Methodology for assessing the effectiveness of design and technological solutions in ensuring the service life of power connections of structures

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Abstract: A methodology for designing the load-bearing capacity of power parts of machines and structures operating under variable loading conditions is presented, which allows assessing the effectiveness of design and technological solutions based on the criteria of fatigue strength, durability and guaranteed service life. The technique is based on the force calculation of parts and assemblies, the formation of an equivalent block of variable loading, the calculation of the endurance limit in a statistical aspect and the determination of the fatigue life at a given level of reliability. The presented methodology is based on a specific example of calculating and assessing the durability of the elements of the fork connector of the fin and fuselage of a passenger aircraft.

1 Introduction

Predicting the load-bearing capacity of load-bearing elements and structural units using an integrated methodology for calculating strength and fatigue resistance at the design stage allows us to quickly consider several design and technological options and ensure the required quality, expressed by the service life of structures at a given level of reliability. A comprehensive methodology for designing airframe power elements includes traditional power calculations under static loads, calculation and formation of a typical block of irregular variable loading, the endurance limit in the design section and its statistical characteristics, assessment of the reliability level and determination of fatigue life. As a result of the calculation, the values of safety factors for ultimate strength, fatigue life and endurance limit are obtained. The calculation is carried out for the individual most loaded sections of the aircraft's power elements at the reliability level specified by the Aviation Regulations.

The safety factor for fatigue life $n_\lambda = \lambda_{Pzap}/\lambda_{\mathrm{Pgiven}}$ shows how many times the calculated durability, determined with a margin, exceeds the durability regulated by the technical specifications for a given reliability. The safety factor for the endurance limit

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$n_{\sigma_{-1DN_G}} = \overline{\sigma}_{\alpha eq}/\overline{\sigma}_{-1DN_G}$ shows how many times the average value of the harmonic vibration stress amplitude $\overline{\sigma}_{\alpha eq}$, equivalent to the accumulation of fatigue damage, exceeds the average the value of the endurance limit required to ensure a given durability at a reliability level corresponding to the specified flight safety [1-4]

In the vast majority of cases, calculations are made of structural structural elements, the destruction of which can lead to disaster. According to the regulations, the probability of a situation leading to a disaster is assumed to be $P = 10^{-9}$ per 1 hour of flight. At a given value of the probability of a catastrophe, it is considered that the operation of the aircraft will be practically safe.

2 Materials and Methods

The proposed methodology links a number of methods and methods for preparing data for calculating safety factors: the method of force calculation under static loads; method of bringing loads from places of application to the design section; method for determining the geometric characteristics of the design section; methods for calculating a loading block or load distribution function in design sections, including methods of schematization; a method for determining the fatigue resistance characteristics of a design section, based on the similarity theory of fatigue failure and including methods for assessing the influence of processing technology and the corrosive environment [5,6]; method of calculating fatigue resistance using secondary fatigue curves using the Sørensen-Kogaev method [7]. Carrying out modeling using the proposed method allows you to evaluate the durability and level of safety, as well as analyze the strength of the structure [8-10].

The methodology is presented using a specific example of assessing the load-bearing capacity based on fatigue resistance of the fin attachment point of a passenger aircraft. The keel attachment point is shown in Fig. 1. It is necessary to determine its fatigue life according to the dangerous section A-A; in the case of insufficient load-bearing capacity for fatigue resistance, it is necessary to determine possible types of hardening technology. In the case of calculating the eye of the keel attachment point, the values of the safety factors are taken $[n_\sigma] = 1{,}1$, $[n_\lambda] = 4$. The structural and power structure of the keel is two-spar, with a riveted stringer panel. The fin is connected to the fuselage using ear-fork butt joints. For the keel fastening unit, the material chosen for the butt bolts is 30KhGSA (σB=110 kg/mm^2), for the keel fastening eye - 30KhGNS2A (σB=165 kg/mm^2)

