TRANSPORT PROBLEMS 2019 Volume 14 Issue 2
PROBLEMY TRANSPORTU DOI: 10.20858/tp.2019.14.2.9

Keywords: aircraft critical systems; ergatic system; system monitoring; system integration; system redundancy

Jan PIĽA*, Jaroslaw KOZUBA
Selesian University of Technology, Faculty of Transport
Krasinskiego 8, 40-019 Katowice, Poland
**Corresponding author.* E-mail: jan.pila@gmail.com

SAFETY OF COMPLEX AIRCRAFT ERGATIC SYSTEMS

Summary. In this paper, aircraft safety of complex critical systems in terms of the automation and safety has been investigated. We think, due to the automation, the role of operators has shifted from active control to passive monitoring. Performing this last task even might be more difficult because of the monotony and needs of realization of the active control in emergency situation. The management of complex ergatic systems is relevant at the present stage of the development of science and technology. It is a particular concern to evaluate the activity of an operator as the element of the ergatic system. New technologies presented by automation should complement and not displace human functions in aircraft control. The paper focuses on new technologies applied in aircraft systems to ensure higher safety and system reliability. The main problem of aircraft safety is addressed to aircraft critical systems as helicopter transmission system monitoring, aircraft system integration, and system redundancy. The research is based on experimental methods and case studies. The subject of the research is to evaluate the importance of complex ergatical systems, e.g., interaction between the subject and the object in its operational process. As the example of helicopter main gearbox diagnostics, as an object of complex engineering system, is stated hypothesis that there is possibility to determine changes in the characteristics of critical flight parameters and to determine the current level of flight hazard. The work is based on experimental and measurement-based testing, systematic and scientific procedure of data collection, analysis and interpretation. The practical implication can be utilized for safety benefits, risk mitigation and avoidance.

1. INTRODUCTION

The scientific and technological advancement of mankind is accompanied by the use of technology with an increasing number of functions performed to manage the operation of technical equipment and technological processes. This allows a person to be exempt from simple instrument control and to be more focused on controlling the executive and managing governing bodies of the system.

The design of aircraft airframe and airframe systems can be considered as a source of increased threat to humans and the environment as well. It is a necessary by-product of scientific and technological progress. The load applied to airframe units, performance and interaction of systems plus human operator operating in a wide variety of changing external conditions, generates dangerous situations.

However, in the modern aircraft, a computer has adopted a range of features and the numbers of software systems have multiplied.

Aircraft software and hardware system integration is, therefore, absolutely necessary discipline but also one of the most complex. Not only each system must function as it was designed but also must work with other systems. It seems that automatization reduces the need for the basic skills.

The automation of the aircraft did not only reduce the need for the basic skills involved in the concept of flying skills but also the requirement of knowledge that was always necessary for pilots.
The word "automation" means the replacement of human functions, performed either physically or by using cognitive abilities, the functions of the machine.

Automation is simplification of certain tasks or part of the tasks performed by the crew members. The definition includes alarm systems and warnings that replace or enhance human control and decision-making (this may not depend on the choice of the crew, but be pre-determined, such as for monitoring systems, the state flight and fire detection).

Automation should complement and not displace human functions in control and control in civil air transport.

The operation of the aircraft functional systems should be simple and understandable so that it is possible to facilitate the detection of faults and their diagnosis.

In the field of aircraft automation, ergatic control systems (ECS) play an extremely important role. The development trend of these systems is characterized by a higher degree of complexity of managed objects; higher degree of potential external environmental hazards; increasing the number of system elements and the level of complexity of functional tasks to be solved; the growth of the volume of processed information; shortening decision time; increasing error rate, accuracy and quality of the decision-making process. In this respect, one of the most important problems of developing highly efficient ECS is the optimal reallocation of functions between the operator and the technical means, taking into account the psychophysiological capabilities of an individual. However, solving this problem goes beyond traditional automation systems. The only way in this situation is to provide intellectual support to the operator's activities through computer technology.

