THE MODEL OF ONE-TYPE AIRCRAFT FLEET BEHAVIOUR WHILE SERVICE AND ADVANTAGES SHM V. NDT IMPLEMENTATION

MODEL ZACHOWANIA SIĘ FLOTY SAMOLOTÓW JEDNEGO TYPU W PROCESIE EKSPLOATACJI ORAZ WSKAZANIE ZALET WPROWADZENIA SYSTEMU DIAGNOSTYKI CIĄGŁEJ SHM W PORÓWNANIU Z NDT

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Abstract: The paper defines the essence of durability characteristics of the designing structure of an airframe in terms of flight safety. Particular attention is drawn to one of the main factors influencing the durability characteristics of the airframe – diagnostics system for the health assessment of the airframe during the process of operation. The effectiveness of the use of integrated solutions to the structure of the airframe providing a continuous assessment of the technical condition is presented. Continuous diagnostics system integrated with the airframe, SHM, is classified as an intelligent solution. This paper presents a model of the behavior of one-type aircraft operating in the air operator's fleet in terms of susceptibility to failure. Justified assumption in the description of this behavior, in the form of a "bathtub curve". The analysis is supported by real data of failures. The benefits of using a continuous diagnostics system integrated with the airframe, SHM, is interpreted in relation to the classical approach with the use of non-destructive testing, NDT, for the three phases of the bathtub curve.

Keywords: civil aviation system, the air operator, airframe, durability, smart technology in health assessment, intensity of failures, diagnostics, NDT, SHM

Streszczenie: W analizie przedstawiono model zachowania się floty samolotów jednego typu w procesie eksploatacji. Analizę oparto na wyznaczeniu i ocenie funkcji intensywności uszkodzeń dla rzeczywistej floty. Przebieg krzywej w czasie eksploatacji pokrywa się z przebiegiem „krzywej wannowej”. Na tej podstawie „krzywą wannową” przyjęto w interpretacji jakościowo przedstawionych zalet zastosowania diagnostyki inteligentnej, zintegrowanej ze strukturą płatowca, umożliwiającej ciągłą ocenę stanu technicznego w locie, w odniesieniu do metod diagnostycznych wykonywanych podczas postoju samolotu.

Słowa kluczowe: płatowiec, intensywność uszkodzeń modelowa, intensywność uszkodzeń rzeczywista, diagnostyka, NDT, SHM

1. Introduction

The aviation development is based on operational experience and know-how targeted at intelligent solutions, including the scope of the assessment of the condition. Design solutions are intelligent and based on intelligent materials and systems. Intelligent materials and systems are structures connecting the modern science of the construction materials with mechanics, electronics, and informatics. The intelligent system allows for detection, processing, diagnosis and response to environmental changes using feedback, often mimicking biological structures, providing adaptability to environmental conditions in the process of operation, using artificial intelligence in data processing, etc. The intelligent systems are designed in order to meet specific properties, including the regeneration, self-diagnosis, self-repair, removing errors of particular system components. This paper presents the benefits of the introduction of a diagnostic system, classified as an intelligent solution, integrated with the structure of the airframe. The analysis was supported by an indication of the efficiency of intelligent diagnosis in relation to changes in the characteristics of the real data of failures as a base curve. The "bathtub curve" was adopted as the base curve (Fig. 1).

Fig. 1 The theoretical course of the real data of failures in the process of operation for a structurally complex technical object

This assumption was supported by the results of the actual operation of one-type aircrafts of the fleet of an air operator (Fig. 2).

Fig. 2 The actual course of the real data failure for seven one-type aircrafts of the air operator, while six aircrafts were introduced at the same time, and the seventh one – after two-year operation of the aircrafts of a given type in the fleet (on the basis of [11])

The infant mortality period is characterised with an increase of the failure intensity exceeding the level of failure intensity characteristic for the so-called normal life period. This period is the manifest of: (1) design errors, (2) breach of production quality, and (3) lack of knowledge resulting from the lack of operational experience. The purchase of a technologically new aircraft is a risk of unplanned failure resulting from the lack of operational experience causing the unplanned services intensification in the initial phase of the operation. From the point of view of risk and uncertainty of the operation, the second phase of normal life is preferred. After this phase, the aircraft enters the third phase – the phase of intensification of aging and wear processes. In the third phase of the operation, there is the greatest uncertainty in modelling the planned and unplanned services resulting from the change of strength characteristics of the used construction materials and connections for the population of aircrafts of a given type.

Due to the existence of the three phases in the aircraft's operation, it is important to articulate the factors influencing the durability in the design with its effective development; in studies of durability proposed in the design with the uncertainty analysis of the accepted models and the uncertainty analysis of acquiring and processing data into useful information about the condition of the airframe construction structure. Using this course, the paper illustrated the advantages of the implementation of continuous diagnostics systems integrated with the airframe

construction structure in relation to the currently used diagnostic systems based on conventional non-destructive testing – NDT – performed during hangar services. In the analysis of measurement data, statistical analyses are used, and a defined distribution of a random variable of usability time is assumed. This assumption has to be verified during the operation process on the basis of the statistical data analysis with the use of parametric and non-parametric methods.

