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MULTIDISCIPLINARY TOPOLOGY-BASED OPTIMIZATION IN DESIGN OF AIRCRAFT STRUCTURAL LAYOUTS

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Abstract

An integrated structural optimization method which includes the use of topology/shape/sizing optimization in the computational environment with analysis of the aerodynamic/inertial loads is proposed. Structural design procedure and main features concerning the optimization problems are discussed. Some test numerical examples and aero-structural optimization of aircraft wings are considered.

1 Introduction

The complexity of aircraft structural design is mainly related to the fact that many operating constraints from various technical disciplines should be under consideration. Multidisciplinary approach is often used to take into account the interactions between distinct disciplines and thus to obtain structure with better characteristics. The optimization results are strongly related on the choice of the initial structural layout. In recent years to predict the reasonable location of the load-bearing structural elements the topology optimization methods have been extensively used [1-4]. The solutions obtained with these methods in the conceptual design stage can significantly differ from ones that were determined by traditional approach [3].

Therefore, the purpose of this research is the mutual use of previously developed methods of multidisciplinary optimization [4, 5] and topology optimization [6, 7] to create an efficient design procedure of aircraft load-bearing structures. The problem is formulated as a multidisciplinary aero-structural optimization where aerodynamics, aeroelasticity and strength requirements are taken into account.

At the present time application of topology optimization has mostly been confined to the design of individual aircraft components such as wing ribs, spars, attachments and so on [8]. A few papers are devoted to the determination of wing structural layouts, for instance [9]. That paper proposes an approach using topology optimization for developing conceptual design of the wing structural layout considering constraints on local displacements and panel buckling. Note that aeroelasticity constraints are not included in that methodology. The below described approach allows to take into account together stress, buckling and aeroelasticity requirements.

In this paper we discuss structural design procedure and main features concerning the optimization problems. Some test numerical examples and aero-structural optimization of aircraft wings are considered.

2 Problem statement

The proposed method consists of two sequential stages: topology optimization stage and shape/sizing optimization stage. At the first stage the specified geometric outlines of mechanical body define the place of load-bearing structure or design domain. Some part of the domain is supposed to be fixed and another part is subjected by external loads. The design domain is divided in detail on 3D finite elements for analysis of displacements and stresses. The problem statement of topology optimization can be formulated as follows:

$$\text{Find } \min \mathbf{f}^T \mathbf{U} \text{ subject to } \int_{\Omega} \rho(\mathbf{x}) d\Omega \le M_0$$

where $\mathbf{f}$ is a vector of external load, $\mathbf{U}$ is a displacement vector, $\rho(\mathbf{x})$ is a material density in the considered design domain, Ω is a set of elements in the design domain, and M_0 is a value restricting the material mass. The solution of the optimization problem is based on the introduction of a design variable **x**, which relates Young's modulus with the density of each finite element of the structure by the following expressions: $\rho(x) = \rho_0 x$ and $E(x) = E_0 x^p$; where ρ_0 and E_0 are the initial density and Young's modulus of material, and p is a penalty factor used in algorithms for selection of the needed and unneeded structural elements.

The second stage is shape/sizing optimization. The mathematical statement of this multidisciplinary optimization problem can be written as follows:

$$\min M(\boldsymbol{\gamma},\mathbf{X})$$

$$\mathit{subjected\ \ to}:$$

$$\begin{cases} \max\limits_{l}\left(\dfrac{\sigma_{il}(\boldsymbol{\gamma},\mathbf{X})}{\sigma_a}-1\right)\le 0, \quad i=\overline{1,\,n}, \quad l=\overline{1,\,LC} \\ \lambda_{1l}\ge 1, \quad l=\overline{1,\,LC} \\ \max\zeta_k(V,\boldsymbol{\gamma},\mathbf{X})\le\zeta_{0k}, \quad k=\overline{NF_f,\,NF_l} \\ V\le 1.2V_D \\ x_i^l\le x_i\le x_i^u, \qquad i=\overline{1,\,n} \\ \gamma_j^l\le\gamma_j\le\gamma_j^u, \quad j=\overline{1,\,p} \end{cases}$$

It is required to find a minimum weight structure $M(\boldsymbol{\gamma},\mathbf{X})$, with the given stress, buckling and flutter constraints. Stress constraints restrict maximum acting stresses σ_{il} in i^{th} design variable for l^{th} load case by allowable value σ_a. Buckling load factors λ_{1l} are determined from eigenvalue problem for given load cases LC. Flutter constraints imply that logarithmic decrement ζ_k must be negative and lesser than some given value ζ_{0k} for some specified modes between NF_f and NF_l at flight speeds V less than $1.2V_D$. Design variables x_i belong to vector **X**. They are sizes of structural elements and bounded by lower and upper values x_i^l and x_i^u, respectively. Vector $\boldsymbol{\gamma}$ of geometric design variables consists of parameters which define the structural shape. Its components have also lower and upper bound constraints. Number of sizing design variables is n, of geometric variables is p.

