DETERMINATION OF AIRCRAFT WING LOADS ON THE ROUTINE FLIGHT MODES WITHIN STRUCTURAL ELASTIC VIBRATIONS

ОПРЕДЕЛЕНИЕ НАГРУЗОК НА КРЫЛО САМОЛЕТА НА ЭТАПАХ ТИПОВОГО ПОЛЕТА С УЧЕТОМ УПРУГИХ КОЛЕБАНИЙ КОНСТРУКЦИИ

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Abstract: *The article deals with a problem of fatigue load calculations when designing the aircraft wing. Much of fatigue damage is done to the wing by occasional air gusts in turbulent atmosphere. Therefore, the author considers the pattern of continuous atmospheric turbulence that gives an idea of low-altitude gusts. It is at low altitudes that nonstandard flights are performed for which it is wrong to use the statistical data on fatigue damage available from the previously operated airplanes of the same class. The method is offered to determine the equivalent bending moments along the wing span in discrete flight modes and within the entire routine flight. The above method takes into account the profile parameters of routine flights, the dynamic vibrations of the wing and fatigue characteristics of the structural material. To prove the reliability of the method the calculation results have been compared to those of medium-range aircraft testing flights.*

KEYWORDS: WING, DURABILITY, DYNAMICS, VIBRATIONS, TURBULENCE, LOAD FACTOR, EQUIVALENT MOMENT

1. Introduction

Requirements for modern aircraft frame durability become ever more sophisticated. Improved calculation techniques for load-bearing structure durability require determining of the loads acting in various aircraft flight modes.

When manufacturing an airplane, the operating conditions must be determined such as routine flight profiles specified by dependences between weight, velocity, altitude and flying hours. The main parameter to determine the intensity of structural load is a load factor in the aircraft center of gravity in various flight modes. The use of statistical data on this parameter is problematic, because they depend both on the aircraft performance and routine flight profiles. Along with the standard flight profiles the aircraft can perform training flights, firefighting fights, etc. These profiles cause fatigue damages which significantly differ from the typical fatigue damages of structural elements.

2. Problem solution

When the aircraft is being designed, consideration must be given to the routine flight profile that provides initial data to determine the structure durability by the airframe fatigue behavior. In flight, the aircraft is continuously exposed to random wind gusts. For non-maneuverable aircrafts, the worst damage to structural elements is done by vertical air gusts. To calculate the fatigue damage, a model of continuous atmosphere turbulence has been adopted under the Industry Standard [1]. The spectral density of intensity of wind gust vertical speed is determined as follows:

$$\Phi_W(\Omega)=\frac{L\cdot\sigma_W^2}{\pi}\cdot\frac{1+\frac{8}{3}\cdot\left(1.339\cdot L\cdot\Omega\right)^2}{\left[1+\left(1.339\cdot L\cdot\Omega\right)^2\right]^{\frac{11}{6}}}, \tag{1}$$

where Ω is space frequency, L is integral turbulence scale, σ_w - intensity of wind gust vertical speed.

The density function of standard deviation for the vertical component of wind gust speed during the aircraft flight in turbulent atmosphere is determined as follows:

$$f\left(\sigma_w\right)=\sqrt{\frac{2}{\pi}}\cdot\frac{P_1}{b_1}\cdot exp\left(-\frac{\sigma_w^2}{2b_1^2}\right)+\sqrt{\frac{2}{\pi}}\cdot\frac{P_2}{b_2}\cdot exp\left(-\frac{\sigma_w^2}{2b_2^2}\right), \tag{2}$$

where P_1 and P_2 are probabilities of flight in mild and intensive turbulence zones, b_1 and b_2 are coefficients of mild and intensive turbulences.

