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ANALYSIS OF MEANS AND METHODS OF STRESS-STRAIN STATE CONTROL OF STRUCTURES DURING OPERATION

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This article defines the basic set of means and methods of the structural health monitoring of metal structures and structures from polymer composite materials (PCMs) used in the construction and aviation industry. The analysis of means and methods of strain-stress state control of a structure during operation (detection of defects and crack growth) and their comparison is provided.

Key words: structural health monitoring systems, non-destructive testing, metal structures, polymer composite material structures, structural strength

INTRODUCTION

Russia needs to meet the challenges of minimizing risks of man-made disasters and preventing environmental damage. Development and implementation of sensor systems for industrial and infrastructural facilities is a prerequisite for recovery of "weak signals" in systems that are associated with high crisis risks.

Some approaches distinguish 3 stages of the crisis: before, during and after the crisis, as described in paper [1]. For disaster prevention, in our country, it is necessary to introduce management practices that facilitate the prevention of accidents and work with them before the beginning of crisis situations, because at these stages the damage is relatively easy to localize and minimize. Internet of things technologies can help in this. These technologies can monitor the condition of buildings, equipment and workers; BIM-class systems help to simulate "stress" situations for engineering facilities to identify and remove weaknesses.

LITERATURE REVIEW

One of the great challenges in the global world is the issue of human safety and the well-being of humankind as a whole, which depends on many factors, including the world around us. Nowadays, more and more industrial and man-made construction is taking place. Roads, bridges, houses, tunnels, subways, airports and everything that fills these facilities are potentially dangerous to humans. How all object conditions are monitored represents one of the challenges for humans. This paper proposes one of the technical solutions to monitor the safety of the structure, whether it is houses, roads or aircrafts. The Structural Health Monitoring (SHM) system is one way to solve the problem. The SHM is a comprehensive system for collecting, transmitting, processing and analyzing data from objects within the system. In other words, it is a system that can provide information about the technical condition of an object at any time. Such a

system is used by leading aircraft manufacturers to continuously monitor the condition of the fleet. It is organized by the introduction of sensors into the aircraft structure, as well as regular inspections and reports from aircraft technicians and experts. Further, the collected data is sent to a common database in which the data are collected and processed. Then, using mathematical models that take into account various factors and operating conditions, the condition of the structure is calculated, the remaining lifetime and time of the recommended inspection, as well as the current condition of the components and units of the structure at this stage of operation, are issued. The aviation industry is one of the most knowledge-intensive and breakthrough at present, so why not to use the accumulated experience of foreign colleagues and apply it in the aviation of our country, as well as in the civil industry, such as the field of construction.

The building of the Pinan Financial Center (PAFC), which has a total height of 600 m, is the fourth highest building in the world. The integrated structural health monitoring system with 553 sensors, developed using the modular design method, was installed in the PAFC building in order to monitor the building's behavior during operation as well as to analyze the effects of external impacts both during construction and during operation. The modular SHM solution guarantees the highest possible performance of this comprehensive monitoring system. The system is also expandable, making it easy to install and complement subsystems to meet new monitoring needs.

Structural health monitoring systems have been widely used in civil engineering, particularly bridge construction, and have been used to obtain information on the condition of working structures through operational measurements to identify and evaluate changes in the basic property coefficient caused by structural damage or wear in the material. For example, the 522-meter Foyle Bridge was equipped with various sensors to monitor truss vibration, bending and deformation. On the 12.9 km long Confederation Bridge, an integrated monitoring system

has been installed to track structural dynamic changes and deformations. Furthermore, the Tsingma Bridge in Hong Kong has been equipped with a monitoring system consisting of almost 500 acceleration sensors, multiple strain sensors and a Global Positioning System (GPS) to monitor the technical condition and safety of the bridge during its lifetime. According to papers [2, 3], Brownjon et al. conducted a long-term study to track the concentration of changes in the dynamic characteristics of the structures of a 65-storey building 280 m high as well as Li et al. conducted full-scale measurements of a number of ultra-high buildings in order to determine the characteristics of resistance to the effects of strong winds. The integrated real-time SHM system and structural change identification system was installed in the Burj Khalifa building to monitor and evaluate the performance of the world's highest building. It should be noted that previous studies related to monitoring the condition of high-rise buildings were mostly conducted during the maintenance phase, focusing on the dynamic resistance characteristics of structures to wind and seismic effects. Several studies have been carried out using SHM systems comprising more than 600 sensors. The SHM systems

were installed on the TV broadcasting Canton Tower in order to monitor the structural condition of the building in real time both at the construction and operational stages.

By implementing the structural health monitoring system, it is possible to significantly reduce the operating costs of buildings and structures, while at the same time respond promptly to worn-out roads or, for example, bridges. It will be possible to repair them at an early stage with the help of the SHM system. Besides, by integrating the SHM system into all industries, we obtain a monitoring and warning system for operating companies. The development and implementation of SHM will have a positive impact on the economic condition of humanity, will address related great challenges, will have a beneficial effect and can play a decisive role in the further development of technological progress.

MATERIALS AND METHODS

Table 1 presents the methods and techniques of application of sensors in construction and industry, details of which can be found in these literature sources.

