI mērījumu metožu izmantošana kā labākās frekvenču joslas izvēle. Lai bojājuma indeksi saglabātu stabilitāti, ir būtiski faktori, piemēram, datu kopas loga platums, paraugu punkti un frekvenču joslas izvēle. Ieteicama saprātīga metode EMI bojājuma indeksu definēšanai. Novatoriska procedūras analīze par EMI rezultātiem. (3) Jauni bojājuma metriki, izmantojot vadīto viļņu tehnoloģiju (GWT). Ņemot vērā, cik svarīgs ir plaisas atvēršanās/aizvēršanās efekts, šo tehnoloģiju var izmantot arī tikko apskatītajā versijā. Izmantojot novatorisku DI, kas neatkarīga no GWT versijas, tiek ierosināta datu apstrādei un bojājumu novērtēšanai. (4) Precīzi indeksi, izmantojot konvolūcijas atbildi ar ievades signālu un mātes funkciju. (5) Varbūtiskais slodzes monitoringa modelis, lai novērstu strukturāli kritisku stāvokli, ko var izraisīt intensīvas slodzes. Akustiskās emisijas monitoringu nodrošina PZT transdusera pasīvā atbilde. Tas darbojas lieliski izturības noguruma testos.

Izdrāzieni noguruma bojājumiem novērtēšanai, lai novērtētu paneļa noguruma stiprību un PZT pārbaudītāju izturības testu, tika veikti RTU Aerokosmētikas institūta struktūru laboratorijā. Attiecībā uz AE kā pasīvām metodēm eksperimenti tika veikti LNT AVIATEST, eksperimentālo rezultātu validāciju veica, izmantojot COMSOL Multiphysics vidi, 3D modelēšanu un moda analīzi, kas tika veikta AUTODESK Inventor.

Visi jaunākie SHM aktīvo un pasīvo metožu tehnoloģiskie risinājumi, uzlabojumi un nozīme, PZT pārveidotāju un piezoelektrisko fenomenu izmantošana, ir apkopoti literatūras pārskata sadaļā, izmantojot vairākas pieejamās datu bāzes internetā.

Promocijas darbs ir rakstīts angļu valodā, tas satur 103 lapas, 71 attēlus, 7 tabulas, atsauces uz līdz 102 literatūras avotiem.

ABSTRACT

In SHM, there are numerous techniques for detecting fatigue damage destruction. In the aviation industry, guide wave technology has demonstrated a wide range of applications. It is well known that comparing the current damage index with its value for intact structure (baseline) is the primary method of structural damage detection. Many SHM system components, in contrast to non-destructive testing (NDT), are integrated into monitored structures and are exposed to the same operational loads and environmental factors as the host component of the structure. All those result in the processes of deterioration of SHM's sensitive components, a decline in measurement accuracy, and occasionally a complete loss of operability. To achieve an acceptable rate of aging and prevent their complete failures within the stated service life, the protection of sensitive elements should be given at the SHM system's design stage and during its installation at the monitored component. The reasons for degradation, however, never go away. Modifying the damage detection process to compare the monitoring findings for two alternative current states of the structure offers a basic opportunity to lessen the detrimental impact on the monitoring results. The concept of piezoelectricity is not new. The following topics are covered in this author's completed work and are closely related to the idea of piezoelectric phenomena and its applications: The following issues need to be addressed: (a) the issue of the sensors' own strength and durability; (b) the investigation of the effects of crack open/close; (c) the effect of crack open/close on EMI and elastic wave propagation; (d) the investigation of the issues with damage indices EMI and guided wave propagation; (e) the issue of crack detection in fuselage hermetic structures; and (f) the experiment and prediction issue of PZT using load and stress monitoring and the use The actual focus of the work is on active Guided wave technology approaches in SHM and employing AE as passive ultrasound diagnostic methods.

The main achieved result of finished work follows, (1) special designing processes are completed. The investigation of the rectangular shape of the PZT-specific analysis's strength issues is carried out and established. Following examination, it was determined that the PZT breaking, which originates from the boundary plane between the transducer and the glue layer, is brought on by static or cyclic tension. It has been demonstrated that stress state analysis can be accomplished during the design phase to increase the durability and lifetime of the SHM system. (2) A novel method of EMI measurements as the best frequency band selection. For the damage indices to remain stable, factors including the data set's window width, sample points, and frequency band selection are crucial. The reasonable method for defining EMI damage indices is suggested to define EMI damage indices logically. Novel procedure analysis of the outcomes of EMI proposed. (3) Novel damage metrics created with guided wave technology (GWT). Because of how important the crack open/close effect is, this technology may also be utilized in the version that was just discussed. For data processing and damage assessment, a novel DI is proposed that is independent of the GWT version. (4) Exact indices created using convolution response with the input signal and the mother function. (5) A probabilistic load monitoring model for the potential prevention of a structurally critical state that can be brought on by intense loads Acoustic emission monitoring is made possible by a piezoelectric transducer's passive response. It works well in tests of endurance fatigue.

Experiments on fatigue damage destruction to assess fatigue strength of panel and PZT transducers durability test were performed in RTU Aeronautical institutes structures laboratory. For AE as passive methods experiments were conducted in LNT AVIATEST, Validation of experimental results with COMSOL Multiphysics environment and 3D modeling and Modal analysis executed in AUTODESK Inventor.

All the latest techniques, advancements, and significances of SHM active and passive

methods, usage of PZT transducer and piezoelectric phenomenon are summarized in literature review section through several database available sources over internet.

The promotional work has been composed in the English language, it contains 103 pages, 71 figures, 7 table, references up to 102 literature sources.

LIST OF FIGURES

LIST OF TABLES

TERMINOLOGY AND ACRONYMS

AE – Acoustic emission
ACM – Aerospace civil mechanical
CCD – Correlation co-efficient deviation
CFRP – Carbon fiber reinforced plastic
CM – Condition monitoring.
DAQ – Data acquisition
DI – Damage index
DMF – Damage monitoring feature
DPM – Dynamic probability modeling
EMI – Electromechanical impedance
EMA – Electromechanical admittance
FEA - Finite element analysis
GWT - Guided wave technology
HUMS – Health and usage monitoring
LWT – Lamb wave technology
NDT – Nondestructive testing
NDE – Nondestructive evaluation
MPB – Morphotropic phase boundary
PAUT – Phased array ultrasonic technique
PZT – Lead Zirconate Titanate
PWAS – Piezoelectric Wafer Active Sensors
PCMCIA - Personal Computer Memory Card International Association
RMSD – Root means square deviation.
SHM – Structural Health Monitoring
SLM – Structural load monitoring
VHM – Vibration health monitoring

INTRODUCTION

The topic relevance

The ultrasonic diagnostic technologies have found wide application in civil, medicine, aerospace, and many other areas. As a basic principle of measurement, the ultrasonic method is one of the most naturally adapted for use in SHM system. The significant advantage of the ultrasonic method is the possibility of multi-optional applications (classical damage detection, guided wave technology, electromechanical impedance technology, stress, and load measurement). Each of those options can be optimally applied in some specific conditions but the combined application can be realized also.

However, there are several problems those negativity influence on reliability of results and effectiveness of in-build monitoring. First, it is the problem of the mechanical strength and lifetime of sensitive elements of SHM system. In contrast to the non-destructive testing (NDT) those elements of the SHM system are in-built to monitored structure and subjected by the same operational load and environmental actions as the host component of structure. Degradation processes can cause partial or full loss of operability of SHM system. The problem can be solved partly by protecting sensitive elements from negative external actions. Another way to increase the reliability of monitoring is to use the so-called “reference-free” approach of evaluation of the damaged state of structural component. This approach joins options in which the technical condition assessment is based on current or accumulated information, without reference to the initial state (baseline). It is commonly understood that ultrasonic monitoring systems exhibit different responses when detecting fatigue cracks that are in a mechanically loaded state (where the crack is open) versus an unloaded state (where the crack is closed). The response of the second state can be taken as the current baseline.

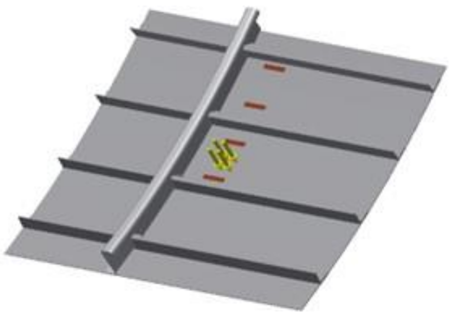

Fig.1. The typical part of metallic fuselage equipped by piezoceramic transducers.

In the present work the relevant problems of realization of mentioned approach are investigated for a skin of the hermetic part of metallic fuselage (Fig.1). In the cruising flight the skin is statically loaded by internal air pressure in cabin, but after landing the skin is unloaded.

Obviously, load monitoring involves an indirect way to assess the structural health of a structure. This estimate can be obtained based on the use of an acceptable generalized damage parameter determined by the results of load monitoring and its comparison with the

strength characteristics of the controlled structural element. Critical value of damage index may be established in accordance with the safety factor approach.
Alternative is the probabilistic approach. Both compared quantities are random. Therefore, the damage index should have a probabilistic formulation and be perceived as a requirement for additional verification and assessment of the technical condition of the structural element in question. The procedure of this type is developed in this work and its fundamental fragment is presented.
A similar use case for the passive response of a piezoelectric transducer provides acoustic emission monitoring. It can be effectively used in endurance fatigue tests.
So, all mentioned problems directly influence operability and reliability of ultrasonic SHM systems. Their investigation and solution are relevant for nowadays applied science.

The aim and Objectives of Doctoral Thesis

The general aim of this research: Solutions for several relevant problems of operability and reliability of ultrasonic structural health monitoring mainly using the current information of embedded piezoceramic transducers working in active and passive regimes of damage detection.

The following objectives should be solved for the achievement of formulated general aim:

1. Analysis of the piezoceramic transducers strength using Internet resources, experimental data, and finite element analysis (FEA) of stress state for typical installation and typical operational loading. Development of recommendations for prevention of damages at the static and cyclical load.

2. Estimation of EMI as primary method of fatigue crack detection, comparison of properties of alternative indices of damage, the development of the detailed procedure of measurement data processing.

3. Investigation of the crack open/close effect on EMI and estimation of this effect suitableness for the crack-type damage detection.

4. Improvement of the damage indicis for the crack-type damage detection by the guided wave technology using fatigue test data and simulation outcome.

5. Demonstration of application of references-free virtual system of SHM (for the skin of hermetic fuselage of aircraft)

6. Analysis of piezoelectrical transducer application for load monitoring. Development of the fatigue damage index with using of the rain-flow method of operational load transformation and concept of safety factor.

7. Probabilistic model of strength for SHM of lifetime by using of load monitoring

8. Analysis of acoustic emission (AE) application as a passive ultrasonic method in respect of its use in laboratory test of aircraft full-scale components.

Novelty of scientific research

1. Novel statistical characteristics on the fatigue lifetime of typical piezoceramic transducers were found.

2. General properties of the stress state of piezoceramic transducers at different options of their embedding to monitored structural component and recommendations on the providing of strength at operational load.

3. The crack open/close effect on the ultrasonic index of damage is theoretical base of the reference-free SHM system which is used the current data of transducer only.

4. Novel procedure of EMI measurements processing which includes selecting of the width of data set window and defining of the frequency band of highest stability of damage index.

5. New damage index for fatigue crack detection using guided wave technology (GWT). This index is the convolution of response with using the excitation signal as mother function.

Practical application of the thesis

1. Obtained realistic estimates of the strength and the fatigue lifetime of typical piezoceramic transducer are useful for designing the PZT-based SHM system.
2. The improved procedure of processing of EMI measurement can raise the trustworthiness of damage detection.
3. The proposed index of damage for GWT of SHM provides higher reliability and accuracy of structural damage detection.
4. The example of hypothetical SHM system for the skin of hermetic fuselage can be useful at design of local SHM system.
5. Direct simulation of the response of piezoceramic transducer as an important stage of its use of load (stress) monitoring.
6. Basic technical requirements for bench testing and full-scale real time testing of helicopters using Acoustic Emission (AE) as a passive ultrasound method have been formulated. It can be effectively used in endurance fatigue tests.

Thesis structure and Its Main Results

The thesis structure has been summarized in 4 chapters.

In Chapter 1, Overview of ultrasonic methods, latest advancement and state of art research is reviewed.

In Chapter 2, The own mechanical strength of piezoelectric transducers and their connection with the monitored host structure as the primary problem of reliability of

SHM of aircraft structures are analyzed and summarized in publication No. 4, with the three main topics covered:

1. More detailed description of problem.
2. Essential results of transducers destruction during the fatigue test.
3. Investigation of stress state of transducers embedded in the thin-walled structure.

In chapter 3, Active methods of SHM using ultrasound techniques analyzed and summarized in publication No. 3and 4 with main topics covered:

1. Electromechanical impedance, its components, and EMI parameters.
2. Other indices of EMI based system of SHM.
3. Experimental study of the crack open/close effect and the perspective of its use in SHM
4. Aim of experimental investigation.
5. The test sample, equipment, and test setup
6. Essential outcomes of experiment
7. Application to the SHM of the skin of hermetic fuselage is analyzed Demonstration of Impedance based SHM of the hermetic fuselage skin.
8. Predictions of fatigue crack growth and estimation of lifetime.

In chapter 4, Other applications: load monitoring and acoustic emission are analyzed with some unpublished results and Summarized publication No. 1,2, with five topics covered:

1. Related applications
2. Load monitoring using PZT response.
3. Equivalent stress and structural health assessment by use of load(stress) monitoring.
4. Probabilistic model of strength for SHM of lifetime using load monitoring
5. Acoustic emission as passive methods of ultrasound techniques.

The Following conclusions are drawn:

1. There is complete analysis of the piezoceramic transducers strength using Internet resources, experimental data, and finite element analysis (FEA) of stress state for typical installation and typical operational loading. Recommendations for prevention of damage to the static and cyclical load are made.
2. Estimation of EMI as primary method of fatigue crack detection is made. There is done comparison of properties of alternative indices of damage. The detailed procedure of measurement data processing is developed.
3. The crack open/close effect on EMI is investigated and the suitableness of this effect for the crack-type damage detection is estimated.
4. The two improved damage indicis for the crack-type damage detection by the guided wave technology are developed. Both damage indicis (RMSD and time-of-flight) are based on the convolution of response signal for which the excitation signal is used as the mother function.
5. The example of application of references-free virtual system of SHM is demonstrated (for the skin of hermetic fuselage of the passenger aircraft). It can be concluded that hermetic fuselage structure is a very convenient field for application of ultrasonic technology of structural health monitoring which uses the crack open/close effect.
6. Application of piezoelectrical transducer for load monitoring is analyzed. The fatigue damage index with using of the rain-flow method of operational load counting, fatigue test data and simulation outcome is developed. The allowable value of the index is mainly defined by the safety factor.
7. Probabilistic model of strength for SHM of lifetime by using of load monitoring is presented. Using this model, it is feasible to address the challenge of accurately determining the maximum allowable parameter or diagnostic sign for cockpit indication, given that the predetermined limit of its actual value is known in advance.

8. Application of acoustic emission (AE) as a passive ultrasonic method is analyzed in respect of its use in laboratory test of aircraft full-scale components. The formulation of fundamental technical prerequisites for conducting real-time full-scale bench tests on helicopters is established. The outcomes derived from these bench tests can be utilized to assess the strength and endurance of helicopter components through testing calculations, specifically in relation to short-term criteria.

Research methodology

The research is completely determined to study fatigue damage detection using piezoelectric phenomenon of transducers. The study is focused on two directions active methods and passive methods of guided wave propagation. First, experimental methods of fatigue damage destruction were conducted. In this experiment, the task was to assess the fatigue strength of the panel, as well as the effectiveness of the monitoring system based on the Lamb wave technology. For this purpose, two groups of five piezoelectric transducers PIC 151 with dimensions of 0.5x10x50 mm were installed on the surface of the lining parallel to the axis of the stringer on each side. At the stage of initiation of the fatigue crack, the technical condition of the transducers periodically (after 20 thousand cycles) was monitored by measuring their electromechanical impedance and comparing it with its value before the start of the tests (baseline).

Secondly, the Finite element analysis was executed by using the COMSOL Multiphysics software of the study option Stationary. Because there is double axial symmetry of model in the coordinate plane xz the outcome of stress analysis is presented for one quarter part of a model. Where the general view of distribution of stresses (in the form of Von Mize’s equivalent stress) and deformed shape of the model at tensile longitudinal load were illustrated.

Thirdly The fundamental tool utilized in this model is the modal analysis of the dynamic response of the system composed of the "host structure - PZT." By applying this analysis, the final equations for electromagnetic interference (EMI) are derived. As easy to see this model directly uses results of modal analysis of structure and is independent from details of structure configuration, boundary conditions and external loading is the main advantage of EMI model. For this study the modal analysis is performed in COMSOL Multiphysics, and its results transmit to MATLAB in which the algorithm of the EMI model is realized.

To showcase the structural health monitoring (SHM) of the hermetic fuselage skin using impedance-based methods, the geometrical modeling process is performed within Autodesk Inventor. To solve the problem of piezoelectricity for any linear piezoelectric device in a constitutive relation in the tensorial form sensing piezoelectrical equations in compressed form are used.

Using Gaussian law of distribution, the mathematical model for probabilistic approach of construction of fatigue damage index is analyzed.

Publications and Thesis approbation

The proceedings of conferences contain the complete texts of papers indexed by SCOPUS and the Web of Science.

1. Urbaha, M., Carjova, K., Nagaraj, P., Turko, V. Requirements for Helicopter's Planer Construction Fatigue Testing. In: Transport Means 2018: Proceedings of the 22nd International Scientific Conference, Lithuania, Trakai, 3-5 October 2018. Kaunas: Kaunas University of Technology, 2018, pp.1268-1270. ISSN 1822-296X. e-ISSN 2351-7034.

2. Nedelko, D., Urbahs, A., Urbaha, M., Carjova, K., Turko, V., Nagaraj, P. Assessment of the Limits of Signs of Health, and Usage Monitoring System for Helicopter Transmission. Procedia Computer Science, 2019, Vol. 149, pp.252-257. ISSN 1877-0509. Available from: Doi: 10.1016/j.procs.2019.01.131.

3. Nagaraj, P., Pavelko, V. Crack Open/Close Effect on Impedance Based System of Structural Health Monitoring. In: TRANSBALTICA 2022: TRANSBALTICA XIII: Transportation Science and Technology pp 797–805, Lithuania, Vilnius, 15-16 September 2022. Lithuania: Springer, Cham, 2023, pp.797-805. ISBN 978-3-031-25866. e-ISBN 978-3-031-25863-3. Available from: Doi:10.1007/978-3-031-25863-3_78

4. Vitalijs Pavelko, Pavitra Nagaraj "On the combined system of structural health monitoring (SHM) of the skin of the fuselage sealed part" Seminars WarshawPoland 2022, November, Article in print.

Author's Contribution to Publications

The scientific publications were produced through a collaborative effort involving the supervisors Professor Vitalijs Pavelko and the late Director Professors Urbahs, A, as well as co-authors and consultants. The authors jointly planned and carried out the work on these publications. Table 1 provides a summary of the author's contributions to the research work included in the scientific publications.

Table1.1

Involvement in the production of scientific publications.

Nr.	**Publikācijas nosaukums**	**Publikācijas vieta**	**Līdzautoru daļa%**						
			Nagaraj P	Pavelko V	Carjova, K	Turko, V	Nedelko, D	Urbaha, M	Urbah A.
1.	Requirements for Helicopter’s Planer Construction Fatigue Testing	Transport Means 2018: Proceedings of the 22nd International Scientific Conference, Lithuania, Trakai, 3-5 October 2018. Kaunas: Kaunas University of Technology, 2018, pp.1268-1270. ISSN 1822-296X. e-ISSN 2351-7034.	30		20	20		30	
2.	Assessment of the Limits of Signs of Health, and Usage Monitoring System for Helicopter Transmission.	Procedia Computer Science, 2019, Vol. 149, pp.252-257. ISSN 1877-0509. Available from: Doi: 10.1016/j.procs.2019.01.131.	10		10	10	50		20
3.	Crack Open/Close Effect on Impedance Based System of Structural Health Monitoring.	In: TRANSBALTICA 2022: TRANSBALTICA XIII: Transportation Science and Technology pp 797–805, Lithuania, Vilnius, 15-16 September 2022. Lithuania: Springer, Cham, 2023, pp.797-805. ISBN 978-3-031-25866. e-ISBN 978-3-031-25863-3. Available from: Doi:10.1007/978-3-031-25863-3_78	90	10					
4.	On the combined system of structural health monitoring (SHM) of the skin of the fuselage sealed part	Seminars Warshaw Poland 2022, November, Article in print.	50	50					

CHAPTER 1. OVERVIEW: ULTRASONIC METHODS IN SHM, LATEST ADVANCEMENTAND STATE OF ART RESEARCH REVIEW

1.1. Fundamentals of SHM

It would be optimal to be able to identify damage rapidly and precisely to aircraft structures to prevent structural failure. There have been significant advancements in guided wave oriented nondestructive assessment (NDI) and health monitoring of structures (SHM) because of years of research and development. [1] The benefits of structural state monitoring include the ability to provide design suggestions to improve performance, perform preventative maintenance as needed, and provide fleet-wide predictive diagnoses. One strategy under consideration involves using onboard structural detection systems to continuously track a set of sensors to determine a structure's health over time, predict its remaining value based on gathered data and design specifications, and alert users when maintenance is required. [2] In contrast to portable nondestructive inspection (NDT) systems, structural health monitoring (SHM) actuators and sensors remain attached to the structure for the duration of the monitoring process. With this setup, data can be collected in real time without human intervention for the duration of the useful life of the structure. Many sensors are typically dispersed throughout the structure to ensure efficient monitoring. Continuous and automatic analysis of the enormous amounts of data generated by these sensors is crucial. The objective of the analysis is to create accumulated stress evaluations for the structure's components and provide alerts to the client (such as an aviation engineer or maintenance professional) if stresses or degradation are detected. [3]

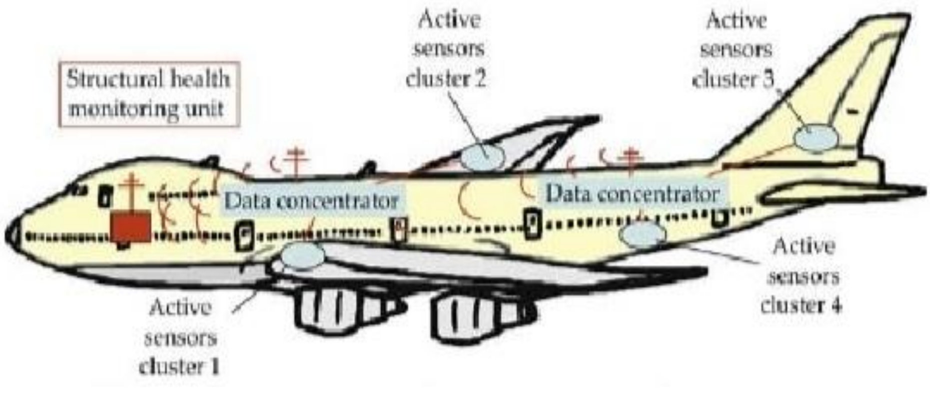

Fig.1.1 Active sensors, wireless connectivity, and the central unit of the SHM system comprise the SHM system of a typical airliner.[4]

Utilizing monitoring of structural health (SHM) techniques for damage detection, assessment, and prediction in aerospace structures may increase aircraft safety and decrease costs associated with operation, maintenance, and repair. Structural Health Monitoring (SHM), a unique maintenance technique based on the airframe's actual condition, may reduce operating expenses associated with scheduled inspections. The objective of the project is to replace scheduled repairs with maintenance based on the actual condition of the system; therefore, research is being conducted to make the transition from time-dependent to condition-based maintenance. The structural health monitoring process combines nondestructive inspection principles with integrated actuators and sensing devices to accurately and virtually in real-time assess an aircraft's structural condition and signal the need for repair. [5]

It can be exceedingly difficult to detect and signal damage in composite structures, as impact-caused damage may not be visible or may be scarcely discernible. A computerized deterministic structural health monitoring (SHM)-data-driven platform will be developed based on the findings to evaluate and predict the health of hybridization material (metal and composite) structures in real time. This structural health monitoring (SHM) system incorporates SHM-specific devices (optical fiber Bragg gratings, laminated piezoelectric sensors) into intelligent architecture at the earliest stages of manufacturing. The proof-of-concept for measuring the longevity of these hybrid structures using embedded sensors. [5] (Fig 1.1) Passive structural health monitoring - building (SHM) and Active structural condition monitoring - building are the two primary methodologies for monitoring the structural health of a building. Passive structures health-monitoring (SHM) focuses primarily on a number of operational metrics and the inference of structural health from these data. As an example, the flight data of an aircraft, such as altitude, airspeed, tumultuous motion, G-factors, vibration phases, stresses in critical sections, etc., could be monitored. Determine the aircraft's residual life and the percentage of its usable life that has been depleted using aircraft design practices. Passive structural health monitoring (SHM) is beneficial, but it does not get to the root of the problem (the structure's condition is not explicitly assessed). Active Structure Health Monitoring (SHM), on the other hand, is concerned with assessing the status of structural health in real time by identifying the presence and degree of structural deterioration. [4] In this regard, the non-destructive evaluation (NDE) methods and the active structure health monitoring (SHM) technique are comparable. The only difference is that active structural health monitoring (SHM) goes one step further by attempting to produce damage sensors that can be permanently affixed to the structure and monitoring methods that can generate structural health bulletins upon request. Recently, there has been considerable interest in the possibility of identifying injury using guided waves. Guided lamb waves are elastic disturbances with minimal amplitude loss in sheets that can propagate exceedingly far in structures with thin walls. The quantity of sensors needed to monitor a structure may be considerably reduced by lamb pulse nondestructive evaluation (NDE). [4] The lamb wave may also be used in conjunction with phased array techniques to scan expansive areas of a facility from a single access point. Lamb pulse nondestructive evaluation (NDE) methods have not been extensively adopted into structural health monitoring (SHM) methodology due in large part to the large size and high cost of traditional nondestructive evaluation (NDE) sensors. Standard transducers for nondestructive evaluation (NDE) cannot be permanently installed in the structure. especially when both dimensions and cost are important for aeronautical applications. Due to the recent development of piezoelectric wafer sensor arrays (PWAS), structural health monitoring (SHM) and nondestructive assessment (NDE) have the potential for significant enhancement. [4] The objective of aerospace monitoring of structural health (SHM technologies is to quickly detect damage or defects in aircraft structures. The following are standard components of a SHM system for aircraft:

1. Sensors: To monitor the structural characteristics of an aircraft, structural health monitoring (SHM) mechanisms in aviation use a variety of sensors, including strain gauges, accelerometers, temperature sensors, and piezoelectric transducers.

2. The data gathered by the sensors is then processed by a data gathering system. Signal conditioning, screening, and amplification may be incorporated into the data collection system to improve the accuracy of the collected data.

3. Thirdly, data analysis software is used to investigate the information collected by the sensors using techniques such as pattern recognition, artificial intelligence, and statistical analysis. The data analysis program provides information regarding the extent, location, and nature of

structural damage.

4. The structure health monitoring (SHM) system alerts the flight crew and/or maintenance personnel if a potential defect or damage is detected. In addition, proposed maintenance or repair procedures may be included in the output of the warning and reporting system.

5. Integrating structural health monitoring (SHM) systems with other aircraft systems, such as the flight control system, can improve safety and performance. Using the structural health-monitoring (SHM) system's information about the aircraft's structural integrity, for instance, flight operations can be fine-tuned, or flight settings can be adjusted.

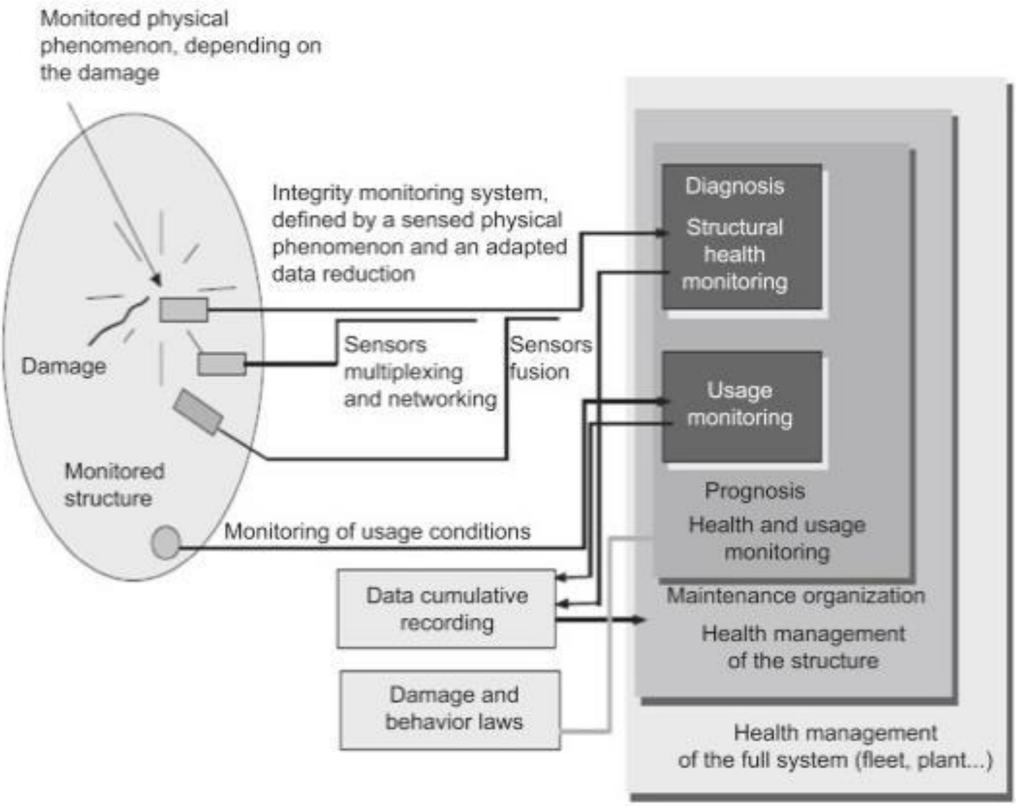

Fig. 1.2. Notion SHM system [7]

Fig. 1.2 depicts a fictitious structural health monitoring (SHM) system. The present diagnostic component approach classifies structural states and evaluates sensory input using pattern recognition techniques. The effectiveness of the developed classifier is evaluated by assigning a score to classification results derived from data that was not used during the design or testing phases. Small quantities of structural health monitoring (SHM) data could save inspection time and money, but low-level approaches have had only sporadic success to date. One reason for this is that training data for these systems must account for all conceivable conditions of damage and operating parameters. [7]
The low levels of structural health monitoring (SHM) have prompted the majority of research,

whereas the high levels have been largely ignored. The information provided by the two larger quantities of structural health monitoring - damage (SHM) pertains to assessing the degree of damage and, ultimately, provides an assessment of the impacts of loss that are most valuable for maintaining, administrating, and managing operations. To fully realize the operational benefits of structural health monitoring (SHM), an innovative data processing methodology is required. [7] The objectives of an aviation system for structural health monitoring (SHM) are to increase passenger safety, reduce ongoing maintenance costs, and lengthen the lifespan of aircraft structures. It is anticipated that structural health monitoring (SHM) systems will play an increasingly vital role in aircraft service and operation soon.

1.1.2. Structural Health Monitoring Paradigm

Modern monitoring of structural health (SHM) is based on four primary categories and their respective applications. Below are the categories and their defining characteristics.

