NONMANEUVER AIRCRAFT WING DURABILITY DEPENDENCE ON DIRECTIVE STRESSES ESTABLISHED IN THE DESIGN

ЗАВИСИМОСТЬ РЕСУРСА КРЫЛА НЕМАНЕВРЕННОГО САМОЛЕТА ОТ ДОПУСКАЕМЫХ НАПРЯЖЕНИЙ, ПРИНЯТЫХ ПРИ ПРОЕКТИРОВАНИИ

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Abstract: *The paper presents a method for calculating the durability of structure regular zones in view of working stresses and aircraft routine flight profile. Application of the method is advisable at the early design stages. The method is based on the discrete atmospheric turbulence model and dependence model for durability calculation by nominal stresses. Fatigue damage for a routine flight has been determined as the amount of damage due to accidental loads and the damage resulting from enveloping ground-air-ground cycle, naturally repeated during each flight. It has been noted that the consideration of the fatigue curve break point in the low-stress area leads to an increase in the calculated durability by 10-15%. A comparison has been made of the calculated durability values for two airplanes with the experimental data of TsAGI. The correlation is satisfactory enough.*

KEYWORDS: WING, DURABILITY, ROUTINE FLIGHT PROFILE, WORKING STRESS, FATIGUE

1. Introduction

Durability requirements should be considered at the earliest stages of design by selecting the working stresses in structural elements. During calculations load-bearing structure is considered as consisting of the so-called regular zones and structural irregular zones. Regular zones include parts of the construction containing the unavoidable stress concentrators such as holes for rivets or bolts in assembled units. Structure durability is on the one hand limited by the durability of regular construction zones.

In some cases, working stresses are selected on the basis of statistical data on the flying airplanes of this class. In so doing, aircraft characteristics, routine flight profiles and the materials used have to be close or the same.

More promising is the approach based on atmospheric turbulence models. In this paper a discrete turbulence model has been adopted. Application of this model is efficient at the early design stages. The model prescribes the discrete assignment of cumulative frequency for vertical wind gust speeds per kilometer on the flight altitude.

Initial data for the calculation of load factors in the aircraft gravity center, and, consequently, the load on the wing include routine flight profile and atmospheric turbulence characteristics. Routine flight profile determines the changes in flight altitude, speed and weight of the aircraft, depending on the flight duration. At the design stage, this profile is determined by the planned data on weights, speeds and altitudes, and it is further refined using the results of flight measurements. When calculating the durability of long-haul airplanes the enveloping cycle is determined within the load program. This cycle determines largely the structure durability, being called the ground-air-ground cycle (GAG). For high aspect ratio wings external loads are further applied as shear forces, torsional and bending moments diagrams, because normal stresses determine the durability of these structures.

Experimental studies of load factors in flight suggest that maneuver load factor magnitudes and frequency to are too little to maintain flight modes of passenger and cargo planes [1]. The main fatigue damage result from load factors during flighst in turbulent air. It is important to take into account the fatigue damage caused by both accidental loads and the enveloping ground-air-ground cycle (GAG).

2. Background for solving the problem of wing load calculation using the discrete gust scheme

The industry standard "Atmospheric turbulence model" OST 1 02514-84 determines the discrete vertical wind gust cumulative frequency per 1 kilometer of aircraft flight depending on the flight altitude. Cumulative frequency characterizes the number of gusts per 1km of the flight greater than the given vertical speed

$$F(w)=F_O\, e^{-\frac{w}{C_W}}, \tag{1}$$

where F_O and C_W are the parameters of the gust cumulative frequency, depending on altitude, F_O is the total number of gusts per 1km of the flight, F (w) is the number of gusts per 1km of the flight with vertical speed exceeding w. Vertical load factor increment Δn_y at the aircraft gravity center depends on the vertical gust speed

$$\Delta n_y = \frac{C_y^{\alpha}\rho_O V_u W}{2p}\cdot K, \tag{2}$$

where K is the gust reduction factor determined as

$$K = 0.8\frac{1-e^{-\chi}}{\chi},\quad \chi = \frac{C_y^{\alpha} q \rho_H \Delta l}{2p},\quad p = \frac{mq}{S_W},$$

where p is the wing specific load at the given aircraft weight m, N/m2; q is gravitational acceleration, m/s2; S_w is wing area, m2; C^{α}_y is a derivative of the lift coefficient against the attack angle, 1/rad; Δl is the length of the trapezoidal gust transition section equal to 30m; ρ_0 and ρ_H are air density according to the table of standard atmosphere at sea level, and at height H, respectively, kg/m3; V_u is the indicated airspeed corresponding to the considered altitude, m/s.

