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SPECIFYING THE AIRCRAFT STRUCTURAL RELIABILITY OBJECTIVES ON THE BASIS OF FLIGHT SAFETY REQUIREMENTS

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ABSTRACT

The evolution of specifying reliability requirements is overviewed. Proposed is a flight safety indicator in the form of the probability of a catastrophic effect during the time interval required for an airplane or a helicopter to fulfil a fixed amount of the assigned air transportation. An illustration is given of a mathematical model that enables optimization of the structural reliability of a component on the basis of the proposed indicator.

1. INTRODUCTION

At the dawn of aviation history, no fewer than half of the aircraft accidents were caused by technical failures. The desired reliability was being approached empirically, that is, by trial and error as well as by paying a hard price in terms of losses, including life.

At present, for turbojet airliners involved in scheduled long-haul passenger operations failure-related occurrences account, at most, for a 10 - 15% of the total amount of major accidents. Whereas for military airplanes and helicopters, which are viewed as a kind of a test bed for developing innovative designs, this fraction is still on the level of 50% or sometimes more. As was the case almost one hundred years ago, finding solutions to the flight safety problem significantly depends even now on the key role of aircraft reliability.

A most important task in these activities is the specifying of the flight safety and structural-reliability objectives. The human life's unique value makes it hardly possible that a convincing justification of exposing a human being to risk will ever be found.

There is another approach to this problem. The means at the disposal of the community at large for ensuring flight safety are limited. Therefore, it is important to optimally allocate the resources to individual vital areas, in keeping with the maximum end result. The idea is to apply maximum effort to the least reliable links in the air transportation system.

This paper describes the results of my effort in investigating a specific problem according to the above-made point. In dealing with this problem and according to my supposition, the reliability of the given structure can be described as a function of mass. Therefore, this mass plays a role as an equivalent means for ensuring flight safety. In this case, an increase in reliability is achieved at the expense of a deterioration in some other capabilities which can also influence flight safety of the aircraft. Therefore under these conditions, we are faced with the problem of finding the optimal balance between the mass of the structural element and its reliability.

2. A historical outline

Attempts to substantiate analytically the reliability of the aircraft structure had been made long before the first successful aircraft flights took place. An AERONEF project, which was developed and presented by a Russian engineer, Savely Notkin, to the Russian Imperial Army General Engineering Department, in 1887, comprised a structural strength analysis of the wooden floor of the fuselage. In 1895, K.E. Tsiolkovsky's "An airplane or a bird-like (aviation) flying machine" was published, a work where the author effectively introduced the reliability coefficient in his calculations of the strength of the wing.

At the initial stage in aviation history, the majority of accidents were caused by engine failures as well as by deterioration in the strength of structural elements. In the 1920s and 30s, the structural strength standards for fixed-wing aircraft under static loads came into being. The Standards for Structural Strength of Airplanes that were introduced into practice in the former Soviet Union on August 1, 1927, established the levels of the accelerations and the values of the safety coefficients for the main design cases of the flight envelope. After that, the work on developing fatigue-strengh standards began in this country. In 1955, the Structural Strength Standards for Rotorcraft was introduced. This document, apart from static strength, established requirements for the dynamic strength of the main and tail rotors, as well as for a number of other mechanisms of the helicopter.

In the 1950s, a more general concept based on the probabilistic character of the factors determining the flight-safety level began to take shape. The growth of insight into these factors resulted in that the corresponding flight safety requirements were eventually formulated in terms of probabilities. One of the first ICAO documents, dating back to

1947, required to provide for such strength and methods of fabrication that could ensure the extremely remote probability of occurrence of a critical fatigue failure in the mainframe of the structure as well as in the components exposed to repeated loads during the proposed service life of an airplane. In his paper published in 1955, B.O. Lundberg presented arguments in favour of establishing the allowable probability of a critical failure in the structure of an airplane at the level of 10^{-9} per one flight hour.

At present, the national airworthiness regulations of various countries contain reliability related requirements formulated in probabilistic terms.