Table 1: Methods of information processing

Methods	Literature sources	Images from papers
<p>A method of clustering signals for structural damage detection. The example for the Z24 bridge is analyzed in this paper.</p>	<p>[4]</p>	
<p>Sequence of information analysis for the SHM system, primarily oriented towards historical buildings remaining lifetime forecasting.</p>	<p>[5]</p>	

Methods	Literature sources	Images from papers
<p>Algorithm for analysis of eigenfrequency changes in order to determine changes in the damaged state of the structure using a special computational algorithm.</p> <p>To demonstrate the performance of the algorithm data were taken about the Gabbia Tower in Italy, which has a height of 54 meters and is located in the city of Mantua. Information on the 200 Hz acceleration vector from 3 vibration accelerometers and a temperature sensor was recorded before and after the May 2012 earthquake.</p>	<p>[6]</p>	<p>Fig. 3. Accuracy of SVM using the proposed strategy. (a) First natural frequency - $R = 576$; (b) Second natural frequency - $R = 437$; (c) Fourth natural frequency - $R = 323$; (d) Fifth natural frequency - $R = 455$.</p>
<p>Algorithm of SHM system operation is based on the application of neural networks (NNs) with dynamic updating. Dynamic NNs means a change in the number of nodes in the width and depth of the neural network depending on the task complexity.</p> <p>To check the performance of this concept, 8 sensors of the real object tilt were emulated during test strokes.</p>	<p>[7]</p>	
<p>Overview of methods to solve the problem of SHM system sensor correct operation.</p>	<p>[8]</p>	
<p>Results of work on the use of SHM system sensors for aircraft UASs and comparison with the results of deflection analysis obtained by FE models.</p>	<p>[9]</p>	

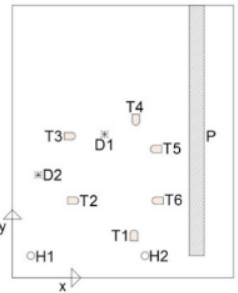
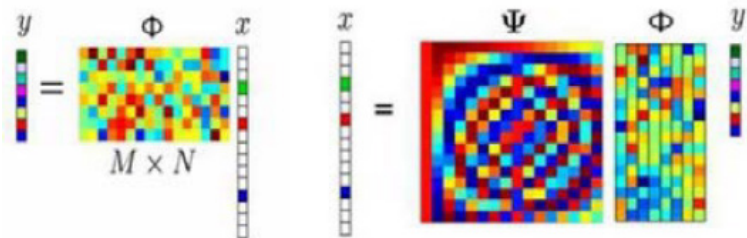
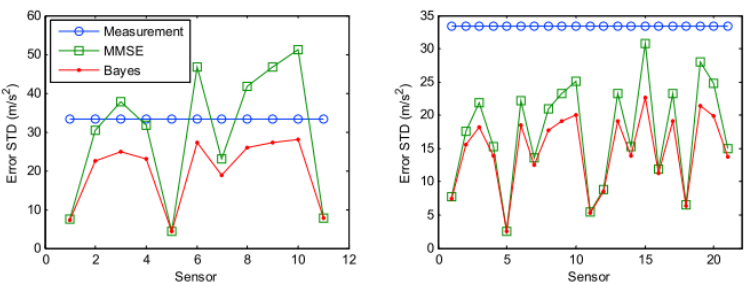
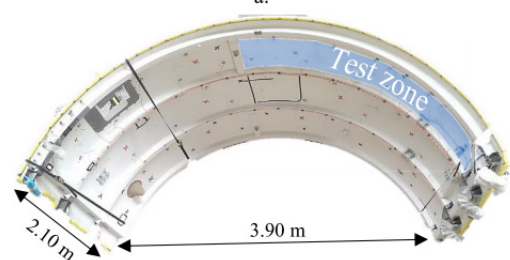
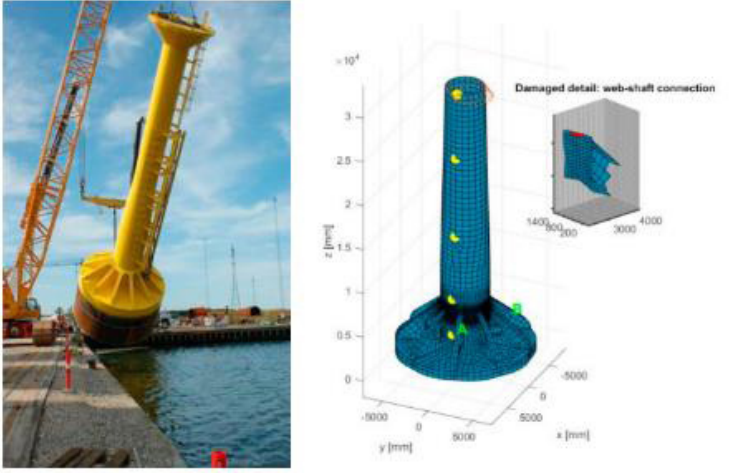
Methods	Literature sources	Images from papers
Use of the videogrammetry technique to analyze the structural dynamic characteristics and for the subsequent analysis of changes in structural behavior.	[10]	
The error effect in the determination of the signal arrival from wireless sensors on the location of the defect in the structure for the SHM system.	[11]	
Operation algorithm to restore the vibration characteristics of aircraft aggregates using a wireless network of sensors-accelerometers with the proposed algorithm of access control to the environment, which involves special procedures for transmitting information from sensors, developed for these purposes.	[12]	
Algorithm for determining the actions of external forces on the structure using superposition of Kalman filters.	[13]	