3. Calculation of structure fatigue damage for routine flight

Each of three main flight phases, including climb, cruise flight and descend will be split into several modes in which aircraft speed, height and aircraft weight are constant. The total number of modes for the entire routine flight will be denoted by r. Height H_j, velocity V_j, weight G_j, the covered flight distance L_j are to be calculated for every j-th flight mode.

Formula (1) determines the number of gusts per 1 km of the flight in accordance with OST 1 02514-84. Considering L_j, covered within the j-th mode, the number of gusts exceeding speed w, will be:

$$F_j(w) = L_j F_{oj} e^{-\frac{w}{C_{wj}}} . \tag{3}$$

Let us substitute the dependence (2) into (3) and introduce the following notation:

$$C_{nj} = \frac{C_y^{\alpha} \rho_o V_{uj} C_{wj}}{2P_j} \cdot K_j .$$

Then

$$F_j(\Delta n_y) = L_j F_{oj} e^{-\frac{\Delta n_y}{C_{nj}}} . \tag{4}$$

The probable exceeding of the load factor Δn_y in the j-th mode

$$P_j(\Delta n_y) = \frac{F_j(\Delta n_y)}{L_j F_{oj}} = e^{-\frac{\Delta n_y}{C_{nj}}} .$$

The probability density of incremental load factor distribution can be determined as

$$\phi_j(\Delta n_y) = \left| \frac{dP_j(\Delta n_y)}{d\Delta n_y} \right| = \frac{1}{C_{nj}} e^{-\frac{\Delta n_y}{C_{nj}}} .$$

The probability of falling into the interval $d\Delta n_y$ is

$$\phi_j(\Delta n_y) d\Delta n_y .$$

Since the total load factors number in the mode is $L_j\, F_{oj}$, the increment of load cycle number equals

$$dn = L_j F_{oj} \phi_j(\Delta n_y) d\Delta n_y ,$$

or

$$dn = \frac{L_j F_{oj}}{C_{nj}} e^{-\frac{\Delta n_y}{C_{nj}}} d\Delta n_y .$$

The accumulated fatigue damage in the j-th mode according to the linear hypothesis of a fatigue damage summation will be equal to

$$D_j = \int \frac{dn}{N} = \frac{L_j F_{oj}}{C_{nj}} \int \frac{1}{N} e^{-\frac{\Delta n_y}{C_{nj}}} d\Delta n_y . \tag{5}$$

To determine the number of cycles before failure N occurs at regular loads on structural element and at stresses corresponding to the incremental load factor $d\Delta n_y$, we need to consider that positive values of vertical gust speeds correspond to the equivalent negative values. During the level flight maximum and minimum loads cycle load factors are as follows

$$n_{y\,max} = 1 + \Delta n_y ,\ n_{y\,min} = 1 - \Delta n_y .$$

In accordance with the Oding formula [2] the equivalent incremental load factor corresponding to zero-to-tension loads cycle, can be determined as:

$$\Delta n_{y\,eq} = \sqrt{2\Delta n_y (1 + \Delta n_y)} .$$

The equivalent stress of the zero-to-tension cycle will be equal to

$$\sigma_{eq} = \sigma_{n_{y=1}} \cdot \Delta n_{y\,eq}$$

or

$$\sigma_{eq} = \sigma_{n_{y=1}} \cdot \sqrt{2\Delta n_y (1 + \Delta n_y)} . \tag{6}$$

During the aircraft flight in turbulent atmosphere high speed gusts are rare, but there is a great number of gusts with relatively low speed. These gusts result in the main fatigue damage. At low speeds of vertical gusts the incremental load factor and, consequently, the equivalent stress are also small. In order not to overestimate the accumulated fatigue damage from the effects of small gusts during the calculation, fatigue curve equation is thought to be a broken line with logarithmic coordinates, then

$$N = N_o \left(\frac{\sigma_o}{\sigma} \right)^m , \tag{7}$$

where N_o and σ_o are coordinates of the structure element fatigue curve breaking point. The exponent of power m depends on the actual stress at $\sigma > \sigma_o$ $m = m_1$, if $\sigma < \sigma_o$ then $m = 2m_1 - 1$.

