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On the matter of the terminology of aeronautical structures survivability

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Abstract. Aim. *The paper examines the existing definitions of survivability and damage tolerance (operational survivability) of aeronautical structures. An attempt is made to unambiguously define the survivability of aeronautical structures that can subsequently be extended to an aircraft as a whole and other complex technical items. The primary goal of this paper is to clearly distinguish between dependability and survivability. In order to ensure efficient operation and flight safety, an aircraft must possess airworthiness, a comprehensive characteristic of an aircraft that is defined by the implemented design principles and solutions and that allows performing safe flights under expected conditions and under the established methods of operation. The expected operating conditions are described in the Aviation Regulations – Airworthiness Requirements. Despite the fact that compliance with the Airworthiness Requirements ensures a sufficiently high level of flight safety, the most vital structural components are designed in such a way as to remain operable even under extreme conditions beyond the expected operating conditions. But dependability cannot be responsible for operability outside the expected operating conditions. Conclusion suggests itself that under extreme conditions beyond the expected operating conditions operability is to be ensured by another property, i.e. survivability.* **Methods.** *This research was conducted using the logical and probabilistic approaches. The author examined literary sources primarily dedicated to the matters of dependability and survivability of aeronautical structures, as well as other complex technical items. In order to ensure an optimal understanding of the differences and correlation between the concepts of dependability and survivability, the probabilistic approach was used.* **Results.** *Upon the analysis of literary sources, survivability was defined as the property of an item to retain in time the capability to perform the required functions under extreme conditions beyond the expected operating conditions under the specified methods of maintenance, storage and transportation. Additionally, the paper proposes the definition of damage tolerance (operational survivability) as the property of an item to retain in time the capability to perform the required functions under extreme conditions beyond the expected operating conditions depending on the methods of maintenance, storage and transportation. The probabilistic approach to the delimitation of the concepts of dependability and survivability of aeronautical structures was examined using the known indicator of operating efficiency of a transport aircraft that is represented as the mathematical expectation of the efficiency indicator. An aircraft may be either in the expected operating conditions or in extreme conditions beyond the expected operating conditions. No third option exists. Then, the sum of the probabilities of an aircraft encountering such conditions must be equal to one. The probability of no-failure can be calculated by means of the probability of the contrary event, i.e. the probability of failure that can be represented as the product of the probability of an aircraft encountering certain operating conditions and the probability of failure in such conditions. For the case of extreme conditions beyond the expected conditions the well-known concepts of perishability and vulnerability with the author's improvements can be used.* **Conclusions.** *A definition of survivability was obtained that is clearly different from the concepts of dependability and fail-safety. Additionally, the concept of damage tolerance (operational survivability) was proposed that was introduced similarly to the previously introduced concept of operational dependability.*

Keyword: *survivability, damage tolerance (operational survivability), dependability, failure, reliability, fail-safety, aeronautical structure, aircraft.*

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Introduction

Any aircraft is characterized by a wide range of properties and parameter, including operating properties, i.e. the set of aircraft properties that manifest themselves in the course of operation. They include dependability, survivability, safety and maintainability. Whereas the terms dependability, safety and maintainability are covered in sufficient detail and with sufficient consistency in specialized literature, and some terms are even part of corresponding standards, the term "survivability" does not have an unambiguous and generally accepted definition. That is true not only in case of the aircraft survivability terminology, but that of other items as well [1–5].

In this paper, an attempt is made to unambiguously define the survivability of aeronautical structures that can subsequently be extended to an aircraft as a whole and other complex technical items. The primary goal of this paper is to clearly distinguish between the concepts of dependability and survivability.

Primary concepts and definitions of the theory of survivability of aeronautical structures

In order to ensure efficient operation and flight safety, an aircraft must possess airworthiness that is defined by its design and is maintained in operation. *Airworthiness* is a comprehensive characteristic of an aircraft defined by the implemented design principles and solutions that allows performing safe flights under expected conditions and under the established methods of operation [6]. Airworthiness Requirements of transport aircraft [7] define *expected operating conditions* as the conditions that are known from practice or whose occurrence can be reasonably predicted within the useful life of an aircraft subject to its purpose. Such conditions include state parameters and external factors that affect an aircraft, operational factors that affect flight safety.

The expected operating conditions do not include the following:

– extreme conditions that can be reliably avoided by introducing operating restrictions and rules,

– extreme conditions that occur so rarely, that observing the Airworthiness Requirements in such conditions would result in a higher level of airworthiness than required and practical.

