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STRUCTURAL DESIGN OF WING TIP PART FROM AEROELASTICITY CONSIDERATION

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Abstract: The paper is devoted to aero-structural optimization of aircraft wing based on a multidisciplinary approach. The focus is on the study of influence of elastic, inertial and aerodynamic forces on optimal shape and structural parameters of the wing tip part. Main features of the proposed bi-level method are presented. Numerical results of structural optimization for middle range civil aircraft are discussed.

1 INTRODUCTION

In the paper [1] the problem of structural optimization of the wing shape together with wing structural parameters was formulated as a multidisciplinary aero-structural optimization problem where aerodynamics, aeroelasticity and strength/buckling requirements were mutually taken into account. That approach included conceptual study of structural flexibility, loads and control effectiveness of aircraft. The optimization goal was to find sweep angle of the wing tip part and structural parameters which minimize the structural mass and provide the best aerodynamic performance in cruise flight. The numerical results for aircraft configuration with engine on wing showed that the airplane wing had wing tip part with slightly larger sweep angle at the leading edge with respect to the wing without a kink at the wing end. The results in the paper [2] also showed that the change of the sweep angle of wing-box at the wing tip part could alleviate loads in extreme load cases and thus reduce the mass of the structure. Note that the optimal sweep angle of wing tip depends on airplane configuration. It was shown that for wing without attached engine slightly forward sweep wing tip with respect to a baseline wing is preferable [3].

In this paper the further investigations on structural design of wing tip part are presented, Additional and more detailed studies were performed to recognize how different types of aeroelastic forces influence on the design parameters of the wing tip part. Change of shape in the plan-form of the wing at the wing tip part affects on stiffness parameters, mass characteristics and distribution of the aerodynamic forces simultaneously. The main factors and their influence on the design variables providing the lighter design at satisfying both strength and flutter constraints have been identified.

2 PROBLEM FORMULATION

We consider middle range civil aircraft with maximum take-off mass of 76500 kg, length of 42 m, wing span of 40 m and wing area of 128 m2. Wing has sweep angle 31.3° at leading edge and aspect ratio of 12.5. In the design studies only extreme cases of symmetrical loading are considered which are listed in Table 1. Free balancing parameters for loads calculations are angle of attack and deflection angle of horizontal tail.

#	Description	M	q, kPa	H, m
1	Maximum lift coefficient and maximum load factor	0.37	9570	300
2	Maximum load factor at maximum speed V_D	0.89	21200	7640
3	Maximum load factor on cruise	0.82	15900	8500

Table 1: Main parameters of load cases

The aircraft structural model includes all major components such as fuselage, wing, horizontal tail, vertical tail, engine on the pylon and etc. The main parameters of aircraft plane have been defined from preliminary researches and studies of prototypes. The design model has been prepared for optimization purposes. It consists of 174 design variables that include domains of skins, stringers, ribs and spars of the airplane wing. Two structural models with different sweep angles of wing tip part are presented in Figure 1.

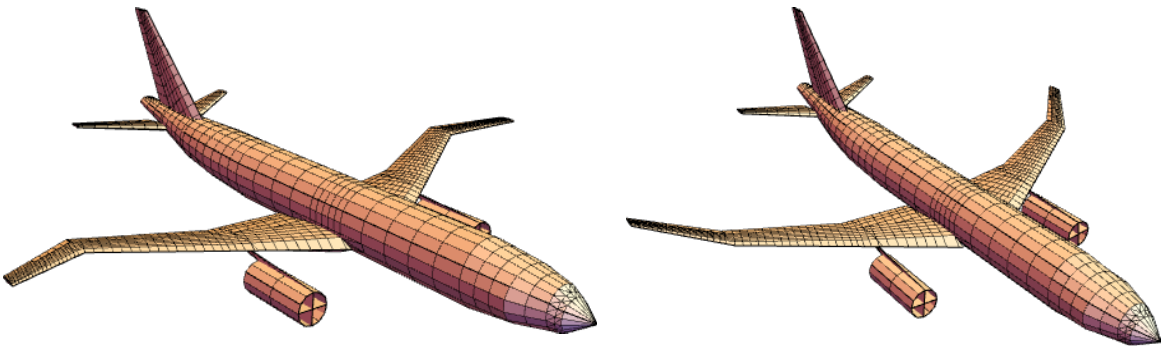

Figure 1: Two airplane configurations with different sweep angle of wing tip part