Standard methods [2, 3] in aviation rely on linear hypothesis for calculating the durability as a sum of the fatigue damages caused by random loading

$$\int_{\sigma}\frac{dn}{N(\sigma)}=1, \tag{3}$$

where dn is an increment of the number of load cycles

$$dn=N_{\Sigma}\cdot\phi\left(\sigma\right)d\sigma, \tag{4}$$

where $\phi(\sigma)$ is the stress distribution density, N_{Σ} is the total number of cycles before the failure

$$N_{\Sigma}=N_{0\,j}\cdot T_i; \tag{5}$$

where T_i is the durability for flying in σ_{wi} which is the constant intensity zone, N_{0j} is the number of mean loads in the j-th flight mode. According to Rice's formula it is determined as

$$N_{0\,j}=\frac{1}{2\pi}\sqrt{\frac{\int_{\Omega}\Phi_M\left(\Omega\right)\cdot\Omega^2 d\Omega}{\int_{\Omega}\Phi_M\left(\Omega\right)d\Omega}}, \tag{6}$$

where: $\Phi_M(\Omega)$ is the spectral density of bending moment power.

In formula (4), $\phi(\sigma)$ shall be determined according to Rayleigh's distribution law

$$\phi(\sigma)=\frac{\sigma}{S_{\sigma}^{2}}\cdot e^{-\frac{\sigma^2}{2S_{\sigma}^2}}, \tag{7}$$

where S^2_{σ} is the power factor dispersion.

Spectral power density of the bending moment is equal to

$$\Phi_M\left(\Omega\right)=\Phi_W\left(\Omega\right)\cdot H_M^2\left(\Omega\right), \tag{9}$$

where: $H_M(\Omega)$ is the transfer function of the bending moment under the action of vertical wind gust with sinusoidal speed variation in the j-th mode of routine flight. We offer to determine it as follows [5]:

$$H_M(\Omega) = M_j \frac{h_j}{g_j} \cdot \frac{\Omega}{\sqrt{\Omega^2 + \left({h_j}/{V_{uj}} \right)^2}} \cdot \sqrt{\frac{1}{1 + \pi \cdot b \cdot \Omega}}\,, \tag{10}$$

where M_j is the bending moment value o in the j-th mode of routine flight under vertical load factor $n_y = 1;$

$$h_j = \frac{\rho_j \cdot V_{uj}}{2 \cdot G_j} \cdot C_y^{\alpha} \cdot S_w\,, \tag{11}$$

where ρ_j is the air density according to table of standard atmosphere at altitude H; g_j is the free-fall acceleration at altitude H; V_{uj} is indicated flight speed at the considered altitude, modified to the air density near the ground; C_y^{α} is the derivative of the lift force coefficient on the attack angle; S_w is the wing area, b is the mean geometric chord of the wing.

Integrating the diagram of load per unit of length in [6] we obtained formula [10] of simplified dependence between the aircraft weight, filled wing tank weight and the bending moment in various cross-sections of the wing

$$M_j = \frac{Y_{wj}}{G_{A0}} \cdot a(z) - \frac{G_{Fj}}{G_{F0}} \cdot b(z) - c(z)\,, \tag{12}$$

where Y_{wj}, G_{Fj} is the wing lift force and the fuel weight in the routing flight mode; G_{A0}, G_{F0} are the aircraft and fuel weights, which have determined the functions $a(z)$, $b(z)$, $c(z)$. Functions $a(z)$, $b(z)$, $c(z)$ are the bending moments due to air and mass loads by the weights of fuel, wing and wing concentrated loads.

Substituting expressions (1, 2, 4-12) in formula (3) and making some transformation, we obtain the dependence for calculation of damage caused by atmospheric turbulence in the routine flight mode under consideration

$$d_j = \frac{N_0 \cdot 2^{m/2} \cdot C_M^m}{C} \cdot I_y \cdot I_W \cdot l_j\,, \tag{13}$$

where

$$I_y = \int\limits_y y^{m/2} \cdot e^{-y} dy\,; \quad I_W = \int\limits_0^{\infty} \sigma_w^m \cdot f(\sigma_w) d\sigma_w\,;$$

l_j is the length of the j-th routine flight mode; C_M is the coefficient that characterizes the dependence between the SD of the vertical gust speeds and the SD of the bending moment

$$C_M = \left(\int\limits_0^{\infty} \bar{\Phi}_W(\Omega) \cdot H_M^2(\Omega) d\Omega \right)^{1/2}. \tag{14}$$