Analyze the status quo.
The operational evaluation phase of a particular application details the qualities and execution reasons for a structural health-monitoring (SHM) system, such as performance, safety, and cost-effectiveness. Costs and savings from implementing a structural health monitoring (SHM) system need to be considered. Damage is such a broad term that it must be refined for the specific context of describing the kind of injury and the location of the damage. Because of their potential impact on system performance, operational and environmental elements must be taken into consideration. Following these guidelines will limit your structural health-monitoring (SHM) system's flexibility but doing so is essential for achieving the desired results. [6]

Collecting and cleaning information
Determining what data is required, what gear and sensors will be most effective in collecting that data, and what kind of initial signal processing will be given to the data before it is suitable for feature extraction are all part of data acquisition (DAQ) and big picture considerations. False positives and negatives in the data may be caused by testing artifacts, thus it is crucial to account for everything that comes up. To ensure that just the appropriate data is obtained via DAQ, careful planning is required. [6]

Extraction of features and compression of data
Feature extraction, also known as information compression or lowering dimensionality, is a technique for gleaning damage-related features from sensor data. the The damage-sensitive characteristics were extracted using signal processing-related techniques. If there are many sensors in the system, their damage sensitivities might be combined using a data-merging technique for more accurate findings. One aspect of signal processing that may help reduce the effects of operational and environmental factors like temperature variation is data normalization. [6]

Building Statistical Procedures
During statistical model creation, the produced features are utilized to construct a probabilistic classification model that can tell the difference between feature changes caused by damage and those that are unrelated to it. The model is constructed via both supervised and unsupervised learning methods. Unsupervised learning designs prioritize data integrity by searching for outliers that pose a problem for the underlying system. Supervised learning architectures incorporate both damaged and undamaged data for regression and classification analyses. [6]

The model may consist of many levels of complexity. Damage assessment begins with a binary stage that serves to establish the existence or absence of damage. The next step is a breakdown of the devastation into its constituent parts, known as a damage classification. Prognosis, the estimation of the structure's remaining useful life, may be performed at the highest levels of the model to provide a more accurate picture of the extent of the damage. This last phase is, however, outside the scope of this thesis. [6]

1.2. Ultrasonic elastic waves

Using directed elastic waves, such as Lamb waves, to inspect metallic and composite materials has come a long way since its discovery. Several studies have been conducted to better comprehend the difficulties associated with GW excitation/sensing, GW transmission throughout the structure, and GW interface with the defect. These waves are of relevance for structural health monitoring (SHM) because they can propagate extended distances within structures with minimal or no attenuation. Thus, SHM on a massive scale is feasible. [8]

Consider an infinitely isotropic medium subjected to a fluctuating stress that induces the propagation of elastic waves across it. When they become agitated, they transmit their energy throughout the medium. However, this medium itself does not move. Both longitudinal waves (which are also referred to as pressure waves) and transverse waves (also known as shear waves) comprise elastic waves. When a medium is constrained by boundaries, refraction and reflection events occur, altering the transmission of elastic waves and possibly producing guided waves. By utilizing the resonation between the boundary and the structure, these ultrasonic waves can travel further than conventional ultrasonic waves. Different categories of GWs are distinguishable based on the structure's form and elasticity. Lamb waves, Ryliegh waves, and Stoneley waves are the three types of GWs found in an infinite plate, a semi-infinite sheet, or the boundary between two structures. [8]

1.2.1. Lamb wave propagation

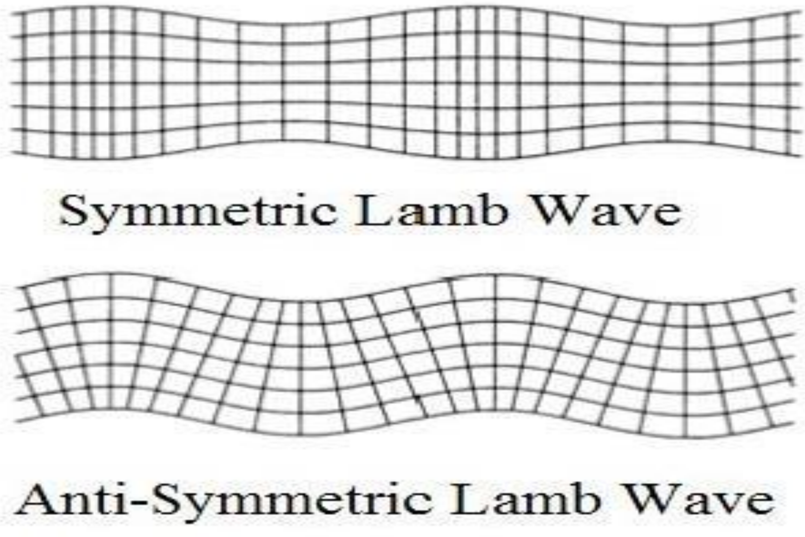

Fig. 1.3. Lamb waves in modes A0 and S0 [10]

Lamb waves are elastic waves that travel over a solid plate with no boundary conditions in the wave's direction of propagation or its path perpendicular to the sheet's plane. The velocity at which a Lamb wave travels through a material depends on the density, modulus of shear, wavelength, and modulus of elasticity of that material. These are known as surface waves, and they can be used to detect defects both on the surface and deeper within a material. Lamb waves have three interactions with fissures: they are routed, refracted, and reflected. The amplitude of the fracture increases in proportion to its profundity. The conceivable phases of Lamb waves are symmetric and antisymmetric. In addition, these modes are referred to as S0-mode and A0-mode. (Fig 1.3) In contrast to the A0-mode's antisymmetric normal displacement with respect to the center line, the symmetric mode's normal displacement of the open boundaries is symmetric. Throughout the procedure, these complex vibrational vibrations travel parallel to the tested surface [9].

1.2.2. Ryliegh waves propagation

A surface wave, or Rayleigh wave, is a guided wave that travels over the surface of a substance. Non-destructive testing (NDT) of composite aerospace structures has made use of Rayleigh waves for locating flaws and damage.

Composite materials are frequently used in aircraft structures because of their outstanding high strength-to- low weight ratio and extended lifespan. Composites' structural integrity may be compromised, however, by damage such as delamination and matrix fractures. Using Rayleigh waves, this type of damage can be detected without destructive testing.

The fundamental concept underlying Rayleigh wave propagation is that a wave moves over the surface of a material at a speed determined by the material's properties and the frequency at which the wave itself propagates. The wave is the superposition of longitudinal and transverse waves, resulting in an elliptic surface movement.

Using a piezoelectric transducer to apply a high-frequency oscillation to the outer layer of the material generates Rayleigh waves. Rayleigh waves are generated by vibration and propagate through the outermost layer of a material; they are sensitive to flaws and damage. Using the additional transducer, the waves can be detected, and the resulting signals can be analyzed to determine the location and extent of the damage.

The aerospace industry could benefit from nondestructive testing (NDT) that uses Rayleigh waves in several ways. Due to their ability to expand over immense distances, they are ideal for building enormous structures. They can travel farther through a material than other types of waves because they are less affected by its thickness. Since composites' anisotropic properties have less of an effect on Rayleigh waves, they are also more reliable for damage detection.

Rayleigh wave propagation is a dependable nondestructive testing (NDT) method for detecting defects and damage in composite-material aerospace structures. As a nondestructive technique, it is less susceptible to the anisotropic properties of composites and can detect damage across large areas.

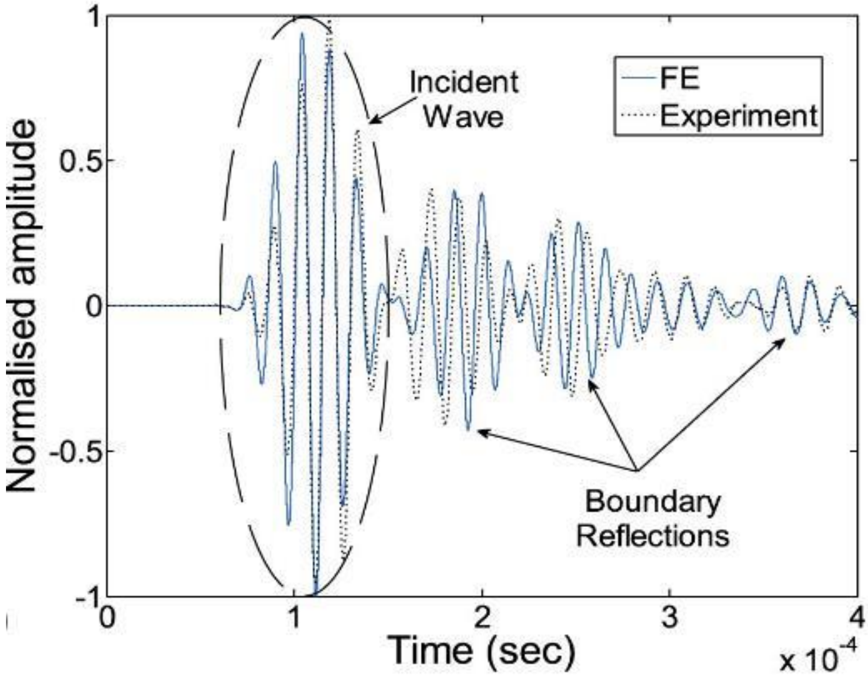

Fig. 1.4. Ryliegh wave propagation [11]

Rayleigh waves are a type of guided wave that propagate across the exterior of a solid with a semi-infinite volume. Rayleigh waves carry the most energy and dissipate more slowly than S- and P-waves when a half-space is subjected to a harmonic stress or displacement. (Fig 1.4) The geometry and mechanics of a medium affect the characteristics of Rayleigh waves. The wave's characteristics change when it encounters imperfections. Therefore, the use of Rayleigh wave techniques to detect concrete surface damage has been considered. The initial application of low-frequency, broad-band Rayleigh waves was for assessing damage to concrete. Investigation into the use of piezoceramic sensors for the generation and reception of Rayleigh waves in the context of damage diagnosis and health monitoring in reinforced concrete structures. [11]

1.2.3. Stoneley wave propagation

The Stoneley waves traveling method is a nondestructive testing (NDT) technique that uses guided waves to detect damage in structures such as pipelines, plates, and beams. As guided waves, low-frequency elastic waves are generated and propagated along the structure as part of the Stanley wave transmission method. Frequently, guided waves are generated and detected by attaching piezoelectric transducers to a structure.

As the directed waves pass through the structure, they will magnify any defects or damage. Changes in the waveguide's frequency, amplitude, or phasing may indicate the presence of damage. The location and severity of the damage can be determined by analyzing these alterations.

Stoneley waves have the advantage of requiring fewer transducers to inspect larger regions of a structure. This methodology is significantly speedier and more efficient than many other types of nondestructive testing (NDT), which also require many measurements.

Damage, oxidation, and delamination are a few examples of the categories of damage that can be detected in a variety of materials using the Stoneley propagation of waves technique. The civil engineering, oil and gas, and aerospace industries can all benefit from this method.
A monopole source can generate both rapid and sluggish configurations of the interface wave Stoneley mode. This wave can be directed in any desired direction as it travels along the interface between the borehole and the formation. Even though this mode is present at all frequencies, most of its energy is concentrated at the lower end of the spectrum. People have historically used the term "Scholte wave" to refer to the wave that travels between two solids, even though it more accurately depicts the wave that travels between a solid and a fluid. In rapid forms, the cluster and phase velocities of the Stoneley wave exhibit anomalous dispersion, meaning that their velocities increase with frequency. This is not the case for slow-moving organisms. The Stoneley wave is threatened by the formation's permeability, the occurrence of fractures and failures, and the harshness of the drilling contact.[12]

1.3. Piezoelectric phenomena and materials

There are many different types of natural and manufactured materials that exhibit the piezoelectric effect. The most common and well-understood synthetic material is Pb (Zr, Ti) O3 ferroelectric ceramics, which are made from solid state solutions of lead zirconate and lead titanate. The crystal quartz (SiO2) is a common natural PZT source. The piezoelectric response of quartz is essentially perfect, being small, linear, steady, and nonhysteretic. When compared to quartz, PZT's piezoelectric coefficients are around two orders of magnitude higher. Commercially accessible piezoelectric PZT is not single crystal but rather produced ceramics that need poling to demonstrate piezoelectric activity. The optimal Zr:Ti ratio for PZT's piezoelectric characteristics is close to 1:1. Between the tetragonal (PbTiO3-rich side) and the rhombohedral (PbZrO3-rich side) crystalline structures of PZT lies the transitional monoclinic structure known as the MPB. In certain materials, the stress and strain are linearly linked to the electric field E, polarization P, and electric displacement D. This association is sometimes referred to as the "piezoelectric effect." Simply put, that "direct piezoelectric effect" is the process whereby mechanical strain or tension produces a field of electricity or electric displacement.[13] (Fig 1.5.)

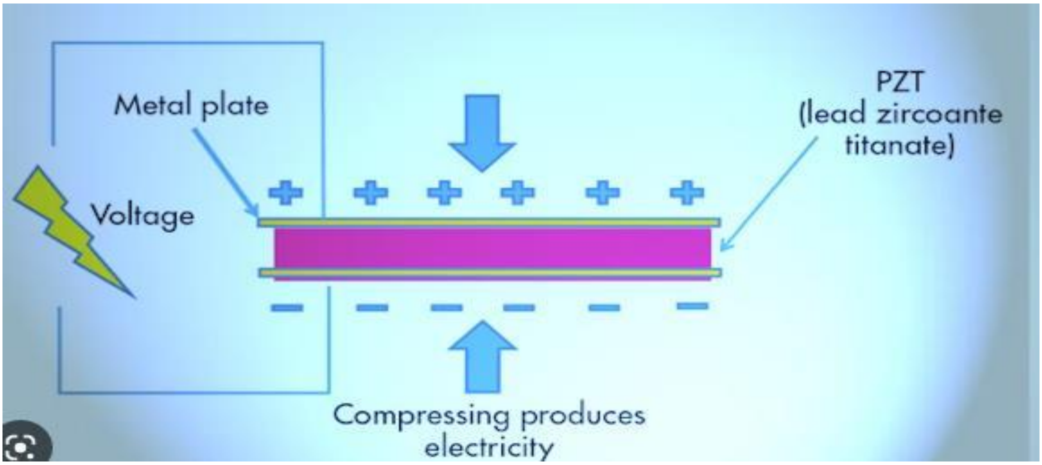

Fig. 1.5. Piezoelectric phenomena effect in crystal [14]

1.3.1. Piezoelectric materials

The piezoelectric substance within might produce energy if squeezed. Such materials may also undergo plastic deformation when exposed to high voltage. The piezoelectric phenomena require a non-conductive substance, and this material must be used in a piezoelectric device. These materials may be broken down into two main classes: ceramics and crystals. Among the piezoelectric materials found in PZTs are lead zirconate titanate, barium titanate, as well as lithium niobate. These materials possess a stronger piezoelectric field than common minerals like quartz. Both quartz crystal as well as Piezoelectric transducers (PZT) exhibit voltage-induced displacement, however PZT has the potential to generate a greater voltage with the same force. The first substance to show these characteristics was quartz, the prototype piezoelectric material. [14]

Piezoelectric transducers (PZT) are made by fusing lead, zirconium, and titanate together at very high temperatures. Zr(1-x) titanium(1-x) lead. O3 is the chemical formula for piezoelectric transducers (PZTs). It is widely used in the manufacturing of various sensors and actuators, including ceramic capacitors, ultrasonic transducers, and others. The ceramic substance barium titanate has piezoelectric characteristics and is ferroelectric. 6 Because of its superior generation time compared to its contemporaries, barium titanate has found widespread use as a generating material. $BaTiO_3$ is the chemical component that makes it up. Lithium niobate may be written as Li_2O, Li_3NbO_4, in addition Ni_2O in its chemical form. Lithium niobate octoxide is its chemical name. It is a ceramic material with identical ferroelectric and piezoelectric characteristics as barium titanate. [14]

1.4. Direct and inverse piezoelectric effects

When compressed, a piezoelectric material generates electricity (a phenomenon known as piezoelectricity). Between the metal sheets is a non-conductive piezoelectric material or crystal called piezoceramic material. By squeezing or compressing the material, piezoelectricity is generated. When mechanical stress is applied, the piezoelectric ceramic substance generates electricity. [14]

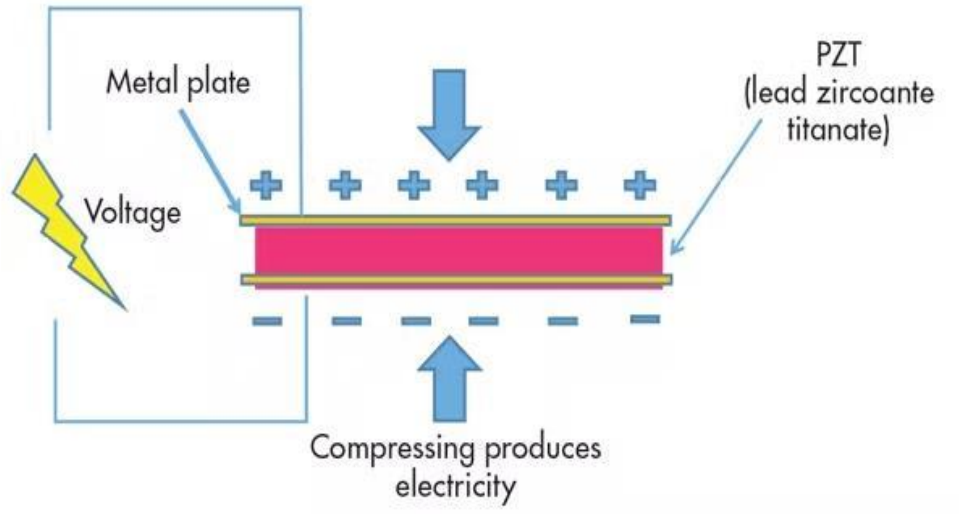

Fig. 1.6. Compression of a piezoelectric material results in a direct piezoelectric effect. [14]

A voltage potential can be observed over the material (Figure 1.6). Two metal plates shield the piezo crystal from the surrounding environment. The metal plates produce piezoelectricity (illustrated by a lightning bolt) by acting as a collector. Because it produces electricity, the piezoelectric effect can be compared to a small battery. The piezoelectric effect is unmediated in this instance. Mics, hydrophones, and pressure gauges are a few examples of devices that utilize the direct piezoelectric phenomenon. [14]

1.4.1. Inverse piezoelectric effect

Inverse piezoelectric impact is the ability to reverse piezoelectricity's direction. This is generated by imparting a voltage to a piezoelectric crystalline material, causing it to contract or expand (Fig. 1.7). In the piezoelectric effect in reverse, power is converted to mechanical energy. [14]

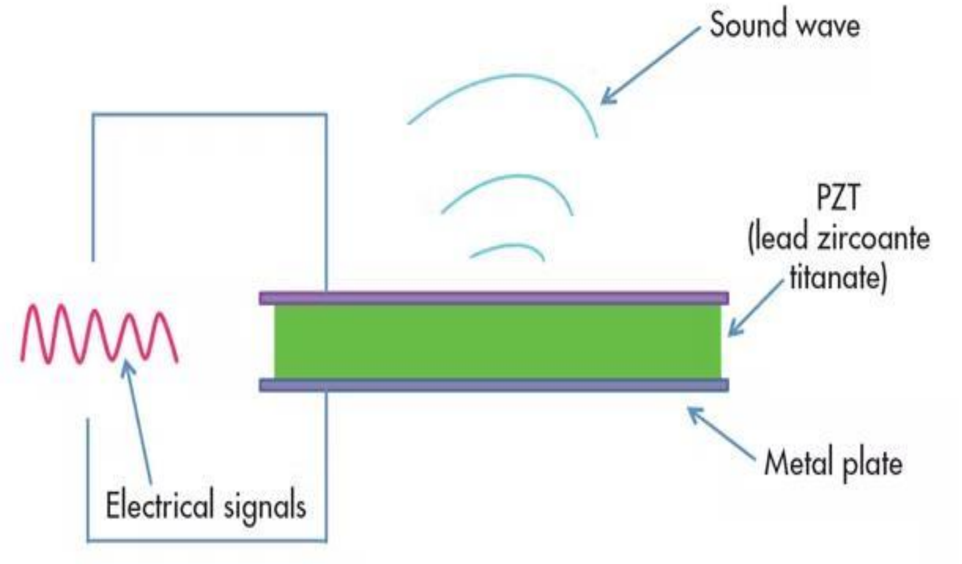

Fig. 1.7. The contraction or expansion of a piezoelectric crystal caused by an applied voltage is known as the "inverse piezoelectric effect." [14]

The reverse piezoelectric effect can be used to create generators and emitters of acoustic sound waves. These piezoelectric acoustic components are widely used in portable electronics, with examples including loudspeakers and buzzers. These speakers are compatible with a variety of mobile devices due to their compact dimensions. The inverse piezoelectric effect is also utilized in sonar transducers and ultrasonography for medical purposes, in addition to acoustic devices. Motors and controllers are just two examples of non-acoustic applications for reverse piezoelectric devices. [14]

1.4.2. Introduction to piezoelectric wafer active sensors

One of the key structural health monitoring (SHM) technologies is piezoelectric wafer active sensors (PWAS), which can be utilized with a variety of damage detection techniques, including standing waves (E/M impedance), phased arrays, and propagating ultrasonic guided waves. Many disciplines must work closely in concert as part of the interdisciplinary process known as structural health monitoring (SHM). (Fig. 1.8) Due to their capacity to cover a wide area with a comparatively small number of sensors, guided-waves techniques are becoming more and more popular for nondestructive evaluation (NDE) and structural health monitoring (SHM) applications. Due to their low cost, simplicity, and versatility, miniature guided-wave transducers, including piezoelectric wafers mounted directly to structural parts, have become quite popular. With the help of guided-wave techniques including pitch-catch, pulse-echo, phased arrays, and electromechanical (E/M) impedance approach, these transducers may actively probe the structure. Moreover, they can be utilized passively for acoustic emission or impact detection (AE). Using nano-fabrication processes, these transducers can be transformed into ultra-thin, integrated ferroelectric thin films that can be produced directly on structural materials. [4]

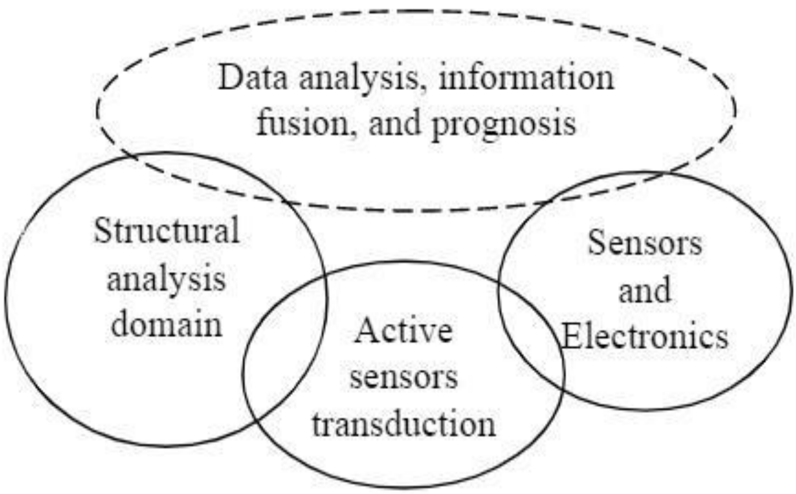

Fig. 1.8. Venn diagram of multi-domain interaction in structural sensing [4]

On-board structural health monitoring (SHM) technologies may consist of electronics, data processing, interactions, sensors, clusters of sensing devices, and electronic devices. The sensors may be passive (e.g., strain, temperature, and acceleration) or active (e.g., Ultrasonic sensors that examine the structure to determine the presence, extent, and severity of damage). Utilizing passive structural monitoring to collect historical information on fleet utilization and structural low advertising. Active structural monitoring nondestructive evaluation (NDE) techniques were utilized to evaluate the structure while performing labor-intensive, spaced-out maintenance tasks. It would be optimal to have an active sensor system on board that could pose queries to the structure and provide health updates as necessary.

When designing active sensing systems, it is difficult to construct compact, integrated transducers that can be permanently affixed to a material and left active until required [4].

In contrast to conventional ultrasonic sensors, which are only tenuously attached to the structure by air, gel, or water, piezoelectric wafer sensors that operate (PWAS) have a strong connection to the structure. Piezoelectric wafer active sensors (PWAS) are an excellent substitute for the single-resonance devices found in conventional ultrasonic transducers due to their adaptability to a wide

range of guided-wave modes.
Second, piezoelectric wafer active sensors (PWAS) are small, lightweight, and can be mounted in multiple locations on the structure, though traditional ultrasonic sensor devices are cumbersome and costly. Lamb waves can be used to detect fractures, corrosion, and delamination in structures with thin walls [4].
Large areas can be inspected for defects such as fractures and delamination using lamb waves that penetrate below the structure's surface. Lamb waves, which are utilized to evaluate the depth or elasticity of a material, produce stationary waves with the greatest displacement at fixed locations.
Phased arrays, also known as phased array ultrasonics (PAUT), can be used to generate a broad spectrum of waves (including stationary and propagating Lamb waves) with high focus and directionality. A phased array inspection with a higher resolution may provide more information about the size, location, and severity of defects. Numerous industries, including aerospace, automotive, civil engineering, and others, benefit from non-destructive testing and assessment of structural integrity using lamb waves and phased arrays.
In-building Using piezoelectric wafer active sensor (PWAS) sensors permits reception and transmission of lamb waves. Thin-walled structures containing piezoelectric wafer active sensors (PWAS) transmitting stations generate Lamb waves in response to an electric signal. Lamb waves propagate through a structure and are affected by its dimensions, composition, and environmental conditions. In order to convert reflected or diffracted waves into electrical impulses, piezoelectric wafer active sensors (PWAS) must be utilized. [4]
Wide-bandwidth strain gauges, wave impulse and receivers, integrated modal sensors, and electromechanical (E/M) impedance-based resonance devices are some of the applications for PWAS transducers. Piezoelectric wafer active sensors (PWAS) are capable of being incorporated into a variety of transducers. I. Active monitoring of far-field losses with the use of pulse-echo, pitch-catch, as well as phased array. Active detection of near-field damage utilizing a high-frequency signals E/M impedance approach as well as thickness-gaging technique. Finally, passively detect detrimental events by listening for low-velocity collisions and acoustic emissions near to the crack's front point. (Fig. 1.9). The primary advantages of PWAS over conventional ultrasonic instruments are its portability, light weight, low cost, and small profile. Piezoelectric wafer active sensors (PWAS) are diminutive, but they can perform many of the same functions as larger, more cumbersome ultrasonic instruments. [4]

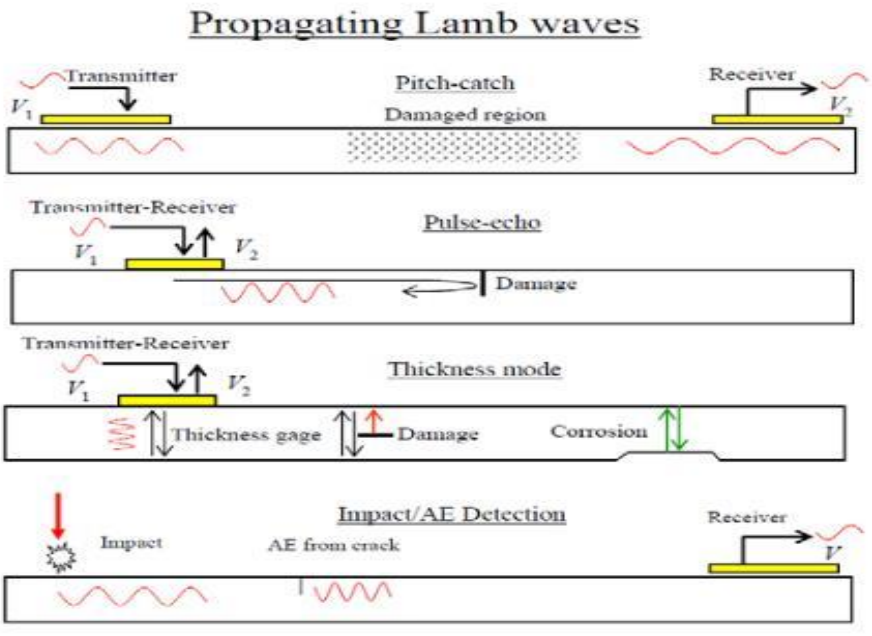

Fig. 1.9. Examples of PWAS utilized for structural sensing include propagating lamb waves, standing lamb waves, and phased arrays. [4]

Conventional active monitoring hardware for wave propagation-based SHM is feature-rich. Supporting numerous channels allows for an array of piezoelectric devices to be used, and generating custom waves for structural diagnostics is also possible. As shown in (Fig.1.10), the hardware consists of an evaluation waveform generator, an amplifier that is used to power each actuator, a multi-channel converting matrix, a board to filter and amplify sensor signals, a data acquisition board to gather sensor data, and tools to store and process the data. The diagnostic waveform produced is generally a five-peak sine wave with a cosine (Gaussian) contour that drives the piezoelectric actuator. [34]
The following components typically make up active SHM diagnostic equipment for aviation:
Utilizing structural health monitoring (SHM) technologies based on wave propagation methods, aircraft structures are routinely examined without causing damage. The following components typically make up active diagnostic equipment for structural health monitoring (SHM) in aviation:

1. Utilizing piezoelectric transducers, it is possible to generate and detect ultrasonic oscillations within the structure. They may be adhered to the exterior of the structure or incorporated into the material.

2. Thirdly, an amplification circuit and signal generator are necessary to amplify the signal that excites Piezoelectric sensors, which generate the ultrasonic waves used to investigate the structure. The amplifier amplifies the signal so that it can pass through the structure without being diminished.

3. A data collection system records the impulses detected by the piezoelectric sensors as the waves pass over the structure. A data capture system typically consists of a rapid digitizer,

signal conditioning hardware, and analysis software.

4. The control and display unit manages the signal generator, booster, and data collection system, and displays pertinent information. It also provides a user interface for examining and analyzing test data.

In order to increase inspection throughput and precision, more sophisticated transmission of waves oriented structural health monitoring (SHM) techniques may employ phased array sensors, multiplexed hardware, and automated scanning systems.