The main design cases when designing the vertical tail are: 1) balancing load in case of failure of one of the engines: $Z_{ur.v.o.} = \frac{P \times h \times f \times n_Z}{L_{v.o.}}$, where P - engine thrust, h - arm between the axis of symmetry of the engine and the axis of symmetry of the aircraft; $L_{v.o.}$ - vertical tail arm; f - safety factor (f =1.5); n_Z- overload along the z axis (z=1.5); 2) maneuvering load when the rudder is deflected - it is proportional to the load per square meter of the wing $p = G/S$: $Z_{\text{MAN}} = f \times n \times n_z \times p \times S_{OP}$; 3) loads when flying in rough air: $Z_{N.V} = 1{,}6 \times V_{0max} \times S_{V.O} \times f \times n_z$, where V_{0max} is the maximum speed of horizontal flight. In addition, since the tail is T-shaped, tensile forces act on the keel, which are calculated as follows: $N = \frac{Y_{go} \times n \times f}{l_{go}} - \frac{G_{go} \times n \times f}{l_{go}}$.

The preliminary calculation determined: wing load p=293.5 daN/m^2; engine thrust P_{max}=3660 daN; tail area S_{op}=13.6 m^2; maximum horizontal flight speed V_{0max}=500 km/h; vertical tail arm $L_{V.O}$=10.72 m; shoulder between the axis of symmetry of the engine and the axis of symmetry of the aircraft h=3.75 m.

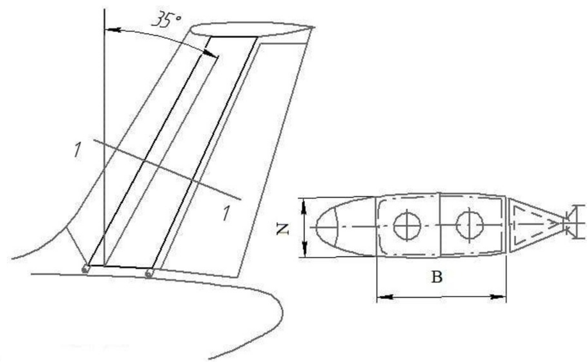

Fig. 1. The keel attachment point for the passenger aircraft being designed

As a result, the value of the balancing load in the event of failure of one of the engines $Z_{ur\ v.o}$ =2880.7 daN; the value of the maneuvering load when the rudder is deflected Z_{MAN} = 8979.7 daN; load value when flying in rough air $Z_{n.v}$=7990.27 daN. Therefore, we take the value of the maneuvering load Z_{MAN} = 8979.7 daN as the maximum load; tensile force N=1136 daN

The values of the bending moment M_{iz}, shearing force Q, and torque M_{kr} of the keel compartment were determined from diagrams of the keel sections constructed at maximum loads. As a result, the loads acting on the keel attachment points were determined: bending moment M_{izg} = 16873.85 daN/m, shearing force Q = 8964.1 daN; torque M_{kr}=3252.94 daN/m; normal force N=1136 daN. The height of the side members in this section is H=440 mm, $N_{izg} = \frac{M_{izg}}{2n} = \frac{16873,85}{2\cdot 0,44} = 19174,83$ daN - the force on each spar belt from the bending moment. $N_p = \frac{N}{4} = \frac{11,36}{4} = 284$ daN - reaction from the tensile force N in each belt. The total normal force on the stretched keel spar belt is 19458.83 daN; compressed - 18890.83 daN.

Strength calculations were carried out and the geometric parameters of the keel butt assembly were determined. When the butt joint is located (Fig. 2), the bolts perceive only the forces arising from M_{izg} and the tensile force N. The forces of the bolts are equal to the normal forces in the side members from these two loads [11].

The strength of the keel butt bolt was calculated for shear. The shearing force acting on one bolt is Q_{bolt}=N_{long}=19458.83 daN. Ultimate strength by tangential stress τ_V=0.6 σ_V=72 daN/mm^2. The bolt calculation is carried out taking into account two bolt cut surfaces. Cross-sectional area of the bolt F_{av}=Q_{bolt}/2τ_V=135.13 mm^2. Bolt diameter $d = \sqrt{\frac{4\cdot F_{av}}{\pi}} = \sqrt{\frac{4\cdot 135,13}{3,14}} = 13,12$ mm. The final bolt diameter is assumed to be d=14 mm. Check for shear of bolt d=14 mm: F_{av}=153.86 mm^2, τ_{av}=63.24<72. Safety factor n_{av}=τ_{av}/ τ_B=72/63,24=1,14.