3 Structural design procedure

The general process presented in Figure 1 includes the topology optimization directed on the search of reasonable structural layouts subjected to several load cases. The solid aerodynamic model which defines the geometric outlines of a structure serves as initial domain for topology optimization. Then the results are interpreted to find out the location of the primary structural elements. The second stage is design of the structural elements in the interpreted thin-walled structural layouts. It includes shape and sizing optimization with the aim to minimize structural weight under stress/buckling/flutter constraints. The auxiliary optimization algorithms in this approach are based on optimality criteria and mathematical programming methods. The final stage is to identify the best structural layout by comparison of the obtained structural weights.

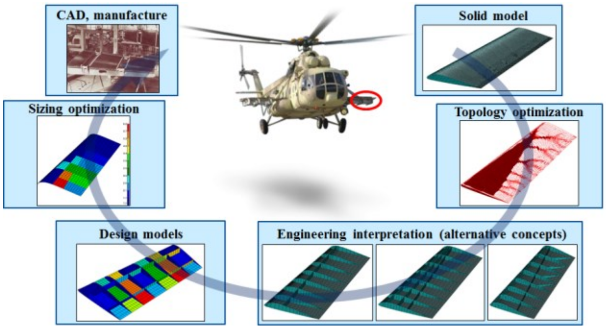


Fig. 1. Design procedure cycle

First stage is characterized by the following aspects:

1. It is important to correctly transfer pressure loads from aerodynamic model to solid finite element (FE) model. It can be performed by interpolation of the obtained pressures with using polynomial function of nodal coordinates on outer surfaces of the FE model.
2. Perform a set of topology optimizations with different control parameters to reveal adequately in global sense where load-bearing material should be located.

3. Use conventional technical solutions for missing information at interpretation of topology optimization results.

On the second stage multidisciplinary optimization problem can be solved by different methods and approaches. For example, it can be solved sequentially by introduction of additional constraints during optimization process, because it is difficult to obtain feasible design solution when many constraints are under consideration. Another important aspect is account of aeroelasticity requirements. Note that extra design cycles are needed to take into consideration effect of structural elasticity.

The above proposed solution pipeline is not strict. In some cases, when initial structural domain is not well defined the solution of design problems can start from shape optimization and this aspect will be shown below in the second example for aero-structural shape/sizing optimization.

Structural, aerodynamic and aeroelasticity analyses are performed by using MSC.Nastran software. Also auxiliary programs to integrate different disciplinary problems into unified design procedure were developed in Wolfram Mathematica environment.

4 Numerical Results

Two examples are considered to demonstrate the proposed methodology. The first one is design of helicopter wing structural layout. In this example we demonstrate full design cycle, including topology optimization, engineering interpretation and sizing optimization. The second example concerns mainly shape and sizing optimization in unified procedure. Here main attention is paid to aeroelasticity requirements, especially to flutter constraints.

4.1 Wing structure optimization

The finite element model of baseline configuration designed by traditional methods is shown in Figure 2. It consists of two spars and eight uniformly spaced ribs that are covered by skins. Mean aerodynamic chord of the wing is 1.3 m and the wingspan is 5.7 m. Structural weight is 69.5 kg.

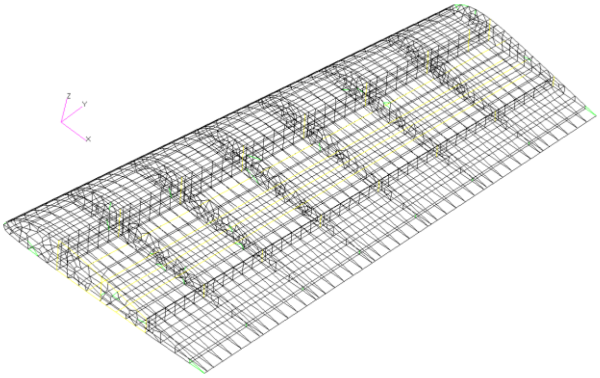


Fig. 2. Baseline structural layout

In this investigations only one extreme load case is considered. It corresponds to a flight of helicopter at maximum angle of attack - 16° with M equal to 0.31.

To determine aerodynamic forces in the extreme load case and to perform aeroelasticity analyses an aerodynamic model of the wing was created (Fig. 3). It is assumed that the design domain of the wing is fixed at root part and aerodynamic pressures are applied to upper and lower surfaces that are the outer edges of solid elements. The wing outlines also serve for generation of a solid FE model which is used in topology optimization. Topology optimization was accomplished with the aim to minimize compliance at saving 50 percent of initial solid model weight in the final design.