2. SYSTEM ENGINEERING OF ERGATIC SYSTEMS

The ergatic system (ES) is understood as the interaction between the subject and the object in work process (activity), and in more expanded form, this is the system "man–machine–environment–society–culture–nature".

An ergatic system is a complex control system whose component element is a human operator (or a group of operators), for example, an aircraft control system. Also, the ES is a purposeful system, which includes a person (group of people), a technical device (means of activity), an object of activity, and the environment in which a person is located.

Ergatic systems are systems in which a human operator does not directly participate in the performance of tasks arising from the designation of a given system but only performs the functions of checking, searching or restoring the system.

In a modern society, a system approach to problem solving is known and widely accepted. Almost in all human activities, there are possibilities to organize any activity systematically. Human activity is also systematic. Man is an active element of nature. If we look at the practical activity of a person, we can say that it is systemic. Mandatory features of practical human activity are follows:

- Structuralism.
- Interconnection of system components.
- System is subordinated to particular goal.

The main objective of systematization of human activity is to increase the efficiency of its activities.

The simplest way to increase efficiency is mechanization. Mechanization is characterized by the use of the simplest tools and devices, machines for performing any manufacturing operations (increases productivity by 5–7 times). The mechanism is always controlled by the person.

For aircraft systems, the most elementary components of the system are the mechanical components (pumps, valves, sensors, effectors, and others) that determine the characteristics of the hardware, software alternative applications or modules that support the overall operation of the system.

A higher level of human productivity is automation. Its main task is to exclude the participation of a person from a particular production process, i.e., to command the machine not only through the work itself but also by managing these processes. The highest degree of systematic human activity is associated with cybernetics (the intellectualization of production). The main difference from previous levels is the use of intelligence.

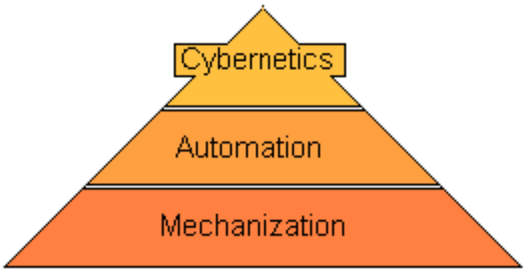

Fig. 1. Step of increasing human productivity

It allows you to orientate in unknown situations, to solve newly created tasks that cannot be formalized and cannot be solved by automated systems. It is used as a natural human intelligence or an artificial intelligence. Systematization belongs to mass; therefore, it can be called a form of existence of matter. We know forms of existence of matter, such as time, space, movement, structure, etc., are also systemic [1].

Systems engineering is an interdisciplinary field of engineering and engineering management that focuses on how to design and manage complex systems over their life cycles. The system is not the same as the system engineering. Simply stated, a system is an integrated composite of people, products, and processes that provide a capability to satisfy a stated need or objective.

Systems engineering consists of two significant disciplines: the technical knowledge domain in which the systems engineer operates and systems engineering management.

Technical complex system (engineering system) function depends on a causal structure. Part of the causal structure of an aircraft system is related to energy and fluid flows in the physical, i.e., mechanical, electrical and fluid, process equipment. Another part or the causal links depends on information flow paths interconnecting the physical equipment that remove degrees of freedom from system states in accordance with the purpose of system operation. The constraints on system states to be introduced by this controlling information network depend on the immediate purpose or operating mode and serve to maintain a state, to change the operating state in a particular system or subsystem or to coordinate and "synchronize" states in several subsystems to prepare for systems reconfiguration.

A typical aircraft is equipped with a set of interacting systems that are combined to enable the aircraft to perform a particular role or set of roles.

The term aircraft systems integration can be interpreted in a number of ways:

- Integration at the component level.
- Integration at the system level.
- Integration at the process level.
- Integration at the information level.