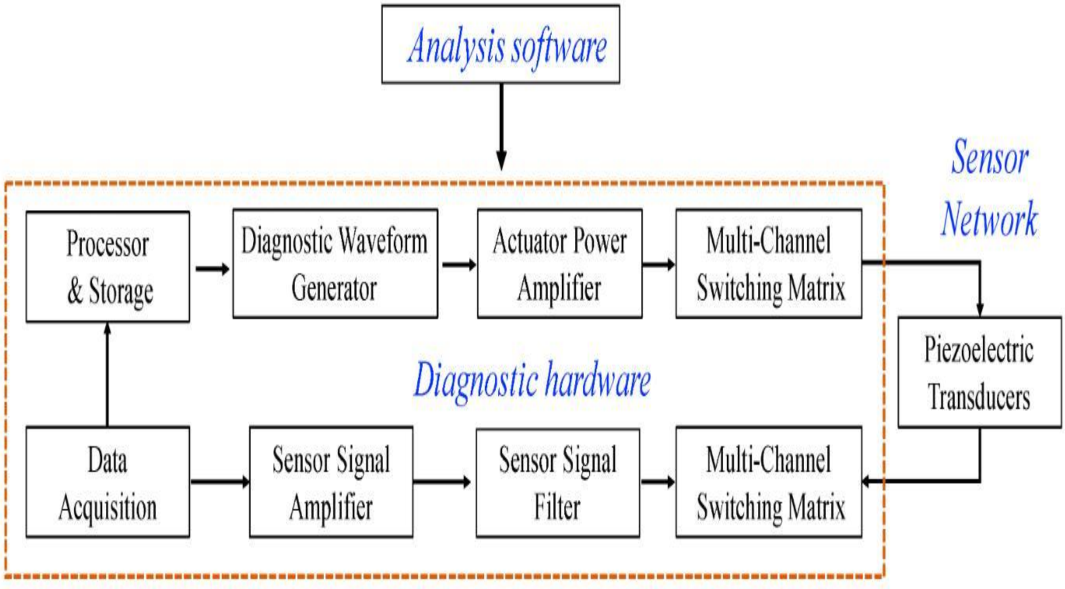

Fig.1.10. Diagram of the integrated active diagnostic hardware [34]

1.5. Ultrasonic methods of load and damage detection

The foundation of ultrasonic inspection is mechanical acoustical waves with frequencies of 20 kHz or higher, and their interaction (transmission, reflection, and absorption) with the investigated structure enables the detection of defects. Traditional ultrasonic bulk wave methods are extensively used for both property estimation and defect detection. Monitoring the velocity of shear in addition to longitudinal waves can be used to estimate the elastic modulus, and the calculation of frequency-dependent attenuation is extensively employed in the evaluation of materials. [15]
Inclusions, delamination, and other flaws are presumed to generate echoes that can be captured by the ultrasonic detector; thus, the outer layer, intermediate echoes, and rear wall of the investigation structure are examined to locate them. Since conventional mass wave ultrasonic methods are so simple to employ, they are frequently the instrument of choice for determining structural integrity. [15]
There are various techniques for generating ultrasonic guided waves, the selection of which depends on the monitoring system's intended application. Direct contact mechanisms can be surface mounted or embedded within a structure. Piezoelectric wafers are a type of inexpensive, lightweight, and simple-to-assemble surface-mounted sensor. These sensors, which utilize both direct and indirect

piezoelectric effects, require minimal hardware to function. Nevertheless, surface-mounted alternatives are not optimal for actual deployments. owing to their effect on the structure's wind resistance. Therefore, it is recommended that aviation monitoring techniques employ sensors that are already integrated into the system. Due to the importance of the monitoring system throughout the life of an aircraft, systems must be durable. [15]

1.5.1. Impact monitoring

Active diagnostic equipment is more sophisticated than passive hardware testing, which consists of a sensor technology amplifier and data collection device. The objective of impact monitoring techniques is to record the occurrence of exterior impacts on aircraft by gathering stress wave signals generated by impacting loads via sensor networks affixed to the structure, determining the impact location, and recreating the resulting energy or impact history. The following is an illustration of the concept of effect monitoring: (Fig.1.11). [34]

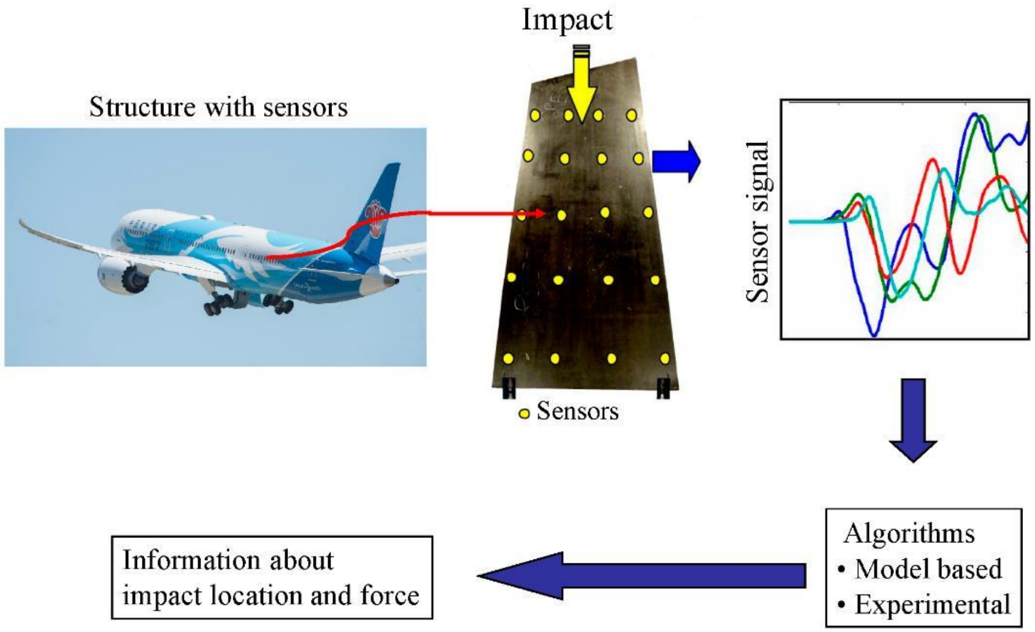

Fig.1.11. Principle of impact monitoring [34]

Active systems, on the other hand, actively conduct duties such as analysis and damage diagnosis, whereas passive systems only exist to detect impacts and burden changes. However, there are limitations associated with the use of completely active damage detection systems. Dynamic systems, for instance, must repeatedly query their structure, squandering resources constantly. Consequently, it is preferable to incorporate both active and passive systems to maximize the benefits of both. By integrating active and passive diagnostic technology in a single sensor layer, we are able to actively monitor the afflicted region with transducers in an active state. Thus, the exact location and extent of any resulting damage zone can be determined. [34]

1.5.2. Damage detection

There exist both baseline and baseline-free guided pulse defect detection techniques. The baseline algorithms require a data set describing the structure in its defect-free state. The existence of injury can then be determined by comparing newly recorded signals to a baseline set. Whenever there is a change in the structure, the incoming waves will be reflected or dispersed. This signal can be used to identify problem areas when subtracted from a reference signal. We can eradicate residual reflections at the edges of our objects using this method. This method is extremely sensitive to environmental factors such as temperature, tension, sensor bonding, age, etc. despite its usability. For instance, according to research, a temperature change of 10 °C can conceal a flaw if the amplitude of the reflected signal from the flaw is at least -30 dB less than the amplitude of the direct arrival, and this is true regardless of the temperature correction measures used. [15]
Since they do not depend on a fixed set of standard signals, baseline-free approaches are more resistant to environmental disturbances, transducer bonding, etc. Without a baseline, time-reversal techniques are an excellent example of damage detection. This method requires at least two sensors, one of which captures the signal in real time and transmits it backwards in time.

1. To introduce the wave into the structure, a voltage of VA(t) is first applied to Transmitter A.

2. The voltage VB measured by sensor B at time t is due to the propagation of the wave.

3. Third, transducer A is sent the time-inverted version of the data VB(t).

4. At time t, the signal VBA(t) from transducer A is compared with the input VA.

The input signal VA(t) and the rebuilt signal VBA(t) should be identical for a structure devoid of defects; otherwise, structural alterations are suspected. Numerous studies have shown that this method is insufficient for identifying notches in metallic structures, as the defect only affects the amplitude of the received signals and does not affect their temporal reversibility. Remember, when analyzing this system, that the return only pertains to pulses traveling in the same direction. Particularly with multimodal wavefields, border reflections and irregularly dispersed attenuation characteristics may cause asymmetrical waveform fields and discrepancies between the initial and returned time-reversed signals. [15]

(SHM), or structural health monitoring, has recently witnessed advancements in piezoelectric sensors, such as:

1. It has been possible to create piezoelectric elements that can alter their properties in response to their environment, making them more versatile and effective. Utilizing self-diagnosing and -repairing piezoelectric components can increase the sensor's durability, for example.

2. Second, malleable and adaptable piezoelectric sensors have been developed; these transducers can better detect defects on curved or irregular surfaces.

3. Thirdly, there are piezoelectric transducers that are capable of sensing, moving, and even collecting energy. The structural health monitoring (SHM) unit and other equipment on board an aircraft may be powered, for example, by piezoelectric sensors that generate electricity from the structure's vibrations.

4. Fourthly, non-contact piezoelectric transducers have been developed, which do not require physical contact with the structure in order to function. These transducers may be useful when inspecting composite structures or inaccessible constructions, as they use ultrasonic air-

coupled waves to detect structural defects.

Overall, advancements in piezoelectric sensors might improve the accuracy, reliability, and efficiency of SHM technologies now in use in the aviation industry and beyond.

1. Despite widespread use and tremendous advancement, piezoelectric transducers (PZT) confront a variety of challenges.

2. Because their piezoelectric properties change with temperature, materials employed in piezoelectric transducers (PZTs) may introduce measurement errors into structural health monitoring (SHM) applications. Improving the thermal stability of Piezoelectric transducer (PZT) materials is a persistent challenge.

3. Environmental resilience is crucial for Piezoelectric transducer (PZT) components since they degrade over time when exposed to humidity and other climatic conditions. New coatings and packaging materials are being investigated by scientists as a means of shielding Piezoelectric transducer (PZT) sensors from environmental hazards and extending their useful life.

4. Bonding sensitivity: The performance of piezoelectric transducers (PZT) may be impacted by the bonding process when they are attached to structures employing adhesives. Researchers are exploring different bonding strategies to reduce the method of bonding's detrimental impact on transducer performance and improve paring between the transducer and the structure.

5. Piezoelectric transducer (PZT) elements exhibit nonlinear behavior when subjected to signals with a high amplitude, which may lead to distortion and other measurement issues. Researchers are exploring alternative signal processing and data analysis methods to account for the nonlinear character of Piezoelectric transducer (PZT) transducers.

Collectively, these problems highlight the need for more research and development in Piezoelectric transducer (PZT) technology for better performance, reliability, and accuracy in SHM applications using PZT transducers.

CHAPTER 2. OWN STRENGTH OF PIEZOELECTRIC TRANSDUCER FOR SHM

2.1 More detailed description of problem

The problem of the own reliability of the elements of the health structural diagnosis system is of the utmost importance. For monitoring systems based on the use of ultrasonic detection, this problem is especially relevant for piezoelectric transducers. It is known that these elements are built into the structure and in the process of operation are subjected to the same external influences as the host structure. First, it is a dynamic load, which can cause damage or complete destruction of the transducer during extreme overloads. Prolonged exposure to variable loads can lead to fatigue cracks in the sensitive elements of the transducers and their connection to the structure. Aging processes of various nature, corrosion, temperature effects can cause failures of transducers or partial loss of their functional performance. There are methods of prevention and protection against adverse external influences. But the most urgent is the problem of strength and fatigue durability of transducers. Known [16] also that piezoceramics have a sufficiently high compressive strength (about 600 MPa) and relatively low tensile strength (about 45 MPa) and bending (about 80 MPa). At the same time, to ensure effective detection of strength defects, transducers must be embedded in a structure that is most often exposed to tensile stresses. The simplest way to avoid sudden destruction or fatigue damage involves the installation of transducers on compressed or weakly loaded stretched sections of the structure. In any case, theoretical and experimental analysis of loading conditions and the establishment of safe loads for piezoceramic transducers are required. In the work [17] the conditions of loss of operability of a typical Piezoelectric transducer (PZT) installed on the surface of the bearing sample under static and fatigue loads are investigated. The results of the study can be used in relation to square-shaped transducers in the plane (7x7 mm) glued to a thin-walled structural element. In the study described in reference [18], the durability tests were conducted on composite panels subjected to both static and cyclic tensile loading, utilizing embedded Piezoelectric transducers (PZT) as the sensing elements. The paper presents the findings of these tests.

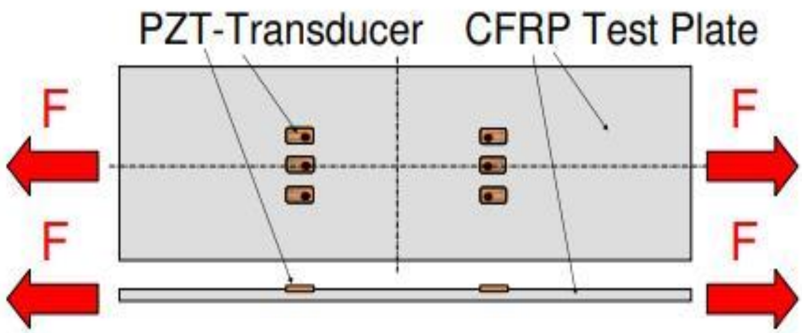

Fig. 2.1. CFRP Coupon for tensile test with integrated PZT-Transducers [18]

Tensile experiments were performed on Carbon Fiber Reinforced Plastic (CFRP) plates, which contained co-bonded (embedded) PZT Transducers (Acellent® SMART Layer®), to study the static plus dynamic failure strain of the PZT-Transducers at room temperature. Each coupon consisted of six PZT-Transducers positioned in two opposing rows, with three PZT Transducers in each row (see Fig. 2.1). The experimental results revealed that the electro-mechanical impedance, particularly the imaginary part of the admittance known as susceptance, exhibited excellent sensitivity in detecting the degradation of PZT Transducers [18]. Additionally, the results demonstrated that both the Mode at 100kHz and the Mode at 250kHz Lamb Wave modes experienced a reduction in amplitude as the Piezoelectric transducer (PZT)-Transducer degradation increased. This effect was observed in both tensile quasi-static and fatigue tests. However, no temporal shift or mode transformation of the propagating wave packages was detected. The study concluded that measuring the electro-mechanical impedance, with a specific focus on the susceptance spectrum, holds promise as a method to be utilized within the aircraft environment [18]. In another paper [17], it was demonstrated that piezoceramic sensors maintain their functionality when bonded to host structures subjected to tensile strain up to 4000με by utilizing an optimal adhesive. In paper [19]

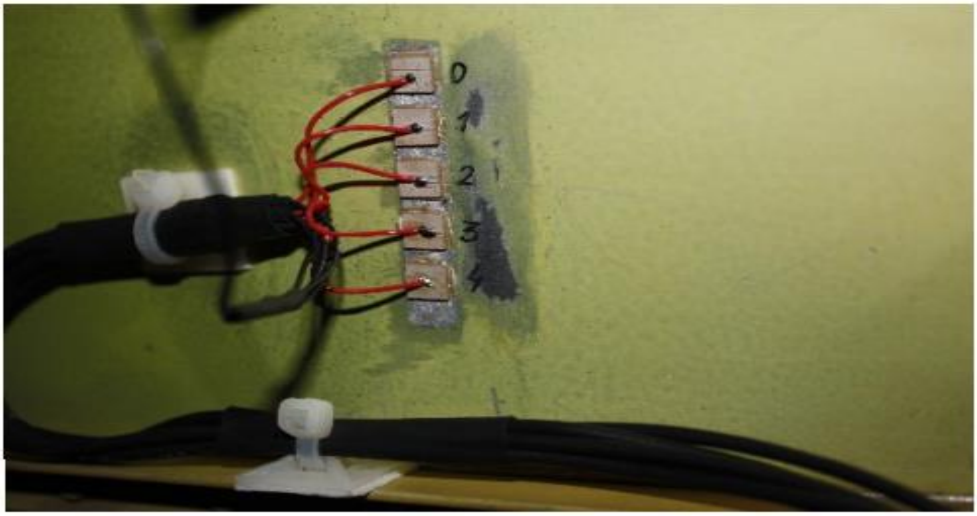

Fig. 2.2. A composite piezoceramics transducer is attached to the exterior of the tail beam of a Mi-8 helicopter. [19]

The first practical application is depicted in Figure 2.2, where the fused piezoceramic sensor is employed in the final dynamic experiments of the structural health monitoring (SHM) technique integrated into the Mi-8 helicopter tail beam. By utilizing an array of small-sized transducers measuring 1x6.35x6.35mm, the stresses are substantially reduced, thereby increasing their operational lifespan [19].

The outcomes of the stress study enable the construction of a theoretical model for the strength of the piezoceramic transducer. Models that are static and cyclic share the same base. Specific destruction is defined by constraints between the transducer and the loaded structural part. The transducer will split into two pieces after the initial crack in a certain cross-section. Each of them experiences less stress, although strength is greater than stressors before a crack first appears. The foundation of a model should be the strength distribution function of a specific small section of a transducer. For each current configuration, it is possible to determine the maximum direct stress following each local destruction. Utilizing the idea of a "weak chin," the history of destruction may be foretold. It is possible to choose the ideal geometrical sizes for a restricted transducer by performing a stress state analysis on a three-layer construction with a break in one of the layers. An important practical suggestion is the structural health monitoring (SHM) system's combined excitation/sensing transducer, which is composed of several tiny transducers that are far less

susceptible to mechanical loading. [19]
Another means of the Piezoelectric transducer (PZT) protection from fatigue is proposed and developed in [20-21]. It is based on the creation in the transducer of a field of residual compressive stresses.
When piezoceramics are subjected to both mechanical and electrical loads, the article [22] analyzes the difficulties with their strength and fatigue. According to the study, piezoelectric materials are widely used in intelligent structures due to their high modulus and robust electro-mechanical interaction. However, the use of piezoceramics as actuators in these technologies necessitates that they operate under more severe electrical and mechanical loads, highlighting the importance of the actuators' durability and dependability. To address these issues, the fracture and fatigue behaviors of piezoceramics are thoroughly analyzed and accurately predicted. Fracture is material failure under monotonic physical and electrical loads, whereas fatigue is material failure under cyclical loads. To construct a model of crack initiation, fatigue tests are conducted on smaller tension specimens subjected to a wide spectrum of electrical and mechanical loads. The experimental results demonstrate that electric fields have a significantly greater effect on crack formation than the evident stress intensity would suggest. [22]
This literature review demonstrates the need for a distinctive design methodology to guarantee the reliable operation of a SHM technology based on piezoelectric transducers (PZTs). This study will also investigate the durability issues associated with the rectangle-shaped Piezoelectric transducer (PZT).

2.2 Essential results of transducer destruction during the fatigue test

In (Fig.2.3) an example of the aeronautical panel that contains a thin skin supported by a stringer of the angular cross-section, is presented. The dimensions of the working part of the panel are width 200 mm, length 380 mm, sheet thickness 1.15 mm. Stringer is made of standard angular profile 20x20x1.5 mm. The skin material is aluminum alloy 2024-T3. The stringer is also composed of an aluminum alloy material. The stringer has a longitudinal technological joint. The two parts of the stringer are connected to each other and to the skin by a rivet joint. In such a structure, an uneven distribution of shear forces on the rivets is inevitable, which is a potential cause of reduced fatigue strength. In this experiment, the task was to assess the fatigue strength of the panel, as well as the effectiveness of the monitoring system based on the Lamb wave technology. For this purpose, two groups of five piezoelectric transducers PIC 151 with dimensions of 0.5x10x50 mm were installed on the surface of the lining parallel to the axis of the stringer on each side.

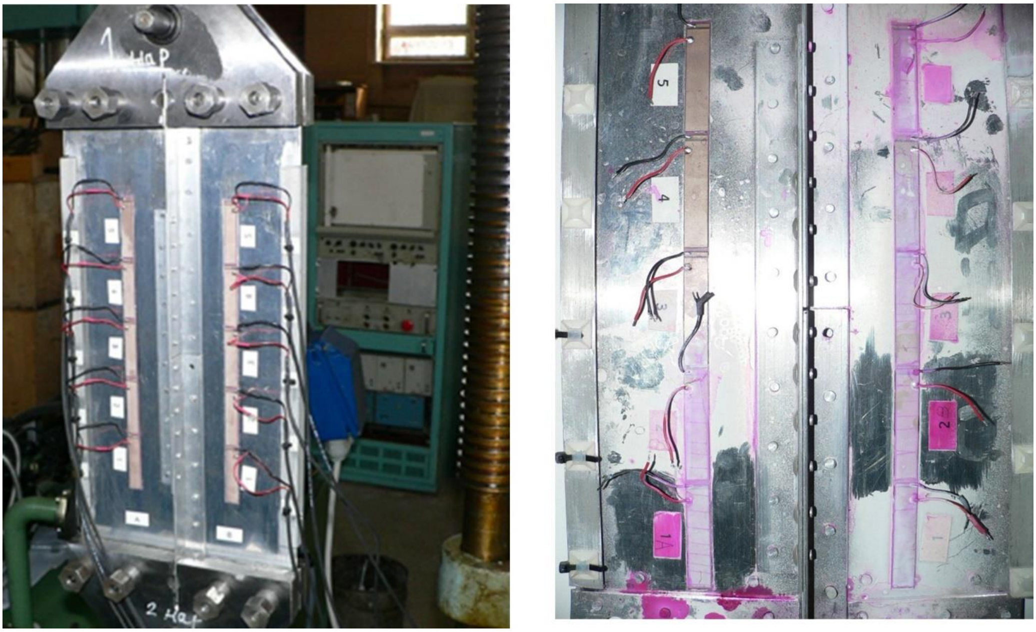

Fig. 2.3. Forced panel prepared for fatigue test and installed for the fatigue test to machine GRM-20 (left picture) and the view of panel after penetration test for finding out of crack in Piezoelectric transducer (PZT) transducers.

Cyclic loading of the panel at a frequency of 10 Hz was carried out with maximum stress in the cross-section of the panel of 150 MPa and minimum cycle stress of 50 MPa. At the stage of initiation of the fatigue crack, the technical condition of the transducers periodically (after 20 thousand cycles) was monitored by measuring their electromechanical impedance and comparing it with its value before the start of the tests (baseline).

After 60000 cycles, electromechanical impedance (EMI) measurements showed that only three transducers remained fully operational. Five transducers were damaged (usually with several cracks) with a complete loss of functional performance. The remaining two transducers had no visible damage under the applied detection method used and partially retained the ability to respond to external excitation. However, the dynamic response to excitation impact was significantly different from the baseline. The statistic for damages is shown in Table 1.

In (Fig.2.4) shows the transducer No. 5 of the right group before the start of the fatigue test (left picture) and after their completion (right picture). On the surface of the transducer after the tests, traces of seven cracks are clearly visible, crossing the sensor across the entire width.

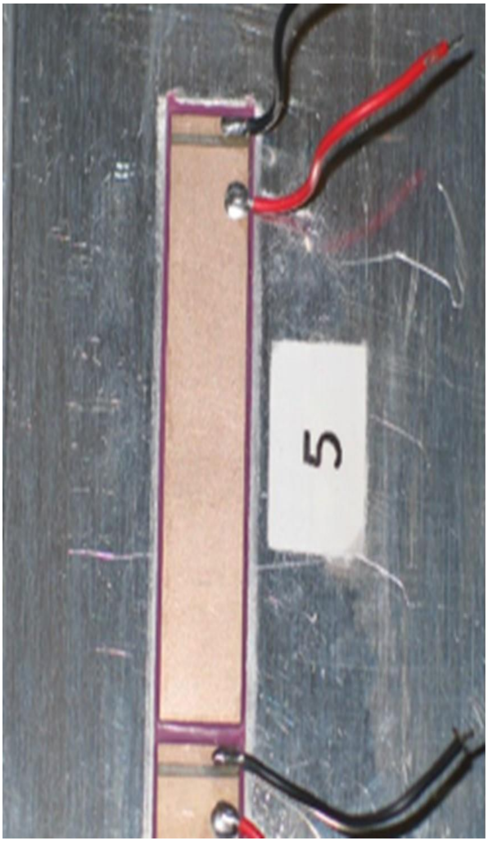 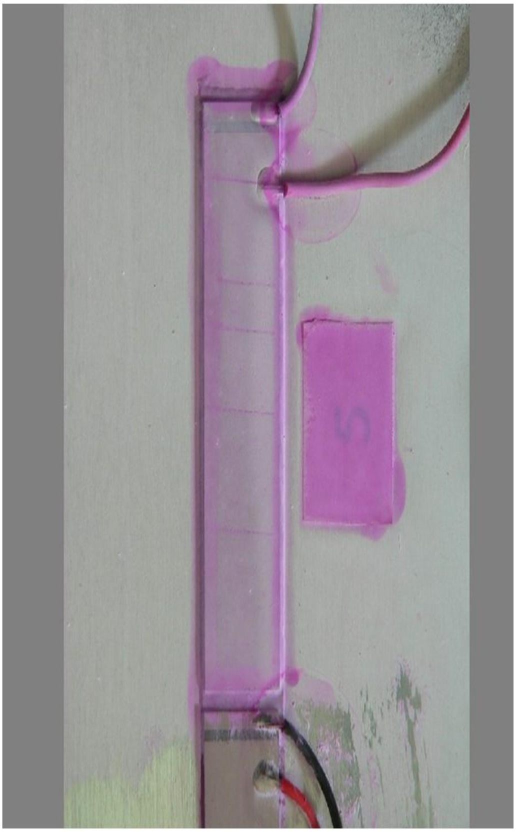

Fig. 2.4. View of the Piezoelectric transducer (PZT) number 5 before (left) and after (right) fatigue test and cracks evaluation by penetration method.

Table.1.

Statistics of damages of PZT transducers

Nr of PZT	1		2		3		4		5	
ID of group	1	2	1	2	1	2	1	2	1	2
Quality	b	s	b	b	s	b	g	s	g	b
Cracks amount	8	1	6	6	1	7	-	1	-	6

ID of group: 1 – left side vertical group
2– right side vertical group

Quality: g - full operability

s - partial operability
b – full loss of operability

Table 1 data gives possibility to estimate the probability of three different events after 60 kilocycles of alternative loading:

1. The save of full operability of Piezoelectric transducer (PZT)…….0.2
2. The save of partial operability of Piezoelectric transducer (PZT)…0.3.
3. The full loss of operability of Piezoelectric transducer (PZT)…….0.5

Some patterns of crack location are observed, considering the position of the sensor:

1) Fatigue cracks occur strongly in the cross-sections of Piezoelectric transducer (PZT) that are perpendicular to direction of tensile load.
2) Along length of a transducer the fatigue cracks distribution is approximately even
3) There is a relatively weak trend of predominant concentration of fatigue cracks in the extreme transducers of vertical groups (numbers 1 and 5): 21 cracks of their 36.

2.3 Investigation of stress state of transducers embedded in the thin-walled structure.

The measurement unit of ultrasound system of structural health monitoring (SHM) contents two principal components: Piezoelectric transducer (PZT) and its supporting member which in this paper are present by the glue layer. The analysis of the stress state of measurement unit is needed for more detailed estimation of conditions of destruction at the operation loading. The geometrical sizes of Piezoelectric transducer (PZT) transducer correspond to the PIC151 that is used in all tests of this paper, the thickness of the Hysol930.3NA glue layer is accepted to equal 0.25 mm. The Al2024-T3 sheet with sizes 1.15x80x240 mm presents the host structure for three collinear transducers with gap 1 mm between them (Fig 2.3). In the same (Fig 2.3) two options of static loading by uniformly distributed stress of 150 MPa are shown. Mechanical properties of all materials of model are shown in Table 2.

Table.2.

Material elastic properties and tensile strength:

Material	E, MPa	Poisson ratio	Tensile strength, MPa
Al2024-T3	71000	0.33	
PIC 151	67000	0.34	~45
Hysol930.3NA	2232	0.42	31

Finite element analysis (FEA) was executed by using the COMSOL Multiphysics software of the study option Stationary. Because there is double axial symmetry of model in the coordinate plane xz the outcome of stress analysis is presented below for one quarter part of a model. In (Fig.2.5) the general view of distribution of stresses (in the form of the Von Mize's equivalent stress) and deformed shape of the model at tensile longitudinal load are illustrated. (Fig.2.6) It is seen that the presence of transducers causes non-homogenous stress state of they and the sheet. Obviously, the mean direct stress of transducer is always smaller than this one of the sheets, and the difference between these stresses is the monotonically decreasing function of relative thickness of a sheet. It can see also that at the boundary of the transducer and the glue layer the direct stress is more than at the free external boundary. It means, if the brittle or fatigue failure of transducer in similar type of structure the destruction of transducer should be started at this internal boundary.

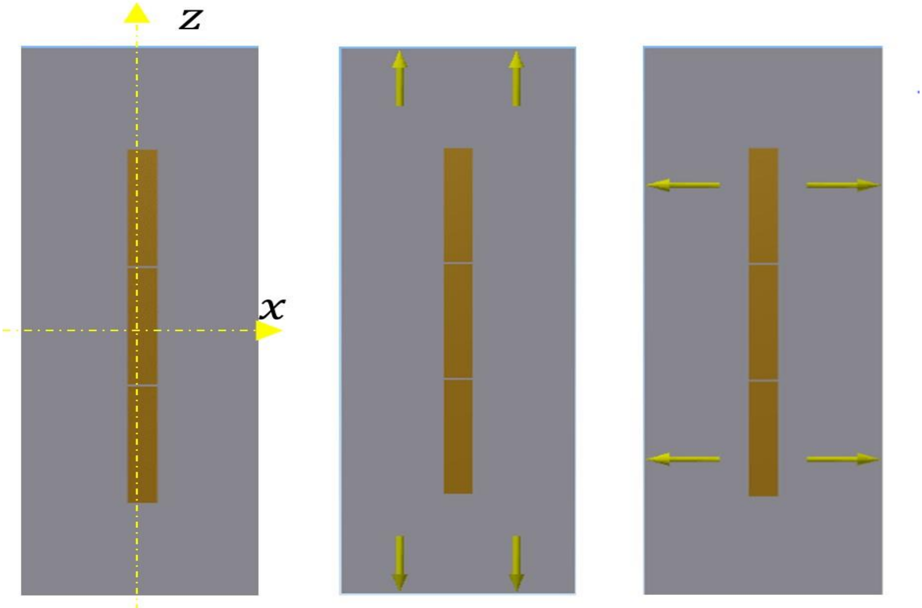

Fig.2.5. The model of a sample for FEA of transducers at two options of loading: tension in longitudinal and lateral direction

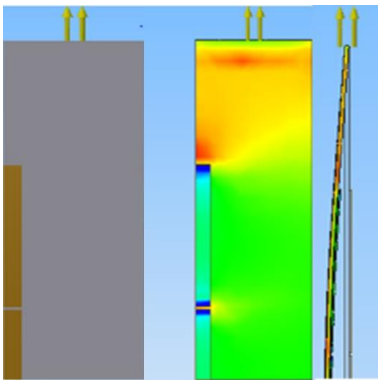

Fig.2.6. General view of stress state of model

For this critical boundary plane more detailed info on the stress state of the transducer is given in (Fig 2.7) Curves in interval of coordinate z∈ [0…25 mm] correspond to half of the middle transducer, and curves for z∈[26…76 mm] correspond to the outside transducer. Simple estimation of these outcomes shows that practically in all points of considered intervals (excluding short end zones) the acting stresses exceed tensile (and bending) strength of piezoceramics. It means that at the established level of external loading of sample at least initiation of brittle cracks in transducers is very probable.

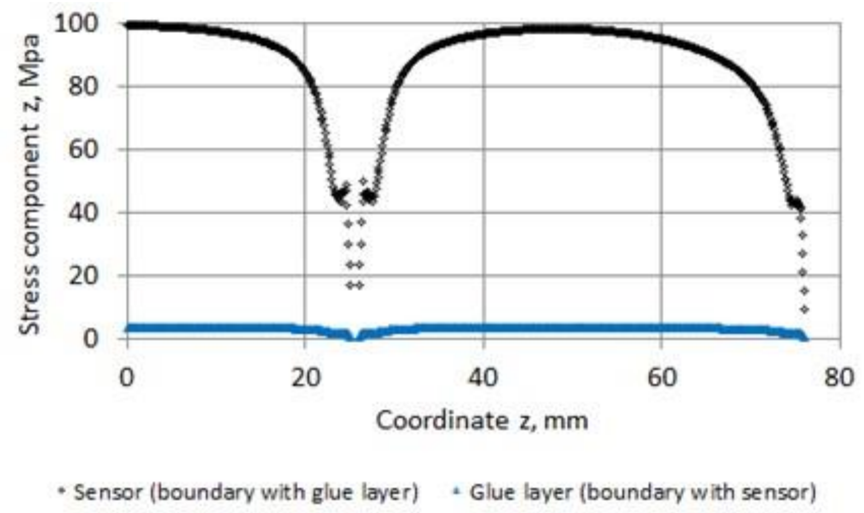

Fig.2.7. Distribution of tensile stresses of transducers and glue layer in boundary plane between them

Similar analysis was also done for the sample loading in direction perpendicular to its longest side (Fig.2.8). Here the general view of distribution of stresses (in the form of the Von Mize's equivalent stress) and deformed shape of the model at tensile load are illustrated. The presence of transducers causes non-homogenous stress state of they and the sheet. The mean direct stress of transducer is always smaller than this one of the sheets, and the difference between these stresses is the monotonically decreasing function of relative thickness of a sheet. But in contrast with previously considered case of tension, (Fig.2.8) demonstrates much less stress in transducers at the same intensity of external loading. Here the critical for strength of transducer is also the same boundary plane between transducer and glue layer.

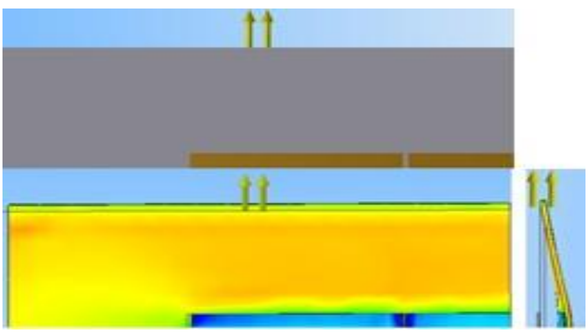

Fig.2.8. General view of stress state of model in tension

More detailed info on the stress state of the transducer in this plane is given in (Fig.2.9). One specific feature of direct stresses distribution is the stress concentration at ended parts of transducer, and the biggest concentration corresponds to outside position of transducer.