Airworthiness depends on the *dependability* of the aircraft, including the dependability of its structure that, in turn, is defined by its strength.

At the stage of design, an aircraft's airworthiness in terms of strength is ensured by correct choice of design solutions, strength, stiffness and fatigue calculations and testing.

In the course of aircraft operation, fatigue and corrosion damage, destruction of non-metallic materials, exposure to extreme operating conditions beyond the expected conditions may cause the loss of airworthiness in terms of structural strength. In this context, aircraft operation requires maintaining its airworthiness by means of appropriate measures as part of service and repair operations.

Despite the fact that compliance with the Airworthiness Requirements ensures a sufficiently high level of flight safety, the most vital structural components are designed in such a way as to remain operable even under extreme conditions beyond the expected operating conditions. But dependability cannot be responsible for operability outside the expected operating conditions, as in accordance with GOST 27.002-2015 Dependability in technics. Terms and definitions [8] dependability is a property of an item to retain in time the ability to perform the required functions in *specified modes and conditions of application*, maintenance, storage and transportation, while in accordance with the terminology of the Airworthiness Requirements, the specified modes and conditions of application are to be understood as the *expected operating conditions*. Conclusion suggests itself that under extreme conditions beyond the expected operating conditions operability is to be ensured by another property, i.e. *survivability*. But does any of the existing definitions of survivability fit this purpose? Let us examine the existing terminology of survivability of aeronautical structures and aircraft as a whole.

Currently, terminology of survivability is not represented in any Russian national standard. In the previous version of the above standard (GOST 27.002-89, [9]) the dependability terminology was covered in an annex, in which survivability was defined, but it was done so in three different ways, which did not contribute to a clear understanding of the term. Let us take a look at those definitions. Survivability is understood as:

1) property of an item that consists in its ability to resist the development of critical failures from defects and damage under the adopted system of service and repair,

or

2) property of an item to retain limited operability when exposed to effects not provided for by the operating conditions,

or

3) property of an item to retain limited operability in the presence of defects or damage of a certain type, as well as in case of failure of some components. An example would be the retaining of the carrying capacity by structural components affected by fatigue cracks whose size does not exceed the specified values.

That is a classification of sorts of the existing definitions of survivability. In the literature dedicated to the survivability of aeronautical structures all of the three above definitions are used to various extents, but the third one is the most common. Let us give examples of the survivability definitions of this type:

– survivability is the property of a structure to retain strength when damaged (including fatigue damage) [10],

– survivability is the property of a structure to perform its functions despite the sustained damage of various nature [11].

In accordance with these definitions, in case of any damage the operability of a structure will depend on its survivability. But a structure may sustain damage under expected operating conditions. That may be the case of partial failures caused, among other things, by design flaws, poor quality of structural components manufacture. Examples include fatigue failure of elements due to miscalculations of fatigue endurance or defects caused at the stage of manufacture of parts that prove to be stress raisers.

If a structure has redundant elements, i.e. its design complies with the principle of safe destruction, the remaining structural components will ensure design load accommodation and the structure as a whole will remain operable. But then the concept of survivability overlaps with the concept of reliability that is a component of dependability. In accordance with [8], *reliability* is a property of an item to continuously retain the ability to perform the required functions during a certain period of time or operation time in specified modes and conditions of application, i.e. under the expected operating conditions in terms of the Airworthiness Requirements. As it is known, component redundancy is one of the simplest ways of improving reliability. If one or even several parallel elements (in case of multiple redundancy) fail, the remaining elements will ensure the operability of the item or its system. Then, what is the difference between the above definitions of survivability and reliability? It is obvious that the difference can only be in the operating conditions, under which a defect or partial failure occurred. If it happened under the expected operating conditions, the operability must be ensured by the dependability (reliability), if it happened under extreme operating conditions beyond the expected conditions, the operability must be ensured by the survivability. But the above definitions of survivability say nothing about that.

Some papers use the term "damage tolerance (operational survivability)" along or instead of "survivability". The understanding of this term varies too. Let us examine the following definitions:

– damage tolerance (operational survivability) is a property that ensures normal performance of the specified functions by all systems of an aircraft in flight in case of failures or damage to individual assemblies, elements, units [12],

– damage tolerance (operational survivability) of aeronautical structures is a property of structures of an aircraft to ensure safe operation in terms of strength in case of partial or complete destruction of load-carrying elements due to fatigue, corrosion, accidental damage in operation, or damage caused in the process of manufacture and repairs [13].