The most typical integration is applied in the flight control system (FCS) as a critical system.

In the earlier time, the integration of aircraft FCS was based on mechanical integration.

There are direct mechanical linkages between the pilot's cockpit controls and the control surfaces that manoeuvre the aircraft, leading to implementations that have high integrity, in terms of the probability of loss of control of the aircraft.

By introduction of the electronic systems, it has become now possible to expand links between the different systems. Today's FCS is an integration of mechanical hydraulic electrical and electronic (information) systems. For the safety and reliability reasons, mechanical systems are gradually replaced by electronic systems allowing better system integration. Information-based integration more and more infiltrates the airframe structure in order to check and control structure integrity and elasticity. Typical airframe–information integration is flight envelope protection, high angle-of-attack protection and others for limiting aircraft performance [2].

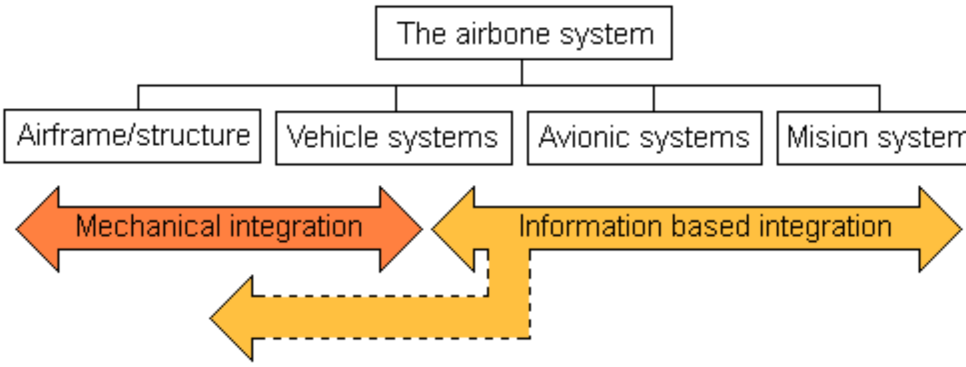

Fig. 2. Information flow paths [2]

In the most general form, the general theory of systems includes the following components: cybernetics, system engineering, and operative research theory, each of which contains a number of particular theories.

The present world as described above can be characterized not just systematic but also ergatic. Man has enormous energy and information resources, and his (her) adaptation to the modern environment is achieved not only through genetic but also rather through technical means.

The use of complex technical systems (CTS) is common in various areas of human activity, and ergatic systems (ES) play a dominant role in the techno-sphere. These are systems with a wide range of options, the ability to self-organize, considerable freedom of behavior, a great deal of information and the speed of information processing. Their lifecycle is the same or longer than human life. Due to the specific characteristics of these systems, they are used in non-traditional management objects. Accordingly, new methods of research and analysis of their processes of operation are being expanded.

3. AIRCRAFT ERGATIC SYSTEMS AND SAFETY

An increase in the number of airplane systems, components and other facilities relates to pre-flight and in-flight control; an increase in the number of critical flight parameters affecting the level of safety requires further automation of non-stop control processes to control aircraft operations, on-board equipment and crew activities, creating control measures and accepting operational decisions at all stages, through pre-flight preparation and ending with the landing of the aircraft [4].

An aircraft ergatic systems belong to the class of large ergatic systems characterized by the existence of a network of mutually connected subsystems linked to the common purpose of operation [5].

It is a complex management system whose main element is a man – operator (or group of operators) in the aircraft management system.

The existence of such a system and the rapid tempo of technology development, particularly in the aviation, greatly accelerate the development of human capabilities, limiting the human interaction capability with aircraft systems.

Impact of technology and initial human factor problems:

- New technology application.
- Increased system capability.
- Information load that makes more complex the general work load.

- More extreme working conditions (risks).
- Taxing human resources (altered strategies and complacency).
- Emerging accidents, errors, training failures, and operator shortages.