Substantiation of the reliability related requirements is usually based on the already achieved operational indicators. Analysis of aviation accidents and of their causes shows that there are sufficiently stable trends that characterize changes in the flight-safety indicators due to the calendar period, cumulative operating time of the fleet, the aicraft type and its role. Figure 1 depicts the domains within which the mean time to an accident T_{AC} for some aircraft types varied during the 90 years of aviation, and Figure 2 shows the best achieved values of T_{AC} as functions of the cumulative operating time of all the world's airplanes and helicopters. The turbojet airplanes in scheduled passenger operations are characterized by T_{AC} values that reach the level of 10^7 h; whereas the Mil-8, which is one of the more reliable helicopters, features the values of this indicator approaching 10^6 h. Based on the understanding that technical failures represent only one of a number of causes of catastrophic effect, the Aviation Regulations require that any occurrence of a catastrophic effect on-board an aircraft due to a functional failure or a combination of functional failures must belong to the class of extremely improbable events. Whenever there is a need to make a quantitative evaluation, it is assumed that the probability of such an event is equal to or smaller than 10^{-9} per one flight hour in the case of the Airworthiness Regulations for airplanes, and the analogous probability is equal to or smaller than 10^{-8} per flight hour for helicopters (NLGV-2, Russia).

The flight safety criterion in the form of probability of a catastrophic occurrence per flight hour has won a wide recognition.

The risk indicator measured in terms of probability of a fatal event during a fixed time period is used in a variety of branches of science, among which demography is just one case in point. The probability for a passenger to experience an aircraft accident during a one-hour flight can be compared with similar figures for other transportation means and other industries as well as with the probability of loss of life from natural causes for a person of a particular age group, place of residence, etc. It should be pointed out that an advantage as well as a disadvantage of this indicator is the fact that it is completely abstracted from, and in no way depends on the costs of achieving the corresponding safety level.

What undoubtedly constitutes a merit of this indicator is the implied idea that the human life is of infinite value. Furthermore, there is also a shortcoming that may manifest itself in a pervasive urge to increase reliability under any circumstance regardless of the expenditures involved. But overspending of limited available material resources in an attempt to solve one problem may adversely influence the solution of another problem whose importance may be by no means sionificant than the first one, from the viewpoint of achieving the end goal. The flight-safety problem should be aimed at minimizing the human as well as material losses that may be associated with the required amount of air transportation.

3. Optimization Model

The level of safety in air transportation, or indeed in any other field of activity, that can be actually attained is determined by the technological and economical means allocated by the community for this purpose. Therefore, developing reliable and safe aircraft involves inevitable constraints.

The indicators of structural reliability and flight safety that are based on the probabilities of the corresponding events (functional failures of the systems and occurrences having a catastrophic effect) during a fixed flying time are the variables of a monotonic function which shows that the greater reliability values correspond to the greater flight safety values, and vice versa. In reality however, if we take into account the reliability assurance costs as well as the technical and economical limitations that are imposed on the aircraft development programme, we are likely to find that the functional relationship between the attained indicators of reliability and safety is a multifactorial one.

The expendable means that are required for reliability assurance can be measured in terms of the structural mass, which is a parameter that is not affected by inflation and is easy to be accounted for. Based on the assumption that the structural mass veflects every property of the product, V.F.

Bolkhovitinov of the Zhykovsky Academy derived what has become known as the so-called existence equation for the airplane. Moreover, there is a large number of cases in which we can determine a quite distinct relationship between the structural mass and reliability in a rather straightforward way. For instance, such a relationship may be determined sufficiently easily in the case when a redundant functional element is being introduced into the system. It should be pointed out, however, that there are quite a few ways of enhancing reliability without causing any increase in the structural mass, namely: strengthening the metal surface of an item, decreasing the stress concentration, etc. Therefore, the formulation of the problem implies the assumption that all the available methods for ensuring higher reliability have already been implemented, and the only option left for the designer wishing to enhance the reliability still further is to increase the size of the design or introduce redundancy.

It becomes possible to optimize the reliability of the structure directly according to the flight-safety criterion, if the flight-safety indicator involved takes into account not only the rate ω of certain undesirable occurrences but also an indicator of the capability of the aircraft.

The combined indicator of flight safety determined as the probability of an accident resulting from any of the possible causes, per flight hour, can be calculated from the following formula:

$$Q_{AC} = \omega_{AC} \cdot \tau_{FLT},$$

where $\omega_{AC} = \omega_{AC}{}^{T} + \omega_{AC}{}^{OP}$ is the rate of aicraft accidents that occurred as a result of all the causes, namely, the technical failures, $\omega_{AC}{}^{T}$, as well as other operational events, $\omega_{AC}{}^{OP}$; and τ_{FLT} is the flight duration that is assigned a certain fixed value, for instance, one hour.