The development of research with a focus on the use of the intelligent diagnosis is due to the laws and principles of operational thinking. The laws and principles of operational thinking given in [5] and developed in the subsequent volumes of the [6-10] monograph series generate an increase in safety and reliability characteristics of the aircraft, including its airframe, while minimising weight, maximising operational vulnerabilities and protecting the structure from structural failure affecting flight safety through applications of the continuous diagnostics integrated with the construction structure of the aircraft design and extension of the approach in the analysis of structure safety with the analysis of uncertainties in the assessment and supervision of the durability of the structure.

Very high operating costs are an important aspect. They are the operational costs that are attributed to the largest share of common costs for the aircraft fleet of the air operator, including 12-18% (according to different sources) incurred for service and repair. Maintenance and repairs costs, including those planned and unplanned, incurred for maintenance of the airframe's state of usability, are the result of degradation processes. The degradation processes cause failures. Effective prevention from them and mitigation of the effects of possible failure must be effectively referred during the design process and, at this stage, the operating costs can be best reduced with the research in determination of the causes and consequences of the possible failure.

The air operator needs effective decision support tools in order to ensure the required level of safety and to minimise operating costs of the fleet operation. Such activities are the result of the application of the philosophy of operation focused on actions preventing threats causing damages to the structure of the airframe construction with the use of prevention services in accordance with the technical condition (Condition Based Monitoring, CBM) [3, 4]. The use of CBM generates the demand for innovative, quick, and reliable methods of assessment of the technical condition, [12, 14] including the traditional non-destructive testing, NDT, and diagnostics systems built on the airframe, SHM. The effective tool in the assessment of the technical condition of the airframe is the self-diagnosis based on a sensor network integrated with the structure of the airframe in order to determine the changes in the structure evaluating the technical condition in two operating statuses. Operational decisions in the SHM are taken on the basis of the results of the statistical evaluation of the failure patterns recognition [1], [2].

2. Relationship of the airframe durability with diagnosis

The airframe durability is seen as an operational property providing macroscopic coherence and structural integrity with defined certainty and is shaped within the system of relationships between a designer/manufacturer, an operator and the air control. Requirements for securing optimal durability taking into account other operating properties are the durability characteristics. The durability characteristics of the airframe include (1) shaping durability at stages before operation: design and manufacture stages; (2) proving durability proposed in the design using accelerated test methods, and (3) the durability management in the process of operation in order to ensure the continuous usability of the aircraft of a given type. Durability is one of the eight dimensions of quality [14]. Therefore, the durability characteristics of the construction structure of the airframe design constitute its design property expressing adaptation/adaptability to operation with a defined certainty/quality supported by quality at the manufacture stage and managed by the quality in the operation process providing a required/ high level of safety.

Development of the operation potential renewal used in the sub-system of the aircraft's use on the basis of the current condition is an important issue in the durability development. The assessment of the condition is executed using periodical inspection, or collection of the data from the diagnostic system built on the airframe. Such developments are the basis of the inclusion of the aircraft to the existing fleet in the company, in which there is a specified continuous usability management system and which generates operating costs incurred by the air operator for services and repairs. So, the effective action is the use of preventive technical services in accordance with the condition, which generates demand for innovative, quick and reliable methods of the condition evaluation.

An important element of the durability development included in construction and research works is the development of the system and the programme of the aircraft operation, including, in particular, the development of the diagnostic system, emphasising diagnostics integrated with the airframe structure. The diagnostics system integrated with the airframe structure enables its continuous, current condition's assessment, or collection of data for such an assessment, used in an external system in relation to the aircraft structure, including ground systems. As a result of the conducted analyses, a set of requirements and recommendations regarding the extent and the frequency of the planned surveys, kinds and tools of service, way and extent of repairs, as well as many other requirements that the user must meet in order to obtain a certificate of flight usability using two kinds of diagnostics systems: the (1) internal one – built on the airframe, collecting data during the flight, as an intelligent diagnostics system SHM, and the (2) external

one, requiring hangar service as a diagnostic system using traditional methods of non-destructive tests, NDT. Such developments are the basis of the inclusion of the aircraft to the existing fleet in the company, in which there is a specified continuous flight usability management system.

Developed at the stage of the aircraft's design, the system of its operation should be characterised with adaptability and provide the opportunity to adapt the aircraft to the existing operation system of the air operator. Reliable methods of assessing the condition and prediction of failures for the purposes of effective determination of preventive actions are sought. These systems consist of a sensor network placed on the surfaces of the structural elements of the airframe, or introduced into the internal structure, for composites, in the process of their manufacture. Information is obtained on the basis of an assessment of symptoms for two states of the construction structure.