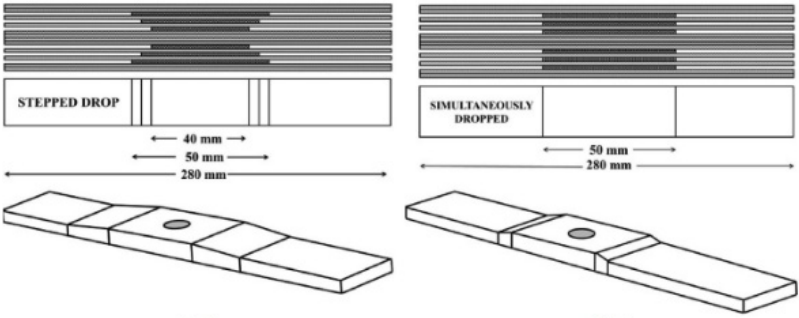
Methods	Literature sources	Images from papers
<p>Algorithm for missing data restoration during steel structural monitoring. The study object is the Hangzhou Stadium structure.</p>	<p>[14]</p>	<p>(a) Top chord (b) Bottom chord (c) Support bar and ring truss</p>
<p>Identification algorithm for the damaged structure. The author proposes to use algorithms for sparse matrix decomposition and methods of low-rank matrix decomposition. The proposed algorithm was used for the analysis of Canton Tower data.</p>	<p>[15]</p>	<p>Measured Structural Responses</p> <p>PCP Denoised Structural Responses</p>
<p>Arrangement of sensors in the plane for optimal restoration of the vibration behavior of the structure. The algorithm is based on maximizing the Fisher information matrix rate.</p>	<p>[16]</p>	<p>Skin: shell elements</p> <p>Two shell elements</p>
<p>Operation algorithm of the continuous monitoring system aimed at detection of delamination growth for adhesive compounds. This is a very important issue for the aviation environment. A piezoelectric layered sensor, which must be permanently glued to the structure, is used for the detection of delamination.</p>	<p>[17]</p>	<p>Film Adhesive Doublers Teflon Tape</p> <p>Host Plate</p> <p>100 mm 500 mm</p> <p>60 mm 15 mm</p>

Methods	Literature sources	Images from papers
<p>Study algorithm of rotating constructions operation on the example of wind-driven power plants for electrical power generation.</p>	<p>[18]</p>	
<p>Methodology of using the similarity criterion of modal parameters for the analysis of the bridge for a high-speed train in France.</p>	<p>[19]</p>	
<p>Method for determining the type of defect in the analysis of natural mode shapes.</p>	<p>[20]</p>	
<p>Compensation of temperature effects for long bridges. The Lueg Bridge in the Austrian Alps is presented as an example.</p>	<p>[21]</p>	

Methods	Literature sources	Images from papers
<p>Method of using conditional decision trees (one of AI algorithms) for the needs of the electric engine monitoring system.</p>	<p>[22]</p>	
<p>The degrees of freedom decrease of investigated systems for application of damage identification algorithms.</p>	<p>[23]</p>	
<p>The task of the damage search algorithm in the analysis of the structure vibration behavior.</p>	<p>[24]</p>	<p>/</p>
<p>Algorithm for detecting damage of wind-driven power plant structures. The algorithm uses elements of fuzzy logic and FE analysis. The turbine blade remaining lifetime is estimated by the proposed method.</p>	<p>[25]</p>	

Methods	Literature sources	Images from papers
<p>Sparse Bayesian learning algorithm for early detection of reducing rigidity.</p>	<p>[26]</p>	
<p>Calculation of structure movement under the influence of seismic waves. To demonstrate the proposed solution, a three-storey laboratory model with one span for each storey is considered.</p>	<p>[27]</p>	
<p>Analysis algorithm of wind-driven power plant condition based on the analysis of the modal characteristics. For example, the model of the wind-driven power plant in reduced form is considered.</p>	<p>[28]</p>	
<p>Method for determining reinforced concrete beam damage under flexural loading.</p>	<p>[29]</p>	