We have an aeroelastic optimization problem for determination of preferable wing shape and wing structural parameters by minimization of the structural mass of wing under stress and flutter constraints. The mathematical statement of the problem is the following:

$$
\begin{array}{l}
\text{Find } \min M(\boldsymbol{\gamma}, \mathbf{X}) \\
\text{subjected to:} \\
\left\{
\begin{array}{l}
\max\limits_{l}\left(\dfrac{\sigma_{il}(\boldsymbol{\gamma},\mathbf{X})}{\sigma_a}-1\right) \le 0, \quad i=\overline{1,\ n}, \quad l=\overline{1,\ LC} \\
\max \beta_k(V,\boldsymbol{\gamma},\mathbf{X}) \ge \beta_{0k}, \quad k=\overline{NF_f,\ NF_l} \\
V \le 1.2V_D \\
x_i^l \le x_i \le x_i^u, \qquad i=\overline{1,\ n} \\
\gamma_j^l \le \gamma_j \le \gamma_j^u, \qquad j=\overline{1,\ p}
\end{array}
\right.
\end{array}
\tag{1}
$$

In (1) M is structural mass, $\mathbf{X}$ is vector of design variables, $\boldsymbol{\gamma}$ is vector of geometric design variables, σ_a is the maximum allowable value of stress, σ_{il} are values of acting stress for i^{th}

design variable in l^{th} load case and β_k is damping value that must be more than some given value β_{0k} for specified modes.

The allowable stresses were chosen for aluminum alloy to be equal 266 MPa that corresponds to 400 MPa for design loads. The flutter requirements are applied only to the first seven modes. For the considered airplane the speed limit V_D = 186 m/s EAS at M = 0.82, according to the Aviation Rules it is necessary to provide the flutter speed more than 1.2V_D = 224 m/s.

3 BI-LEVEL OPTIMIZATION PROCEDURE

The flowchart of the proposed method for solving this optimization problem is shown in Figure 2. It consists of two main stages shown by the dashed line rectangles. At the first stage structural optimization with stress constraints is preformed and in the second one flutter optimization is done. The pre-processing stage includes the parametrization of baseline wing model and generation of structural and aerodynamic models with different design parameters.