After substituting (6) into equation (7)

$$N = N_o \left(\frac{\sigma_o}{\sigma_{n_{y=1}}} \right)^m \left(2\Delta n_y \left(1 + \Delta n_y \right) \right)^{-\frac{m}{2}} . \tag{8}$$

The dependence used for calculation of the cumulative damage in the j-th mode (5) considering (8) is as follows:

(9)

$$D_j = \frac{L_j F_{oj}}{N_o C_{nj}} \int \left(\frac{\sigma_{n_{y=1}}}{\sigma_o} \right)^m (2\Delta n_y (1 + \Delta n_y))^{\frac{m}{2}} e^{-\frac{\Delta n_y}{C_{nj}}} d\Delta n_y .$$

The integral in equation (9) must be determined numerically. The upper limit of integration can be set to operating load factor. In numerical integration process the equivalent stress must be found according to (6) and the exponent value is to be set depending on whether the equivalent stress exceeds the stress value corresponding to the breaking point of structural element fatigue curve.

Fatigue damage caused by accidental loads in all modes of the routine flight can be determined as

$$D_{rand} = \sum_{j=1}^{r} D_j .$$

Let's consider the definition of fatigue damage within the GAG cycle. Equation (4) sets the number of exceedings of the incremental load factor Δn_y for the j-th mode of the routine flight. The total number of Δn_y value exceedings for the routine flight would be equal to

$$F_{rand}(\Delta n_y) = \sum_{j=1}^{r} F_j(\Delta n_y)$$

or

$$F_{rand}(\Delta n_y) = \sum_{j=1}^{r} L_j F_{oj} e^{-\frac{\Delta n_y}{C_{nj}}} . \tag{10}$$

In accordance with the TsAGI regulations, to determine the maximum increment of load factor corresponding to the GAG cycle, the following parameter must be considered:

$$F_{rand}(\Delta n_{y\,max}^{GAG}) = 0.694 . \tag{11}$$

Dependence (11) with the consideration of (10) provides a condition needed to determine the GAG cycle incremental load factor

$$\sum_{j=1}^{r} L_j F_{oj} \, exp(-\frac{\Delta n_{y\,max}^{GAG}}{C_{nj}}) = 0.694 . \tag{12}$$

Equation (12) can be easily solved numerically with respect to $\Delta n_{y\,max}^{GAG}$. Maximum GAG cycle load factor will be

$$n_{y\,max}^{GAG} = 1 + \Delta n_{y\,max}^{GAG} .$$

The maximum stress in the structural element is calculated as

$$\sigma_{max}^{GAG} = \sigma_{n_y=1} \cdot n_{y\,max}^{GAG} .$$

The average value is usually taken as minimum GAG cycle stress

$$\sigma_{min}^{GAG} = -L \cdot \sigma_{n_y=1} .$$

Coefficient L depends on the aircraft construction-load diagram and the given construction zone with respect to the landing gear arrangement. The average value of L is within the range of 0.5 - 0.8.

The equivalent stress of the zero-to-tension loads cycle corresponding to the GAG cycle can be determined as follows

$$\sigma_{eq}^{GAG} = \sigma_{n_y=1} \sqrt{n_{y\,max}^{GAG} (n_{y\,max}^{GAG} + L)} .$$

The number of cycles before failure occurs at regular loads with these stresses can be derived from formula (7). Usually $\sigma_{eq}^{GAG} > \sigma_0$ and $m = m_1$.

GAG cycle fatigue damage within one routine flight is

$$D_{GAG} = 1 / N_{GAG} .$$

The total damage for a routine flight is

$$D_{total} = D_{GAG} + D_{rand} .$$

The number of routine flights before failure of the structural element occurs can be determined as

$$\lambda = 1 / D_{total} .$$

The structure durability expressed by the amount of routine flights will be

$$T_{\lambda} = \lambda / \eta_{\Sigma} ,$$

where η_{Σ} is the total safety factor.