Methods	Literature sources	Images from papers																																																
<p>Algorithm for detection of defects in the metal plate by analyzing the ultrasonic signals received by the in-phase array.</p>	<p>[30]</p>	 <table border="1" data-bbox="1077 336 1452 638"> <thead> <tr> <th></th> <th>x [mm]</th> <th>y [mm]</th> <th>notes</th> </tr> </thead> <tbody> <tr> <td>T_1</td> <td>419</td> <td>152</td> <td>-</td> </tr> <tr> <td>T_2</td> <td>216</td> <td>267</td> <td>-</td> </tr> <tr> <td>T_3</td> <td>203</td> <td>489</td> <td>-</td> </tr> <tr> <td>T_4</td> <td>425</td> <td>540</td> <td>-</td> </tr> <tr> <td>T_5</td> <td>489</td> <td>445</td> <td>-</td> </tr> <tr> <td>T_6</td> <td>495</td> <td>267</td> <td>-</td> </tr> <tr> <td>H_1</td> <td>64</td> <td>76</td> <td>diameter = 13 mm</td> </tr> <tr> <td>H_2</td> <td>457</td> <td>76</td> <td>diameter = 13 mm</td> </tr> <tr> <td>P</td> <td>610 – 660</td> <td>76 – 864</td> <td>width = 51 mm</td> </tr> <tr> <td>D_1</td> <td>318</td> <td>495</td> <td>diameter = 38 mm</td> </tr> <tr> <td>D_2</td> <td>89</td> <td>356</td> <td>diameter = 38 mm</td> </tr> </tbody> </table>		x [mm]	y [mm]	notes	T_1	419	152	-	T_2	216	267	-	T_3	203	489	-	T_4	425	540	-	T_5	489	445	-	T_6	495	267	-	H_1	64	76	diameter = 13 mm	H_2	457	76	diameter = 13 mm	P	610 – 660	76 – 864	width = 51 mm	D_1	318	495	diameter = 38 mm	D_2	89	356	diameter = 38 mm
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<p>Structure failure prediction using data from mathematical models.</p>	<p>[32]</p>																																																	
<p>Estimation of the temperature field for the engine cowling using piezoceramic transducers.</p>	<p>[33]</p>																																																	
<p>Algorithm for detecting a damaged structure using the approach proposed by Mechalanobis.</p>	<p>[34]</p>																																																	

Methods	Literature sources	Images from papers
Stretching glass-reinforced plastics articles from PCM with simultaneous tracking of acoustic emission signals.	[35]	

The technical condition of steel structures shall be determined based on the assessment of factors given in paragraph 5.3.3.1 of GOST 31937-2011.

Determination of geometrical parameters of structural elements and their cross-sections shall be carried out by direct measurements.

Width and depth of crack opening shall be determined by inspection using a magnifying glass or a microscope. The signs of cracks can be rust leaks, paint peeling and others.

When estimating corrosion damages of steel structures, the type of corrosion and corrosion qualitative (density, structure, color, chemical composition, etc.) and quantitative (area, depth of corrosion pits, cross-sectional loss value, corrosion rate, etc.) characteristics shall be determined.

The area of corrosion damage, indicating the zone where corrosion is spread, is expressed as a percentage of the surface area of the structure. The thickness of the elements damaged by corrosion shall be measured at least in three the cross-sections most damaged by corrosion along the length of the element. At least three measurements shall be made in each cross-section.

The value of the cross-sectional loss of a structural element is expressed as a percentage of its initial thickness – thickness of the element that is not damaged by corrosion. For an approximate estimation of the cross-sectional loss value, the thickness of the oxide layer is measured, and the thickness of the damaged layer is taken equal to one-third of the oxide layer thickness.

Weld inspection consists of slag removal and external inspection to detect cracks and other damage. Hidden defects in welds shall be determined according to GOST 3242.

Control of bolt tension shall be carried out with a torque wrench according to GOST R 51254.

In the absence of certificates, insufficient or incomplete information given in certificates, detection of cracks or other defects and damages in structures, physical, mechanical and chemical characteristics of steel structures shall be determined in accordance with GOST 1497 and GOST 7564.

In accordance with the "Regulations on the unified state system of prevention and liquidation of emergency situations" (RSES) (introduced by Resolution of the Government of the Russian Federation No. 794 of December 30, 2003 [41]), the Russian Ministry of Emergency Situations is responsible for the establishment and development of monitoring functional subsystems, laboratory control and forecasting to reduce the risk of arising and development of emergency situations as well as minimization of damage from them.

In order to ensure the safety of buildings and structures in accordance with GOST R 22.1.12-2005 [42], the objects of social, residential and of other applications are equipped with structured systems of monitoring and management of engineering systems of buildings and structures (SMIS) communicatively coupled with automated systems of duty-dispatching services (DDS) of buildings and structures as well as unified duty dispatching services (EDDS, USODM) of the city or district for prevention and elimination of emergency situations, including those caused by terrorist attacks.

SMISs monitor destabilizing factors in real time in order to prevent emergency situations.

The objects of SMIS control are:

- Load-bearing structures of buildings and facilities;
- Engineering systems for life support and security;
- Technological systems.

For the solution of the control problem of the state changes of load-bearing structures of buildings and facilities, the monitoring system of load-bearing structures of buildings and facilities condition (SMIC) is included into the structure of the SMIS as a subsystem.

The monitoring system of load-bearing structures of buildings and facilities condition carries out the control of the indicators characterizing reliability of a building or facility, in order to prevent situations when the values of registered parameters will exceed their maximum permissible values.

Monitoring systems are one of the elements providing scientific and technical support for the construction and operation of buildings and facilities.

Analysis of complex engineering products monitoring systems development

The developed methods of SHM have been successfully enough tested as applied to the control of the responsible elements of various building structures (load-bearing elements of high-rise buildings, bridge anchorages, etc.) and began to be gradually introduced into the aviation.