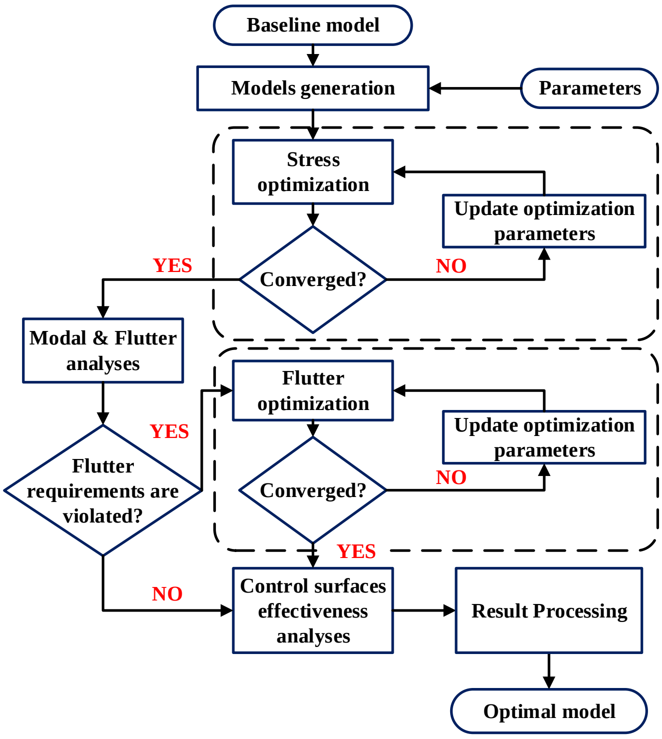

Figure 2: Flowchart of optimization procedure

The sweep angle of wing tip part is one of geometric design variables. Changing of structural model shape is defined by some plane with respect to which the transformation of coordinates take place. The matrix coefficients of linear transformation are determined to correctly change location of boundary nodes of wing tip part at changing the sweeping angle of wing tip part. The obtained transformation matrix is also used to calculate the new nodal coordinates of wing tip part. The orientation angle of an unbalanced layer in skin composite laminate at zone of wing tip part can be also treated as geometric design variable.

At the first stage of optimization the strength requirements are under consideration for several extreme load cases. Usually the fully-stressed design algorithm is used for the first few iterations to get a good starting point for the sequential quadratic programming method. Then the obtained thicknesses are considered as the lower limits for the corresponding design variables at the second stage of optimization where the requirements for flutter speed should be satisfied. If flutter requirements are satisfied, then control surface effectiveness is analyzed to verify the static aeroelasticity characteristics. The bi-level aeroelastic optimization is performed for each considering sweep angle of wing tip part. The best solution is found by ranking the obtained optimal designs.

4 RESULTS OF FIRST STAGE OF OPTIMIZATION

Initially loads were computed for the dominant load cases for “rigid” aircraft. For these loads the stress optimization gives mass of 2660.7 kg for baseline model (without kink at wing end). But account of wing flexibility substantially decreases the bending moment as shown in Figure 3.

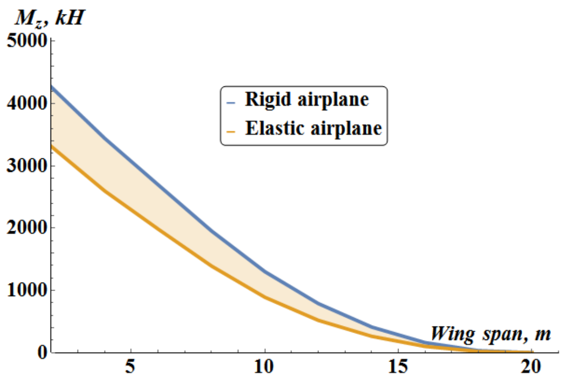

Figure 3: Bending moment for “rigid” and “elastic” aircraft

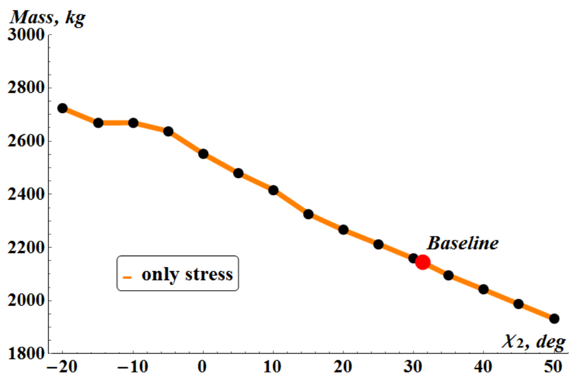

Figure 4: Dependence of structural mass on sweep angle of wing tip part

The optimal structural mass at design for the “elastic” loads is 19% lighter and equals to 2155.2 kg. Therefore, it is important to optimize structure with taking into account aircraft elasticity. It should be noted that none of the obtained designs does satisfy flutter constraints. The flutter speeds are less the needed one by 5% - 26%.

5 RESULTS OF SECOND STAGE OF OPTIMIZATION

At the second stage, structural optimization is performed with taking into account flutter constraints and the minimum values of structural sizes are taken from the results of stress optimization. The obtained structural masses for first and second stage of optimization are shown in Figure 5.