The complexity of the systems may result from complex, e.g., nonlinear relationships, but, in this context, it is primarily intended to express unexpected behavior – the interaction in ergatic system, i.e., a system with a large number of subsystems and a human operator. This interaction can have three layers of physics, communication, or control that are very tightly linked to create another complexity attribute.

Relation between aircraft system components of complex aircraft systems is often created by networks or layers of networks. The network structure may be relatively rigid, but it may also evolve depending on internal or external inputs or events.

Ensuring a high level of safety, in modern, potentially dangerous aircraft systems, is only possible by combining the capabilities of modern aircraft alert and warning systems and their management by highly qualified operators, psychologically prepared for timely and adequate response in conditions that can lead to accidents. Such an operator can mitigate the consequences of dangerous situations and prevent the further occurrence of an accident.

Depending on the level of development of technology and technological possibilities, the capacity of the human operator (primary psycho-physiological) is increasing, increasing the quality of general and special education and increasing the usage of equipment by automated control, management systems, etc. Gradually, human capacities are increasingly lagging behind at a rapid tempo of technological development. Such a situation is, inter alia, associated with a certain delay in the complex assessment of new technology as regards its potential (emergency) danger. It is very difficult (and almost impossible) to assume all types (and variants) of those risks in the phases of creating and testing new equipment and technologies.

Human errors that can lead to an aircraft accident not only occur at the design and construction stage, but they can also occur at all stages, from design, production, maintenance, operation to their decommissioning.

This is due to the fact that the complexity and improvement of technology, its quantitative growth, and the emergence of possible technical failures (or little analysing) inevitably create assumptions to increase the probability (risk) of accidents.

Human skills in the prevention of accidents have also grown by improving education, higher qualifications, quality selection, use of computerized equipment, automatic process management, improving the whole system and means of safety. Nevertheless, the possibilities of man are still lagging behind the accelerated development and expansion of the possibilities of modern technology.

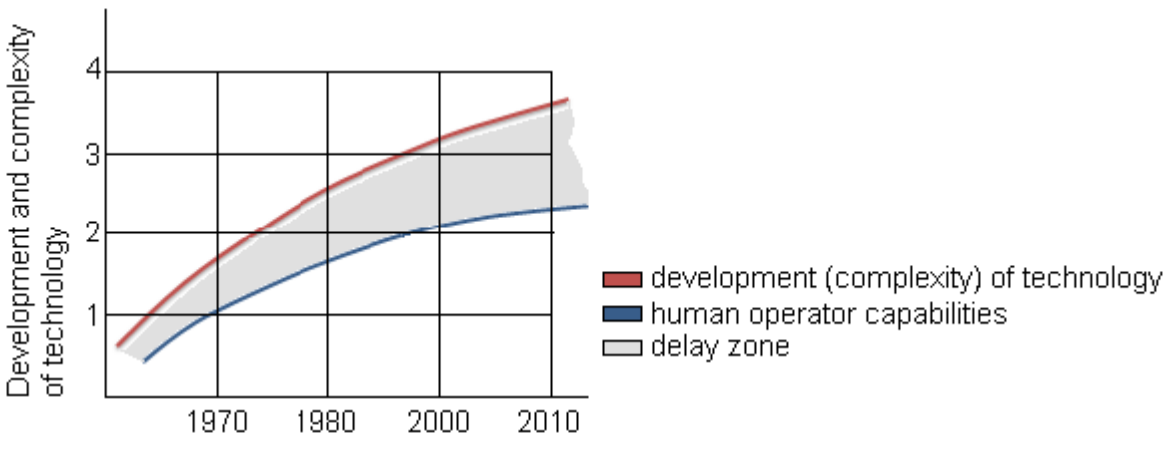

Fig. 3. The ratio of technology development (complexity) and the growth of human operator capabilities [6]

The result is different types of conflicts. Under such conditions, the conflict has acquired a new meaning as it is currently understood to be a way of interacting objects based on the fact that conflicting parties do not separate or clash with each other in opposition, but, in some cases, they join together and work together. There is a new system characterized by new features that do not belong to any of the objects but have a significant impact on them. In such a situation, neither the observer nor the super-system nor the subjects have comprehensive information about themselves and their relationships but use their own subjective solutions and judgments.