Methods of building monitoring systems are especially important, taking into account that the processes of occurrence and growth of damages in PCM significantly differ from fatigue behavior of metals. The most dangerous reasons of the possible destruction of a structure made of PCM during operation are the technological defects which have not been detected in the manufacture of the structure as well as damages of PCM in the result of mechanical shock impacts in flight and on the ground [39]. The similar damages caused by low crack resistance of modern high-strength PCM can lead to the development of a defect inside an element, not leaving visible traces on its surface, but then lead to the catastrophic distribution of cracks under the action of fatigue loadings [40].

Over the past fifty years, the ability to receive and process data has been keeping pace with the "Moore's Law", according to which "the number of transistors on the chip of produced integrated circuits doubles about every two years". Today it is already possible to connect information from the atoms of the material to the structure of the aircraft as a whole in a single information system (IS). Also, more and more sensors are placed on the aircraft, and these sensors are connected in a single information space (Figure 1). In this diagnostic toolkit, its tools are closely linked together at different scales in order to optimize knowledge about products throughout their life cycle.

In contrast to the area of non-destructive testing methods, the introduction of advanced technologies for the technical state monitoring was quite limited. As shown in Figure 2, there should be a more integrated solution in the future where the structure and design criteria are developed together with advanced monitoring technologies of technical state.

Implementation of aerostructures' life values in operation

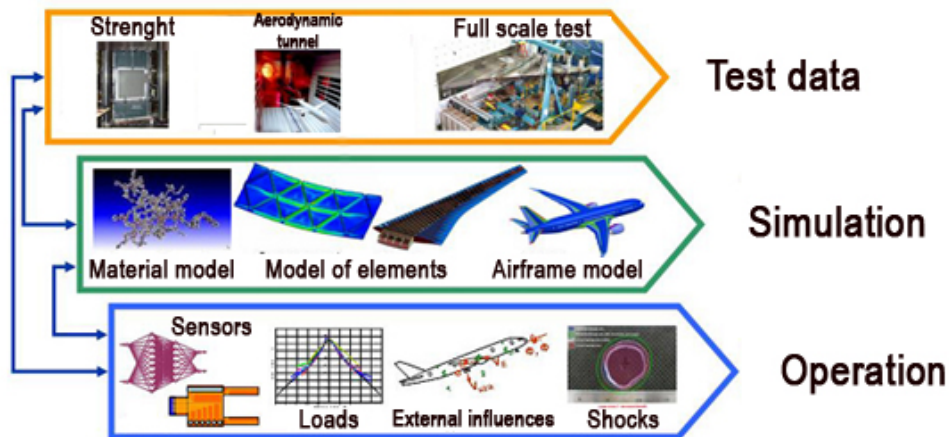


Figure 1: Single information space

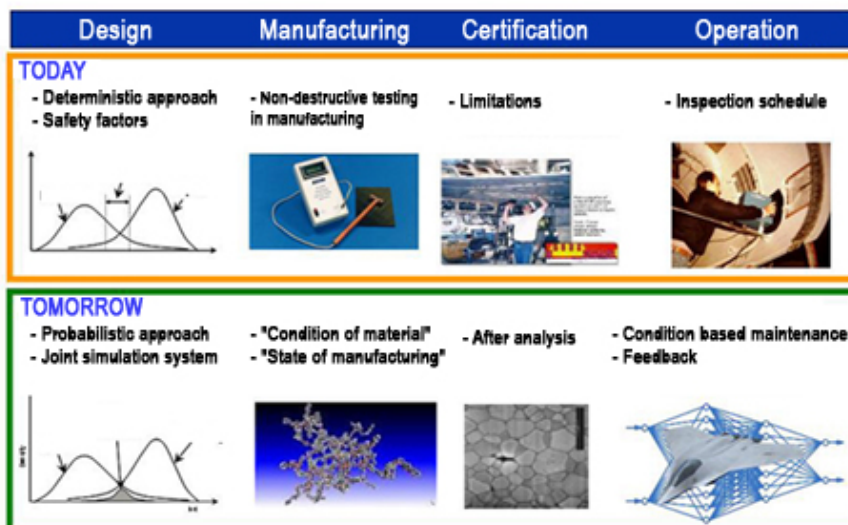


Figure 2: Trends in the use of technical state monitoring system

is ensured by two currently existing main approaches, which are laid down in their design. These are the safe life approach and the safe damage approach, described in paper [36].

In the case of the safe life approach, the aircraft structure is operated for a certain initially specified period of time measured in hours, minutes and/or a strictly limited number of flight cycles (takeoffs and landings). It is assumed that after the expiration of the established time interval and/or when the established limit of flight cycles is exceeded during further operation of the aircraft structure beyond the established limits, the accumulated damage in it may lead to the destruction of any structural elements. In this case, for the possibility of further aircraft operation, the principle of step-by-step determination of appointed terms and limits for strength and reliability under the long-term operation of the structure with the possibility of their prolongation up to the moment of aircraft write-off is applied.