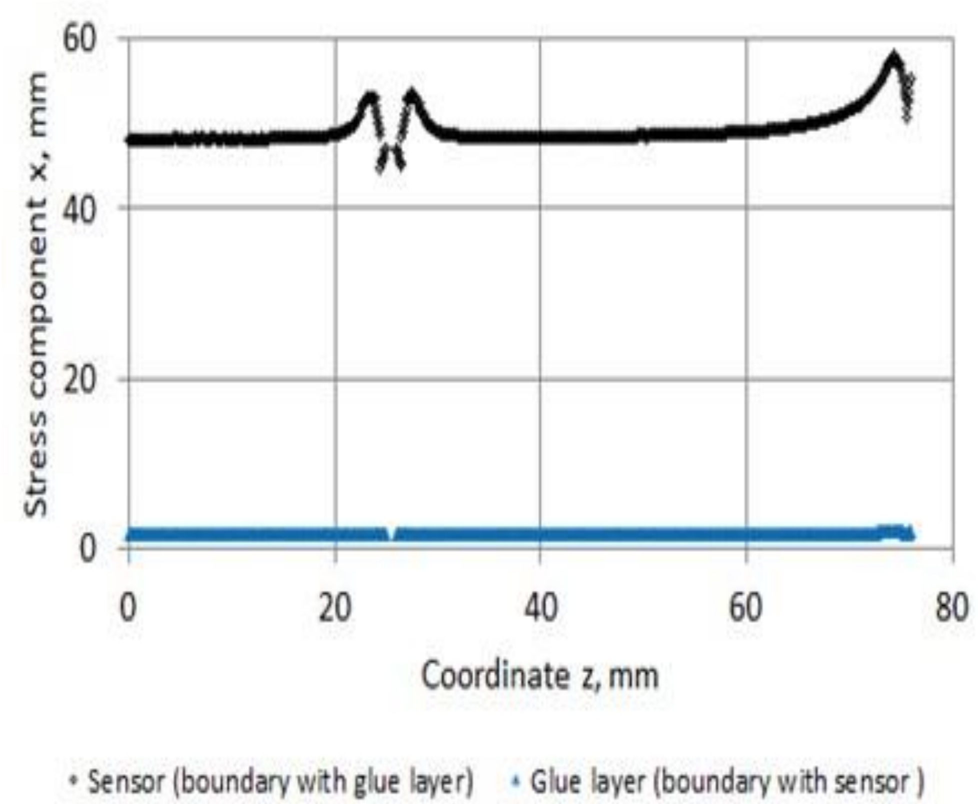

Fig.2.9. More detailed view of distribution of tensile stresses of transducers and glue layer in boundary plane between them

The information of performed investigation which is the most important as for the further use in this paper or for other applications is given in the Table 3. Here the maximum of direct stress parallel to direction of the tensile load is presented for all boundary planes of each component of model. Strength of all actual materials also is given in the table and that allows estimating the correspondence of any option of transducer installation to the static strength requirement.

Table.3.

Maximum direct stress in boundary planes of measurement unit

Component, its layer	Load direction		Strength, MPa
	long	cross	
Sensor,upper free urface	75.03	24.66	45 (80)
Sensor,boundary with glue layer	98.22	58.12	45 (80)
Glue layer,boundary with sensor	3.29	1.94	31
Glue layer,boundary with skin	10.25	3.07	31
Skin, boundary with glue layer	306.31	91.71	350*

In this table the color of cell indicates the status of static strength requirement: green color – requirement is satisfied, yellow –partly satisfied, red - is not satisfied.

2.4. Conclusions of chapter 2

1. In contrast to the conventional structural health monitoring (SHM) the system of current references requires installation of transducers to the surface of loaded structural components and they are subjected also by the operational load.
2. The problem of piezoelectric transducer (PZT) mechanical interaction with the thin-walled structural tensioned component at typical kind of joint investigated, and the main features of this interaction were defined.
3. In general, it can be concluded that static or cyclic tension causes the piezoelectric transducer (PZT) cracking which is stared from the boundary plane between the transducer and the glue layer.
4. Note, that at the same nominal tensile stress of structural component the tensile stress of piezoelectric transducer (PZT) is more for thicker component.
5. In general, the analysis of stress state of piezoelectric transducer (PZT) should be done at the designing stage for providing reliability and lifetime of structural health monitoring (SHM) system.

CHAPTER 3. ACTIVE METHODS OF SHM USING ULTRASOUND TECHNIQUES

3.1 Electromechanical impedance as primary method of crack detection and load monitoring

3.1.1 Electromechanical impedance, its components, and EMI parameters

The primary challenge in enhancing the effectiveness of electromechanical impedance (EMI) inspection lies in developing reliable methods to predict the impact of damage on impedance. Numerous approaches have been proposed for interpreting electromechanical impedance (EMI). This investigation particularly focuses on the mathematical simulation of the EMI for the system composed of a structural element and an ultrasonic transducer, which is considered one of the most promising methods.
The electromechanical impedance (EMI) technology has been chosen as the primary method for detecting fatigue cracks in the hermetic fuselage skin. This technology is known for its simplicity, reliability, and the ability to be implemented effectively using low-cost and straightforward measurement equipment. In this paragraph, a novel approach to applying EMI is discussed. This approach involves selecting the index of damage (IOD), determining its critical value, and estimating damage detection solely based on the current information from Piezoelectric transducers (PZT). To address the challenges, an EMI model and the results of specialized tests are utilized. Several models for electromechanical impedance (EMI) have been developed in previous studies [23-32]. In recent articles [33], a novel EMI model was introduced and applied for aircraft structural health monitoring (SHM). This model provides an expression for the electromechanical impedance that is applicable to models of any dimension (1D, 2D, 3D) and is not influenced by imposed constraints. The fundamental tool for this model is the modal analysis of the dynamic response of the system composed of the "host structure - PZT."The final electromechanical impedance (EMI) equation is: (Eq 1,2,3)

$$Z(\omega) = \frac{1}{i\omega C}\left[1 + \frac{k_{31}^2\omega^2}{\left((1-\nu)-2\frac{E}{E'}\nu'^2\right)A\mathrm{h}}\Phi(\omega)\right]^{-1} \tag{1}$$

Where,

$$\Phi(\omega) = \sum_{k=1}^{\infty}\frac{\int f(\xi)dW\int\rho(\xi)(\xi-\xi_C)U_k(\xi)dW}{M_k\left(\omega_k^2-\omega^2\right)} \tag{2}$$

And

$$f(\xi) = (\epsilon_{1k} + \epsilon_{2k} + 2\nu'\epsilon_{3k}) + \frac{d_{33}}{d_{31}}\left(\nu'(\epsilon_{1k} + \epsilon_{2k}) + \frac{E'}{E}(1-\nu)\epsilon_{3k}\right) \tag{3}$$

$k_{31}^2 = d_{31}^2/(\varepsilon_{33}s_{11})$ is the electromechanical coupling coefficient, s_{11} is the component of mechanical compliance at zero field, ε_{33} is the dielectric constant at zero stress, and d_{31} is the induced strain coefficient, i.e., mechanical strain per unit electric field, E and E' are the elasticity modulus, and ν and υ' are the Poisson ratios of transverse isotropic material of PZT, $C = \varepsilon_{33}A/h$ is the capacitance, A and h are the electrodes area and the thickness of PZT, $\epsilon_{jk} = \frac{\partial U_{jk}}{\partial x_j}$,

$(j = 1,2,3)$ and $\boldsymbol{U}_k(\boldsymbol{x})$ and ω_k is k-th mode shape and frequency.

As easy to see this model directly uses results of modal analysis of structure and is independent from details of structure configuration, boundary conditions and external loading. It is the main advantage of this electromechanical impedance (EMI) model. In this research the modal analysis is performed in COMSOL Multiphysics, and its results transmit to MATLAB in which the algorithm of the electromechanical impedance (EMI) model is realized.
Below the model of 240x80x1.15 mm Al alloy sheet equipped by two sensors PIC151 is shown (Fig.3.1) and used for electromechanical impedance (EMI) simulation and define the relationship between the electromechanical impedance (EMI) index and a crack size in the symmetry plane. Results of simulation give information for comparative estimation of different types of damage index, and for establish the reliable procedure of index value determination.

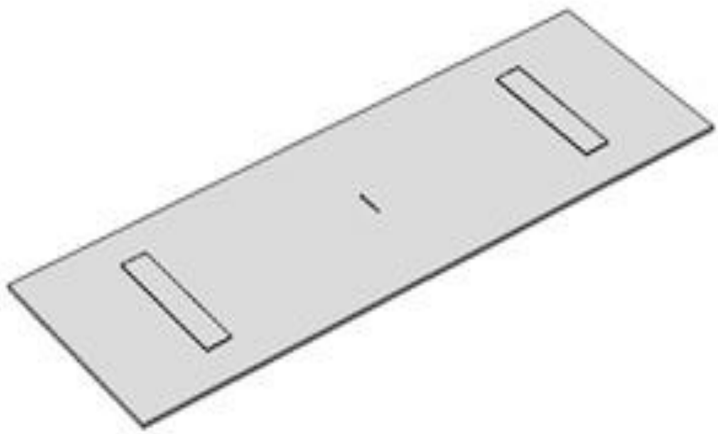

Fig.3.1. The plate with crack is equipped with two PZT transducers.

The two types of integral DI considered here and obtained information for the comparable estimation: 1) Root mean square deviation (RMSD), and Correlation coefficient deviation (CCD).

The Root mean square deviation (RMSD) index is defined by follow equation:

$$RMSD = \sqrt{\frac{\sum_{k=1}^{N}[y(\omega_k) - y_0(\omega_k)]^2}{\sum_{k=1}^{N}[y_0(\omega_k)]^2}} \tag{4}$$

Here y is the current realization of some signature of electromechanical impedance (EMI) that changing should be estimated, $y_0(\omega_k)$ signifies this electromechanical impedance (EMI) signature in the initial (unloaded) state, N is the number of sample points in the frequency band of interest. (Eq 4)

The correlation coefficient deviation (CCD) index is defined by follow equation:

$$CCD = 1 - CC = 1 - \frac{Cove\big(y(\omega), y_0(\omega)\big)}{\sigma_y\, \sigma_{y0}} \quad (5)$$

where CC is the correlation coefficient that indicates the statistical relationship between two signals $y(\omega)$ and $y0(\omega)$ of the electromechanical impedance (EMI) signature. (Eq 5)

Above mentioned simulation procedure was done for all six signatures of the electromechanical impedance (EMI) (magnitude of EMI, resistance, reactance, magnitude of EM admittance, conductance, and susceptance). But essential features of all these signatures as reaction to damage are similar. Therefore, those features are illustrated below for some separate signatures (Fig.3.2-3.4). Graphs in those Figures are results of simulation in frequency band from 4 to 300 kHz with step of discretization 100 Hz. Damage index (DI) was calculated in the window of 2000 samples which corresponds to the width of window in frequency domain 200 kHz. So, (Fig.3.2-3.4) frequency corresponds to the initial point of selecting window and the ordinate shows value of DI in this window.

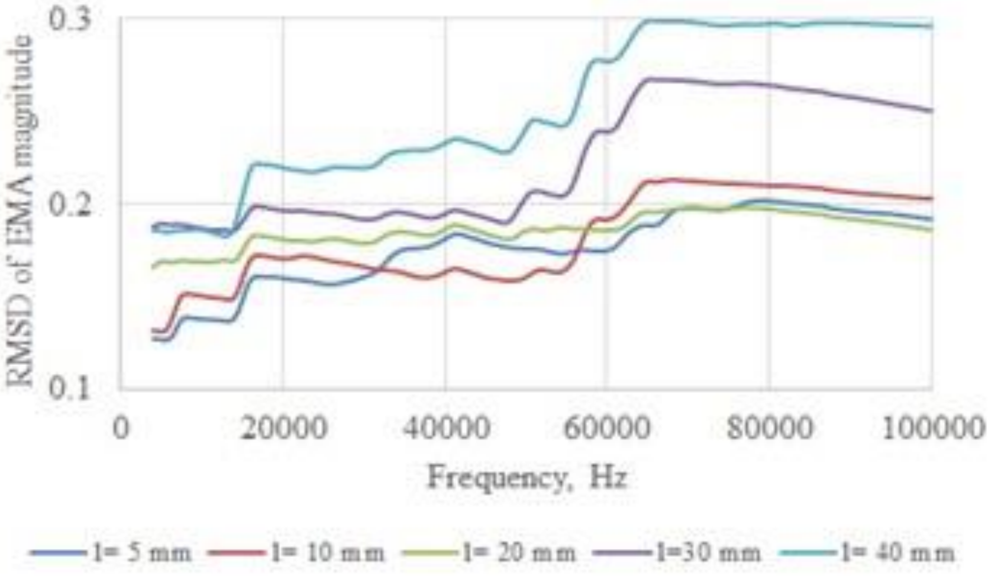

Fig.3.2. The RMSD of EMI magnitude as a function of initial frequency of selecting window.

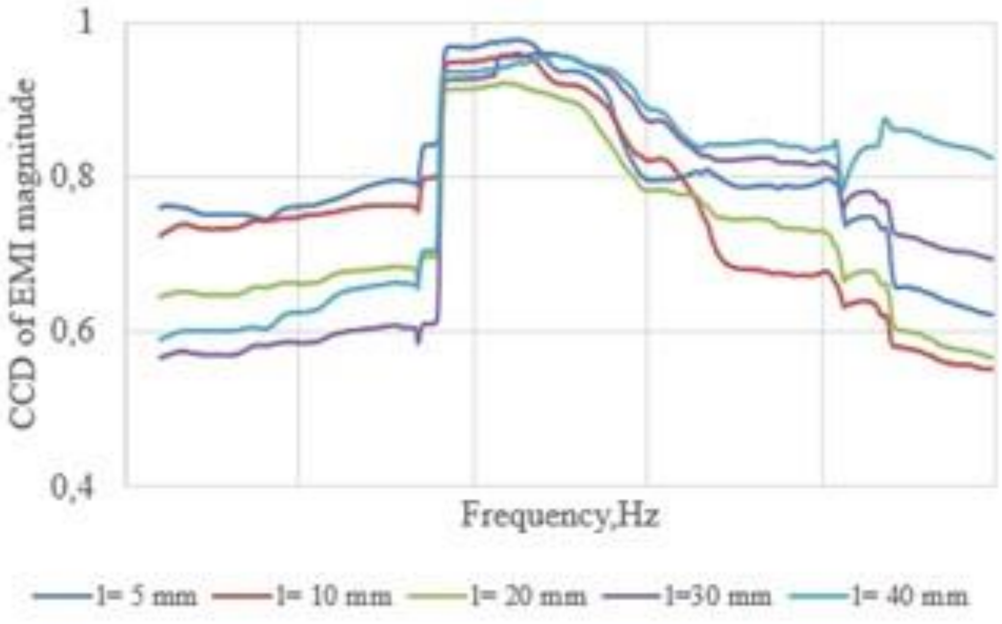

Fig.3.3. The CCD of EMI magnitude as a function of initial frequency of selecting window

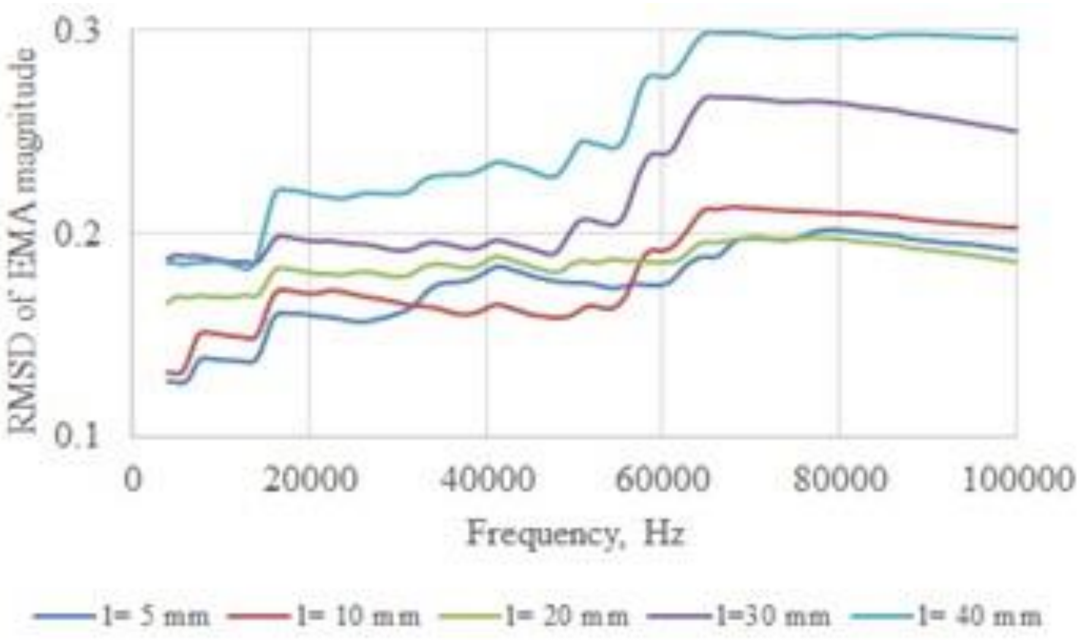

Fig.3.4. The root mean square deviation of (EMA) magnitude as a function of initial frequency of selecting window.

3.2. Other indices of electromechanical impedance (EMI) based system of SHM.

The effect of damage usually is estimated by the index of damage (DI) like to root mean square deviation (RMSD), correlation coefficient deviation (CCD) and others less popular ones. All those indices are integral but discrete records of electromechanical impedance (EMI) curve causes many local sampling problems. Selection of width of window of data set, number of sample points, frequency band are important for stability of damage indices. The rational procedure of electromechanical impedance (EMI) damage indices defining is proposed.
Within the impedance-based system of structural health monitoring (SHM), various indices of electromechanical impedance (EMI) exist. However, in this case, only one index is utilized, which is the average or mean value of the EMI signature within a selected frequency range. This specific index proves to be effective in estimating the vertical shift of the EMI curve in the frequency domain.

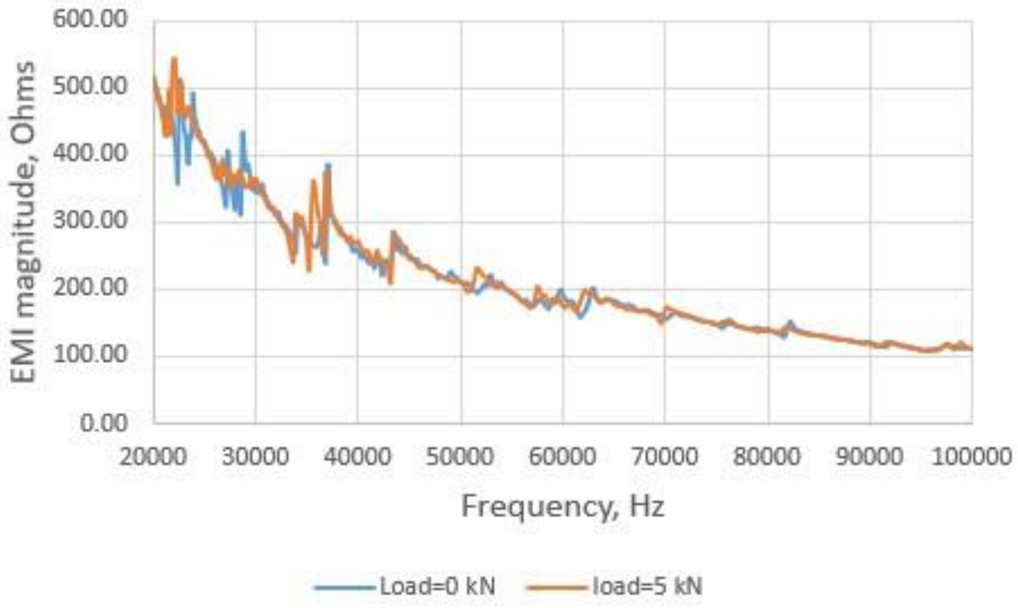

Fig.3.5. The effect of loading to the spectrogram of electromechanical impedance (EMI) magnitude

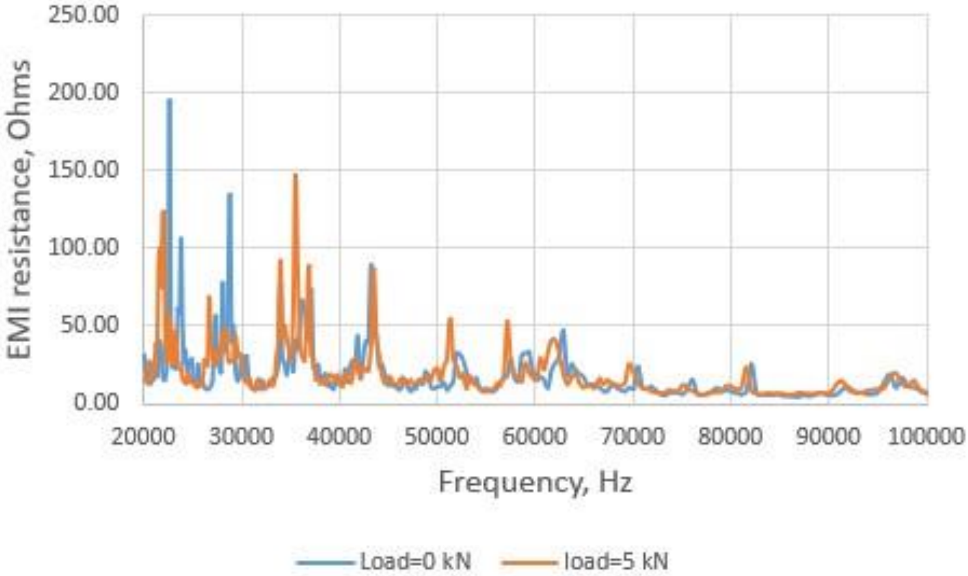

Fig.3.6. The effect of loading to the spectrogram of electromechanical impedance (EMI) resistance

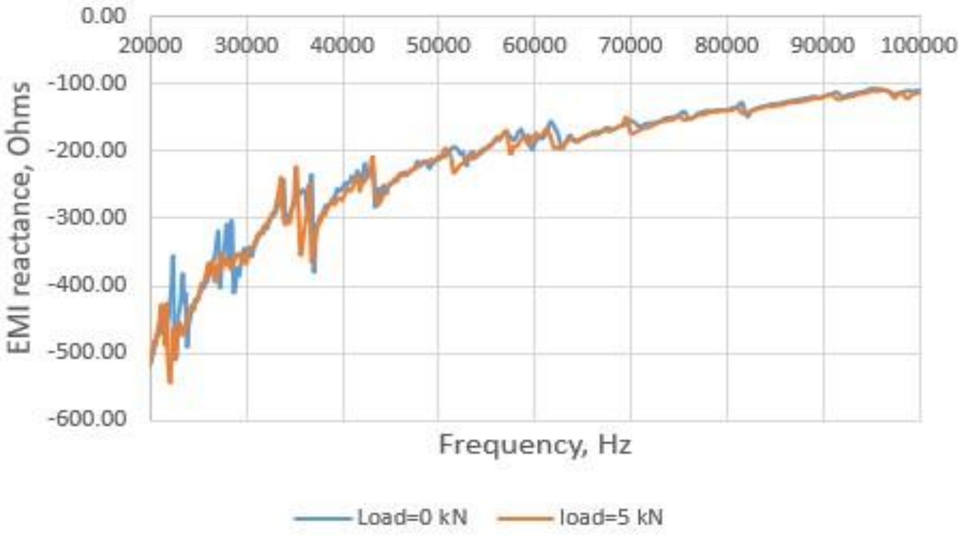

Fig.3.7. The effect of loading to the spectrogram of electromechanical impedance (EMI) reactance

The calculations are based on data obtained from the Cypher Graph. The impact of load on electromechanical impedance is assessed by plotting various graphs that depict the relationship between loads and the Root Mean Square Deviation (RMSD) of the electromechanical impedance (EMI). Each graph illustrates the RMSD values of different signatures plotted against the load, with the graphs generated for multiple iterations. Throughout the test, the sample underwent periodic loading and unloading, with the RMSD values consistently starting from zero.

In (Fig. 3.5,3.6, 3.7) plot the graph has been obtained between root mean square deviation of resistance against load. These graphs were generated through six different iterations, revealing significant variations in the resistance signature. All the readings were acquired from sensors attached to the sample plate.

3.3. Experimental study of the crack open/close effect and the perspective of its use in SHM (Structural health monitoring)

Aircraft structures are typically made from a variety of different aluminum alloys, each with specific properties that make them suitable for different structural components. Here are some commonly used aluminum alloys in aircraft structures:

1. 2024-T3: This is a high-strength alloy that is commonly used in aircraft structures, particularly for wing and fuselage structures.
2. 6061-T6: This is a general-purpose aluminum alloy that is commonly used in aircraft structures, including wing and fuselage structures.
3. 7075-T6: This is a high-strength alloy that is commonly used in aircraft structures, particularly for high-stress applications such as landing gear and wing spars.
4. 5086-H32: This is a marine-grade alloy that is sometimes used in aircraft structures, particularly for applications that require corrosion resistance.

The specific alloy used in an aircraft structure will depend on several factors, including the structural requirements, weight considerations, and cost. It is also important to note that while aluminum alloys are commonly used in aircraft structures, other materials such as titanium alloys and composites may also be used in some applications.

2024-T3 and 6061-T6 are both commonly used aluminum alloys in aircraft structures and share several similarities, including:

1. Due to their high strength-to-weight ratios, both alloys are suitable for applications requiring strength, such as aircraft structures.
2. Both alloys have a high corrosion resistance, which is crucial for aircraft structures exposed to a variety of environmental conditions.
3. Weldability: Both alloys can be welded using a variety of techniques, making them easy to fabricate and repair.

These two alloys can be shaped using a variety of methods, including bending, contouring, and rolling.

However, there are differences between the two alloys. 2024-T3 is an extremely strong alloy that is commonly used in applications where strength is of the uttermost importance, such as wing and fuselage structures. 6061-T6, on the other hand, is an all-purpose alloy used in a variety of structural applications, including wing and fuselage structures, hydraulic systems, and engine components. In certain applications, 6061-T6 is also easier to work with than 2024-T3 due to its superior machinability.

Aluminum 2024-T3 is one of the most popular materials for aircraft structures, particularly due to its high strength-to-weight ratio and extraordinary fatigue resistance. Common applications include ingots, extrusions, and forgings.

Depending on the application and design requirements, the precise quantity of 2024-T3 utilized in aircraft structures may vary. However, it is accurate to say that aluminum 2024-T3 has a significant application in the aerospace industry, with estimates indicating that it accounts for as much as 40 percent of all aluminum-alloy aircraft structures. Other frequently utilized aluminum alloys in the aerospace industry include 7075-T6, 6061-T6, and 2024-T4. Each of these alloys possesses a unique set of properties, and they are selected based on the needs of the designed aircraft structure. Since research focuses on hermetic fuselage structures made of 2024-T3 aluminum alloy, experimental evaluation and simulations were considered.

3.3.1. Aim of experimental investigation

The goal of experimental study is more detailed investigation of features of the crack open/close effect, comparison of efficiency of deferent kinds of the damage index and, finally, estimation of real perspective of creation of structural health monitoring (SHM) system on the base of mentioned effect. Guided wave technology (GWT) is considered mainly for fatigue crack evaluation after its detection. But because the crack open/close effect is very significant, the use of this technology in the mentioned version also may be used. To prove the novelty of damage index (DI) and independently from version of guided wave technology (GWT) can be used for data processing and damage evaluation.
The key benefit of this approach lies in leveraging current information regarding the structure and technical conditions of the monitoring system. The evolution of electromechanical impedance (EMI) is influenced by various factors, including degradation of the structure and sensors (such as fatigue, corrosion, and delamination in layered composites), as well as environmental effects like temperature and humidity variations and mechanical loading. By adopting this approach, the detrimental effects of aging on monitoring results can be effectively minimized or eliminated altogether.

3.4. The test sample, equipment, and test setup

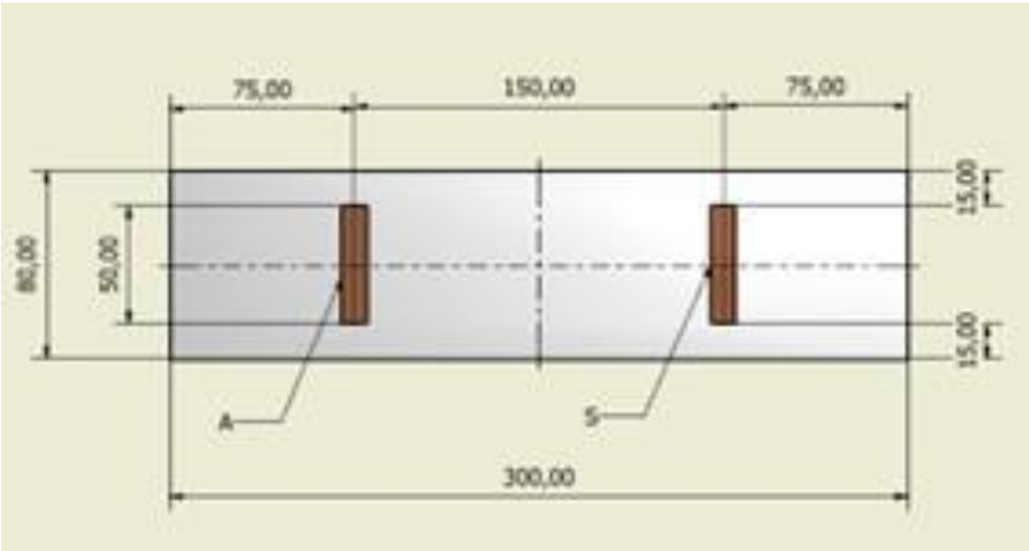

Fig.3.8. The sample for fatigue test

The test sample of Al2024-T3 sheet 300x10x1.15 mm with the central hole 4 mm. Two transducers PIC 151, 0.5x10x50mm (PI Piezoceramic) connected to the sample by Epoxy Paste HYSOL EA 9309. 3NA QT SYSTEM (general view of sample is shown in (Fig.3.8). The scheme of transducers installation is shown in (Fig.3.8). Fatigue test performed using Instron 8800 test machine at cyclic load of maximum 12kN and minimum 4kN, and frequency of 10 Hz.
At the stage of crack initiation after each 20 kilocycles, and at the stage of fatigue crack propagation the loading was interrupted for ultrasonic measurement.

There were measured:

1. Sensor response to specific excitation impulse (five sine waves of frequency 250 kHz modulated by Gauss error function)
2. Electromechanical impedance (EMI) of system ‘transducer/sample’. Measurements were performed for unloaded and statically loaded states.

The measurement equipment includes:

a. Lamb wave electronics LWDS45 (Cedrat Technology) for generation of excitation impulse
b. Software for LWDS45 (KUL) coupled with LWDS45 hardware.
c. USB450-25: 4 Ch Oscilloscope 25 MHz version (Acquitek) for sensor response measurement
d. Impedance measurement C60 (Cypher Instruments Ltd)

3.5. Essential outcomes

In (Fig.3.9) the result of this research in respect of the Electromechanical impedance (EMI) is shown. The root mean square deviation (RMSD) index for conductance is used here. For other components of Electromechanical impedance (EMI), the response is similar. The effect of loading.