The calculation of the strength of the keel joint assembly eye was carried out for crushing and rupture σ_{cm}=σ_V =165 daN/mm^2. Eye thickness a=N_{long}/($d\sigma_{sm}$)=8,42 mm. The thickness of the eyelet is assumed to be a=10 mm. The eyelet is checked for compression σcm= N_{long}/(da)=139, σ_{cm}<σ_V,, because 139<165 daN/mm^2. Safety factor n_{cm}=σ_B /σ_{cm}=165/139=1.19. The eyelet is checked for tensile rupture with its width b>2d=30 mm. The coefficient kr is determined, taking into account the influence of the material and geometric parameters of the eye on the average breaking stress with a side jumper x=(b-

d)/2= 8 mm and an upper jumper y = 6 mm, k_r=0.565+ 0.48x/y-0,1b/a=0.845, σ_p =$N_{long}/(k_r \cdot (b-d) \cdot a)$, σ_p = 134, σ_p< =σ_V, because 134 <165 daN/mm^2. Safety factor n_r =σ_B / σ_r= 165/134 = 1.23.

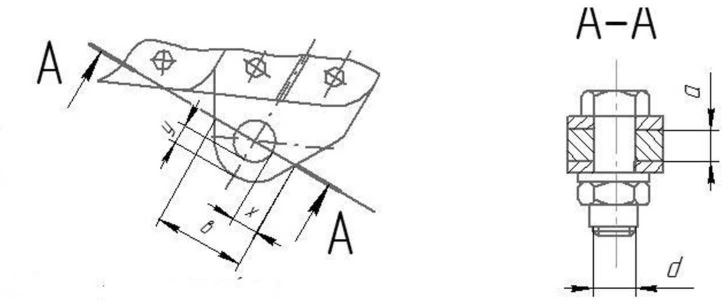

Fig.2. Wing mounting eye parameters

Determining the characteristics of variable operational loading of the design section of the eye consists of determining a typical loading block for 1 flight from all active loads and the coefficient of variation of the amplitudes of the loading block in the block stage. The main loads that must be taken into account in a typical loading block when designing a vertical tail include: the balancing load acting on the keel in the event of failure of one of the engines $Z_{ur.v.o}$, the maneuvering load when the rudder is deflected Z_{man}, the load when flying in rough air $Z_{n.v}$, tensile load from the impact on the keel of the T-shaped tail $Z_{n.v}$.

3 Research and results

Based on statistical analysis during maneuvers, it was found that the distribution of extreme values of maneuvering overloads for all types of aircraft is close to the normal distribution law. Analysis of maneuvering overloads based on the results of flight tests showed that the influence of overloads from rough air on the repeatability of maneuvering overloads has practically no effect [12]. In the calculations, it was assumed that the average number of significant maximum maneuverable overloads of a transport aircraft is 7 per flight. Statistical analysis showed that the distribution of extreme values of buffeting overloads from rough air is close to the double exponential law [13]. For further calculations, it was assumed that the average number of significant increments of extreme values of overloads from turbulent air is equal to 10 for every 100 km, i.e. for1| During an average flight of 1000 km, 100 significant increments of extreme values will be observed [14].

To estimate the balancing load acting on the keel in the event of failure of one of the engines, it was assumed that three engine failures are possible over the entire service life.