Research in the area of safety of air traffic technology today requires the use of new approaches, methodologies, and technologies. This is due to the following reasons:

- a rapid increase in flight speeds and altitudes; reduction of meteorological limitations in air traffic;
- increase of air traffic intensity;
- more complex design due to larger dimensions and a higher level of automation of new generation of aircraft;
- other factors related to the operation and aircraft aging;
- the need for further training and retraining of aircraft engineering staff and air traffic controllers; information technology processes related to flight operations and their support; and
- introduction of "glass cockpit" or pilot's compartment with a high degree of information technology.

The growing complexity of aircraft systems and software may make it difficult to assess compliance to air worthiness standards and regulations. Systems are increasingly software-reliant and interconnected, making design, analysis, and evaluation harder than in the past. Although new capabilities are welcome, they require more thorough validation and verification. Complexity could mean that design flaws or defects could lead to unsafe conditions that are undiscovered and unresolved.

Examination of the effects of system complexity on aircraft safety is assigned to investigate the nature of complexity, how it manifests in software-reliant systems such as avionics, how to measure it, and how to tell when too much complexity might lead to safety problems and assurance complications.

The research (by Sarah Sheard, 2015) addressed several questions, including:

- What definition of complexity is most appropriate for software-reliant systems?
- How can that kind of complexity be measured? What metrics might apply?
- How does complexity affect aircraft certifiability, validation, and verification of aircraft, their systems, and flight safety margins?

This gives rise to a question: where there is a line of safety between two systems that can be considered a safe interface?

If we consider the system to be complex, it is necessary to explore what is problematic and what is beneficial due to its complexity. The complexity attribute of the system must take into account its safety and performance, which is a redundancy resolved. The system has not just two identical units instead of one, but it also has a switching mechanism between two units and the way each one works is little complicated. This feature is often supported by software, which is now much more complicated than when there was only one unit.

The complexity of aircraft systems affects aircraft design and troubleshooting activities, e.g.:

- complicated software planning;
- difficulties in design process, as the existing techniques may not have a sufficient safety level in real-time systems operation. Individual safety cases cannot be assessed solely on the basis of simulations and laboratory tests, but it usually requires a wait for operational data to increase the level of safety;
- complexity of systems may cause operators to be less able to predict the properties of a system composed of new hardware and subcomponent components;
- complexity of systems makes it difficult to define and diagnose problems; and
- system complexity makes aircraft line maintenance more difficult [7].

The system approach to studying the "aircraft-environment-operator" ergatic system requires the clarification and coordination of some concepts, in particular, system security, system diagnostics, and the information system of the ergatic system and technical risks.

4. INTEGRATION AND REDUNDANCY OF AIRCRAFT SYSTEMS

System integration (SI) is an IT or engineering process or phase concerned with joining different subsystems or components as one large system. It ensures that each integrated subsystem functions as required.

The integration of aircraft systems (ILS) is an aspect of system engineering, integration, and testing process. Modern aircraft has power and control system integration by reasons for the need to extend their mutual cooperation.

The main objectives of ILS are to:

- increase the level of safety, the use of diagnostics and prognostics to detect faults before approaching dangerous situations,
- improve the operational readiness through a better planning of maintenance,
- improve reliability through a better understanding of the current technical condition of the system and maintenance-based forecaster, and
- reduce overall maintenance costs by reducing unnecessary and unplanned maintenance.

There are two main directions of integration: horizontal (single interface between all other subsystems) and vertical (subsystems are integrated according to functionality) [5].