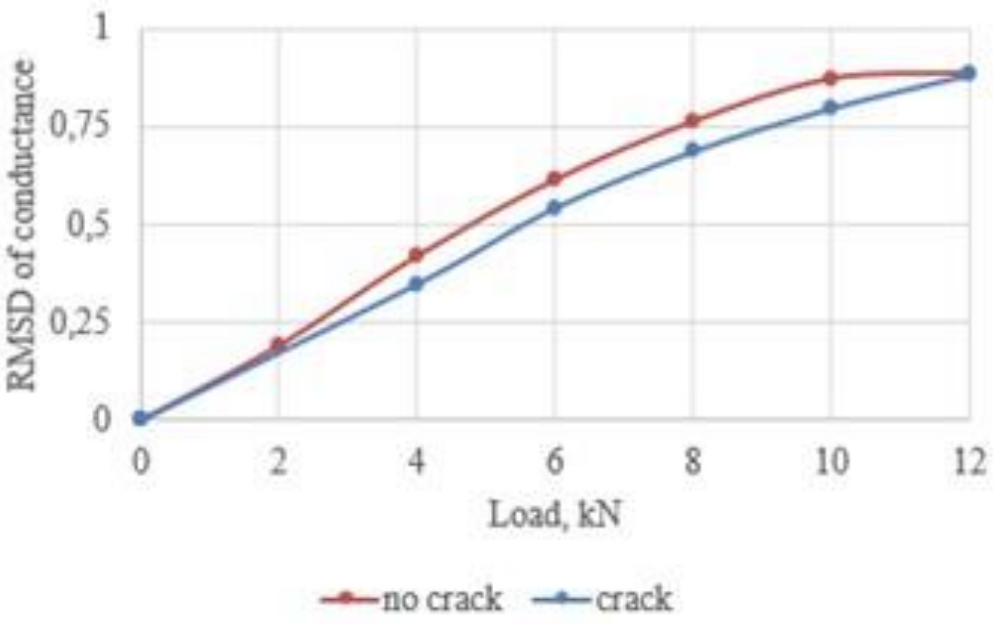

Fig.3.9. The effect of loading to conductance of system

The novel kind of damage index (DI) used here for detection of crack size using guided wave technology. Very briefly the sense of damage index (DI) is explained below. If the function $f(t)$ is

signal that is induced by the excitation impulse $\varphi(t)$ at the crack length l. (Eq 6)
Then the integral transform is convolution of these two functions.

$$\Phi(\tau, l) = \left| \int_0^\infty f(t)\varphi(t-\tau)\,dt \right| \tag{6}$$

Here τ is the shifting variable with a unit of time. The first global maximum of $\Phi(\tau)$ is selected as a measure of damage. It can be obtained by construction of the left-upper envelope $\mathrm{E}(\tau, l)$ of the signal transform $\Phi(\tau, l)$ as follow: (Eq 7)

$$\mathrm{E}(x, l) = \max[\Phi(x, l)], \qquad for\ \ x\epsilon\ [0, \tau) \tag{7}$$

The value of variable $\tau_c\epsilon\ [0, \tau)$ that corresponds to mentioned maximum can be accepted as the time-of-flight. The $\mathrm{E}(\tau, l)$corresponds to the first global maximum of signal transform.
The procedure of $\mathrm{E}(\tau, l)$determination for crack length $l = 13\ mm$ is showed in the (Fig.3.10)

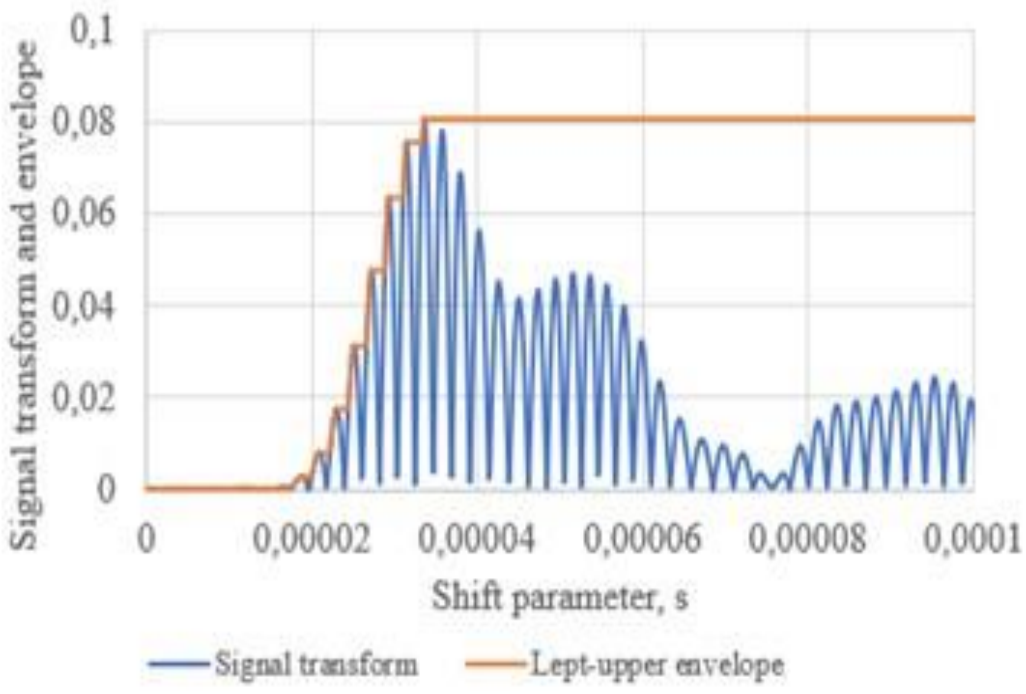

Fig.3.10. Signal convolutions transform and Damage index determination.

The dimensionless damage index DI(l) is defined by (Eq 8)

$$\mathrm{DI}(l) = 1 - \frac{\mathrm{E}(\tau, l)}{\mathrm{E}(\tau, 0)} \tag{8}$$

In (Fig.3.11) the outcome of experimental study is presented. Damage index (DI) is monotonic function of crack length. Another important result is the time-of-flight characteristics (Fig.3.12)

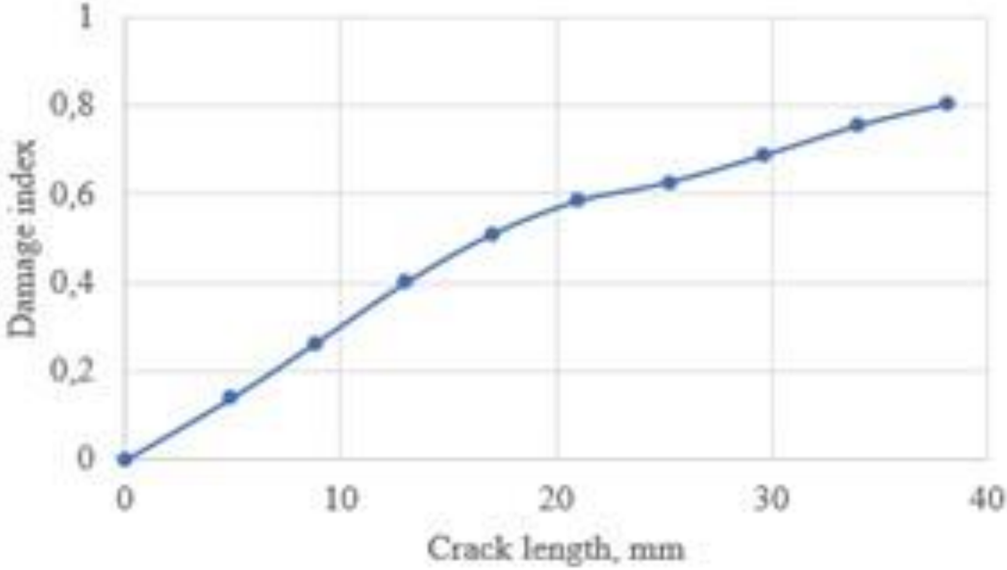

Fig.3.11. Damage index via crack length

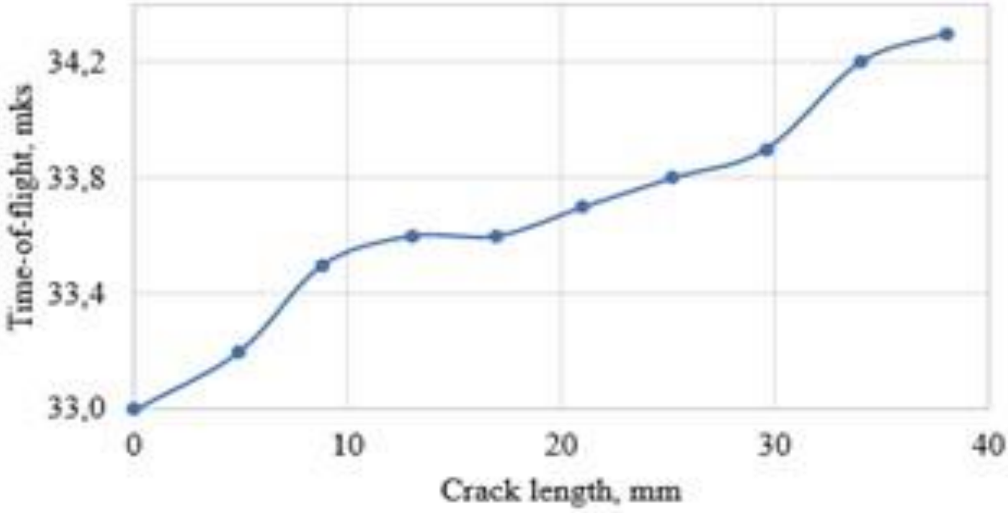

Fig.3.12. Time-of-flight via crack length

The formation of fractures in aircraft structures can be considered linear or nonlinear depending on the surrounding conditions and the materials used.
In the linear domain, crack propagation is governed by the ideas of linear elastic fracture mechanics (LEFM), where it is assumed that the material responds elastically and that the stress field at the point of the crack is unique and well-defined. In low to moderate stress circumstances, linear equations that form the foundation of linear elastic fracture mechanics (LEFM) can potentially be used to predict the rate at which cracks will develop.
However, under extreme stress and because of intricate loading and environmental variables, nonlinear behavior such as deformation owing to plasticity, crack branching, and crack coalescence may arise. Nonlinear fracture mechanics theories may be required since crack development behavior is no longer governed by straightforward linear elastic principles.
The atmospheric and material elements at work determine whether crack formation in aircraft structures is linear or nonlinear. Engineers and designers have to consider these different behavioral regimes while creating and assessing aircraft structures in order to optimize safety and dependability. Since the major goal of the research is to identify the critical condition of the structure, the work is linear in nature.

3.6. Application of SHM (Structural health monitoring) on the skin of hermetic fuselage structure

3.6.1 Demonstration of Impedance-Based SHM (Structural health monitoring) of the hermetic fuselage skin

To illustrate previous structural analysis and establish the fundamental framework for its structural health monitoring (SHM) system, a selected portion of a typical aeronautical panel from the hermetic fuselage, made of Al-alloy (2024-T3), is utilized.

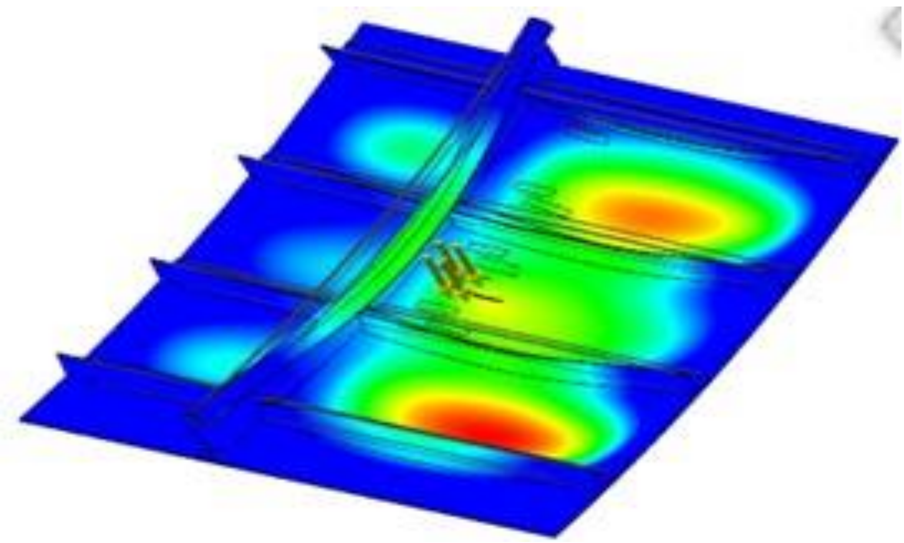

Fig.3.13. Stress state analysis of pressured fuselage

A small part of typical aeronautical panel of the Al-alloy (2024-T3) hermetic fuselage is shown in (Fig.3.13.) The direct distance between transducers is equal to 77 mm and the thickness of the skin is equal 1.5 mm, and the principal curvature radius is equal 2000 mm. It means that conditions of problem of crack detection in the skin are close to ones considered in this paper. The problem of the transducer's own strength can be estimated as well as the expected values of the damage indices for a crack of a given length.

First, stress state simulation of selected unit at the pressured cabin (Fig 3.13) shows that maximum stress of transducer at the boundary with the glue layer is not more than 17 MPa. It means that the requirement of static strength is completely satisfied (Earlier in Chapter 2, see Table 3) and probably also there will not be a problem of fatigue strength.

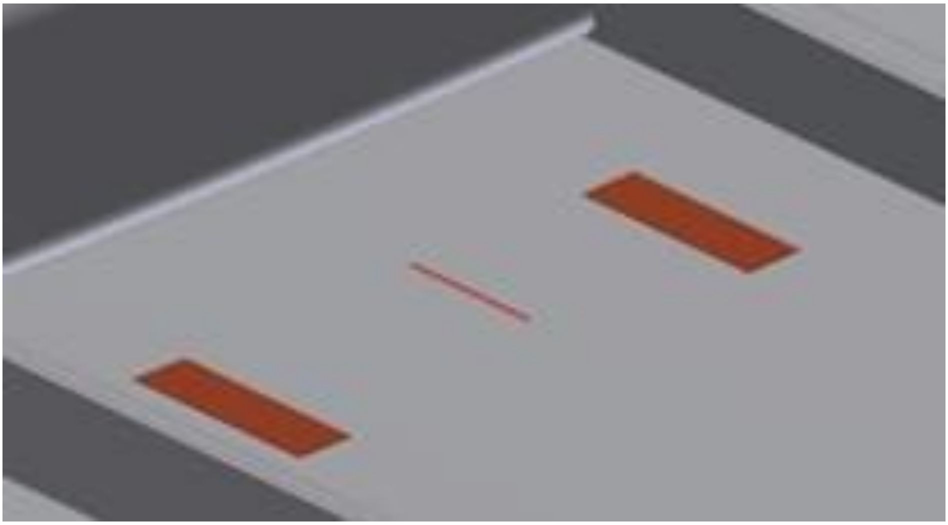

Fig. 3.14. Fragment of a skin with two transducers

In (Fig.3.14) is presented the fragment of a skin with two Piezoelectric transducers (PZT) and with the crack 35 mm between them. These damage indices can be approximately estimated using the results of the above investigation.

For Electromechanical impedance (EMI) in term of Root mean square deviation (RMSD) of Electromechanical admittance (EMA) magnitude

non-pressured cabin………….0.285
pressured cabin………………..0.27

For guided wave the damage index

non-pressured cabin……DI=0.655, To F=34.2 mks
pressured cabin……… DI=0.785, To F=35.0 mks

3.7. Predictions of fatigue crack growth and estimation of lifetime

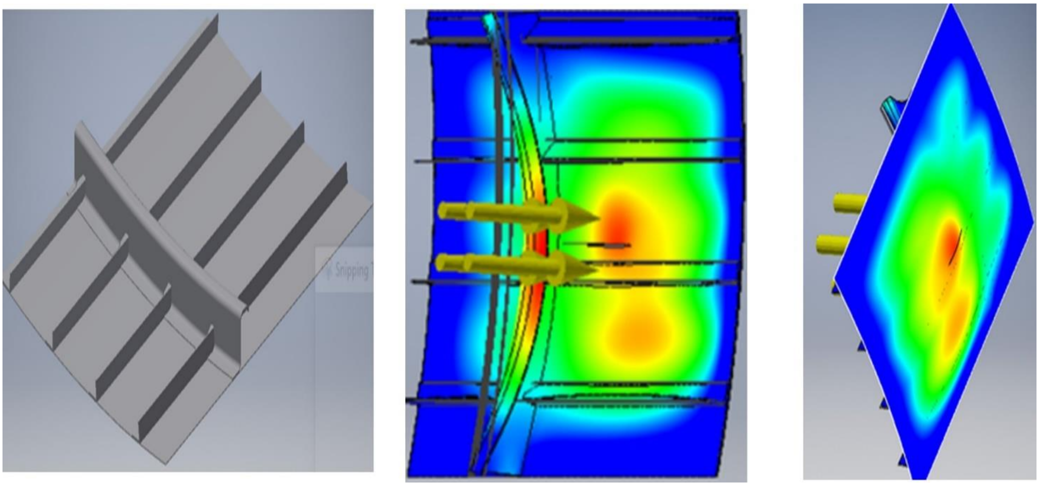

Fig.3.15. Aeronautical panel and results of stress state analysis in presence of possible fatigue crack

The geometry modeling is carried out in Autodesk Inventor. First a panel (Fig.3.15, left fragment) is designed and satisfies Airworthiness Requirements. The direct and shear stresses in the skin of fuselage caused by bending and torsion were neglected. It is assumed that in the skin of the panel circumferential direct stress is two times more than meridional direct stress and those stresses are caused by air pressure of 100 mPa inside cabin. So, in the mentioned stress field the fatigue crack propagates to the longitudinal direction (Fig.3.15, middle and right fragments). The stress state analysis is carried out using the Autodesk Inventor module Environments (option Static Analysis). Two views of full displacements are represented at the same (Fig.3.16).

Critical length of the fatigue crack is defined by condition of crack start of growth:

$$K_I = K_{Ic} \tag{9}$$

where K_I is the Stress Intensity Factor (SIF) that is a crack size function, and K_{Ic} is a constant of material which called by the fracture toughness (Eq 9). It is accepted that,

$$K_I = \sigma\sqrt{\pi l}\, Y(l) \tag{10}$$

where l is a crack half-length, σ is circumferential direct stress in the skin of panel, $Y(l)$ is correction multiplier. It can be exactly calculated by using results of Finite element analysis (FEA), and approximately is equal to 1. (Eq 10)

Material of a skin mechanical properties defined its crack resistance at static and cyclic loading is given in Table 4. The C and m are constants of Paris' law which describes the crack grow rate at cyclic loading (Eq.11). Using Eqs.9 and 10 the critical length of the fatigue crack corresponding to the remaining strength of skin 34.6 MPa (circumferential direct stress at maximum pressure in a passenger cabin) is equal 265 mm.

Table .4

Mechanical properties of Al alloy 2024-T3

Materials	K_{Ic}, MPa·m$^{0.5}$	m	C
2024-T3	26	4.2	$8.8 \cdot 10^{-11}$

Prediction of the fatigue crack propagation is done using the Paris' law for the rate of fatigue crack growth, (Eq 11)

$$\frac{dl}{dN} = C(\Delta K_I)^m \quad (11)$$

It is a simple first order differential equation. Solution is obtained by numerical integration at the initial condition: the length of the initial crack is equal to 20 mm. It is a size that can be detected reliably by the method of Electromechanical impedance (EMI).

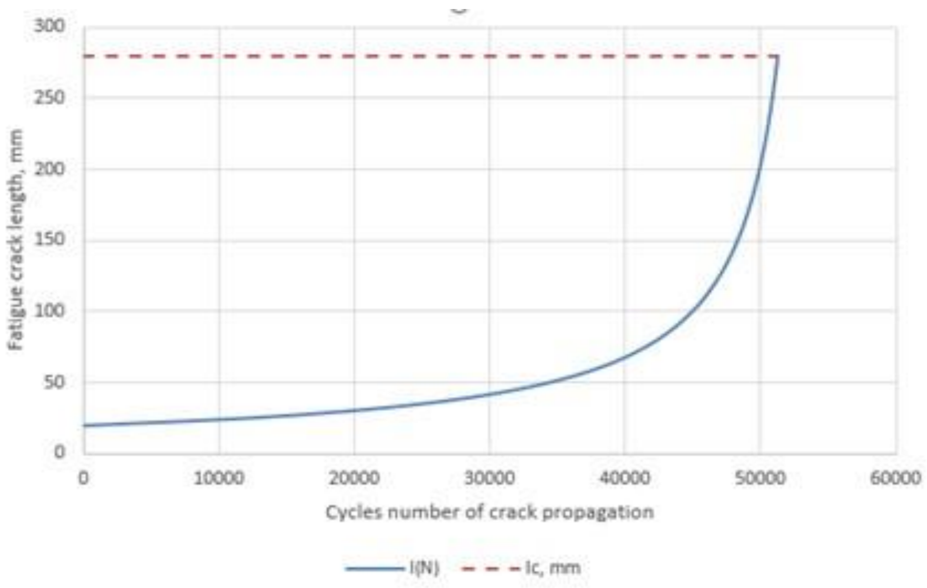

Fig.3.16. Prediction of the fatigue crack growth and estimation of lifetime

The result of prediction is shown in the picture. It is seen that the predicted lifetime of crack propagation to the critical length is equal to about 50000 flights. (Fig.3.16)

3.8. Conclusions of chapter 3

1. For obtaining of the stable value of both RMSD and CCD indices the width of window of indices evaluation should be sufficiently large.
2. At the same width of evaluation window value, the DI depends on position of window in the frequency domain.
3. The sensitivity of DI to the crack size depends on position of window in the frequency domain and signature of EMI. For instance, sensitivity of RMSD index of electromechanical admittance (EMA) magnitude (Fig. 12) for windows of initial frequency in diapason 18-22 kHz higher than this one of EMI magnitude (Fig.3.2).
4. In general, RMSD is more preferred than CCD.
5. Guided wave technology (GWT) is considered mainly for fatigue crack evaluation after its detection.
6. Since the crack open/close effect is very significant, the use of this technology in the mentioned version also can be used.
7. The novel DI is proposed and independent from version of GWT can be used for data processing and damage evaluation.
8. The skin of hermetic part of fuselage is a very convenient field for application of ultrasonic technology of structural health monitoring which uses the crack open/close effect.
9. Outcomes of this paper and previous our research show that this kind of SHM system is perspective.

CHAPTER 4. OTHER APPLICATIONS: LOAD MONITORING AND ACOUSTIC EMISSION

4.1. Related application

This chapter discusses other structural monitoring options in which the technical condition assessment is based on current or accumulated information, without reference to the initial state. First, this situation is developing if the load and other external influences should be monitored. The intensity of the mechanical load, its variable nature, dynamic effects, temperature effects, corrosion damage and other effects of the concomitant influence of the environment are the main factors that determine the degradation of the structure during operation. If the influence of each of these factors and their mutual influence on the lifetime of the structure are measured and properly considered, then on this basis it is possible to build a built-in monitoring system, able in a statistical sense to predict the degree of damage and to estimate the degree of danger of approaching a critical state. Such a comprehensive system for monitoring external influences would allow a more accurate assessment of their cumulative effect but would be cumbersome and expensive to produce and operate. Therefore, in practice, to ensure the optimal combination of forecast accuracy and economic efficiency, they are limited only to measuring the parameters that have the greatest impact on the lifetime of the structure in operation. In many cases, the load is the determining parameter. In particular, the mechanical load is the main external influence that determines the fatigue life of the components of the main structure of aircraft made of metallic materials. On the principle of monitoring the external load and assessing its cumulative effect, a monitoring system for the main structure and power units of modern helicopters has been built [34,35], demonstrating high efficiency in operation.

Obviously, load monitoring involves an indirect way to assess the structural health of a structure. This estimate can be obtained based on the use of an acceptable generalized damage parameter determined by the results of load monitoring and its comparison with the strength characteristics of the controlled structural element. The fundamental problems of implementing this approach in relation to fatigue damage to a metal structure are discussed in chapter (4.2). Both compared quantities are random. Therefore, the damage index should have a probabilistic formulation and be perceived as a requirement for additional verification and assessment of the technical condition of the structural element in question. The procedure of this type is developed in the work [36] and its fundamental fragment is presented in chapter (4.3)

A similar use case for the passive response of a piezoelectric transducer provides acoustic emission monitoring. It can be effectively used in endurance fatigue tests [37] and is described in chapter (4.4)

4.2. Load monitoring using PZT response.

In the aerospace, civil, and mechanical (ACM) industries, structures often experience various types of loads during their operational lifespan. It has been observed that approximately 75% of failures in aerospace structures occur due to cyclic loading fatigue. Therefore, it is crucial to effectively monitor ACM structures throughout their entire lifespan, especially considering their involvement in public safety and significant investments. Implementing such monitoring techniques not only reduces life cycle costs but also enhances reliability. To meet this need, researchers worldwide are continuously working on developing efficient monitoring techniques based on smart sensors. Electromechanical impedance (EMI) evaluation and piezoelectric (PZT) sensors are two SHM techniques. This method is based on the premise that a PZT sensor will endure harmonic vibrations in response to an applied sinusoidal electric field in a specific frequency range, thereby producing a unique electromechanical (EM) admittance characteristic. The health of the structure is then evaluated based on its unique characteristics.

As axial, transverse, and fatigue stresses are crucial factors in structural deterioration, structural health monitoring (SHM) places a premium on understanding their effects. This paper analyzes the efficacy of electromechanical impedance (EMI) methods in this context using the structural load monitoring (SLM) component of structural health monitoring (SHM). This research intends to gain a deeper comprehension of the operation of EMI technology and its utility in monitoring loads on structures, which will aid in the assessment of structural health and the detection of damage. [39]
As reported in the study's publication [40], experiments demonstrate that a dynamically coupled piezoelectric (PZT) patched sensor can effectively monitor structural responses in critical areas. In addition to sensing load intensity through acceleration, this sensor is beneficial for determining the state of a structure. The effect of damage on sensor correlation was also investigated in this study. The findings indicate that damage significantly modifies the perceived engineering parameters received from the PZT patch. However, by establishing appropriate correlations with data collected from a healthy structure, it becomes possible to detect and assess damage-related information. This concept of sensor correlation holds promise for applications such as load monitoring, health monitoring, and structural control. [40]
The fatigue testing of full-scale bench experiments is an essential factor in determining the service life of aircraft structures, and this is the subject of Chapter (4.5) of the research paper. Due to their design, these structures have a finite operational longevity. Currently, research is being conducted to identify methods for extending this operational lifetime. To effectively extend the operational lifespan of the structures, the study presents a comprehensive approach that involves gathering realistic data on the loading experienced by these critical elements during regular flight conditions. This includes obtaining data from real-scale model testing and conducting strength analyses. By evaluating the short-term strength and durability of these components using the collected data, it becomes possible to make informed assessments and extend the lifespan of the limiting elements, thus optimizing their usage. [38]

4.2.1. On the stress and load measurement

Below three approaches of load (stress) measurement by the way of the mechanical parameter transforming to proportional electrical response briefly considered.
1) The strain gauge is an instrument used to determine the amount of mechanical stress placed on a conductor because of changes in the conductor's geometrical dimensions, but not its material properties. According to article [52], scientists investigated how mechanical stress modified a metal wire's electrical resistance. The piezoresistive behavior in graphene ribbons was also modeled using first-principles electronic-state calculations. This research aimed to develop novel piezoresistive materials with desirable properties such as high flexibility and low manufacturing cost.
To achieve this goal, we modified the fundamental idea underlying modeling piezo resistivity so that it may be used to conductor systems as well as semiconductor ones. The goal of the investigation was to propose a technique for calculating the strain-induced modifications to carrier conductivity for both the armchair type and the zigzag type of graphene ribbons. The effective masses and carrier densities from a one-dimensional electronics spectrum diagram were used in these computations. Weak conductivity and high effective mass were observed in the armchair-type graphene nano-ribbon prototypes, contrary to the conductivity of two-dimensional graphene sheets. Band energy diagrams are sensitive to strain in general, but the sensitivity was greater in the zigzag-type graphene nano-ribbon designs. These models were shown to have quite large gauge factors in both the longitudinal as well as transverse directions, indicating the zigzag-type graphene ribbons offer tremendous potential as high-piezo resistivity materials. Based on these results, the zigzag-type graphene ribbon emerges as a promising candidate for high-performance piezoresistive materials, particularly for the fabrication of highly sensitive strain gauge sensors.[52]
This phenomenon was investigated for large number of materials in wide range of strain in paper [53]. The dynamic technique of electrical resistance measurement was presented in [54]. A novel

approach for measuring the resistance change of metals under tension has been devised and utilized for fifteen different metals. The method involves passing a direct current through the wire being tested, and as longitudinal vibrations occur within the wire, the resistance, and subsequently, the potential drop across the wire, fluctuates. These variations are then amplified and recorded. Through this method, it has been determined that bismuth, aluminum, manganin, and constantan exhibit a decrease in resistance as tension is applied, whereas all the other metals investigated demonstrate an increase in resistance with tension. [54]

1. There was established and embedded in practice linear relation between elastic strain ε and the relative resistance of strain gauge $\Delta R/R$.(Eq.12)

$$\frac{\Delta R}{R} = GF \cdot \varepsilon \tag{12}$$

GF is constant which is called the gauge factor.
In case of metal the total change of resistance caused by geometry changes of wire: length l and cross-section area A.(Eq.13)

$$R = \rho \frac{l}{A} \tag{13}$$

where ρ is specific resistance (resistivity) of material.

2. The piezo resistance effect.

The term piezo resistance was first used in paper [55].
For semiconductors the resistivity is not constant, but changes also at loading, and as it shows in [54]

$$\frac{\Delta R}{R} = \frac{\Delta \rho}{\rho} + (1 + 2\mu)\varepsilon \tag{14}$$

where μ is the Poisson's ratio.
For linear strain the relation (Eq12) remains the same, but its value is more than 50 times larger in comparison with metallic strain gauge. (Eq.14)

The tensor theory of piezo resistance was developed in [56], and all recent year's achievements are described in [57].

3. Piezoelectricity effect

The relationship between the electrical and mechanical properties of linear piezoelectric materials is characterized by a tensorial constitutive relation. Constitutive relation describes the mathematical relationship between the mechanical and electrical properties of a substance. Because of the capability of piezoelectric elements to transform electrical energy to mechanical energy as well as vice versa, both electrical and mechanical values are connected in this instance.
The piezoelectric tensor is a matrix that expresses the constitutive relationship between mechanical and electrical variables in tensorial form. The piezoelectric tensor is the fourth-order tensor that connects electrical field, mechanical stress, and mechanical strain. There are 36 components to the tensor that describe the relationships between the material's properties. The piezoelectric tensor can be written in different forms, depending on the reference frames used for the electrical and mechanical variables. The most common reference frames used are the engineering notation and the Voigt notation.
In the engineering notation, the piezoelectric tensor is a 6x6 matrix that relates the three components of the electric field and the three components of the mechanical stress to the three components of the mechanical strain. In the Voigt notation, the piezoelectric tensor is a 3x3 matrix that relates the three

components of the electric field and the three components of the mechanical stress to the three components of the mechanical strain.
In the tensor theory of piezoelectricity, the 6x6 matrix that relates the stress and strain in a piezoelectric material is a linear matrix. This matrix is called the piezoelectric tensor or the electromechanical coupling tensor.
The piezoelectric tensor relates the stress and strain in a linear manner and is characterized by its coefficients, which are constants that depend on the material properties. These coefficients are assumed to be constant within the linear regime of the material, which means that the relationship between stress and strain is linear and can be described by a linear equation. Therefore, the 6x6 piezoelectric tensor matrix is linear, as it describes the linear relationship between stress and strain in a piezoelectric material. Furthermore, the linearity assumption is important in the context of piezoelectricity because it allows for the use of linear algebra to analyze and predict the behavior of the material under various conditions. This includes the ability to use techniques such as matrix inversion and eigenvalue analysis to solve for the stresses and strains in the material, as well as to calculate other important properties such as the piezoelectric charge and voltage coefficients. It is worth noting, however, that the linearity assumption may not hold under certain extreme conditions, such as high electric fields or large mechanical deformations, which can cause the material to exhibit nonlinear behavior. In these cases, more complex nonlinear models may be necessary to accurately describe the material's behavior.
The piezoelectric tensor is a fundamental property of piezoelectric materials, and it is used to describe the behavior of these materials in various applications, such as in sensors, actuators, and transducers. By understanding the relationship between the electrical and mechanical variables of piezoelectric materials, it is possible to design and optimize devices that use these materials for a wide range of applications.
The interaction between the electrical and mechanical variables of linear piezoelectric materials can be described by a constitutive relation in the tensorial form. Below are presented so called sensing piezoelectrical equations in compressed form. (Eq.15)

$$\begin{cases} \{\boldsymbol{S}\} = [\boldsymbol{s}]\,\{\boldsymbol{T}\} + [\boldsymbol{g}]\{\boldsymbol{D}\} + \{\boldsymbol{\alpha}\}\boldsymbol{\theta} \\ \{\boldsymbol{E}\} = [\boldsymbol{g}]^{\boldsymbol{t}}\,\{\boldsymbol{T}\} + [\boldsymbol{\beta}]\,\{\boldsymbol{D}\} + \{\boldsymbol{B}\}\boldsymbol{\theta} \end{cases} \tag{15}$$

Here:
$\{\boldsymbol{S}\}$ is the strain vector which presents strain tensor in compressive form;
$[\boldsymbol{s}]$ is the compliance matrix;
$\{\boldsymbol{T}\}$ is the stress vector which presents stress tensor in compressive form;
$[\boldsymbol{g}]$ is the matrix of the coupling between the electrical and the mechanical variables;
$\{\boldsymbol{D}\}$ is the vector of electric displacements;
$\{\boldsymbol{\alpha}\}$ is the vector of coefficients of thermal expansion;
$\{\boldsymbol{E}\}$ is the vector of electric field;
$[\boldsymbol{\beta}]$ is the vector of impermittivity;
$\{\boldsymbol{B}\}$ is the vector of piezoelectric voltage coefficients;
$\boldsymbol{\theta}$ is the temperature.