We then substitute the constant τ_{FLT} in the above indicator with the quantity τ_{REQ}, which is the time required for completing a certain specified (fixed) amount of air transport work. This superficially insignificant transformation does not only change the value of the flight safety indicator, but provides for applying alternative methods for investigating the flight safety problem.

After this transformation, it becomes impossible to compare the flight-safety levels of aircraft that are designed for different tasks; for example such, as the most modern airplane which is not capable to complete some of the helicopter tasks, and a rotorcraft.. However, the flight safety level becomes a function of the aircraft's capability in terms of the time required for completing the specified amount of air transportation.

Paper [1] examines the possibility to optimize the mass-reliability system of parameters on the basis of the above discussed flight safety criterion. The relationship between the mass and the *i*th structural element in the case of an exponential distribution of the longevity indicator is described in this case by a function having the following sufficiently general form:

$$|\omega_i|^* = |\omega_i|^{r^s},$$

where r is the coefficient of the change in the mass, s is a positive value whereas $|\omega_i|$ and $|\omega_i|^*$ are the failure rates for the *i*th element before and after optimization, respectively. Consider the criticality coefficient γ_i as the conditional probability of an accident occurring in the case of the *i*th element's failure.

According to the above point, the mean flight time to an accident, which is a parameter that determines the probability of such an event per flight hour, can be predicted with a sufficient accuracy for a given type of aircraft, depending on the duration of the operating period or on the cumulative operating time of a fleet of these aircraft. Therefore, the initial version of the prototype at the design stage is characterized by a predicted value of the indicator Q_{AC}. To verify whether a given structural element is designed in accordance with the optimal value of the proposed criterion, we should consider a design arrangement of this component that is modified so as to provide for a different reliability level as a result of a change in the component's mass. The relationship between the probabilities Q_{AC} and $Q_{AC}{}^*$ for the initial and modified versions of the component, respectively, can be written in the following form:

$$Q_{AC} = \alpha \cdot Q_{AC}{}^*,$$

where α is a nondimensional coefficient that is greater than unity if the design modification results in an increase in the safety level.

Then we compile the equation $\tau = F(r)$ and analyze it for extremes.

One of the possible optimization models is made clear below. Consider the development stage of a transport aircraft that must be designed within the constraints of the specified flight weight: an increase in the mass of an item causes a corresponding decrease in the aircraft payload. Therefore, an increase in reliability results in an additional increase in the mass of the component involved. One of the ultimate versions of the design may result in zero payload as well as in the minimal non-zero failure rate. This is the case for which the time τ_{REQ} tends to infinity and the probability of an accident that may be related to the failure of the given component approaches unity.

The other ultimate version is characterized by the structural mass approaching zero, the failure rate tending to infinity and the probability of an accident being close to unity. Between these two ultimate cases, there exists an optimal set of the mass and reliability values for the component, in the sense that the corresponding probability of an accident is minimal.

The analysis of the mathematical model yields the relationship between the optimal values of the falure rate and the structural mass of the component in the following generalized form:

$$\omega_i \cdot \ln \omega_i = - \bar{m}_i \cdot \omega_{KC} \cdot K / \gamma_i ,$$

where m_i is the ratio of the mass of the component to the payload m_{PL} of the aircraft and K is the factor determined by the value s as well as by the conditions under which the given airlift work is supposed to be done. This factor attains the value $K = 1$ for $s = 1$ when the following condition holds true:

$$\tau_{REQ} = W / m_{PL} ,$$

where W is the fixed amount of airlift work.

The difference in the approaches to specifying the reliability requirements on the basis of the conventional and proposed flight safety indicators, respectively, is illustrated in Figure 3.

The structural components whose damage builds up increasingly in the course of operation, and consequently, whose life is determined by either the lognormal or Weibull distribution can be characterized by the optimal service life limit that is a function of not only the parameters of longevity but of the mass of the component as well.

4. Conclusions

One of the notable and sufficienty clear results of this investigation is the relationship between the optimal value of the safety indicator of a given item and the item's mass. As the design process advances through the stages during which more detailed features of the structure are being finalized, the reliability requirements applicable to these items become increasingly stricter. It means that under otherwise equal conditions, including the same criticality of all the items, the required reliability of a bolt, for instance, will be stricter than the required reliability of the entire assembly comprising this bolt.