Redundancy in engineering should be understood as a “design paradigm” that frames regulatory assessments and interpretations of all complex technical systems. In modern engineering, it is equated with safety and integrity [8].

Redundancy in engineering has a specific meaning. It is the duplication of critical components or functions in order to increase system reliability, usually in the form of advances (back-up) or fail-safe system.

In general, the number of redundancy indicates the number of independent members, i.e., triple redundancy indicates three independent members, whereas a quadraplux redundancy indicates four independent members. A triple redundant system is used in flight control and is a natural evolution of all hardware resources of the airplane flight controls.

There is mechanical, computer, and hydraulic redundancy on the airbus A320 (340).

5. MONITORING OF HELICOPTER TRANSMISSION SYSTEM AS A PART OF ON-BOARD ERGATIC SYSTEM

A significant part of the helicopter operators is associated with the on-board ergatic system (OES): crew–on-board equipment–helicopter. These include peculiarities of helicopter aerodynamics, flight dynamics, helicopter control, crew failures, engine failure, inappropriate external conditions, or special flight modes. Due to the accidental emergence of these factors during flight, unwanted air situations arise.

These means must not only monitor the functioning of the OES elements but also determine changes in the characteristics of critical flight parameters, immediately alert the crew when approaching the limits of operational limitations, and determine the current level of flight hazard. Determining the level of danger allows pilot to avert the consequences of equipment failure, crew failures and adverse external influences, correct automatic control algorithms, as well as timely decisions about the need to change control mode or helicopter route.

The essence of monitoring is the determination of the necessary and sufficient set of indicators characterizing all the studied properties of the system and the formation of dependencies characterizing the total effects of the use of the system or its elements.

The goal of parametric analysis of any complex engineering system is to assess the effectiveness of the system based on the determination of the quantitative values of its indicators.

The objects of the research and study are the parametric analysis of vibration indicators forming vibration spectra.

Using the vibration indicators, it is possible to determine the internal properties (health condition) of the engineering system being analysed.

The research of helicopter transmissions monitoring is focused into the vibration diagnostics of helicopters Mi-24, Mi-17 most critical parts. Main, intermediate, and tail gearboxes are the objects of monitoring.

The transmission system of any helicopter is the most critical systems because it transmits power from an engine to the main and tail rotors for helicopter thrust, lift, and flight control. Helicopter transmission vibrations are closely connected to helicopter`s dynamic stress, condition of bearings, gear-units, unbalance, abnormal alignment between shafts, cracks in vital components, deterioration, etc. For this reason, undetected faults in the transmission can lead to a catastrophic failure.

The primary objective of helicopter transmission vibration monitoring is to supply information about machinery operating and technical condition.

Purpose of research

The purposes of this research are:

1. The primary analysis of vibrational spectra (calculation of the expected gear and bearing fault frequencies of tail, intermediate and main helicopter gearboxes).
2. Secondary analysis of measured vibration spectra.
3. Design methodology for gearboxes frequency measuring.
4. Creating a database of gearboxes vibrational spectra for tertiary (maintenance) analysis.

In Fig. 4, different main helicopter gearbox frequency spectra interpretations are shown. After downloading, the data should be reviewed by a maintainer for advisories and threshold exceedances, followed by detailed analysis by an analyst or an engineer. The analyst should look for threshold exceedances as well as data trending.

Thresholds are limits set in order to quantify the degree of possible degradation. In Fig. 4, no thresholds are shown, as there are preliminary results received from measurement at different working hours. In Fig. 4, vibration energy growth measured in RMS values in different axes is shown. The interpreting aspect of the vibration spectra is to depict importance of the helicopter diagnostic system as an integrating part of ergatic system.

Discussion

All machines with rotating components give rise to vibration. Each machine has a specific vibration spectrum related to the structure and the health condition of the machine. If the state of the machine changes, the vibration signature will also change. A change in the vibration signature can be used to detect incipient defects before they become critical.