The safe damage approach is fundamentally different from the previous principle and is based on the basic position which consists in the statement that defects in the structure have a permanent presence not excluding new structures and those which are in the manufacturing process. When designing an aircraft structure according to this principle, the developer provides in advance for the possibility of damage and/or destruction of any of its elements, and at the same time, the developer has to ensure that these elements cannot lose their operability in the event of such damage. In this case, flight safety will be based on the assumption of fatigue cracks formation in some or other structural zones of a separate airframe specimen with the possibility of their further growth and propagation exactly until they reach a predetermined and strictly limited length. If this approach is used, it is necessary to ensure sufficient survivability of the airframe structure elements and their increased controllability. In this case, when implementing this principle, the need to constantly monitor the technical condition of each separate aircraft specimen in the park, as well as the ability to predict its subsequent serviceability with a reliable assessment of the remaining lifetime comes on the foreground.

The application of the safe damage principle, supplemented by appropriate methodologies and means of controlling the condition of the aircraft structure elements in operation, makes it possible to avoid strictly limited (designated) terms and life values in the entire fleet and to move to the operation of each particular aircraft specimen according to its actual technical condition. Thus, the operator has greater opportunities for more efficient use of the existing aircraft fleet. It is reflected in an increase in commercial flight hours as a whole and a decrease in downtime caused, in particular, by the work on service life extension and, therefore, in the overall reduction of operating costs.

Thus, effective assessment of the current technical

condition and forecasting of the remaining lifetime of a separate aircraft specimen becomes one of the most important tasks in the implementation of this principle. The methodology of this assessment and forecasting the remaining lifetime of separate aircraft in any fleet is based on the use of a continuous stream of data on the current control of specific aircraft specimens and their subsequent processing. Information on the technical condition of aircraft comes mainly from two large groups of sources:

- Results of the operational control of the aircraft and data of defect finding during operation. In this case, the control procedures can be both continuous (in the form of permanent structural health monitoring) and periodic (in the form of scheduled preventive inspections, etc.);
- Information on operational loads, flight modes and other conditions of the interaction of the controllable object with the environment (for example, parameters of system operation and flight data recorded by onboard aircraft systems).

Obtaining the most complete and reliable information for recovery of operational loads carried by the aircraft structure and a picture of external impacts is a more difficult task in this case. The use of various sensors (both external and integrated into the structure) and non-destructive testing devices, as well as systems for storage and processing of information, their algorithms and special programs for making the final decision, is a prerequisite for reliable obtaining of diagnostic information and information about the history of loading of controllable objects and their subsequent processing.

Integrated use of these two sources of information, namely, data on monitoring and diagnostics of aircraft structure and data on its loading and interaction with the environment in the course of operation, which in this case are closely related, as well as the very obtaining of such information, is one of the main problems. Its solution lies in the field of improvement of information acquisition, its processing and decision-making on the concept of measures for maintenance and repair of a separate aircraft specimen, as well as forecasting its remaining lifetime. The forecasting can be implemented only as part of complex systems designed for the structural health monitoring of the aircraft structure in operation throughout its entire life cycle.

Types of used sensors and building control systems

An effective monitoring system for the technical condition of the shock impact registration should include the following components:

- Position location and quantitative evaluation of the shock impact;
- Determining the kind of damage;
- Damage source assessment.

One of the problems in the diagnostics of shock impacts

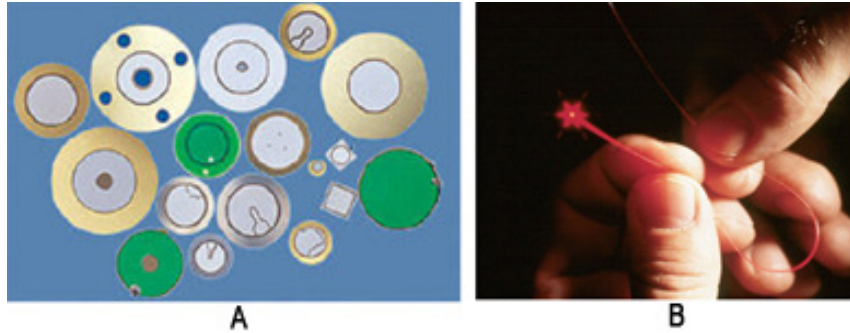


Figure 3: Voltage sensors (A – strain sensors, B – FBG sensors)

is the recognition of the damage source. It can be assumed that each damage to the structure has a unique pattern that relates to a specific operating condition of the aircraft. Thus, the system must have the necessary set of different sensors to match them to the specific type of damage. For an aircraft monitoring system to be approved by certification authorities, it must operate with an acceptable level of accuracy and reliability.

Various approaches can be used for the structural health monitoring made of PCM. The three most common approaches are listed below:

- Voltage sensors (Figure 3) (strain sensors and sensors based on fiber optic Bragg grating (FBG)). Any damage to the structure causes a change in the strain distribution that can be detected with these types of sensors;
- Vibration sensors. Structural failure causes a change in the vibration response to the structure, which is measured with accelerometers, piezoelectric or fiber optic sensors;
- Primary sensitive element breakage (vacuum sensors and breakage of integrated optical fibers).

Table 2 shows the most common types of sensors depending on the type of defect (where, "++" is the main method, "+" can be used, "-" cannot be used, "0" can be used but is not used due to technical constraints).