It is believed that the load on the keel attachment unit when an overload occurs increases from a zero value, i.e., it comes from a zero cycle: to obtain symmetrical loading cycles, a reduction is carried out using the formula $\sigma_{pri} = \sigma_i/2 + \psi \cdot g\sigma_i/2$, ψ- coefficient taking into account the asymmetry of the loading cycle. Based on the above patterns and assumptions, a standard block was built (Fig. 3)

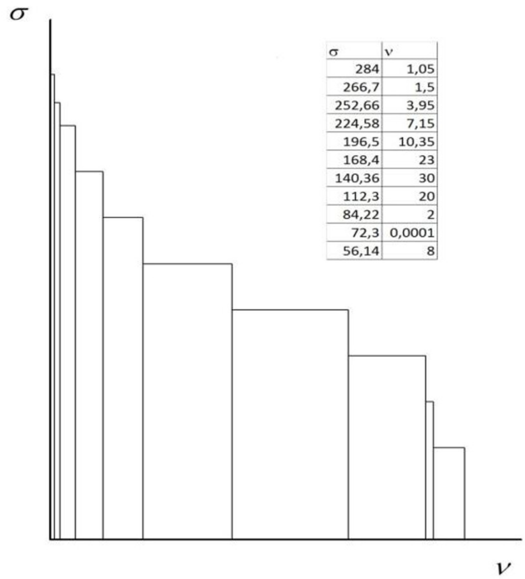

Fig. 3. Graph of a typical keel loading block for 1 flight

The coefficient of variation of load amplitudes in the loading stage is assumed to be V_a = 0.075

Determination of the fatigue resistance characteristics of the design section of the keel attachment eye was carried out using the similarity equation for fatigue failure of the sample and the part, developed by Professor V.P. Kogaev and regulated by GOST 25.504.

When calculating the fatigue resistance characteristics of the eye section using the similarity equation, data on a standard smooth laboratory sample with a diameter of do = 7.5 mm made of 30KhGSN2A steel were used [15].

As a result of the calculation using the similarity equation of V.P. Kogaev, the coefficient of reduction in the endurance limit was determined:

$$K = (K_\sigma/K_{d\sigma} + 1/K_{F\sigma} - 1)/(K_V \cdot K_A \cdot K_{kor} \cdot K_T).$$

where K_V — influence coefficient of special additional surface hardening; K_A — coefficient of influence of anisotropy of material properties; K_{kor} — influence coefficient of operation in a corrosive environment; K_T — coefficient of influence of manufacturing processes; $K_\sigma/K_{d\sigma}$ — ratio of the effective concentration coefficient to the influence coefficient of the absolute values of the cross section; $K_{F\sigma}$ — surface roughness influence coefficient [16-18].

By value K = 3,28 wen K_V=K_A=K_{kor}=K_T=1 the endurance limit of the design section of the eye was determined $\overline{\overline{\sigma}}_{-1D} = \frac{\overline{\overline{\sigma}}_{-1}}{K}$ =190,0438 MPa. The value of the slope of the fatigue curve m1, m2 was calculated using the formula recommended by GOST 25.504:

$m_1 = (5 + \sigma_B/80) = 7{,}811$ (σ in MPa). As a result of laboratory tests of standard samples made of steel 30XGCH2A with a concentration coefficient α_σ = 3 the value of the slope of the fatigue curve was obtained m_1 = 7,4 which confirms the calculation result. The value of the slope of the right branch of the fatigue curve m_2 calculated according to the formula recommended by the methodological recommendations of GOSSTANDARD RD 50-607 m_2 = $2m_1$ - 1 = 14,623.

The construction of the secondary fatigue curve was carried out based on the application of the corrected linear hypothesis of summation of fatigue damage. Serensena-Kogaev [19].

To construct the VKU, the values of the limiting load factor nr were set in the range from 0.02 to 1.5 and the values of fatigue life were calculated in the number of flights determined by the formula:

$$\lg\lambda_P = \lg\left(\frac{a_{p\sigma}\cdot N_G}{\nu_\sigma}\left[n_{p\sigma}^{m_1}\sum\left(\frac{\sigma_{ai}}{\sigma_{a\max}}\right)^{m_1}\frac{\nu_i}{\nu_\sigma} + n_{p\sigma}^{m_2}\sum\left(\frac{\sigma_{ai}}{\sigma_{a\max}}\right)^{m_2}\frac{\nu_i}{\nu_\sigma}\right]^{-1}\right) + U_p S_{\lg\lambda}.$$

where $S_{\lg\lambda}$ = 0,491 — standard deviation of logarithm of fatigue life; U_p = 0,846 — quantile of normal distribution for probability R =6·10^{-5}.