This particular damage can be added by the application of one non-zero loading cycle with the maximal value of M_{eq}

$$d_j = \frac{\left[\sigma\left(M_{eq} \right) \right]^m}{C}\,. \tag{15}$$

As the left parts of equations (13) and (15) are equal, we can make their right parts equal too, where the equivalent bending moment in the j-th mode of the routine flight will be equal to

$$M_{eq\,j} = \sqrt[m]{N_0 \cdot 2^{m/2} \cdot C_M^m \cdot I_y \cdot I_W \cdot L_j}\,. \tag{16}$$

To determine the equivalent loads during the aircraft operation in combined modes, it is necessary to know the value of equivalent bending moment during the routine flight. It can be determined similarly to (16), taking into account that the total damage in (13), which occurs due to the turbulent atmosphere in the routine flight, is equal to

$$d = d_{gag} + \sum_j d_j\,, \tag{17}$$

where: d_{gag} is the damage resulting from the ground-air-ground (GAG) cycle. To calculate the loads of the GAG-cycle, the value of bending moment in level flight is determined as

$$M_{lev} = \frac{\sum_j M_j \cdot d_j}{\sum_j d_j}\,. \tag{18}$$

The regularity of the bending moment increments in separate routine flight modes is determined according to [1]

$$F_j\left(\Delta M_{gag} \right) = N_0 \cdot \tau_j \cdot \left[P_{1j} \cdot e^{-\frac{\Delta M_{gag}}{b_{1j} A_{wj}}} + P_{2j} \cdot e^{-\frac{\Delta M_{gag}}{b_{2j} A_{wj}}} \right], \tag{19}$$

where A_{wj} is the ratio between the vertical gust transfer function and the bending moment increment for every j-th mode of the routine flight

$$A_w = \sqrt{\frac{\int\limits_{\Omega} \Phi_M(\Omega) d\Omega}{\int\limits_0^{\infty} \Phi_W(\Omega) d\Omega}}\,. \tag{20}$$

The total number of exceeded ΔM_{gag} in the routine flight is

$$F_c(\Delta M_{gag}) = \sum_j F_j\left(\Delta M_{gag} \right). \tag{21}$$

According to TsAGI regulations to determine the maximal GAG-cycle bending moment increment, the below parameter must be

$$F_{rand}(\Delta M_{gag}) = 0.694\,. \tag{22}$$

Maximal and minimal GAG-cycle bending moments in the flight are equal to

$$M_{max} = M_{lev} + \Delta M_{gag}\,, \quad M_{min} = -0{,}5 \cdot M_{lev}\,. \tag{23}$$

The GAG-cycle loads need to be modified to the non-zero cycle maximum by Oding's formula

$$M_{gag0} = \sqrt{M_{max} \cdot \left(M_{max} - M_{min} \right)}\,. \tag{24}$$

3. Findings and discussion

The method described has enabled the calculation of the bending moment along the wing of medium-range aircraft with the take-off mass of 42 t, wing span of 32 m and with 30 ribs in the wing. Fig 1. shows the typical firefighting flight profile including 7 water lifts:

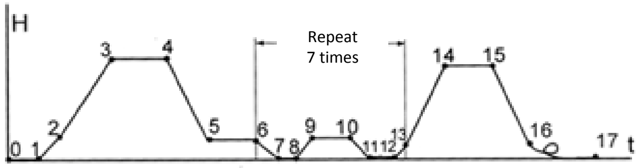

Fig. 1. *Typical firefighting flight profile*

The bending moment calculations are done for the next modes of routine flight (see fig. 1): 0-1 – taxiing, 1-2 – takeoff, 2-3 – climbing up to 2000 m, 3-4 – level flight at 2000 m, 4-5 – descending from 2000 m, 5-6 – level flight at 400 m, 6-7 – descending from 400 m, 7-8 – water lift, 8-9 – climbing up to 400 m, 9-10 – level flight at 400 m, 10-11 – descending from 400 m, 11-12 – water release, 12-13 – climbing up to 400 m, 13-14 – climbing up to 2000 m, 14-15 – level flight 2000 m, 15-16 – descending from 2000 m, 16-17 – circling and landing.