It may be rather difficult to agree with the other result of this investigation that implies the possibility of a decrease in flight safety when there is an increase in reliability of the structure. Regarding this, one should take into account the following two circumstances:

(a) The proposed relationship between the optimal value of the safety indicator and the mass of the item holds true only in the case when the former parameter is determined as the probability of a catastrophic event during the time interval that is a function of the capability of the aircraft to fulfil a specified amount of airlift work. The probability of such an event during a fixed period of time, for instance during an hour, is a monotonic function of reliability of the structure.

(b) The above discussed investigation is made under assumption that any increase in reliability requires an increase in mass.

Application of the proposed flight safety indicator significantly eases the ethical aspect related to setting up the standards for the risk to human life. Instead of such standards, which are always open to some sort of criticism, it is sufficient to evaluate the expected flight safety level for the aircraft at the design stage.

The above-discussed optimization of the mass-reliability parametric system on the basis of the flight safety criterion, despite its importance, remains only a problem of limited scope. To broaden the setting of this problem, we should take into consideration the entire air transportation system and optimize the reliability for each of its components.

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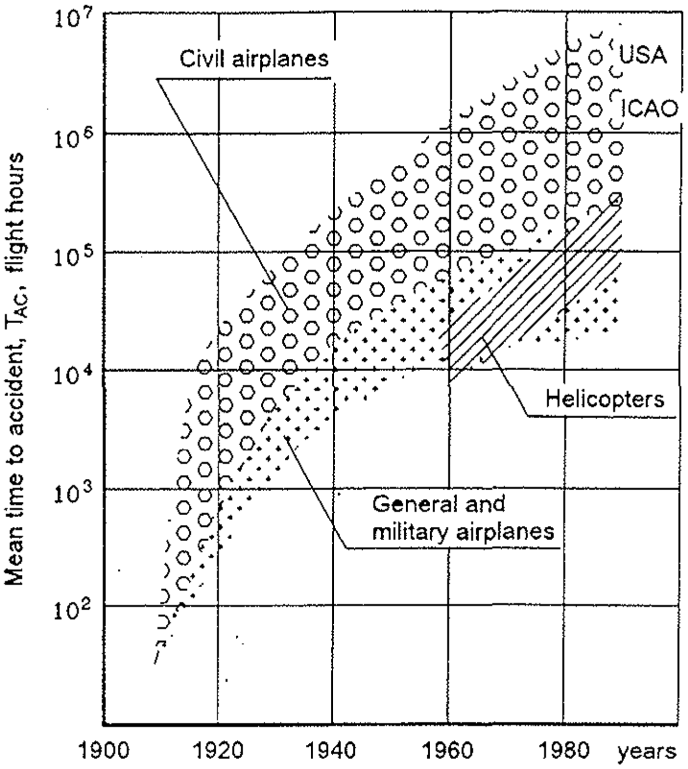