Military air operations in helicopters are examples of activities that require high performance of the operator.

Good automation reduces pilot workload and frees attentional resources to focus on other tasks, but ‘management’ of the automation is needed, particularly when involving data entry.

Aircraft condition (-ing) monitoring system (ACMS) monitors aircraft functions (condition in machinery) and also produces messages detailing failures and in certain cases. The monitoring system displays data concerning aircraft systems and also failures, and sometimes it displays corrective action to be taken by the pilot and system limitations after the failures. It is a major component of predictive maintenance. The use of conditional monitoring allows maintenance to be scheduled or other actions to be taken to avoid the consequences of failure, before the failure occurs.

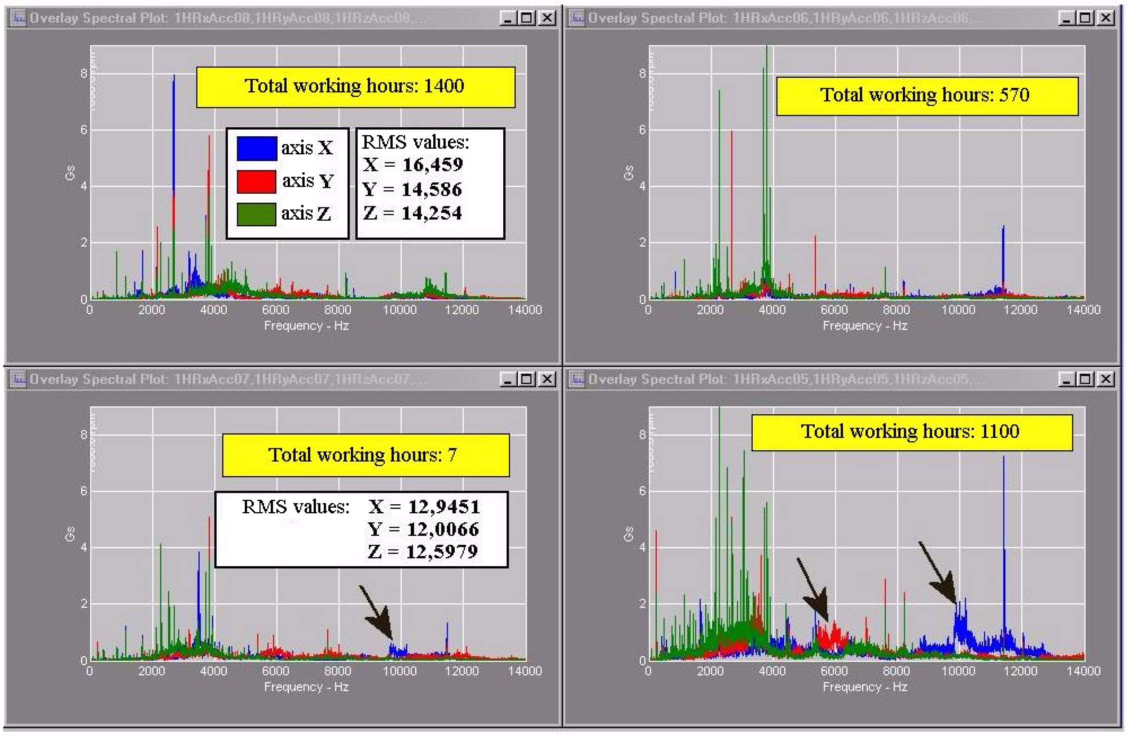

Fig. 4. Comparison of vibration spectra from main helicopter gearbox

6. CONCLUSION

Up-to-date aircraft systems present serious matters relating to automation and human–machine system errors. These matters are associated with certain various errors and omissions occurring in the human operator states. These deficiencies include decrease in attention, negligence, and a loss of situation awareness (SA).