The equations (15) describe the linear piezoelectricity and together with system of equations for the theory of elasticity allow to solve the problem of piezoelectricity for any linear piezoelectric device. Below several types of piezoelectric devices are considered in respect to use of them for stress or load measurement.

4.2.2 Homogenous stress state of the PZT

For this case the solution can be easily obtained directly from (Eq.15) using properties of piezoelectric transducer (PZT) constants of material. But here and anywhere in this paragraph solutions obtained by numerical way using COMSOL Multiphysics software. It allows to save single style of results presentation and convenience of their comparison. The stationary study of the free sensor at homogenous loading is presented in this subparagraph. (Table 5) The electrical potential of piezoelectric transducer (PZT) is response which is proportional to load (stress). (Fig 4.1- 4.10)

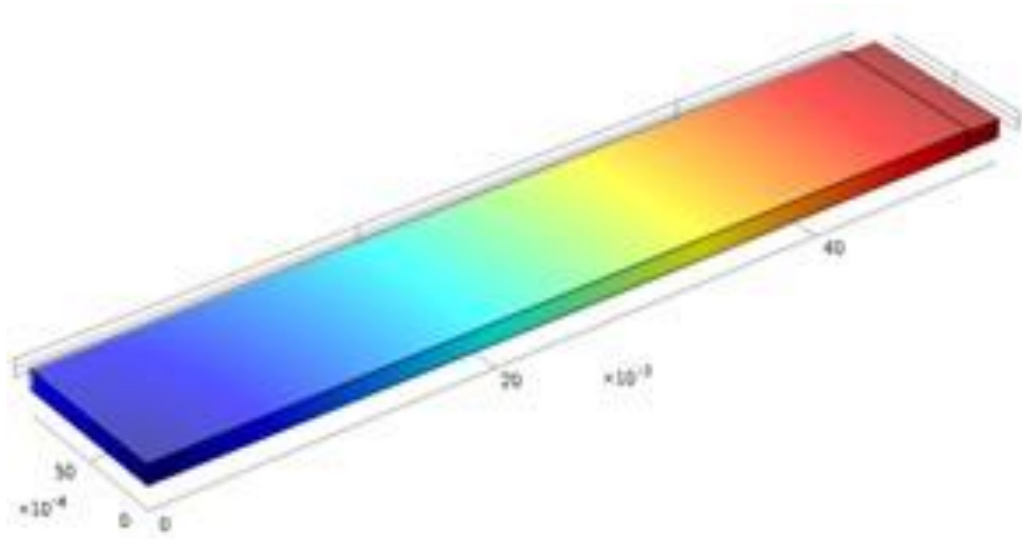

Fig.4.1. Unidirectional tension in the longitudinal direction of the PZT

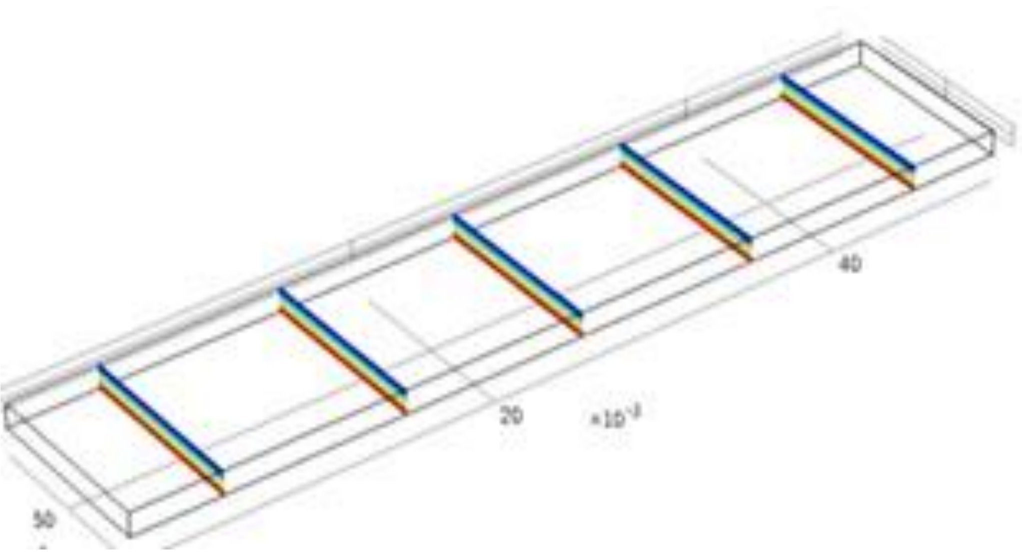

Fig.4.2. Displacement of Unidirectional tension in longitudinal direction of PZT

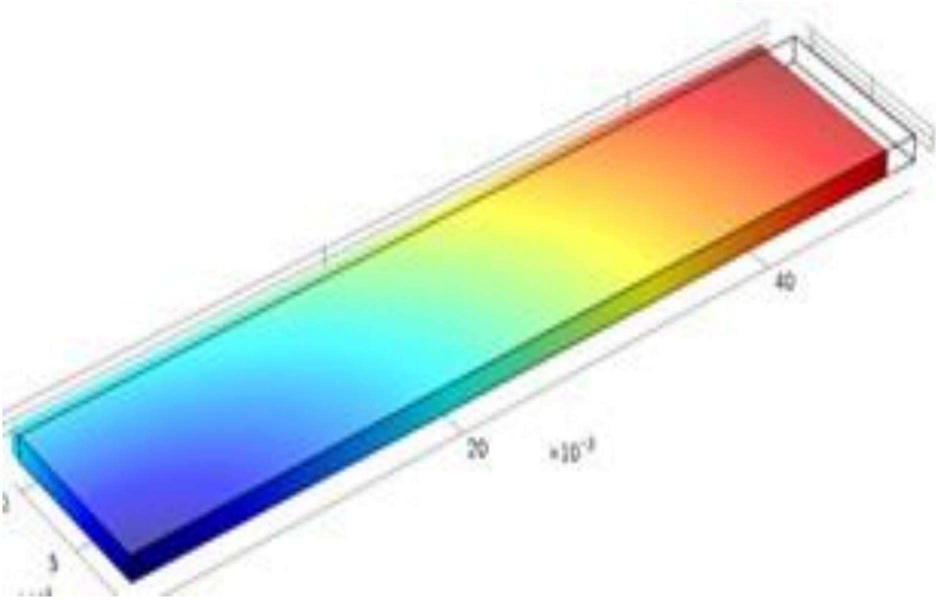

Fig.4.3. Unidirectional tension in the lateral direction of the PZT

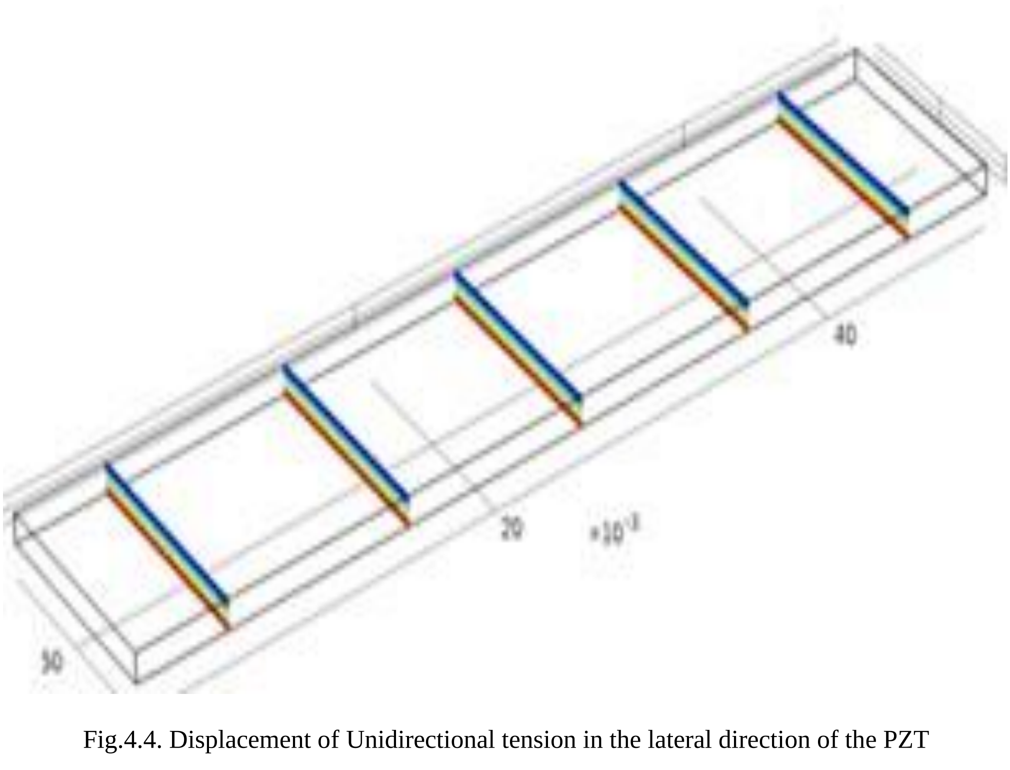

Fig.4.4. Displacement of Unidirectional tension in the lateral direction of the PZT

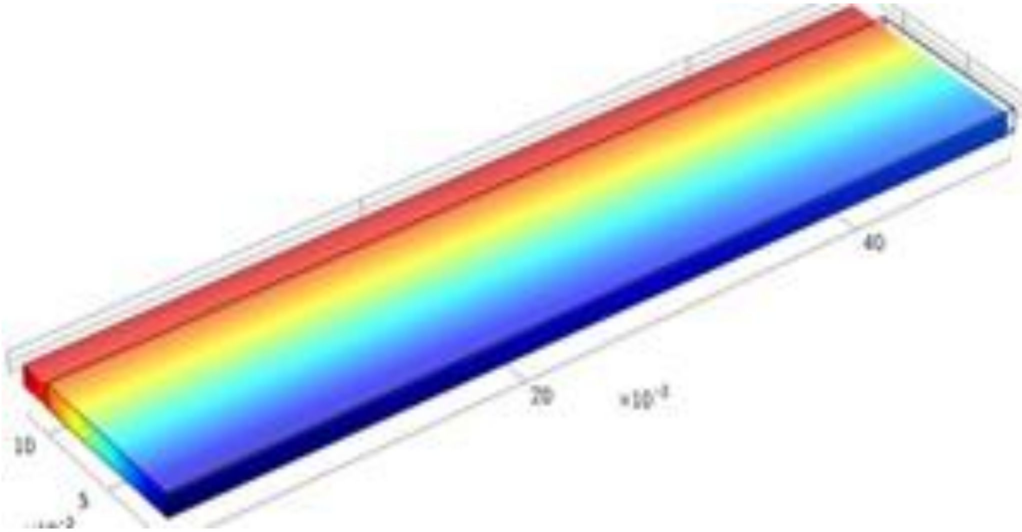

Fig.4.5. Uniform tension in all direction in a plane

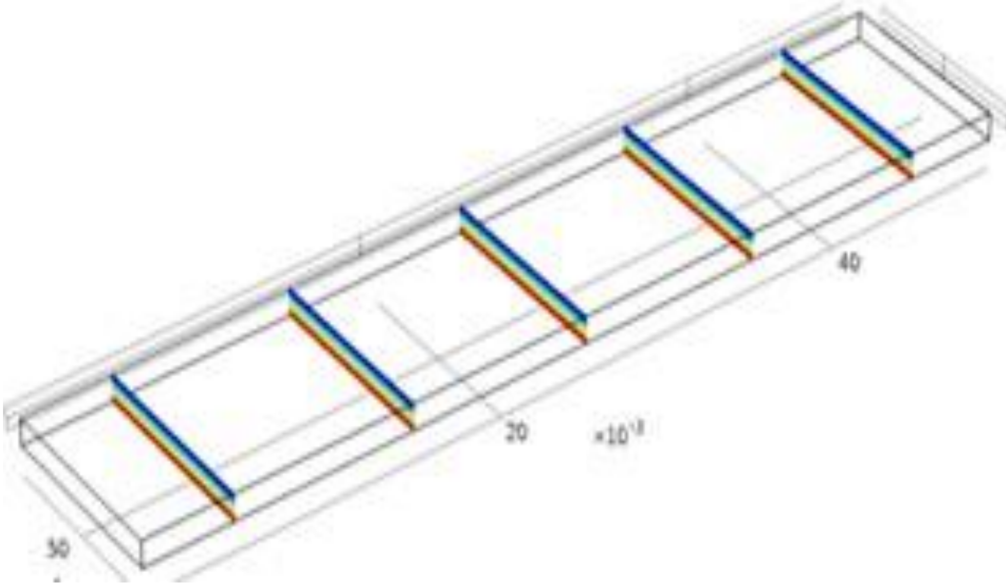

Fig.4.6. Displacement of Uniform tension in all direction in a plane

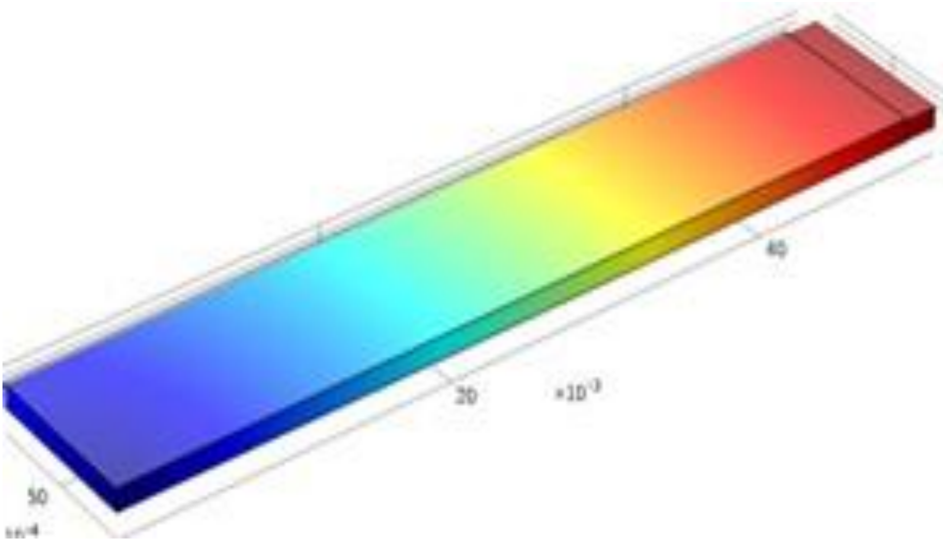

Fig.4.7. Tension in two perpendicular directions in a plane Sx=5 MPa, Sy=10 MPa

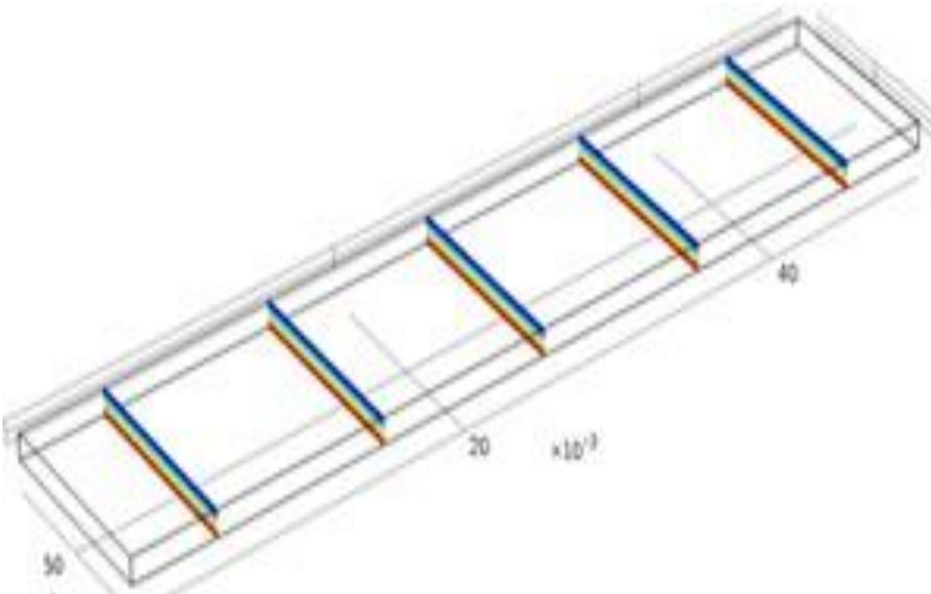

Fig.4.8. Displacement of Tension in two perpendicular directions in a plane Sx=5 MPa, Sy=10 MPa

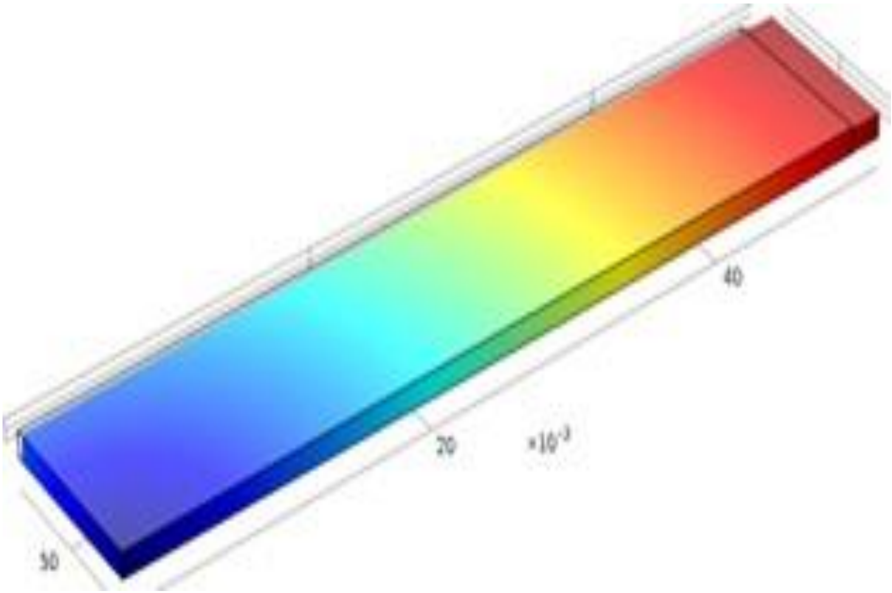

Fig.4.9. Pure shear (in terms of principal stresses Sx=5 MPa, Sy=-5 MPa)

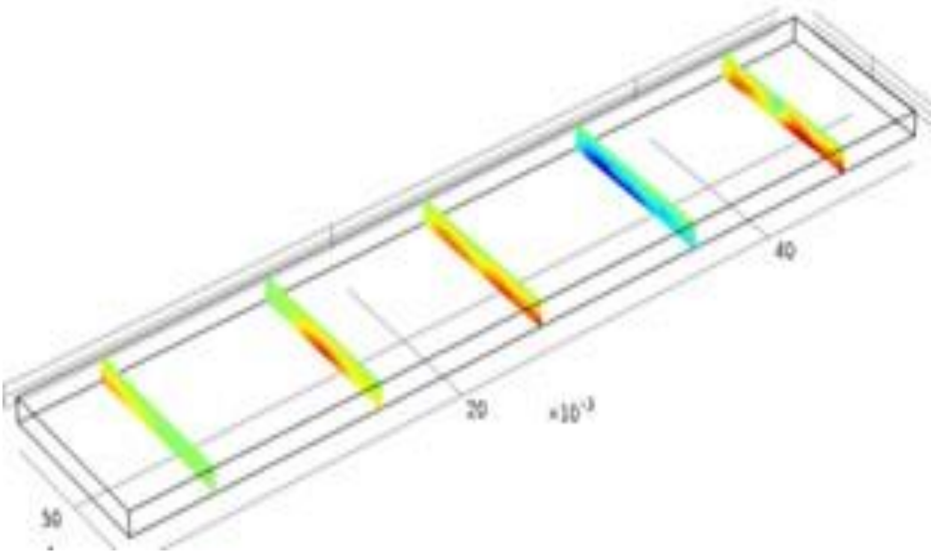

Fig.4.10. Displacement of pure shear

Table.5

Generalized information on the homogeneous stress state of the PZT

Type of plane stress state			Total displacement, mm	Potential, V
σ_x, MPa	$\sigma_{y,} MPa$	τ_{xy}, MPa		
5	0	0	0.0036	65.3
0	5	0	0.0020	65.3
5	-5	0	0.0056	0
5	5	0	0.0017	130.6
5	10	0	0.0006	196.0

4.2.3. Non-homogenous stress state of PZT

The lower plane of the sensor is constrained: displacement which perpendicular to this plane is equal to zero (w=0). The loading of sensor is executed by uniform tension (compression) of constraining plane. (Fig 4.11 – 4.18).

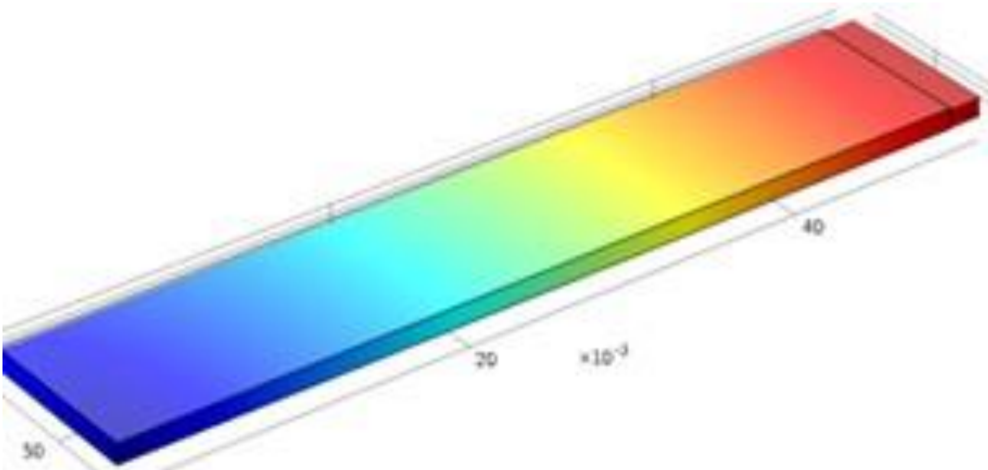

Fig.4.11. Unidirectional tension of the constraining plate in the longitudinal direction of the PZT

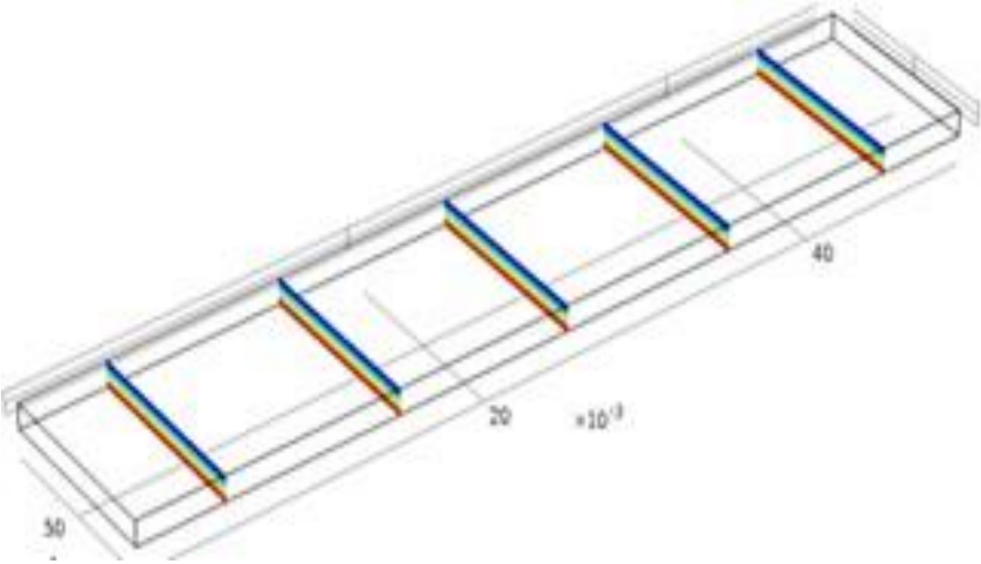

Fig.4.12. Displacement Unidirectional tension of the constraining plate in the longitudinal direction of the PZT

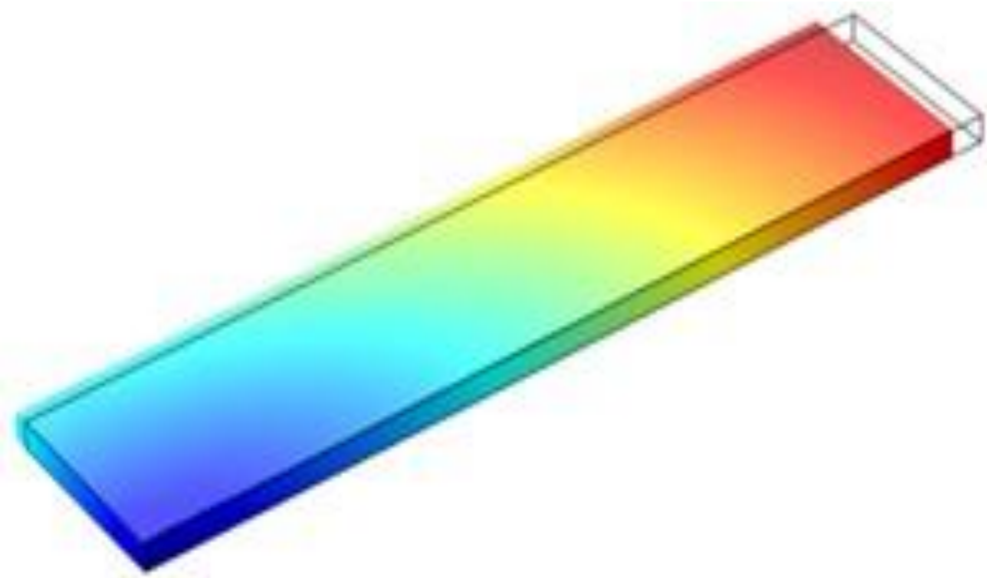

Fig.4.13. Unidirectional tension of the constraining plate in the lateral direction of the PZT

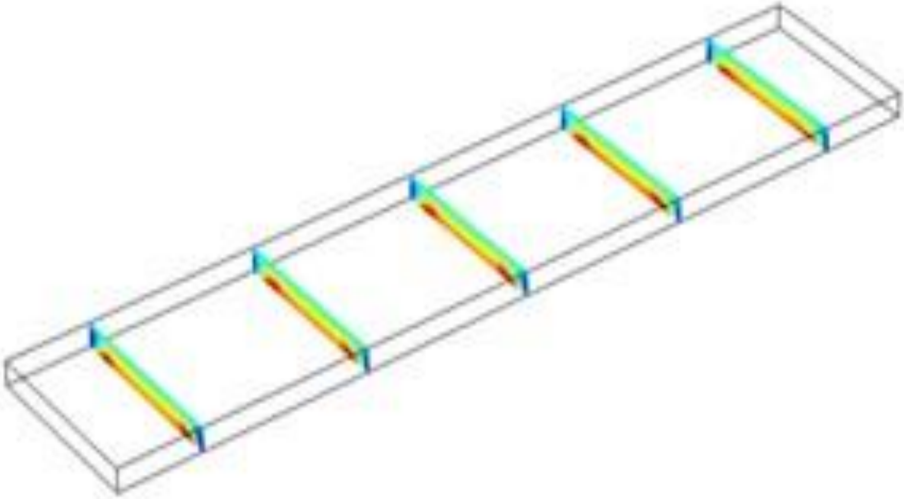

Fig.4.14. Displacement Unidirectional tension of the constraining plate in the lateral direction of the PZT

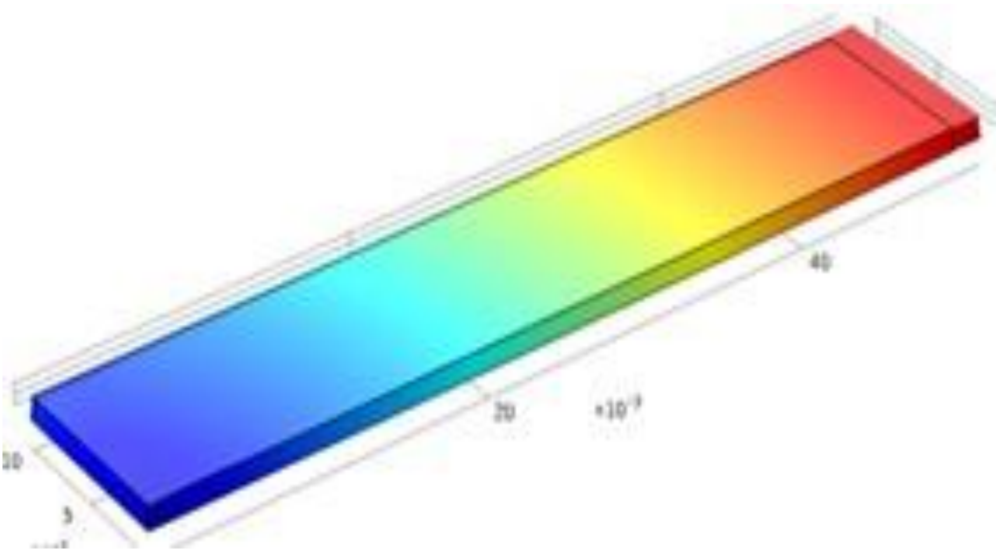

Fig.4.15. Uniform tension of the constraining plate in all direction in a plane

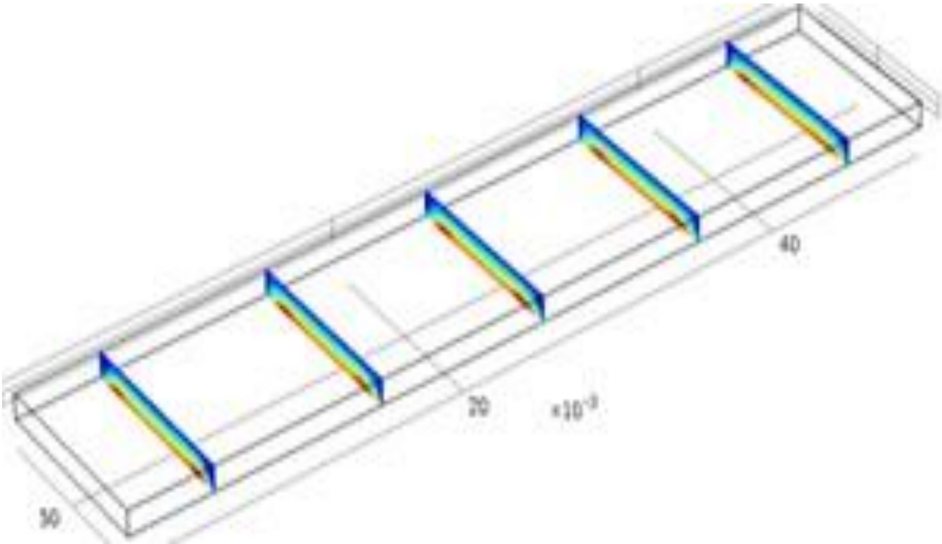

Fig.4.16. Displacement of Uniform tension of the constraining plate in all direction in a plane

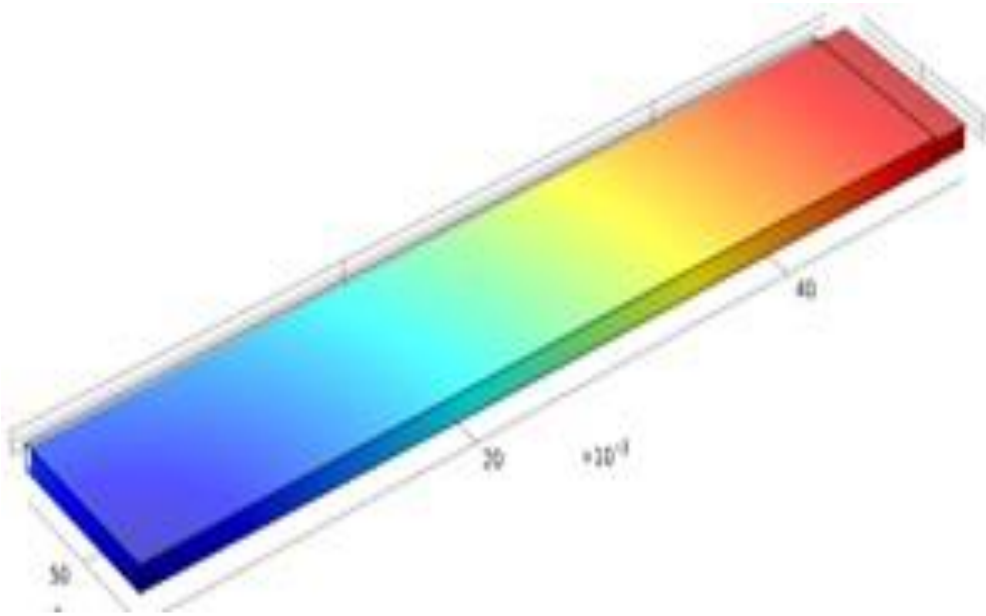

Fig.4.17. Pure shear of the constraining plate (in terms of principal stresses)

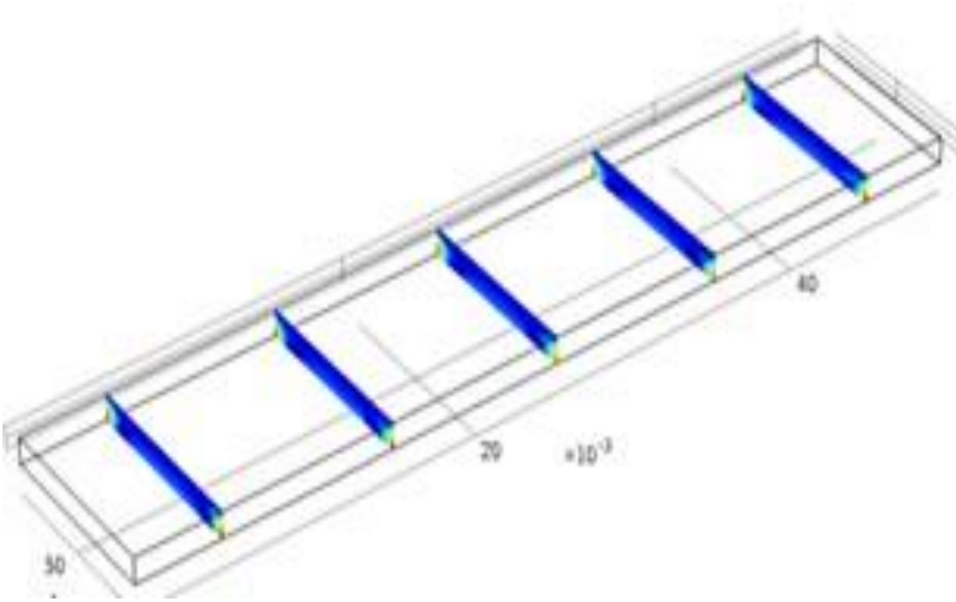

Fig.4.18. Displacement of Pure shear of the constraining plate (in terms of principal stresses)

Table.6

Effect of the PZT stress state type to its electrical potential

Type of plane stress state			Potential, V		
σ_x, MPa	$\sigma_{y,} MPa$	τ_{xy}, MPa	Homogeneous stress state	Non-homogeneous stress state	
				Boundaries	Volume
5	0	0	65.3	64.0	65.3
0	5	0	65.3	59.1	65.3
5	-5	0	0	20.7	20.4
5	5	0	130.6	114.6	122.1
5	10	0	196.0	151.7	138.7

It is shown that:

1) The type of piezoelectric transducer (PZT) stress state (relation between components) significantly defines the induced electrical potential.
2) The value of electrical potential at quasi-static loading is mainly defined by increment of

surface.