In terms of their meanings, those definitions are no different from the above definitions of survivability, while the word "operational" is apparently used to indicate that in this case combat survivability is not implied – the latter being the kind of survivability associated with the effects of munitions – and only survivability in "normal" operation is covered.

But in some works [10, 11] the concept of "damage tolerance (operational survivability)" implies something different:

damage tolerance (operational survivability) is a generalized term that characterizes the properties of a structure and ways of ensuring its safety in terms of strength and includes the allowability of damage and safety of destruction (damage). *Allowability of damage* is a property of a structure and way of ensuring its safety in terms of strength by specifying the time of the first and subsequent inspections of the structure in operation in order to detect possible damage and repairs or replacement of the damaged element before the onset of such state, when degraded strength is unacceptable. *Safety of destruction (damage)* is a property of a structure and way of ensuring its safety in terms of strength by designing a structure in which, after possible significant damage or destruction of one of the main load-carrying elements, the residual strength, despite the structure being unrepaired, will not go below the allowed level over an interval of time, within which the damage (destruction) will be undoubtedly identified.

This definition is quite cumbersome and complex, but essentially it comes down to survivability being the property that ensures safety through the capability to resists the development of critical failures out of defects. This understanding of damage tolerance (operational survivability) can be attributed to the first type of definitions in the above classification of definitions of survivability. But in this case, it overlaps with the standardized definition of *fail-safety,* the property of an aircraft as a whole and/or its functional systems that characterizes the capability to ensure safe completion of the flight in the expected operating conditions in case of possible failures onboard [14].

Given the above, the second type of definitions of survivability appears to be the most logical and consistent. In [15], a definition is set forth that is the closest to the second type: survivability is the property of an airplane to retain its operability when affected by projectiles and off-design loads, as well as subject to the existence of accumulated damage.

If we remove "as well as subject to the existence of accumulated damage" from this definition, it can be deemed quite acceptable.

Thus, similarly to the above definition of dependability, survivability can be defined as follows:

survivability is the property of an item to retain in time the capability to perform the required functions under extreme conditions beyond the expected operating conditions under the specified methods of maintenance, storage and transportation.

Thus, any item or aircraft may be, among other things, either in the expected operating conditions, or in extreme operating conditions beyond the expected operating conditions. No third option exists. Under expected operating conditions the operability of an item is the responsibility of dependability, while under extreme operating conditions it is the responsibility of survivability.

The concept of "damage tolerance (operational survivability)" has the right to exist as well. If we examine the definition of dependability and the above recommended definition of survivability, in both cases the specified methods of maintenance, storage and transportation are covered. But real operating conditions are characterized by a significant variety and instability due to the varied environmental conditions, level of training of the flight and maintenance personnel, physical infrastructure, organization of service and repair, etc. Thus, the methods and conditions of maintenance, storage and transportation of an item may differ from the specified ones. Due to that [16] introduced the concept of *operational dependability* that can be formulated as follows: the property of an item to retain in time the capability to perform the required functions under the expected operating conditions depending on the methods and conditions of maintenance, storage and transportation. Similarly to this definition the definition of *damage tolerance (operational survivability)* can be formulated as the property of an item to retain in time the capability to perform the required functions under extreme conditions beyond the expected operating conditions depending on the methods of maintenance, storage and transportation.

Thus, dependability and survivability are interrelated, yet clearly delimitated concepts each of which has its own area of responsibility.

In order to better understand this delimitation, let us examine the difference and correlation between the dependability and survivability using the probabilistic approach.

Probabilistic approach to the delimitation of the concepts of dependability and survivability of aeronautical structures

In order to ensure a better understanding of the differences and correlation between the concepts of dependability and survivability, let us use the approach described in [15].

Let use examine the indicator of operating efficiency of a transport aircraft that can be represented in the form of mathematical expectation:

$$W = W_0 P_{dep} P_{sur},$$

where W_0 is the initial efficiency indicator that is defined by the aircraft's functional properties (most importantly its performance), under conditions of its absolute dependability and survivability. That may be, for instance, the indicator of productive capacity [17] $W_0 = m_{pl} L/m_0$, where m_{pl} is the maximum mass of payload, L is the flight distance with the maximum mass of payload, m_0 is the maximum takeoff mass of the aircraft,

P_{dep} is the dependability indicator (probability of retained operability under the expected operating conditions),

P_{sur} is the survivability indicator (probability of retained operability under extreme conditions beyond the expected operating conditions).