According to the secondary fatigue curve with the probability of a disaster R=6·10^{-5} $durability\ will\ be$ λ_P= 10^{2,742} = 552,068 flights. Since the service life of the designed aircraft is assigned to 30,000 flights, the safety factor for fatigue life will be $n_\lambda = \lambda_p/\lambda_{pspecified} = 552{,}068/30000 = 0{,}0184$, and should be$n_\lambda$ = 4. Thus, it is necessary: either to reduce the loads, increasing the cross-sectional area, and, consequently, the weight of the keel attachment point, or to increase the endurance limit, carrying out special strengthening methods to increase the resistance to fatigue; or increase the stability of the properties of the assembly material and manufacturing technology; or use a new material with a higher endurance limit.

It is proposed to choose a method of increasing the safety factor for fatigue life by increasing the endurance limit of the keel mounting eye, carrying out hardening to increase fatigue resistance [20]. Therefore, it is necessary to determine the value of the hardening coefficientK_V. Based on the received value K_V it is possible to determine technological methods of hardening and their modes.

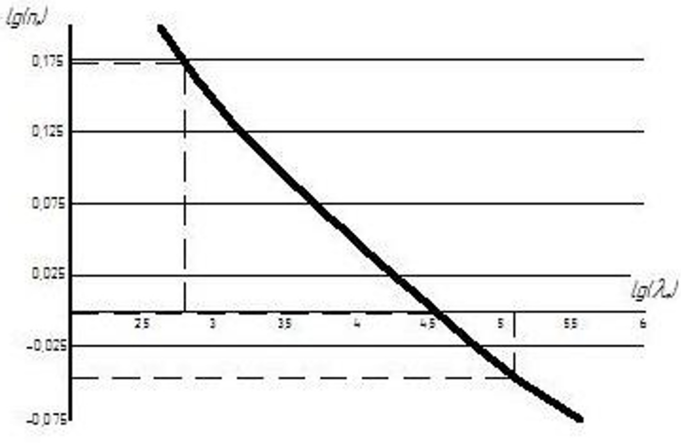

Fig. 4. Secondary fatigue curve with probability of failure P — 6·10^{-5}

The values of the specified durability are deposited on the VKU $\lambda_{pspecified}$ = 30000 and the corresponding value of the maximum load factor is determined: n_{rz} = 0,9929. Then the durability value is set aside taking into account the safety factor n_λ= 4·λ_{pzap}= 120 000, by which the corresponding value of the maximum load factor is determined n_{pzap} = 0,9016.

4 Conclusion

Based on the data obtained, the following are determined: the actual margin of endurance limit $n_{\sigma\phi}$=$n_{rz}/n_{r\phi}$ =0,9929/1,4846 = 0,669 (short); required margin for endurance limit

$n_{\sigma \text{zap}}$=$n_{\text{rz}}/n_{\text{rzap}}$ = 0,9929 /0,9016 = 1,101 (satisfying the task); the value of the hardening coefficient of the eye to ensure a given resource with a margin K_V =$n_{\sigma \text{zap}}/n_{\sigma \text{ф}}$ =1,101/0,669 = 1,65.

For this type of eyelet, it is possible to use various types of hardening treatments that provide the required hardening coefficient K_V=1,65 — for example, by methods of surface hardening, methods of local deep plastic deformation, methods using radial tension with pressing of the bushing, etc..

After selecting a specific technological hardening or finishing process, the fatigue calculation should be repeated in order to take into account in the fracture similarity model the new parameters of the fatigue curve of the part after the hardening process and their statistical scatter. Thus, when new information about loading and resistance characteristics is obtained after testing and operation, the VCU should be clarified, obtaining updated safety factors for fatigue resistance and fatigue life. The use of modeling the load-bearing capacity of load-bearing elements and structural units using the proposed method for calculating strength and fatigue resistance at the design stage will help improve the quality of the structure by choosing the optimal structural and technological option with the necessary hardening coefficient to ensure safe operation.

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