A man's role in control systems was presented by Bibby et al. [10]. They stated that many control engineers have a hidden dream: complete automation, in which a man's role is only that of a consumer. However, the reality of today still shows that a considerable human involvement in design and operation is absolutely necessary for a system to function.

A new class of design-induced human factor accidents is apparent in a number of the new highly automated aircraft. These human factors accidents are associated with design features that eliminate or interfere with the communication between the aircraft and its systems and the operator. This interference involves the removal of tactile, audible or visible feedback that was usually present in earlier systems. The inevitable conclusion is that manufacturers, certification authorities, and airlines have been accepting certain basic design philosophies that have introduced new human factor problems. This trend should be reversed [9].

The ergatic system analyses the relationship between technical objects and the psychophysiological capabilities of a human operator operating a system. Thus, aeronautical ergonomics is a specific branch of cybernetics that studies the general principles, processes, and laws governing ergonomic systems in order to design and use these systems as efficiently as possible.

The main objective of aviation ergonomics is the scientific substantiation and development of recommendations for designers, technologists, production managers, and operators on the creation and use of optimal ergatic systems, based on the technical requirements of the system.

References

1. Чернышов, В.Н. & Чернышов, А.В. *Теория систем и системный анализ*. Учебное пособие TGTU 2008, ISBN 978-5-8265-0766-7. [In Russian: *Theory of systems and system analyses*]. Available at: http://window.edu.ru/resource/188/64188/files/chernyshov.pdf.
2. Moir, J. & Seabridge, A.G. *Military Avionics Systems.* John Wiley & Sons. Ltd. 2006. ISBN: 0-470-01632-9.
3. Мехоношин, В.С. *Основы теории авиационных эргатических систем*: учеб. пособие / сост. УВАУ ГА (И). 2011. – 75 с. [In Russian: *Fundamentals of the theory of aviation ergatic systems study guide*]. Available at: http://venec.ulstu.ru/lib/disk/2015/Mekhonoshin_11.pdf.
4. Макаров, Н.Н. *Системы обеспечения безопасности функционирования элементов бортового эргатического комплекса в контуре управления летательного аппарата.* Научная электронная библиотека диссертаций и авторефератов. [In Russian: *Security systems for the operation of elements of the on-board ergatic complex in the control circuit of the aircraft].* Available at: http://www.dissercat.com/content/sistemy-obespecheniya-bezopasnosti-funktsionirovaniya-elementov-bortovogo-ergaticheskogo-kom#ixzz5VLqlshxY.
5. Уфимский Государственный Авиационный Технический Университет. Лекции по АП и ИВК / Лекции / Глава 16. *Средства отражения информации.* [In Russian: *Layout of aviation ergatic systems*]. Available at: https://studfiles.net/preview/942781/page:5/.
6. Либерман, А.Н. *Техногенная безопасность: человеческий фактор,* Издание осуществлено при поддержке Центра информатики „Гамма-7” Санкт-Петербург 2006 [In Russian: *Technogenic safety*: *the human factor*]. Available at: http://liberman.de/books/arkadi_n_liberman_technological_safety.pdf.
7. Sheard. S. *Aircraft Systems*: *Three Principles for Mitigating Complexity.* Available at: https://insights.sei.cmu.edu/author/sarah-sheard/.
8. Downer, J. *When Failure is an Option.* Available at: https://gulfnews.com/opinion/off-cuff/when-failure-is-an-option-1.2117729.
9. Masrtensson, L. *Are operators and pilots in control of complex systems?* Division of Work Science/INDEK. The Royal Institute of Technology, S-100 44 Stockholm. Sweden, 1998. Available at: https://www.sciencedirect.com/science/article/abs/pii/S096706619800197X.
10. Bibby, C.J. & Green, R.E. & Pepler, G.R.M. & Pepler, P.A. Sedge Warbler migration and Reed Aphids. *Brit. Birds.* 1976. Vol. 69. P. 384-399.

Received 21.01.2018; accepted in revised form 10.06.2019