3) The non-homogeneity of piezoelectric transducer (PZT) stress state weakly influences electrical potential. (Table 6)

4.2.4. The PZT embedded to thin-walled plate

In this subparagraph the effect of load typical transmission to the PZT PIC 151, 0.5x10x50mm (PI Piezoceramic) is simulated and analyzed. The rectangular Al-alloy sheet of 1.15x80x150mm is equipped by the PZT of 0.5x10x80 mm as it shown in (Fig.4.19) below. The PZT is attached to sheet by 0.25 mm layer of above-mentioned Epoxy Paste HYSOL EA 9309. 3NA QT SYSTEM.

Below are presented results of simulation for two different options of loading on this sample.

1) Imitation of tension on a sheet in test machine.

The upper and bottom edges are clamped and tension direct stress in cross-section of a plate is equal to 40 MPa. It is seen that the presence of PZT causes local bending of the sheet and complex loading of PZT (Fig.4.19).

The mean (in PZT volume) stress component $\sigma_y = 5.72\ MPa.$
The mean (in PZT volume) stress component $\sigma_x = -\ 5.05\ MPa.$

Considering symmetry of a structure about axis ‘x’ and ‘y’ can conclude that the stress state of a PZT is close to the pure shear. In this case, as shown above, the electric potential is relatively low and is equal to 3.81 V.

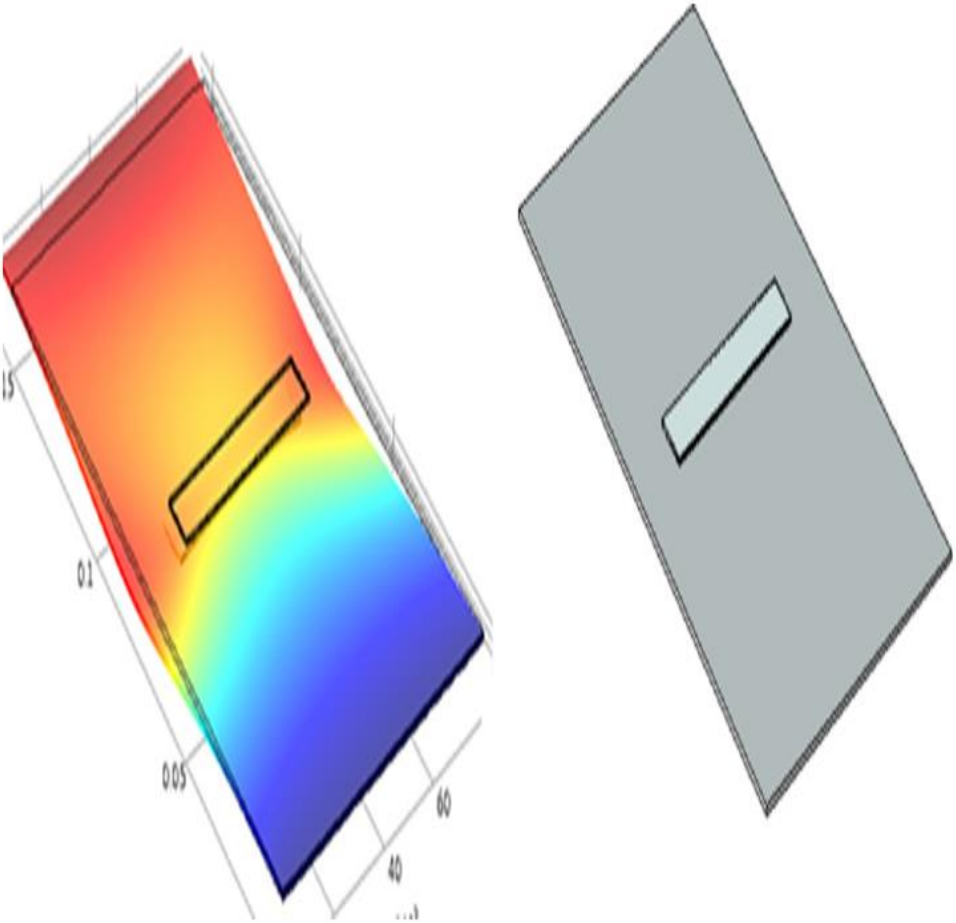

Fig.4.19. The Al plate with PZT at tension by stress 40 MPa

2) Two-directional tension. Imitation of in-plane loading of a skin of hermetic fuselage.

The boundary conditions at outer counter are set in displacements. The total elongation:

1. in axis x direction is equal to 0.0229 mm
2. in axis y direction is equal to 0.0852 mm

It is seen that a presence of PZT causes local bending of the sheet, but deflection is significantly less than at unidirectional tension (compare Fig.4.19 with 4.20).

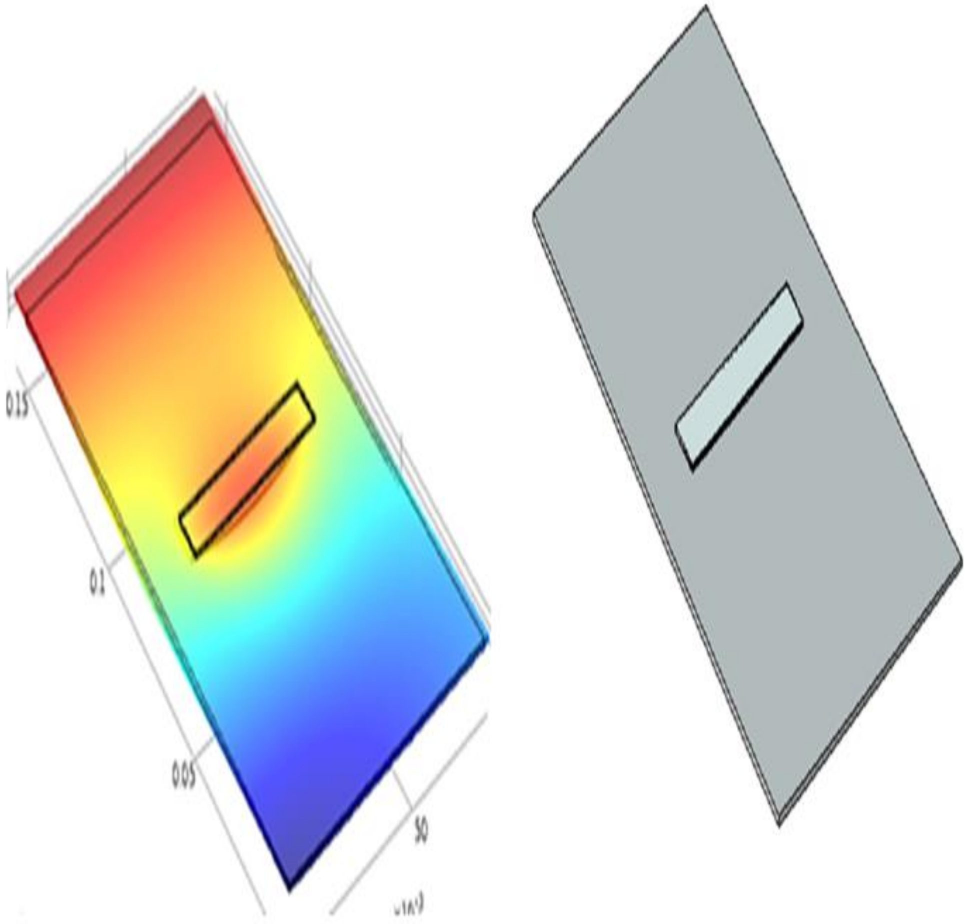

Fig.4.20. The Al plate with PZT at two-directional tension

Those displacement boundary conditions correspond to average boundary stresses:

1. for horizontal boundaries the stress component $\sigma_y = 54.7\ MPa$.
2. for vertical boundaries the stress component $\sigma_x = 35.5\ MPa$

The complex stress state of PZT is:

1. the mean (in PZT volume) stress component $\sigma_y = 6.99\ MPa$
2. the mean (in PZT volume) stress component $\sigma_x = 13.8\ MPa$

The electric potential is equal to 117.9 V.

4.3. Equivalent stress and fatigue limit

To enhance the longevity of aircraft and minimize defects, a study described in paper [41] employed

Using the finite element method (FEM), an aircraft's structure is evaluated for stress and its fatigue life is predicted. As internal pressure is one of the primary stresses placed on the fuselage, the FEM method was employed to evaluate the stress distribution throughout the aircraft structure. The objective of the stress analysis was to identify the area of the structure that was experiencing the most pressure. The fatigue life of the structure was then estimated by performing a local evaluation at the maximum stress point.
Fatigue loading refers to the type of loading that induces cyclic variations in applied stress or strain on a component. Therefore, any form of variable loading can be considered as a form of fatigue loading.[41]
Load monitoring is relevant for dynamically loaded structures, especially for metallic units of machines and mechanisms. This is caused by the effect of fatigue which is produced by alternative long-time-acting load and expressed in the fatigue cracks initiation. When it comes to structural deterioration, cracks are among the most concerning because induce progressive very significant decreasing of strength.
Airworthiness requirements allow fatigue cracks of the bearing components of aircraft in operation (the safe-fail principle) [60]. But the remaining structural strength cannot be less than an established minimum and structural health monitoring (SHM) system size should not cause the last one usually in operation.
Miner proposed the linear cumulative damages principle [61] to explain the phenomenon of cumulative damage occurring under repeated pressures. The quantity of energy consumed by a specimen's networks is assumed to be proportional to the amount of injury it sustains. By dividing the total number of loading cycles by the number of failure cycles at the specified stress level, the amount of usable life lost can be determined. The fatigue sample is predicted to fail when the cumulative damage reaches 100 percent, as specified by this concept. On an aluminum alloy, this concept was experimentally tested using a variety of specimen types, stress ratios, and loading cycle mixtures. When an S-N graph for a given stress ratio is available, the resulting data is analyzed to shed light on the behavior of the other ratios. The article contains a review of a subset of experiments. Using the concept of cumulative injury from fatigue enables a straightforward and conservative analysis, according to our findings.[61]
The results of a battery of experiments with varying amplitudes involving the Miner rule are summarized in [62]. Understanding how a material behaves within a structure under a variety of cyclic pressures over the duration of its service life is a significant topic of study [62]. To effectively manage fatigue-related issues, it is necessary to comprehend the fatigue mechanism within the component and how it can be altered by a variety of operational conditions. Throughout the design phase of any structure subject to dynamic loading, the effects of fatigue must be considered and mitigated. This includes not only the conception of the structure in terms of safety and cost, but also the management of minute details such as design, junctions, manufacturing methods, and material surface quality. In addition, the designer must make educated estimates regarding the fatigue resistance of the structure. Predictions in this field have inherent limitations and flaws; therefore, this task requires knowledge of the numerous causes of fatigue. When service fatigue becomes a problem, similar factors must be considered prior to taking corrective action. [62] The research reveals a wide range of values for the aggregate cumulative Miner summation at failure, ranging from values significantly less than 1 to values significantly greater than 1. As highlighted in the study [63], which introduced the concept of the true Miner rule, the improvement of fatigue longevity prediction requires test results under loads analogous to procedure.
It is known that Miner damage count significantly depends on a means of description of loading history [62-64]. The most popular is so-called is the rain flow counting method. [65] Similar method was proposed in [66].

4.3.1. The model of structural health assessment by use of load(stress) monitoring

The passenger aircraft operation process can be considered as some sequence of flights each of them can be estimated by two general parameters: the working time τ_i of flight number i and intensity of external load which there is estimated by the fatigue damage of this flight D_i . Both are random variables. Also, there is accepted the assumption that the load of all flights is statistically similar.
In the (Fig.4.21) the schematic structure of stresses in the skin of a wing panel is showed for two flights i and $i+1$. The blue line corresponds to the load which is recorded by the system of structural health monitoring (SHM). It is shown that difference between both general parameters of two sequential flights.

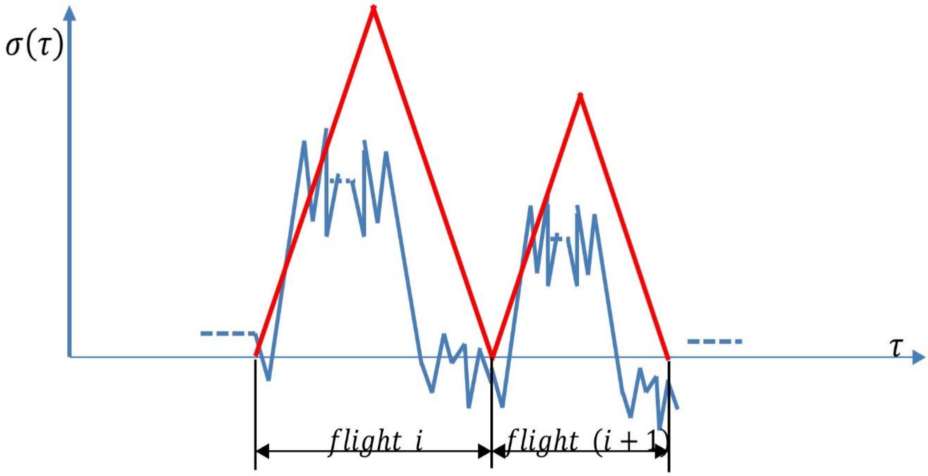

Fig.4.21. The schematic record of the skin stress by SHM system (blue) and equivalent cycle of stresses (red).

The Miner's count of separate flight D_i calculated by the rain flow counting method is used as the estimate of fatigue damage. (Eq 16)

$$D_i = \sum_{k=1}^{m} \frac{\tilde{n}_k}{N_f(\sigma_k)} \tag{16}$$

where σ_k is the level k of cyclic stress in the spectrum of flight i,
m is total number of levels of cyclic stresses in the spectrum of flight i,
$\tilde{n}_k$ is number of cycles of the level k in the spectrum of flight i,
$N_f(\sigma_k)$ is the fatigue lifetime of structural component at test with stress of level k.
Here is accepted that for considered structural component the full Wohler curve is the function between number of cycles N_f for the fatigue failure (fatigue lifetime) at action of cyclic load with maximum stress σ_f and stress ratio R (Eq 17)

$$F(\sigma_f, R, N_f) = 0 \tag{17}$$

There are several parameters of fatigue curve. For the full curve must also be the probability of failure.

For each flight the equivalent flight can be established: it is hypothetical flight in which all fatigue damage is produced by one cycle of loading. In the (Fig.6.22) the equivalent flights i and $i+1$ are represented in red line. The condition of equivalence in fatigue damages equality in real and equivalent flights (Eq 18) is:

$$D_i = \sum_{k=1}^{m} \frac{\tilde{n}_k}{N_f(\sigma_k)} = \frac{1}{N_f(\sigma_{ei})} \tag{18}$$

where σ_{ei} is equivalent stress of the flight i.

As a result, the damage index can be established as follows.

1. For the current number of flights N, the estimate of average equivalent stress should be calculated. (Eq 19)

$$\bar{\sigma}_e(N) = \frac{1}{N} \sum_{i=1}^{N} \sigma_{ei} \tag{19}$$

2. For the same N from fatigue life curve the fatigue resistance stress $\sigma_f(N)$ can be obtained (for example, mathematic expectation $\bar{\sigma}_f(N)$).

3. The convenient shape of damage index is:

$$in(N) = \frac{\bar{\sigma}_e(N)}{\bar{\sigma}_f(N)} \tag{20}$$

This index increases from 0 (before operation start) till 1 at (full consumption of fatigue life). (Eq 20)

At the use for index calculation mathematic expectations of comparable parameters, then the allowable value of index $[in]$ must be restricted using the reliability coefficient f. (Eq 21)

$$[in] = \frac{1}{f} \tag{21}$$

Example (1). Define the fatigue damage index of the structural component as a function of number of flights, if the fatigue lifetime curve is described by power function:

$$\sigma_f^{\alpha} N_f = C \tag{22}$$

where α and C are parameters of the fatigue lifetime curve of material, σ corresponds to maximum stress in cycle at constant stress ratio $R = 0$. Accept that the average equivalent stress at large number of cycles is stable and equal to 50 MPa. The parameters of the fatigue lifetime curve are $\alpha = 2$ and $C = 5 \cdot 10^5$. (Eq 22)

Easy to see that for this simple example:

$$in(N) = \frac{\bar{\sigma}_e(N)}{\left(\frac{C}{N}\right)^{\frac{1}{\alpha}}} \tag{23}$$

Results of calculation are presented in the (Fig.4.22). The allowable value of index $[in]$ is defined using $f = 1.5$. (Eq 23)

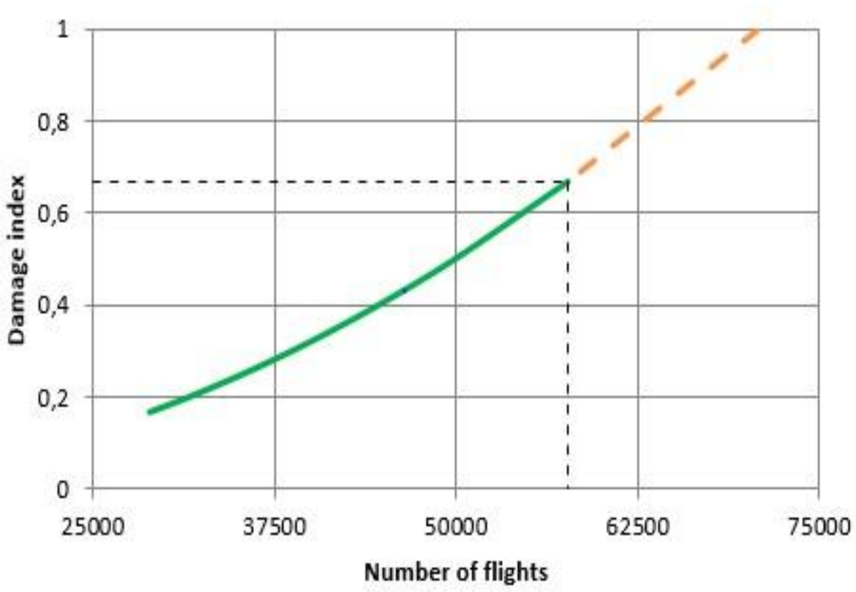

Fig.4.22. Damage index as the function of number of flights

The probabilistic approach of construction of fatigue damage index is analyzed in our paper [37] and presented in the next paragraph.

4.4. Probabilistic model of strength for SHM of lifetime usage load monitoring

The authors of article [58] propose a new framework for structural health monitoring (SHM) of aircraft structures based on dynamic probability analysis. This framework provides a modular organizational structure for the development of SHM algorithms applicable to aircraft constructions. The system employs twin probability models as long- and short-term dynamic modifications to the models to reliably monitor damage under changing temporal conditions, which is the approach's primary challenge. It is proposed that an adaptive construction strategy based on Gaussian combination models will provide potent SHM capabilities within the framework. By quantifying the degree of similarity between models as they are continuously updated, this method enables frequent and rapid detection of damage without compromising the stability of the probability models employed. The framework is validated utilizing guided wave-based monitoring of structural health systems in conjunction with full-scale aircraft fatigue assessments that simulate in-flight conditions on the ground. [58]

1) Retrieval and damage monitoring are essential components of every structural health monitoring (SHM) procedure, regardless of SHM methodology or application method. This fact remains the foundation of the framework, but its defining characteristic is the dynamic dual probability model design that takes into consideration both the time-varying nature of the issue and the fluctuating

requirements of operational applications.

2) The design of the framework consists of only four construction components, six strategies, and three information connections. The framework is simple and uncomplicated, making it suitable for the implementation of the vast majority of structural health monitoring (SHM) techniques. It may aid those developing SHM systems in experimenting with various techniques to enhance the dependability and reliability of the resultant SHM methods.[58]
The aircraft SHM concept is intended to have a scalable hierarchical structure, as shown in (Fig4.23). The blocks are exemplary structural functional components. Block 1 represents the dynamic base probabilities model, while Block 2 represents the dynamic monitoring of probability concept. SHM data, DMFs, feature spaces, and probability models all contribute to the data development procedure that establishes the two blocks. Block 3 of the damage monitoring process consists of identifying and assessing damage using the disparity between the two probability frameworks. The combination of the three modules provides the core SHM functionality. Block 4 is a SHM database used to modify the original probability models over time.[58]

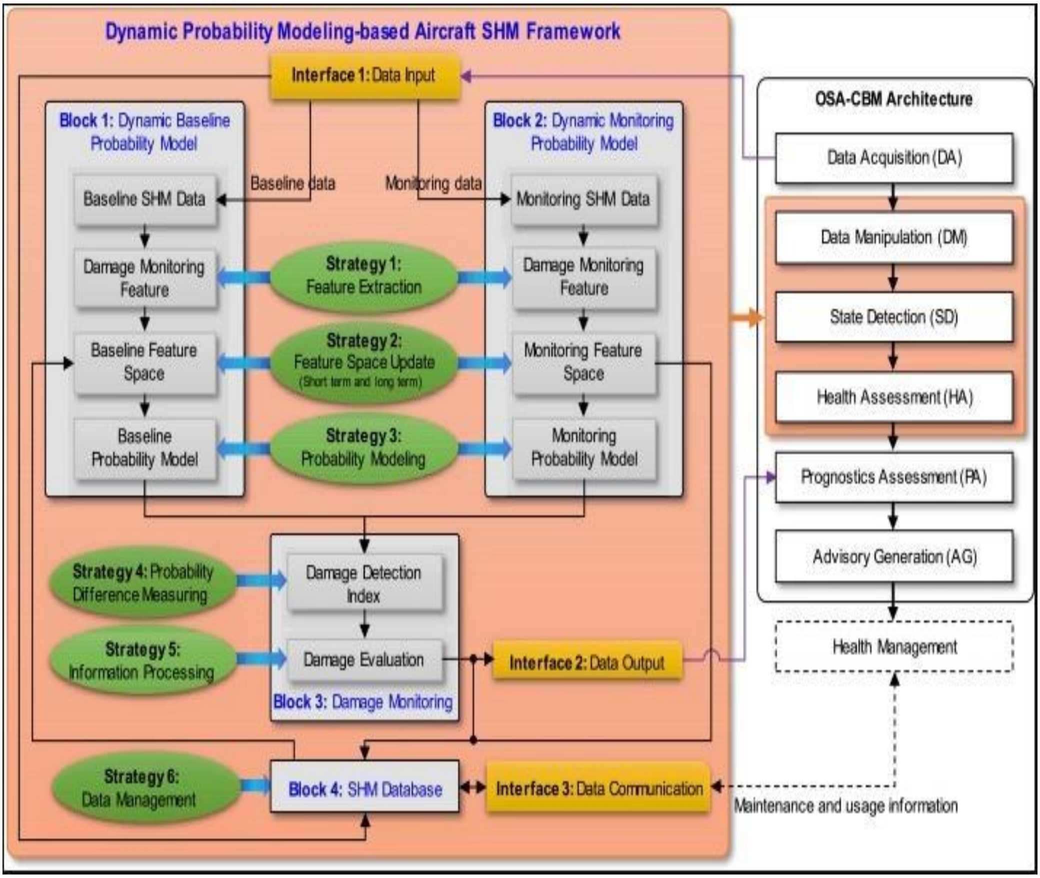

Fig4.23. Dynamic probability modeling-based aircraft SHM framework [58]

Dynamic Probability Modeling (DPM) is a statistical method used to predict the probability of a failure or a fault in a mechanical or structural system, such as an aircraft It is a method of prognostic

health surveillance that employs quantitative modeling and evaluation to extrapolate information about the system's anticipated future behavior.
SHM, or structural health monitoring, is the practice of constantly monitoring an aircraft's framework and subsystems for indications of wear and tear. SHM can estimate the remaining service life of an aircraft by employing multiple sensing technologies to detect alterations in structural integrity and performance.
Dynamic Probability Modeling (DPM) and SHM (structural health monitoring) data can be combined in order to estimate the likelihood of a failure or defect in an aircraft. Utilizing a variety of sensors, such as vibration detectors, strain gauges, and temperature gauges, to collect information about the aircraft's performance is frequently required for the structure.
Using Bayesian models and other probabilistic estimation and evaluation tools, sensor data are used to calculate the likelihood of an aircraft failure. With the aid of predictions, service and repair plans can be optimized, resulting in less downtime and fewer calamities or calamitous failures.
Aircraft concept of structural health monitoring (SH frameworks based on Dynamic Stochastic Estimation offer a number of advantages. By anticipating and forecasting likely defects, proactive inspection and repair may decrease downtime and increase the likelihood of disasters or catastrophic failures. It may also help reduce repair costs and improve aircraft maintenance schedules, all of which contribute to an extended aircraft lifespan.
In summary, a framework for Aircraft Structural Health Monitoring (SHM) based on Dynamic Probability Modeling is a powerful tool for predicting the probability of failure or fault in an aircraft. By continuously monitoring the aircraft and analyzing the data using statistical modeling and analysis techniques, it is possible to optimize maintenance schedules and repair efforts, reducing downtime and minimizing the risk of accidents or catastrophic failures.

4.4.1. On the Health and Usage Monitoring System (HUMS)

The data collected through Health and Usage Monitoring (HUM) can be used to schedule maintenance and repairs more effectively, allowing for more efficient use of resources and reduced downtime. Health and Usage Monitoring (HUM) can also be used to optimize equipment performance by identifying areas where improvements can be made, such as through changes to operational procedures or the use of different materials.
Health and Usage Monitoring (HUMS) can be used to detect potential problems before they become serious enough to cause an accident, and it can also be used to optimize aircraft maintenance schedules, leading to significant cost savings.
Using a system known as a Health and Usage Monitoring Unit (HUMS), helicopters are able to monitor critical systems and components. Its purpose is to identify developing problems or warning indications of potential problems so that they can be resolved prior to having a significant impact on functional safety. PCMCIA (Personal Computer Memory Card International Association) equipment for recording and storing data are an integral element of the system. This data may be transferred to a computer on the ground for the purpose of analyzing maintenance requirements. Airworthiness concerns prompted the introduction of HUMS in the early 1990s, and since then, the system has played a crucial role in augmenting aviation safety and dependability [35]. A HUMS system typically consists of detectors mounted at various locations on an aircraft's framework. Trend analysis of stored data is necessary for identifying problems and determining whether they require correction [35].
Health and Usage Monitoring Systems (HUMS) may collect numerous types of data. Standard operating metrics collected by fundamental systems include takeoffs, landings, engine starts, pulley lifts, and a certain quantity of engine and transmission health data. Modern systems, on the other hand, can monitor everything that rotates, from the engine to its transmission to the drive shaft to the fans and rotors. These systems record the operational configuration of occurrences, allowing maintenance teams to conduct a comprehensive analysis of trends and condition-based, preventative maintenance. Modern HUMS systems collect data that can be utilized either on board an aircraft or

at the base station, providing invaluable versatility. Some systems even permit real-time data transmission via satellite connection while in flight, enabling control and maintenance units to strategically plan for post-flight delay reduction. In addition, these infrastructures can be configured to immediately notify administrators and producers of any abnormal or emergency situation. In the linked article, Health and Usage Monitoring Systems (HUMS) are described in greater detail.[35]

The framework's vibration health monitoring is a crucial component of any HUMs system. Accidents involving helicopters have decreased dramatically, according to statistics and studies. Consequently, the U.K. Civil Aviation Authority (CAA) mandated the use of Health and Usage Monitoring (HUMS) (CAP 753) on all aircraft with nine or more passengers, continuing the trend established by the previous mandate. In addition, research indicates that these types of systems have effectively identified approximately 70 percent of failure modes associated with the components and variables they were designed to monitor. [36]

The benefits of Prognostic Health Monitoring (PHM) are numerous. By predicting and anticipating potential failures, it allows for proactive maintenance and repair, which can reduce downtime and minimize the risk of accidents or catastrophic failures. Prognostic Health Monitoring (PHM) can also help to increase the life of equipment and machinery, reduce repair costs, and optimize maintenance schedules.

The objective of prognostic health monitoring (PHM) is to detect and diagnose system or equipment problems before they become catastrophic malfunctions. In conjunction with sensors and mathematical techniques, machine learning algorithms are used to predict future outcomes and anticipate probable errors. Prognostic Health Monitoring (PHM) is advantageous for a variety of systems because it aids in avoiding risks, minimizing delay, and optimizing maintenance efficiency. Using data from regenerated vibration signals, the earliest phases of failure or degradation in mechanical integrity can be determined. The result of applying algorithms to the analyzed data is a singular number that indicates the overall health of various failure categories. In terms of vibration health monitoring (VHM), the most significant metrics are those that immediately trigger alarms. Nevertheless, additional Vibration Health Monitoring (VHM) indicators are not suited for immediate alerting applications and are instead used for analysis after an alarm has been generated. [36]

The basic principle of Vibration Health Monitoring (VHM) is that machines generate specific vibration patterns or signatures as they operate. These vibration patterns are influenced by various factors, including machine speed, load, bearing wear, and other mechanical factors. By monitoring these vibration patterns, it is possible to detect changes in the machine's performance and diagnose faults or defects before they lead to failure.