Figure 1. Domains of the changes in T_{AC} values for airplanes and helicopters

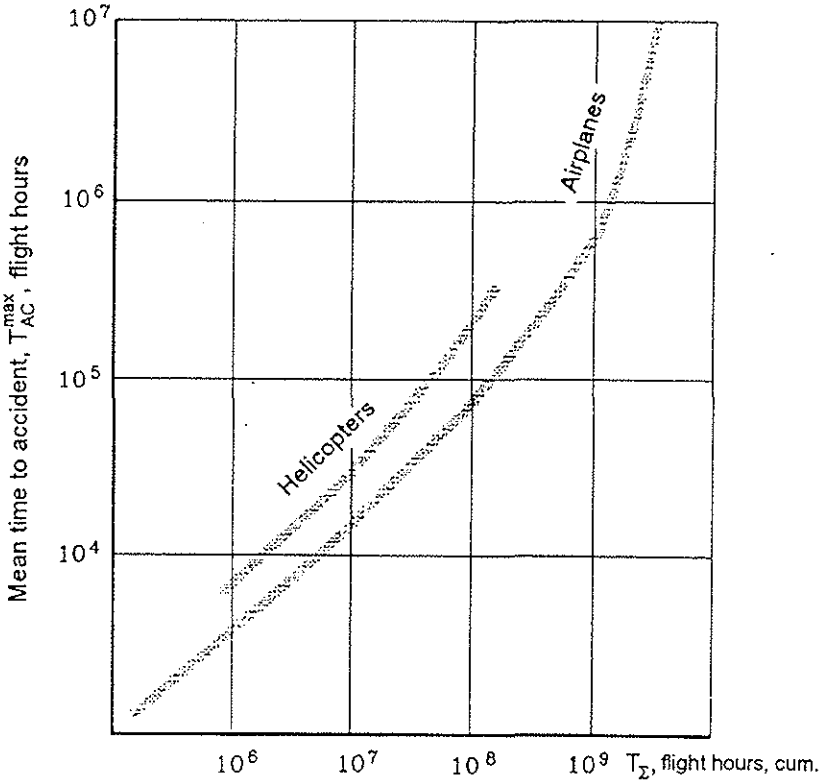


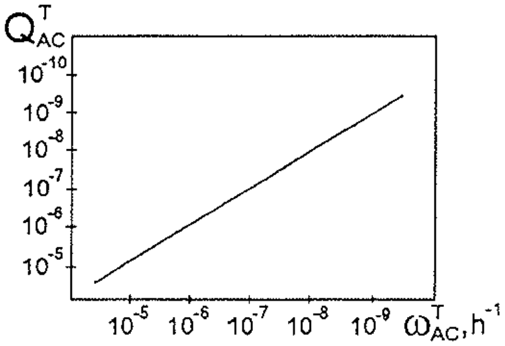
Figure 2. Indicator T_{AC}^{max} as a function of the cumulative in-flight operating time of the world's airplanes and helicopters

Airworthiness regulations

$$Q_{AC}^{T(*)} = \omega_{AC}^{T} \times \tau_{FLT}$$

for $\tau_{FLT} = 1h$

$$Q_{AC} = 10^{-9}$$



Safety Indicator Involved in the Analysis

$$Q_{AC} = \omega_{AC} \times \tau_{REQ}, \qquad \omega_{AC} = \omega_{AC}^{OP} + \omega_{AC}^{T}$$

where ω_{AC} - predicted rate of catastrophic occurrences related to all causes

τ_{REQ} - required time for completing the specified amount of operating work

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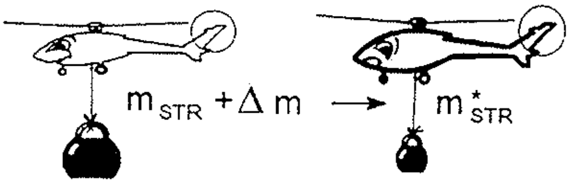
Aircraft parameters:

Total Mass	M_A	(const)
Mass of the Structure	m_{STR}	(var)
Payload	m_{PL}	(var)

$$M_A = m_{STR} + m_{PL}$$



$$m_{STR} + \Delta m \longrightarrow m^{*}_{STR}$$

$$m_{PL} - \Delta m \longrightarrow m^{*}_{PL}$$

$$\omega_{AC} \times \tau_{FLT} = \alpha \times \omega^{*}_{AC}\downarrow \times \tau^{*}_{REQ}\uparrow$$

Optimisation of the system of m_i and ω_i parameters for a structural element

Versions

Initial Optimized

$m_i; \omega_i$ $m_i^*; \omega_i^*$

$$\frac{m_i^*}{m_i} = r \qquad |\omega_i| = |\omega_i^*|^r$$

$$\omega_{i\,OPT} \ln \omega_{i\,OPT} = -\frac{\overline{m}_i \times \omega_{AC}}{\gamma}$$

where

$$\overline{m}_i = \frac{m_i}{m_{i\,PL}};$$

γ - criticality coefficient of the element

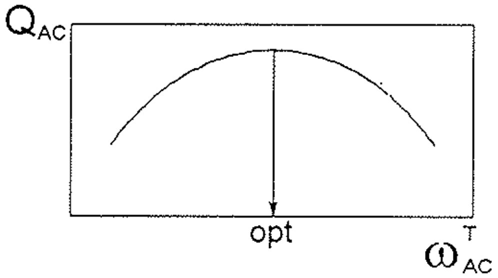


Figure 3. Specifying the structural reliability objectives on the basis of the safety requirements