Table 2: Sensor types depending on the type of defect

Monitoring technologies	Type of defect	
	Shock impact	Fatigue crack/delamination
Passive piezoelectric sensor	++	+
Active piezoelectric sensor:		
• phased array	-	++
• Lamb waves	-	+
• Hybrid systems	+	+
Optical FGB	+	-
Accelerometer	0	-
Strain sensor	++	-

Besides deformation, FBG sensors also make it possible to monitor loads on the structure. The point is obviously in the use of correct material properties and appropriate factors to convert wavelength data initially into deformation and then deformations into a load.

Application of augmented reality technologies for building structural health monitoring systems

One of the SHM's objectives is to improve the reliability of the results of non-destructive testing, its performance control and quality. So, for example, the Volkswagen Group has developed the application MARTA (Mobile Augmented Reality Technical Assistance) for mobile devices (Figure 4), which helps the service engineer not to make a mistake when performing the service task, as demonstrated in [37].



Figure 4: MARTA application

Another example of a more technologically sophisticated product of augmented reality is Google Glass (Figure 5). It is a headset for a computing device based on the Android operating system, developed by Google Company in "Google X" laboratory, according to information [38]. The device in its original form is not a kind of any glasses or mobile phone (smartphone). In the final version, the device must combine and implement three separate functions simultaneously: augmented reality, mobile communication and the Internet.

The device itself uses in its design a transparent display (in the form of a prism and a compact image projector), which is located at the top of the right eye area of vision and is held on the head by a special mount, equipped with a microphone, and also has a digital camera capable of recording video signal of high quality.

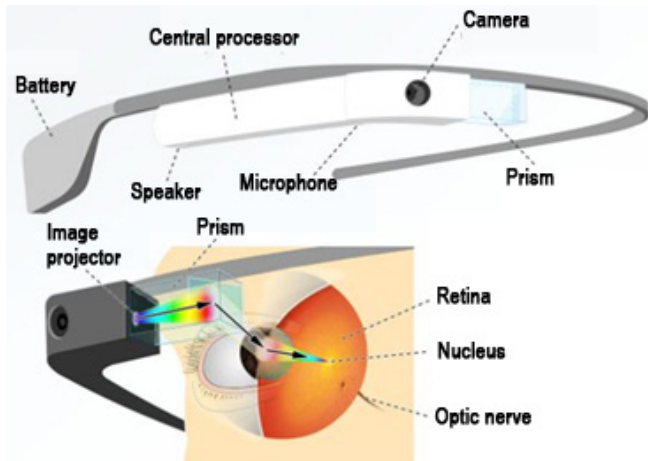


Figure 5: Google Glass device

The capabilities set out in the device make it possible to control the service engineer's actions, and all his actions can be synchronized with the advanced system of monitoring and data collection on aircraft operation and maintenance.

Radio-frequency identification technology is a method of automatic object recognition, in which data recorded and stored in so-called RFID labels (RFID is an abbreviation of Radio Frequency IDentification) or transponders attached to the surface of the identified object, or located directly within its structure, are read or recorded through radio signals (Figure 6).

Systems based on radio frequency identification, as a rule, consist of a standard list of the following components:

- Devices for receiving and transmitting information (antennas);
- Devices for reading and recording information (readers);
- Devices for input-output of external control signals;
- Sensors of executive or warning devices;
- Devices for storage of identification information (labels);
- Software package;
- Control system unit;
- Communication infrastructure in the form of a wired and/or wireless network.

Systems based on the technology of radio-frequency identification are built on a modular principle. At that, the radio-frequency system is easily built into the already existing (for example, installed aboard the aircraft) information system. Depending on the type of current tasks and object of automation identification data can be used both separately and in a complex of sources of information from external information systems.

Since the beginning of jet aircraft operation, requirements to airports and maintenance personnel have been constantly increasing. Different satellite systems (GPS and Galileo) help record the movement of both service



Figure 6: Typical view of RFID label

personnel and vehicles, as well as synchronize data with different devices. Since the Boeing 787 began operating, airports receiving this type of aircraft have been required to implement a wireless local area network (WLAN) in accordance with IEEE802.11 b/g standard (Figure 7). This requirement has been introduced in connection with the transmission of large amounts of data between the aircraft and air traffic control facility. Because this data transmission standard is used in both home and industrial routers, therefore, the implementation of such a system is cost-effective.