The dependability indicator can be represented as the product of probabilities:

$$P_{dep} = P_a P_f P_{ff},$$

where P_a is the availability coefficient,

P_f is the probability of flight execution under conditions of the aircraft being operable,

P_{ff} is the probability of no-failure during the flight under the expected operating conditions.

Let us examine these probabilities.

In order to perform the flight mission, an aircraft must be initially in the up state which depends on its availability. Quantitatively, that is evaluated with the corresponding probability P_a named availability coefficient.

In order to perform the flight mission, an aircraft, being in the up state, must conduct the flight. That depends on many factors, including managerial ones, but if we only talk about the aircraft properties, that depends, for instance, on the capabilities of the flight and navigation equipment (capability to ensure flights in nighttime, in poor weather conditions). The capability to conduct a flight under conditions of the aircraft being operable is defined by the corresponding conditional probability P_f.

However, during a flight, *special situations* may arise as the result of the effect of adverse factors or their combinations that cause reduced flight safety [7], including accidents and crashes that prevent the flight mission performance. Adverse factors include failures, extreme operating conditions, crew errors and maintenance errors.

In this classification of adverse factors, failures are normally understood as disruptions of operability that occur under expected operating conditions. They may include failures caused by design flaws, poor quality of structural components and aircraft equipment manufacture. The possibility of such failures is estimated by the corresponding probability Q_{fl}, while the probability of no-failure under the expected operating conditions is identified according to formula:

$$P_{ff} = 1 - Q_{exp} Q_{fl}, \tag{1}$$

where Q_{exp} is the probability of an aircraft encountering expected operating conditions.

As an aircraft, as stated above, may be either in the expected operating conditions, or in extreme conditions beyond the expected operating conditions while no third option exists, the sum of the probabilities of an aircraft encountering such conditions must be equal to one:

$$Q_{exp} + Q_{ext} = 1,$$

where Q_{ext} is the probability of an aircraft encountering extreme operating conditions.

Fortunately, $Q_{exp} >> Q_{ext}$, while $Q_{exp} \cong 1$, so in formula (1) it is usually omitted.

But failures may also be caused by an aircraft encountering extreme conditions beyond the expected operating conditions. In other words, failures may be caused by anomalous external effects (for instance, single gusts with the speed higher that the value specified in the Airworthiness Requirements, which can cause the destruction of structural components or appearance of permanent deformations, excessive continued air turbulence, whose parameters are also specified in the Airworthiness Requirements, which may cause premature depletion of operating life and, as consequence, fatigue failure of a structural component, effects of munition), crew error (for instance, hard touchdown or excess of maximum allowed value of maneuver load factor, which may cause the destruction of structural components or occurrence of permanent deformations) or maintenance error (for instance, damage to structural components as the result of careless performance of service and repair operations and, as consequence, premature fatigue failure). In this case mission performance relies on the survivability.

In accordance with [15], aircraft survivability is defined by the perishability and vulnerability. Let us make improvements to the definitions of these concepts in accordance with the above considerations. Then, *perishability* is the property of an aircraft that characterizes the possibility of it encountering extreme conditions beyond the expected operating conditions (the indicator of perishability is the probability of an aircraft encountering extreme operating conditions, Q_{ext}). *Vulnerability* is the property of an aircraft that characterizes the possibility of disruption of its operability as the result of effects beyond the expected operating conditions (the indicator of vulnerability is the probability of loss of aircraft operability under condition of effects beyond the expected operating conditions, Q_{vul}). Given the above, similarly to formula (1), the expression for the survivability indicator, i.e. probability of retained operability under extreme conditions, is as follows:

$$P_{sur} = 1 - Q_{ext}Q_{vul}.$$

Conclusion

In this paper, an attempt was made to unambiguously define the survivability of aeronautical structures. The obtained definition can be extended to an aircraft as a whole, as well as other complex technical objects.

There is no point in singling out the concept of combat survivability, since the effect of munitions is covered by the concept of the effects of adverse factors.

The advantage of the obtained definition of survivability consists in its clear difference from the standardized terms for dependability and fail-safety.

Additionally, the concept of damage tolerance (operational survivability) was proposed that was introduced similarly to the concept of operational dependability.

In the author's opinion there is a long-standing need to stipulate the concept of survivability in an appropriate national standard or at least issue an annex to GOST 27.002-2015 similar to an annex to the previously effective GOST 27.002-89, but taking into account the proposals made in this paper.

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