The directive stresses (considered in the calculation of the ultimate load factor for structural element), which corresponds to the durability, can be determined as

$$\sigma_{dir} = \sigma_{n_y=1} \cdot f \, n_y^{op} ,$$

where f and n_y^{op} are safety factor and operating load factor established in the structure design.

Knowing the required structure durability, the required value of $\sigma_{n_y=1}$ can be selected.

4. Findings

The aircraft receives the greatest fatigue damage during and its climb and descend phases. In cruising mode, despite its long duration, it is damaged less. In this regard, the aircraft durability should be rather expressed in the number of flights instead of flight operation hours.

When selecting routine flight parameters it is rational to limit the flight speed at low altitudes, focusing not only on the optimal speed for fuel consumption, but also for construction fatigue damage.

It is challenging to compare the results of durability calculations depending on the working stresses with experimental data already determined.

Figure 1 shows the dependence between the regular zones durability of the lower wing panels made of D16T and the calculated working stresses for Tu-134 and Il-76 routine flight profiles. Markers denote the TsAGI experimental data given in [3] for the lower wing panels made of D16T on modern passenger airplanes with an average reliability coefficient equal to three.

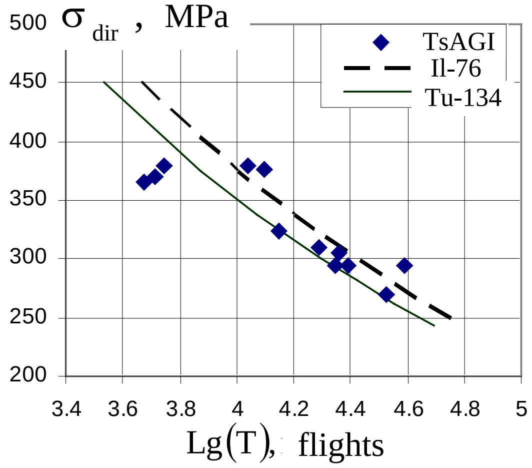

Fig. 1. Structure durability dependence on the working stresses. Markers denote the experimental data. The lines show the calculated dependences for two airplanes.

The correlation of the calculated structure durability depending on the working stresses is satisfactory enough.

It should be noted that consideration of structure material fatigue curve breaking point in the low-stressed area results in the increase of durability by 10- 15 %.

The weight of the aircraft decreases in the routine flight due to the fuel consumption leading to both a greater load factor caused by the gusts, and to smaller stresses on structural elements with a single load factor because of the wing load relief through fuel consumption. The lifting force of the wing, including the bending moments and normal stresses, depends on the load factor value in the aircraft gravity center and the value of balancing load on the horizontal tail. In the early design stages the balancing load may be neglected, whereas the stress caused by the single load factor can be represented as the stress (with the aircraft weight calculated only) multiplied by the ratio of the actual aircraft weight to the calculated one.

If the changing stress is not considered at the single load factor, it can lead to errors in structure durability calculation. The greater the change in aircraft weight due to fuel consumption is, the greater might be the error.

The aircraft designers tend to obtain equal structure strengths and, if possible, the same durability for regular and irregular structural zones. Irregular structure zones include panel transverse joints, stringer joints and end zones, cutouts and skin joints etc.

Since the stresses caused by the single load factor and the effective stress concentration factor in irregular structure zone [2] are included in the equation for calculation of fatigue damage (due to accidental loads and the GAG cycle) as a product, one should follow the recommendations below to design irregular structure zones:

- one should provide the lowest possible value of the effective stress concentration factor by soft start of the force elements, with the bearing stress on fasteners reduced;
- taking into account the provided value of the effective stress concentration factor, one should tend to decrease the working stresses in irregular structural zone.

5. Conclusion

1. The calculated working stresses providing the required structure durability well correlate with the TsAGI experimental data. It is necessary to take into account the fatigue curve breaking point and the change in stresses caused by the single load factor due to fuel consumption.

2. The durability calculation method based on the discrete gust scheme, allows setting the dependence between the working stresses and the required structure durability for a particular structure material using its fatigue curve and the aircraft routine flight profile.

3. The structure gets the greatest fatigue damage at low flight altitudes, in this connection, it is necessary to establish the optimal climb and descend speeds by both fuel consumption and the durability limits.

6. References

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