The power equation for fatigue behaviour curve has been accepted for maximal “brutto” stresses, MPa within non-zero loading cycle

$$N \cdot \sigma^m = C, \tag{8}$$

where *m, C* are experimentally determined parameters. For the most conventional wing alloy D16T, $m = 4$, $C = 1.767 \cdot 10^9$.

Figures 2 – 5 show the dependence between the calculated equivalent bending moment and M_{eqTF} which is the value obtained after processing the flight test data from spanwise cross-sections of the wing in different flight modes. The line shows the equality between the calculated M_{eqTF} and the experimental M_{eqTF}.

Figure 6 shows the dependence between the calculated equivalent bending moment and $M_{eq\ FT}$ in different wing cross-sections within the entire routine firefighting flight.

4. Conclusion

The equivalent bending moment for the entire flight calculated by the offered method is 10% different from the equivalent bending moment obtained from the flight test. The offered calculation method for wing loads in routine flights can be used when the durability must be estimated for regular zones of the wing.

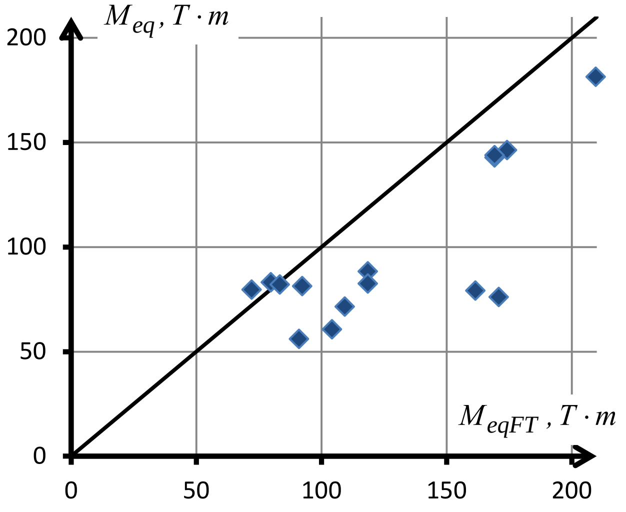

Fig. 2. *Dependence between the calculated equivalent bending moment and M_{eq} obtained from the flight test data in the cross-section between ribs 2 and 3*

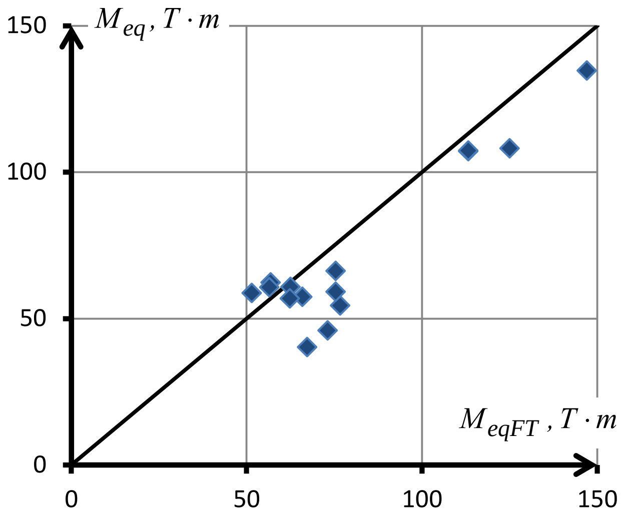

Fig. 3. *Dependence between the calculated equivalent bending moment and M_{eq} obtained from the flight test data in the cross-section between ribs 6 and 7*