Vibration Health Monitoring (VHM) typically involves the use of vibration sensors and analysis software to monitor and interpret the vibration patterns generated by the machine. Vibration sensors can be attached to the machine at critical locations to capture the vibration data. The data is then analyzed using advanced software that can identify specific patterns and trends, detect anomalies, and diagnose potential faults.

The benefits of Vibration Health Monitoring (VHM) are numerous. By detecting and diagnosing potential faults in machines, it is possible to perform maintenance and repair activities proactively, reducing downtime and minimizing the risk of catastrophic failures. Vibration Health Monitoring (VHM) can also help to extend the life of machines, reduce repair costs, and optimize maintenance schedules.

Vibration monitoring systems can track the health of machines and mechanical parts by analyzing the patterns of vibrations they create. With the help of VHM, preventative maintenance and repairs may be carried out ahead of schedule, downtime can be reduced, and catastrophic failures can be prevented. Industries as varied as manufacturing, transportation, and power production all use vibration health monitoring (VHM).

The technique works by recording and processing in-flight data on the vibration parameters of critical spinning components. By analyzing vibration data, Vibration Health Monitoring (VHM) systems may offer warnings about impending component failure or unsafe operating conditions. A vibration health monitoring (VHM) system can keep tabs on a wide variety of mechanical assemblies and parts, including the engine, transmissions, gears, shafts, bearings, oil cooler, main and tail rotors, and the connecting shaft between the engine and the main gearbox's feedback drive shafts. [36]

4.4.2. Mathematical Model

System operations and attendant random variables all conform to the Gaussian distribution. The Gaussian distribution, also known as the normal distribution, is a continuous probability distribution that is symmetrical about its mean. It is a linear distribution because it follows the linear combination of its mean and standard deviation. However, it is important to note that the term "linear" in this context does not refer to a linear relationship between variables, as it would in the case of linear regression, for example. Instead, it refers to the linearity of the mathematical operations involved in calculating the distribution.
A Gaussian distribution, also known as a normal distribution, is a type of probability distribution that is continuous and has a bell-shaped curve. It is a linear distribution because it follows a linear equation, specifically the equation for a normal density function. The equation is linear with respect to the parameters of the distribution, such as the mean and standard deviation.
However, when we talk about linear or nonlinear, it is usually in the context of relationships between variables. In this case, the Gaussian distribution is not inherently linear or nonlinear because it does not represent a relationship between variables. It describes the distribution of a single variable. (Eq 24) Assuming that this is true for the random variables $\Delta\sigma$ and $\delta\sigma$, expressions will be as follows:

$$P_{fa} = \frac{1}{2\pi}\int_{-\infty}^{\sigma_{pl}-m_\sigma}\frac{1}{s_1}e^{-\frac{(\Delta\sigma-m_\sigma)^2}{2s_1^2}}\int_{\sigma_{pv}-m_\sigma-\Delta\sigma}^{+\infty}e^{-\frac{(\delta\sigma)^2}{2s_2^2}}\,d\delta\sigma d\Delta\sigma \qquad (24)$$

$$P_{pv} = \frac{1}{2\pi}\int_{\sigma_{pv}-m_\sigma}^{+\infty}\frac{1}{s_1}e^{-\frac{(\Delta\sigma-m_\sigma)^2}{2S_1^2}}\int_{-\infty}^{\sigma_{pv}-m_\sigma-\Delta\sigma}\frac{1}{s_2}\,d\delta\sigma d\Delta\sigma \qquad (25)$$

where S1 and S2 represent the mean square deviation of the values $\Delta\sigma$ and $\delta\sigma$.
For the convenience of the numerical integration of equations (24) and (25), let us change the variables by analogy with a similar probabilistic task solution described in the book [51]. Here we will introduce new variables. (Eq 26, 27)

$$y_1 = \frac{\Delta\sigma - m_\sigma}{S_1} \text{ And } y_2 = \frac{\delta\sigma}{S_2} \qquad (26)$$

And designate parameters $c = \frac{\sigma_{pv}-m_\sigma}{S_1}$ (27)

Then, expressions (24) and (25) will be as follows:

$$P_{fa} = \frac{1}{2\pi}\int_{-\infty}^{c}e^{-\frac{y_1^2}{2}}\int_{b-ay_1}^{+\infty}e^{-\frac{y_2^2}{2}}\,dy_2 dy_2 \qquad (28)$$

$$P_{pv} = \frac{1}{2\pi}\int_{c}^{+\infty} e^{-\frac{y_1^2}{2}} \int_{-\infty}^{b-ay_1} e^{-\frac{y_2^2}{2}} dy_2 dy_1 \qquad (29)$$

Where, $a = \frac{S_1}{S_2}$, $b = \frac{\sigma_{pv}^{i} - m_{\sigma}}{S_2}$

The result of solving the system of equations (28) and (29), obtained by using the well-known numerical methods, is given in (Fig.6.24) in the form of nomograph for the parameters a, b, and c.

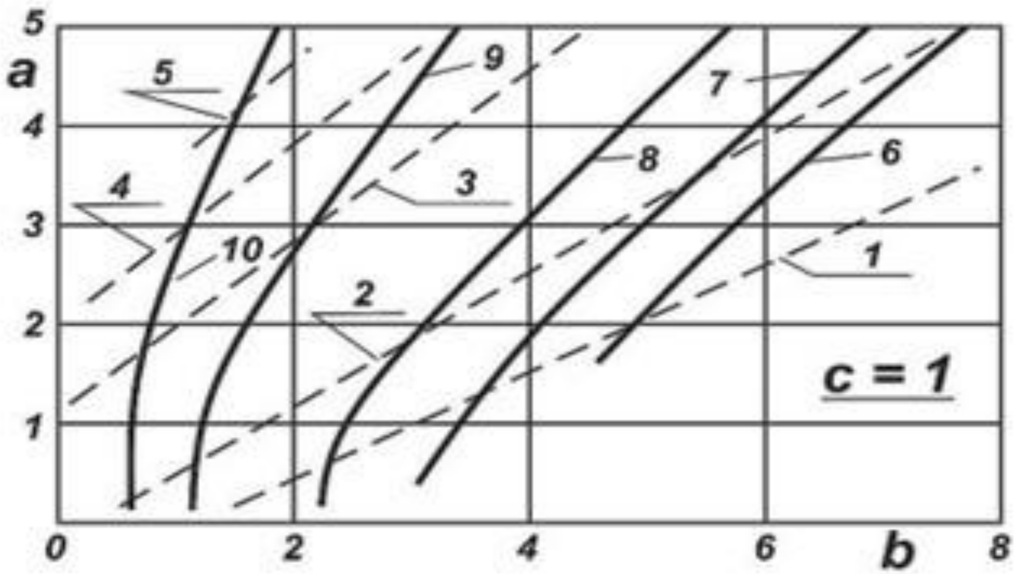

Fig.4.24. Nomograph for determining the parameters a, b and c:

The probability of omitting a dangerous situation with disastrous effects (1- Ppv=1.5 ·10-1; 2- Ppv=10-1; 3- Ppv=10-2; 4- Ppv=10-3; 5- Ppv=10-4).

The probability of the false actuation of the display system
(6- Pfa=10-4; 7- Pfa=10-3; 8- Pfa=10-2; 9- Pfa=10-1;10- Pfa=2 ·10-1).

As we can see from (Fig.4.24), at the given probabilities P_{fa} and P_{pv}, as well as at the parameters of the distributions of the random variables m_{σ}, S_1 and S_2, and at the given value σ_{pv},, the value of the limit parameter σ^{ι}_{pv} can be determined.

4.4.3. Conclusion of probabilistic model

1. Thus, it is possible to solve the problem of the proper determination of the maximum allowable parameter or diagnostic sign for indication in the cockpit when the predetermined limit of its actual value is known in advance.
2. It should be noted that the above-mentioned method can be used not only for determining the limiting values for critical parameters requiring indication in the cockpit.

3. The measurement procedure is always used to obtain reliable information for each diagnostic sign, so, accordingly, a record of unavoidable errors of measurement for each diagnostic sign is also required.
4. Thus, a decision about exceeding or not exceeding its limiting values should be made also considering the upper (or lower) tolerance of the limit condition range $\Omega^{\iota}_{tol,}$, the limits of which can be determined by the method stated above.

4.5. Acoustic emission as passive methods of ultrasound techniques

Acoustic emission (AE) is a passive ultrasonic technique used in structural health monitoring (SHM) to measure the discharge energy from a material as a consequence of a fracture, deformation, or other types of injury. It is a diagnostic method that causes no harm and requires no external stimulation.

In AE, ultrasonic measurement instruments are attached to the exterior of the monitored structure. During stress or deformation, the material itself generates high-frequency stress waves, which are detected by the sensors. Rapid energy release at the site of injury generates stress waves that are detectable and evaluable by sensors. Transducers are calibrated to specific frequency regions in acoustic emission (AE) to identify the type of injury. For instance, damage in ductile materials can be detected with low-frequency sensors, whereas damage in brittle materials requires a sensor with a higher frequency.

Unlike other ultrasonic monitoring techniques, AE does not require the application of an external energy source to the investigated object. This technology is optimal for the long-term, continuous monitoring of structures, as there is no risk of causing additional harm to the structure during the monitoring process.

However, one potential drawback of AE is that it is not always simple to identify the type of injury based merely on the frequency spectrum of the stress waves. In addition, trained analysts are required to decipher the AE sensors' data and correctly classify the numerous types of damage.

Acoustic Emission (AE) may be utilized as a Prognostic Health Monitoring (PHM) instrument in order to anticipate and locate potential problems in mechanical and structural systems. AE is a passive ultrasonic technique that detects the energy released by a material as a consequence of a fracture, deformation, or other injury. Consequently, AE may be a useful method for monitoring the condition of mechanical systems such as aircraft and other essential apparatus.

The use of AE as a PHM technique involves the continuous monitoring of AE signals from sensors placed on or within the system being monitored. The sensors can be used to detect high-frequency stress waves generated by the system when it undergoes stress or deformation. These stress waves can be caused by the rapid release of energy at the site of the damage, which can be detected and analyzed by sensors. By continuously monitoring AE signals, it is possible to identify patterns and trends that may be indicative of future failures or problems.

Machine learning algorithms can be applied to the data collected from AE sensors to develop models that can predict future performance and anticipate potential failures. These models can then be used to optimize maintenance schedules and repair efforts, reducing downtime, and minimizing the risk of accidents or catastrophic failures.

The benefits of using AE as a PHM technique are numerous. By predicting and anticipating potential failures, it allows for proactive maintenance and repair, which can reduce downtime and minimize the risk of accidents or catastrophic failures. AE can also help to extend the life of equipment and machinery, reduce repair costs, and optimize maintenance schedules.

AE can be used as a Prognostic Health Monitoring technique to predict and detect potential failures in mechanical and structural systems. By continuously monitoring AE signals and using machine learning algorithms to develop predictive models, it is possible to optimize maintenance schedules and repair efforts, reducing downtime and minimizing the risk of accidents or catastrophic failures.

Using acoustic emission (AE) for structural health monitoring (SHM) is a prospective new area of study. Due to the fact that it is both sensitive and non-intrusive, it can be used to monitor a building in real time and capture information that would otherwise be inaccessible. AE depends on the ability to detect and analyze elastic vibrations caused by events such as the initiation and propagation of fractures within a material. In order to understand the origins and characteristics of these signals, sensors are used to detect and convert them into electrical pulses. [59]

AE is a beneficial instrument for the laboratory-based development of materials across multiple platforms. Periodically or continuously, it can be used to evaluate the degradation condition of materials and structures in real time. Compared to other monitoring technologies, the advantages of AE for evaluating the quality of building materials and structures are obvious. In addition to identifying various varieties of failure using recorded waveforms, the instrument's high sensitivity enables the identification of the precise onset of micro-cracking. AE allows for the localization of sources in one, two, or all three dimensions. [59]

Investigations of acoustic emission (AE) rely significantly on source localization. Utilizing numerous detectors, precise localization of active sources within defined boundaries in one, two, or all three dimensions is possible through the application of efficient engineering. This enables the approximate location of a fracture to be determined, even if it is concealed within an unobservable substance. The primary basis for localization is the detection of successive impulses from a single source event at distinct detectors. Moreover, the source's precise location can be determined by measuring the pace of wave transmission through the material using the same sensors. However, the existence of multiple wave transmission modes may muddle the waters when evaluating plate-like aircraft structures. However, there are available methods for overcoming these obstacles. [59]

This chapter intends to present recent trends and applications of AE as passive methods for damage detection technique for helicopter structures.[59]

Evaluations of helicopter structural integrity must take service life into account. Numerous structural components, the majority of which have a finite service life, contribute significantly to flight safety. These components consist of the main gear-reducer, the sub-reducer, the tail reducer, the main and tail shafts, and the numerous structural components of the rotor blades. Due to their direct impact on the helicopter's dependability and safety, these components require constant monitoring and evaluation. [38]

One of the most effective methods to extend the life of a helicopter is to increase the durability of its wearable components so that they last as long as the aircraft itself. Accurate information on the loading of these limiting components during normal flight operations, as well as the results of full-scale model testing and a strength analysis, are required to effectively extend their service life. Due to the current scarcity of suitable materials, extensive full-scale testing in controlled environments is required to determine their flight reliability values. The collected data may be used in subsequent calculations to evaluate the structural components' short-term strength and durability. The results of these computations should be compiled into a final report detailing the justifiability of the service life extension.

Fatigue testing is a crucial part of the design procedure to make sure the tail beams and fin are durable and that the mid reducers are securely affixed in their designated locations. [38]

Based on the test results, the following actions should be taken:

1. Determine the value of the technical lifetime: This refers to the period during which it is economically viable to operate the helicopter's planar components, considering economic considerations.
2. Establish the duration of operation until the first maintenance or observation: Specify the length of time the helicopter can operate before requiring initial maintenance or inspection.
3. Define the duration of maintenance work: Determine the amount of time required to perform maintenance tasks to make sure the helicopters are safe operation.
4. Define the appropriate parameters for operational loads: Determine the loadings that the helicopter's components can withstand within a specific period, considering the presence of fatigue cracks in the construction.

It should be noted that addressing these tasks solely through isolated "stand" testing of individual parts (reducers, engine, etc.) is not sufficient due to it does not considering the influence of adjacent components. Therefore, it is necessary to subject planar constructions to loading in a way that each zone experiences an indicated load. Fatigue testing is conducted on the helicopter's planar components to ensure their durability and performance. (Fig.4.25). [38]

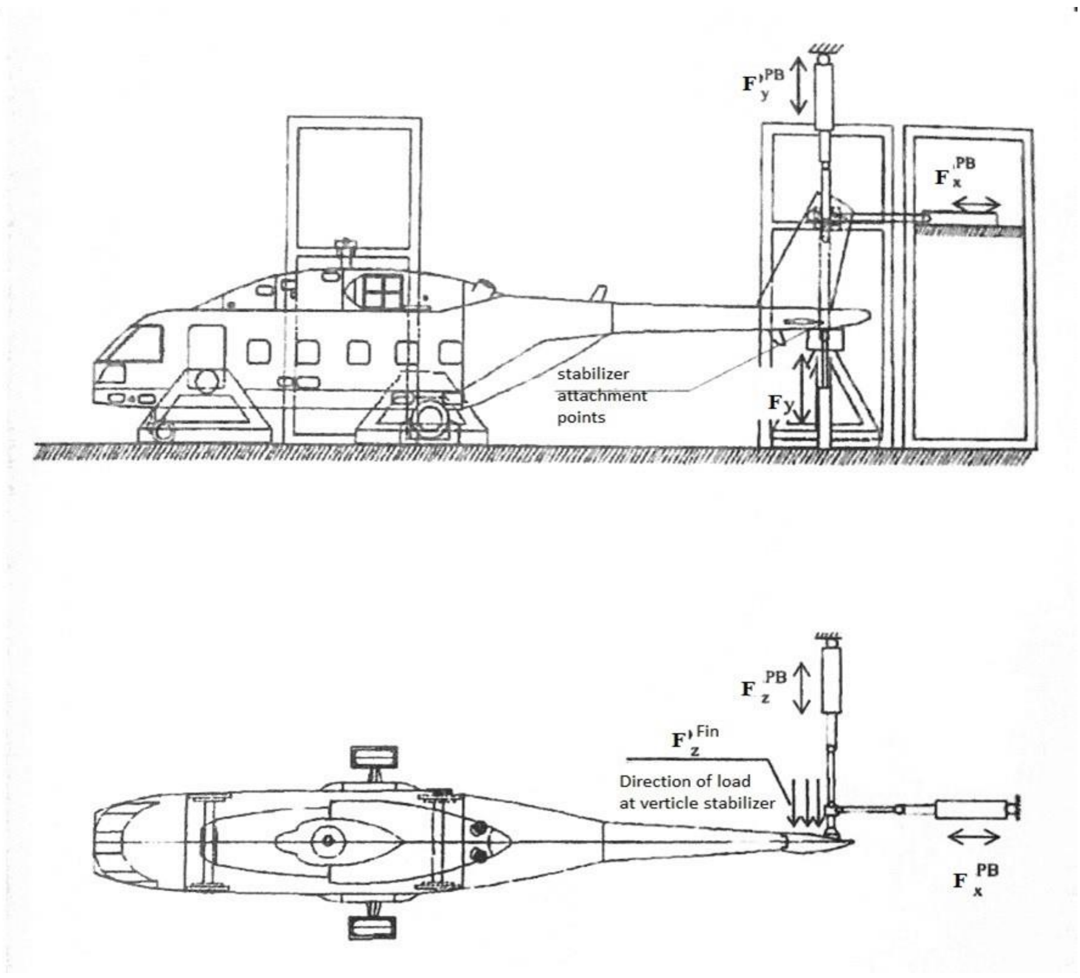

Fig.4.25. Model of experimental stand for testing of fatigue life of tail beam and vertical stabilizer of helicopter. [38]

“The co-ordinate system used in this experiment is shown in the (Fig.4.26)
X axis is aligned to flying direction (it is in the middle of the fuselage)
Y axis id perpendicular to X axis and is oriented up
X and Y axis are in the middle of the fuselage (narrow plane)
Z axis is perpendicular to XY plane
The zero point of coordinate system is located on X axis, where it is being crossed by power frame.

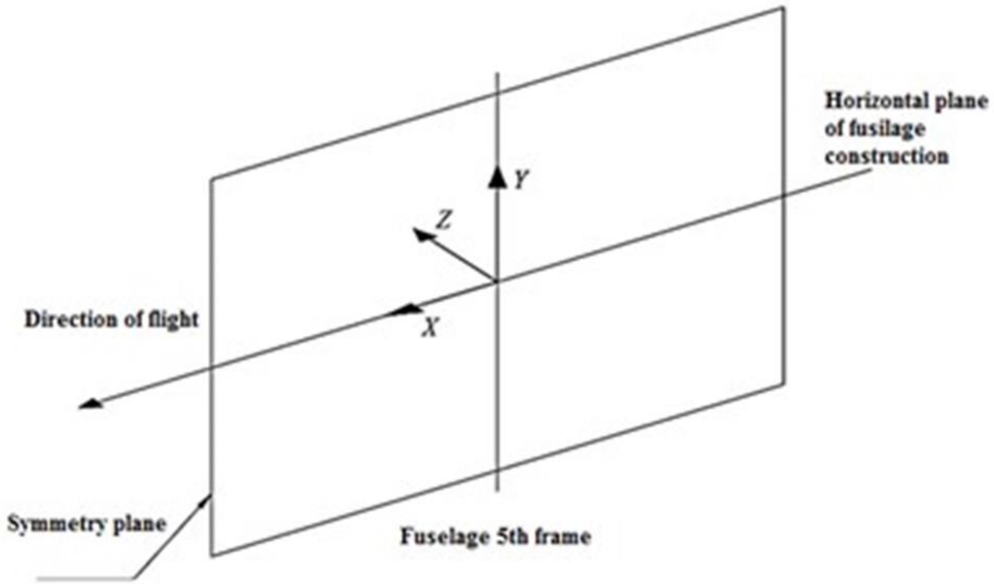

Fig.4.26. Defined system of Co-ordinates [38]

All measuring equipment must be certified and must have a proper precise rate. This equipment must not exceed +/- 5% error in measurements.
The laboratory is responsible for selecting the type of deformation sensors. Error measurement for deformation sensors must not exceed +/-5% from maximum value of tension.[38]

Requirements for testing stand:
Testing stand must have all necessary equipment, which provide possibility to do testing, if planer is fixed in one of the following ways:
a. [on power floor] structural chassis frame is being used b. planer is fixed by tail rotor shaft, landing gears do not touch the ground. [38]

- Stand equipment must be able to apply static load (Fig.4.25)
a. to tail rotor at points FPBx,FPBY,FPBZ.
b. to the joint point of fin.
c. to spread load F finz, which is applied to fin. [38]

- Stand must be equipped with system, which allows rapid control of applied loads and automatic registration of results".

4.6. Some results for full scale test of passive SHM system by using Acoustic emission (AE)

As an illustration of utilizing integrated piezoelectric sensors to monitor the structure during bench tests, an example of planning and conducting fatigue tests of a full-size component of a light helicopter structure is given below, in which the author of the work took an active part. The main task of the tests was to experimentally demonstrate the fatigue durability of the most loaded (ceiling) part of the frame of the helicopter body with an equivalent bench Loading. To control the technical condition of the tested structure, it was envisaged to use the method of acoustic emission, as a passive method of ultrasound diagnostics.

4.6.1 Brief information about the installation of piezo converters Acoustic emission (AE)

In the process of conducting fatigue tests of the right ceiling part of frame No. 4 of the helicopter, an 8-channel Vallen System AMSY-6 system was used. Registration of AE signals was carried out through seven channels (2-8 AE sensors). AE sensors were installed in the application area of a cyclic load with a positive according to the terms of reference (Fig.4.27).

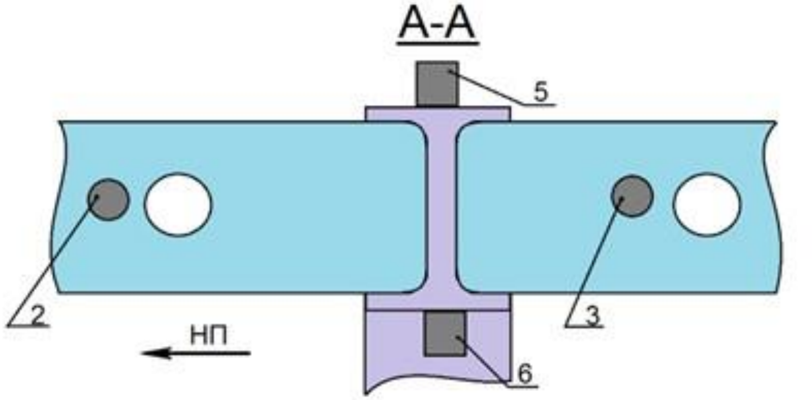

Fig.4.27 Locations and numbering of acoustic emission sensors on the right ceiling side of the frame No. 4 (2-8 AE sensors)

During the test, signal amplitude, energy, total score, signal duration, signal rise time, voltage at the parametric input, threshold value, signal strength, average signal strength was recorded.

4.6.2 Additional test modes during AE control and presentation of some outcome

The main criterion characterizing the formation and development of fatigue cracks is the change in the total account for each registration channel. In addition to the current control of changes in the specified AE parameters in each loading cycle, to increase the reliability of the control, measurements of the AE parameters were made under static loading according to the following program: periodically every 500 thousand. Loading cycles produced a stepped static loading with shutter speed shelves of 4 minutes according to a special program (Fig.4.28).

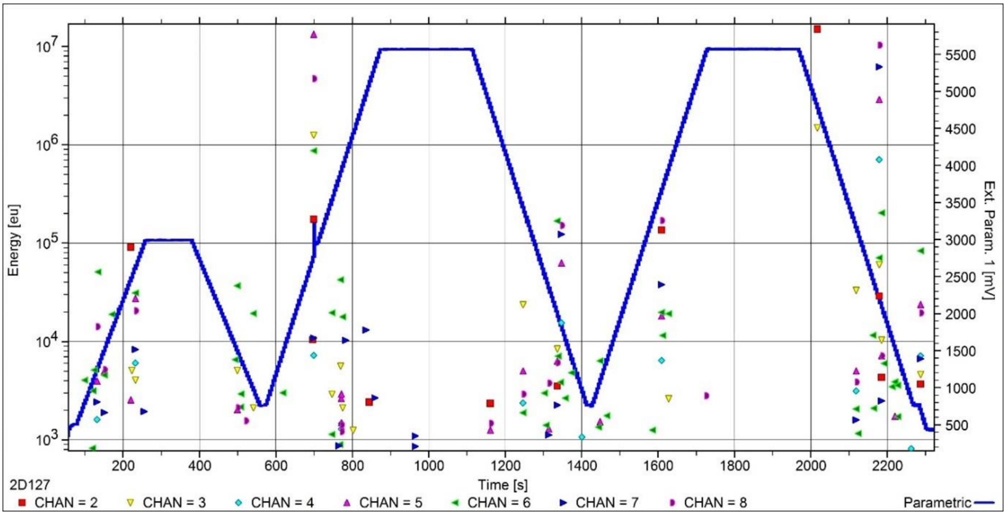

Fig.4.28 Example of a graph of the dependence of the amplitude of AE signals on time during stepped static loading with shelves (With an operating time of 1,000,000 loading cycles)

For subsequent confirmation of the time of formation of the fatigue crack, periodically every 1,000 thousand cycles, a marker loading mode was made with a load 50% lower than the working one for stage No. 2 for 15 minutes. The marker mode provides the possibility of visual fixation of the time of the formation of a fatigue crack during subsequent fractographic studies of the microrelief of fracture destruction.

In (Fig.4.29) shows the results of the current graphs of the dependencies of the change in the total AE account on the number of load cycles separately for each channel.

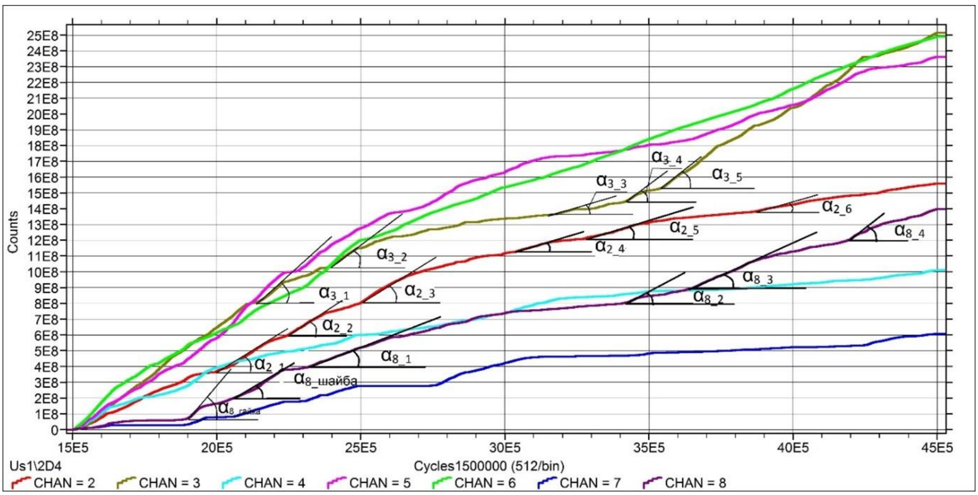

Fig.4.29 General graph of the dependence of the change in the total AE account on the number of cycles of load application by channels at the operating time stage from 1.5 to 4.5 million cycles (the second loading mode)

It follows from the graph that the change in the total account of the AE is not stationary. The appearance at various stages of loading of sufficiently pronounced α criteria should indicate the occurrence and development of damage in the structure. The nature of the damage was established based on further analysis and comparison of AE measurement data with the results of subsequent visual inspection.
Along with the certification tests, assessments of the prospects for using the implemented piezoceramic transducers as sensors for passive ultrasonic monitoring during fatigue tests of full-scale structures were carried out. The peculiarity lies in the fact that the intensity of the load of the structure during testing, as a rule, is higher than in operation. The "equivalent duration" shall be several times the lifetime of the aircraft in service. The results obtained here make it possible to make an optimal choice of parameters of piezoelectric transducers for their use in passive monitoring: functional and strength properties of piezoceramics, geometric dimensions, modal characteristics, method of introduction into the design, method of protection against external influences.

4.7. Conclusion on load monitoring

Ultrasonic monitoring of the health of the structure through continuous fixation and analysis of the external dynamic load is an important component of the combined system based on the use of current information. This type of monitoring is free from references to the original intact state of the structure, which is directly consistent with the subject of this study. The following significant results have been obtained in this direction:

1. The high sensitivity of piezoelectric transducers embedded in the structure to the level of loads usually affecting the load-bearing elements of aircraft structures is shown. At the same time, an ambiguous dependence of the electrical signal on the type of loading and the degree of heterogeneity of the stress state was revealed.
2. An adequate model for assessing the damage index based on the results of load monitoring is proposed, based on the use of the safety factor concept typical for civil aviation aircraft. An example of using such an index is given.
3. A probabilistic model for assessing the strength and lifetime of the supporting structure based on the results of monitoring the load in operation has been developed. A nomogram of the damage index assessment was obtained, convenient for practical use.
4. Acoustic emission is considered as an option for passive monitoring, free from references to the intact state of the structure and convenient for use in full-scale bench tests. The primary results of bench full-size fatigue tests of the structure with continuous monitoring by the AE method are given.

GENERAL CONCLUSIONS

Analysis and solutions to several relevant problems of operability and reliability of ultrasonic structural health monitoring mainly related to using the current information of embedded piezoceramic transducers working in both active and passive regimes of damage detection are presented in this doctoral thesis.

The following objectives should be solved for the achievement of formulated general aim:

1. There is a completed analysis of the piezoceramic transducers strength using Internet resources, experimental data, and finite element analysis (FEA) of stress state for typical installation and typical operational loading. Recommendations for prevention of damage to the static and cyclical load are made.

2. Estimation of EMI as primary method of fatigue crack detection is made. There is done comparison of properties of alternative indices of damage. The detailed procedure of measurement data processing is developed.

3. The crack open/close effect on EMI is investigated and the suitableness of this effect for the crack-type damage detection is estimated.

4. The two improved damage indicis for the crack-type damage detection by the guided wave technology are developed. Both damage indicis (RMSD and time-of-flight) are based on the convolution of response signal for which the excitation signal is used as the mother function.

5. The example of application of references-free virtual system of SHM is demonstrated (for the skin of hermetic fuselage of the passenger aircraft). It can be concluded that hermetic fuselage structure is a very convenient field for application of ultrasonic technology of structural health monitoring which uses the crack open/close effect.

6. Application of piezoelectrical transducer for load monitoring is analyzed. The fatigue damage index with using of the rain-flow method of operational load counting, fatigue test data and simulation outcome is developed. The allowable value of the index is mainly defined by the safety factor.

7. A probabilistic model of strength for SHM of lifetime by using of load monitoring is presented. Using this model, it is feasible to address the challenge of accurately determining the maximum allowable parameter or diagnostic sign for cockpit indication, given that the predetermined limit of its actual value is known in advance.

8. Application of acoustic emission (AE) as a passive ultrasonic method is analyzed in respect of its use in laboratory test of aircraft full-scale components. The formulation of fundamental technical prerequisites for conducting real-time full-scale bench tests on helicopters is established. The outcomes derived from these bench tests can be utilized to assess the strength and endurance of helicopter components through testing calculations, specifically in relation to short-term criteria.

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Pavithra Nagaraj was born in Chitradurga, Bangalore City, India, in 1985. She received a Bachelor's degree in Aeronautics from VSM Aerospace Bangalore, India, in 2009, a qualification of aircraft maintenance engineer (Avionics licensed) from DGCA India in 2008 and a Professional Master's degree in Aviation Transport from Riga Technical University in 2017. Since 2017, she has been a research assistant with the Aircraft Structures Laboratory of RTU. She has participated in 2 European projects. She is also a teaching assistant at the Aeronautical institute of MTAF, RTU. From 2010 to 2015, she was an avionics licensed maintenance engineer at Zephyr Aerospace Bangalore, ADE, (Defence laboratories) DRDO. She has participated in 6 defence projects in India. From 2007 to 2008, she was a trainee technician in the helicopter division of Deccan Chartered. Her research interests include NDT, acoustic emission, aircraft structures, vibro-acoustics, helicopter structures, numerical analysis, composites, and UAVs.