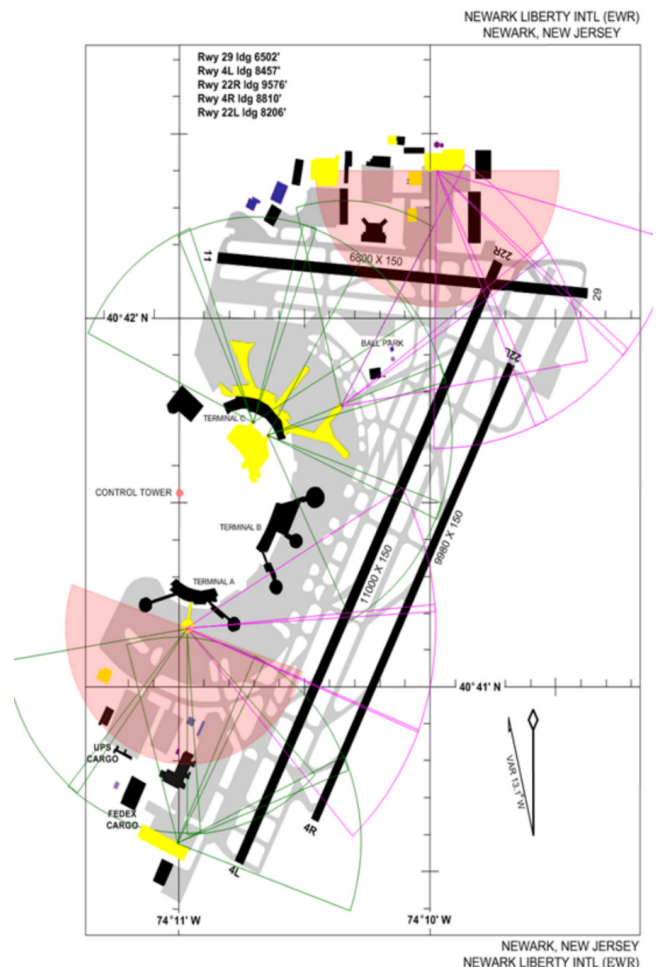


Figure 7: Configuration of routers at Newark Liberty International Airport, the USA

DISCUSSION

The questions were answered in the discussed paper: "What means and methods of control of a stress-strain state of structures exist nowadays?" and "How are systems of structural health monitoring applied abroad and in the Russian Federation?"

For comprehensive structural health monitoring in construction and aviation industries, the SHM system (there are also similar systems) has been developed, which collects, processes, analyzes and transmits data from objects in the system. In foreign experience, there are many illustrative and interesting examples of the application of this technology in bridges, TV towers, stadiums, wind farms, elements of aircraft structures and much more. The number of monitoring methods proposed at these facilities is also quite extensive, and they are used in structures made of any (popular in construction and manufacturing) materials, including composite ones, with the use of sensors of various types: FBG sensors, strain sensors, piezoelectric sensors, fiber-optic sensors, vacuum sensors, etc.

It should be noted that the development and application of such systems of structural control in Russia lag far behind the leading Western and Asian countries and (in a small volume) finds its place mainly in construction, while one of the main application abroad is the aviation industry.

With the process of development of new, more autonomous and "smart" sensors, structural health monitoring systems will be used in the objects of transport and construction much wider than at present. The Russian Federation, in order to minimize risks of various disasters, needs to follow the experience of foreign countries and invest more money in digitalization in the aviation and construction industries.

RESULTS

Based on the analysis of open sources and patent applications, we can conclude about the level of development and introduction of monitoring systems in the Russian Federation is characterized by the following features:

1. Autonomous monitoring systems are completely absent. All systems under development are part of the complex and depend on other methods, including subjective control methods;
2. Most systems assess only the current state for defects detection and are not aimed at tracing the defect growth and collecting data for the remaining lifetime assessment;
3. Most of the developments on this topic relate to manual control methods;
4. Automated control systems have narrow applications, such as building footings, aircraft wing panels, bridge supports and wheel bogies of train carriages, which makes it extremely difficult to unify the meth-

ods and approaches for building such systems and their scaling;

5. The area of data transmission and processing is extremely underdeveloped;
6. Neural networks are not used, which also negatively affects the flexibility of such systems;
7. The main areas of application are construction, gas and oil pipelines, as well as railway transport;
8. The main developers are scientific centers, which are mainly governmental ones.

The development level of this area outside the Russian Federation is characterized by the following features:

1. The general development level of this area is significantly ahead of the development level in the Russian Federation;
2. The building of monitoring systems is aimed at controlling the state of the facility as a whole, rather than its separate elements;
3. There are developments in the application of such systems for remaining lifetime assessment;
4. Much attention is paid to methods of data transmission and processing as well as to the application of neural networks;
5. There are attempts to create interdisciplinary systems;
6. The main applications are aircraft industry and construction;
7. Developers (ordering customers), as a rule, are manufacturers of a final product;
8. The main developers of these systems are companies in the USA, Great Britain, and France and, in recent years, China.

CONCLUSIONS

As a response to the great challenge, which combines the provision of technogenic safety and increasing the digitalization of the economy, the technology of introducing structural health monitoring systems for the aviation and construction industries has been identified.

Within the framework of implementing structural health monitoring systems development, it is extremely necessary to define existing scientific and technical reserve in this area in the Russian Federation and abroad. From this perspective, the analytical review of modern literature in the area of developing health monitoring systems of structures and complex engineering products has been conducted. These works will make it possible not only to determine the existing level of development in this area but also to identify possible directions for the development.

Solutions for application of different types of sensors such as vibration, fiber-optic and radar sensors as well as hybrid control systems have been considered. Issues of data processing and their analysis depending on dif-

ferent types of building and aircraft structures as well as developed methodologies of sensors arrangement have been considered.

Within the framework of the historical analysis of the development of monitoring systems, it has been found that for today due to the development of data processing technologies it is possible to significantly expand the functionality of monitoring systems using the means of finite element analysis and the transition from the current control of the situation to the forecasting of structural behavior.

Advantages and disadvantages of existing structural health monitoring systems for the aircraft structures have been analyzed, and ways of their development have been proposed, taking into account the great challenges facing the aircraft industry.

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