Symptoms indicating dangerous changes, threatening with failure, are determined in the reliability and durability accelerated tests. The data about the condition of the airframe's structure from the diagnostic systems integrated with it influence reduction of uncertainty and, thus, increase the construction's safety. These methods use the latest achievements in the rapidly developing field of scientific research, *the structural health monitoring and failure prognosis* (SHM&DP), covering research in the scope of the assessment of the condition of the construction structure and modelling of future behaviour, and they are classified as intelligent solutions. The sources of knowledge in the field of research and development of the SHM method are monographs, including [2], the enormous number of publications in scientific journals, including the *Structural Health Monitoring: An International Journal*, *The Journal of Civil Structural Health Monitoring*, *The Journal Structural Control and Health Monitoring*. Workshops on this subject are organised, including the international one, organised annually at the Stanford University: International Workshop on Structural Health Monitoring; in Europe – every two years: The European Workshop on Structural Health Monitoring, on an annual basis; in Australia: Annual Workshop for Australian Network of Structural Health Monitoring; in Asia: Asia Pacific Workshop on Structural Health Monitoring. A compendium of knowledge on the SHM, in the form of an encyclopaedia, was collected in the [Encyclopedia of Structural Health Monitoring, eds. Boller C., Chang F.-K., Fujino Y., John Wiley&Sons Publishing House, Chichester, UK, 2009].

The diagnostic systems developed at the design stage can be modernised at the operation stage for the specified reliability structure, but it must be kept in mind that the division into reliability elements is subjective and based on the know-how.

3. SHM system versus NDT

Figures 3÷6 present the courses of real data of failures showing the efficiency of application of the diagnostics systems integrated with the structure of the airframe – SHM – in comparison with the use of hangar services based on the classic non-destructive tests – NDT.

The three particular periods on the "bathtub curve" (Fig. 3), showing the behaviour of the one-type aircraft fleet, including I – the infant mortality period, II – the normal life period, and III – the period of increase in failure intensity associated with the intensification of aging and wear processes, can be optimised, and the failure intensity minimised with the application of continuous diagnostic systems integrated with the structure of the aircraft, including its airframe. The application of the SHM diagnostic systems shortens periods I and III and extends period II.

Fig. 3 The courses of real data of failures showing the efficiency of application of the diagnostics systems integrated with the structure of the airframe – SHM – in comparison with the use of hangar services based on the classic non-destructive tests – NDT

The infant mortality period may be reduced with the application of a continuous diagnostic system integrated with the structure of the aircraft, including the airframe. The SHM diagnostics system will also reduce the maximum failure intensity of the infant mortality period (Fig. 4).

During the normal life period, a constant failure intensity associated with accidental failures is assumed. The level of failure intensity is determined through reliability tests for the population of samples.

Fig. 4 Representation of the advantages of the application of the system of the diagnosis integrated with the structure of the airframe – SHM – in comparison with the use of hangar services based on the classic non-destructive testing – NDT – for the first period of the "bathtub curve"

The inversion of the intensity failure ratio is assumed as the average time between failures. Since this time, the derogation referred to as the standard deviation which is the square root of the variance defining the central of the second row has been possible. Therefore, the designated maintenance period times depend on the adopted model for the distribution of a random variable of the usability time,

which is dependent on the measuring data, which, in turn, is dependent on the applied system of diagnosis. The assumed distribution should be verified in the process of operation with collection of information about failures in the usage process. The parametric distributions have a limited ability to approximate distributions due to the limited known number of such distributions in the knowledge base. With the big amount of data, it is possible to use non-parametric methods, which better define the distribution of a random variable of usability time. The data from the SHM diagnostic system continuously and proactively approximate the failure intensity to the natural one for a given population (fig. 5). The verified surveys and the resulting effective renewal extend the normal life period, preventing operating failures.

Fig. 5 The courses of real data of failures showing the efficiency of application of the diagnostics systems integrated with the structure of the airframe – SHM – in comparison with the use of hangar services based on the classic non-destructive tests – NDT for the second period characteristic for the "bathtub curve" – the so-called normal life period.

The last phase of operation of the aircraft in the fleet of the air operator is the period of intensification of aging and wear processes resulting from the characteristics of the materials and their combinations used in the construction of

the aircraft. This period may be postponed in time and/or mitigated with the SHM diagnosis and the effective renewal of the operation potential (Fig. 6).

Fig. 6 The courses of real data of failures showing the efficiency of application of the diagnostics systems integrated with the structure of the airframe – SHM – in comparison with the use of hangar services based on the classic non-destructive tests – NDT for the third period characteristic for the "bathtub curve" – the life wear-out period.

4. Conclusion

The development of the adaptive model of the future operation system, taking into account randomisation, with particular direction towards the diagnostics system for the assessment of its condition and the development of activities preventing failures in order to eliminate threats with catastrophic failures and to restrict the occurrence of unplanned services, is the key problem in the reliability development of the airframe. The reliability characteristics of the aircraft, taking into account the particular phases of the "bathtub curve", should have a property of adaptability, adaptability to the operation system, and shape the relationship between the subsystems of the usage and the maintenance of the fleet in the continuous flight usability. The collection of data for the assessment from the intelligent diagnostics

system built in the airframe based on the sensor network-based, integrated with the system of information collection and processing, is the most effective way of condition assessment. Information is obtained on the basis of occurrence of symptoms resulting from the change of the states of the airframe's construction structure.

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