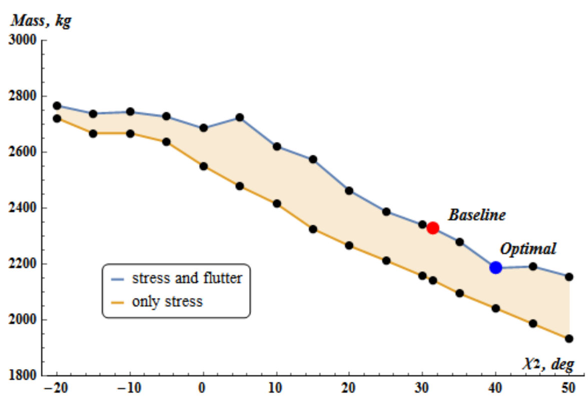

Figure 5: Dependence of structural weight on sweep angle of wing tip part

As can be seen for the negative sweep angles the differences in the structural masses for two stages are little and it significantly increase when the angles of sweep angle of wing tip part become positive. Optimal sweep angle is about 40°. Mass of optimal structure is 2173.4 kg and it is lighter by 6.7% than for the baseline configuration.

Figures 6 and 7 illustrates areas where it is necessary to add the material to compensate flutter constraints. It can be seen that the biggest difference in thicknesses is observed in zones of front spar and skin between root section and section of engine attachment.

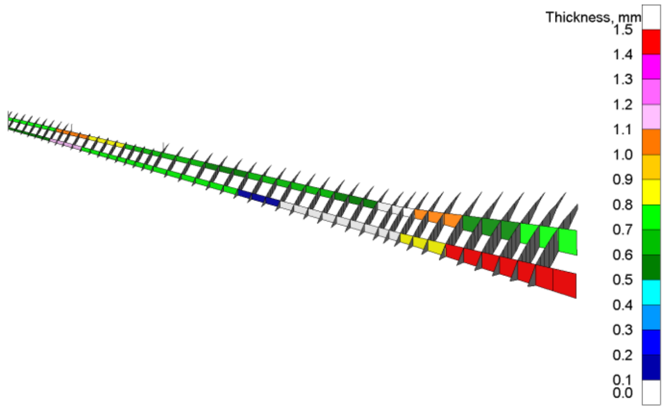

Figure 6: Differences in thicknesses between two stages of optimization for spar/rib webs

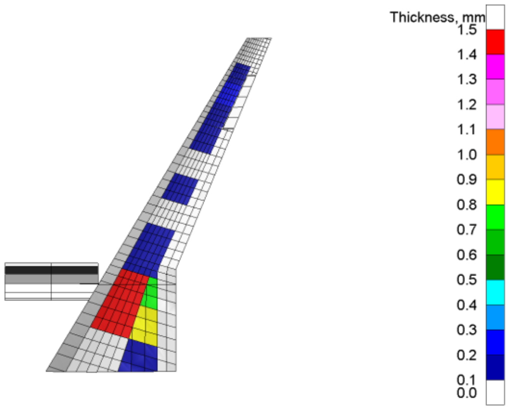

Figure 7: Differences in thicknesses between two stages of optimization for upper skin

It should be noted that the main drawback associated with the increase of sweep angle of wing tip part is its influence on outer aileron effectiveness. Aileron reversal is observed for wing when sweep angle is larger than 45° at low flight speeds (M=0.37) and at higher speeds an effectiveness of outer aileron is also not sufficient for the optimal wing shape with sweep angle of 40°. The introduction of material with anisotropic elasticity properties would make it possible to achieve the optimal result without loss at roll effectiveness.

6 CONCLUSION

Aeroelastic optimization with stress and flutter constraints has been performed to determine the optimal shape of wing tip part and structural parameters such as skin/web thicknesses, spar/rib cross-section areas. Numerical results show that the optimum design has wing tip part in the back direction of about ten degrees with respect to the baseline wing. The structural mass for the obtained optimal wing structure at satisfying strength and aeroelasticity constraints is about 6.7% less than one for optimized baseline configuration.

Future design investigations will be directed to understand what structural material would be preferable to achieve the optimal result without loss at roll effectiveness. In the case of composite material, it is needed to determine the optimum orientations of fibers and percentage fraction of composite layers in laminate. The introduction of composite material into design process will increase the feasible region for finding the optimal design. Also it will allow to get optimal results as in the case of the aluminum alloy but without loss at roll effectiveness.

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