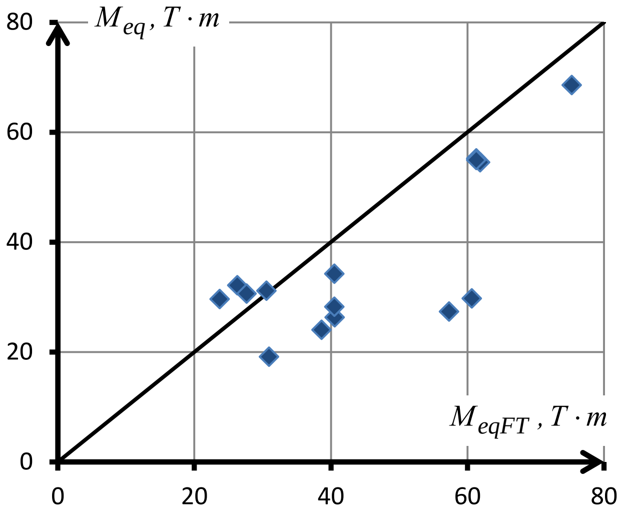

Fig. 4. *Dependence between the calculated equivalent bending moment and M_{eq} obtained from the flight test data in the cross-section between ribs 12 and 13*

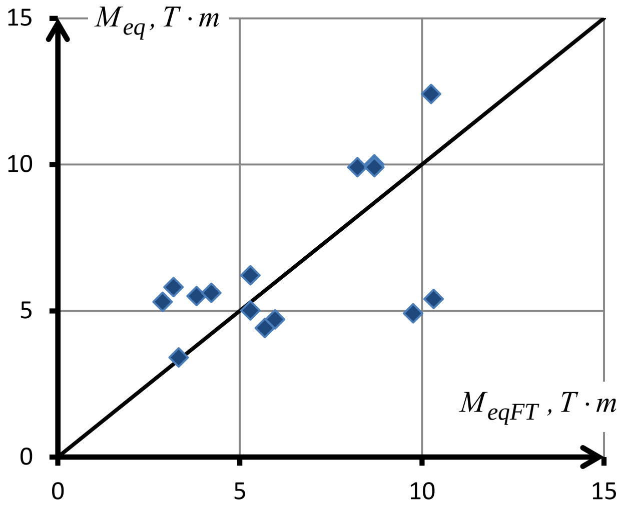

Fig. 5. *Dependence between the calculated equivalent bending moment and M_{eq} obtained from the flight test data in the cross-section between ribs 22 and 23.*

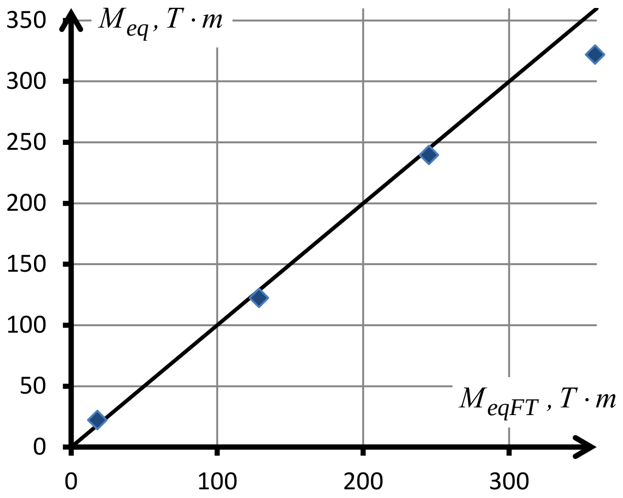

Fig. 6. *Dependence between the calculated equivalent bending moment and M_{eq} obtained from the flight test data in various wing cross-sections within the entire routine firefighting flight.*

The divergence of the results can be explained by the fact that to calculate the transfer function of the bending moment affected by the wind gust, only the aircraft gravity centre vibrations have been taken into account. According to the preliminary research [8], the consideration of the wing vibration against the aircraft gravity centre can increase the wing spanwise bending moments by 20% which would be the object of our future research.

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