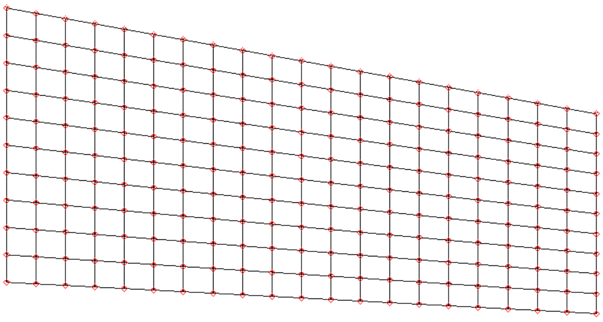


Fig. 3. Aerodynamic model

The obtained pattern where the load-bearing material should be distributed is shown in Figure 4. It is seen that some wing-box together with a set of cross rib elements in the trailing part of the wing can be considered as structural layout. However, it is difficult to choose explicitly one layout corresponding to this pattern. That is why it is worth to consider several possible layouts. Ribs are suggested to be located at the same places as in the baseline configuration.

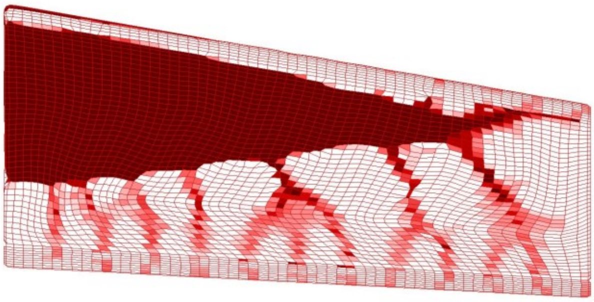
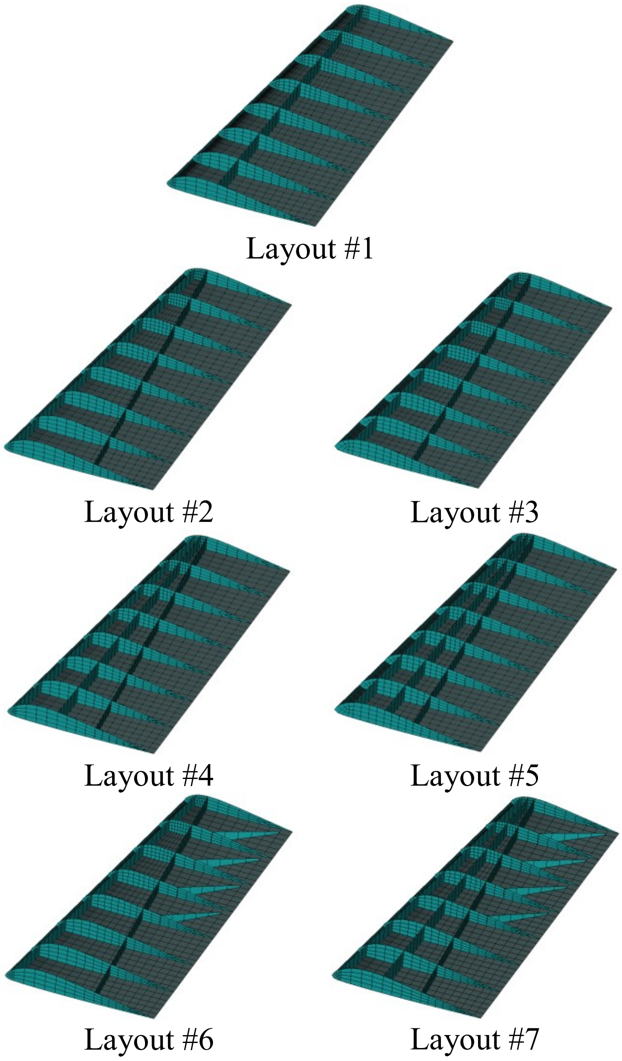


Fig. 4. Topology optimization result

As it can be seen from the pattern, additional ribs could be needed at the end part of the wing. The following seven structural layouts based on engineering intuition were proposed. They are shown in Figure 5 with hidden upper skin of the wing.



Layout #1

Layout #2

Layout #3

Layout #4

Layout #5

Layout #6

Layout #7

Fig. 5. Alternative structural layouts

Structural optimization with stress and buckling requirements shows that the best layout is the three-spar wing with additional ribs (layout #7). Weight of this structure is 42.4 kg. The second layout in weight rank is two-spar wing with additional ribs (layout #6) with weight of 43.2 kg. Optimum thicknesses for the two-spar wing layout are shown in Figure 6. It is worth to mention that thicknesses in wing-box root part significantly change both in spanwise and chordwise directions.

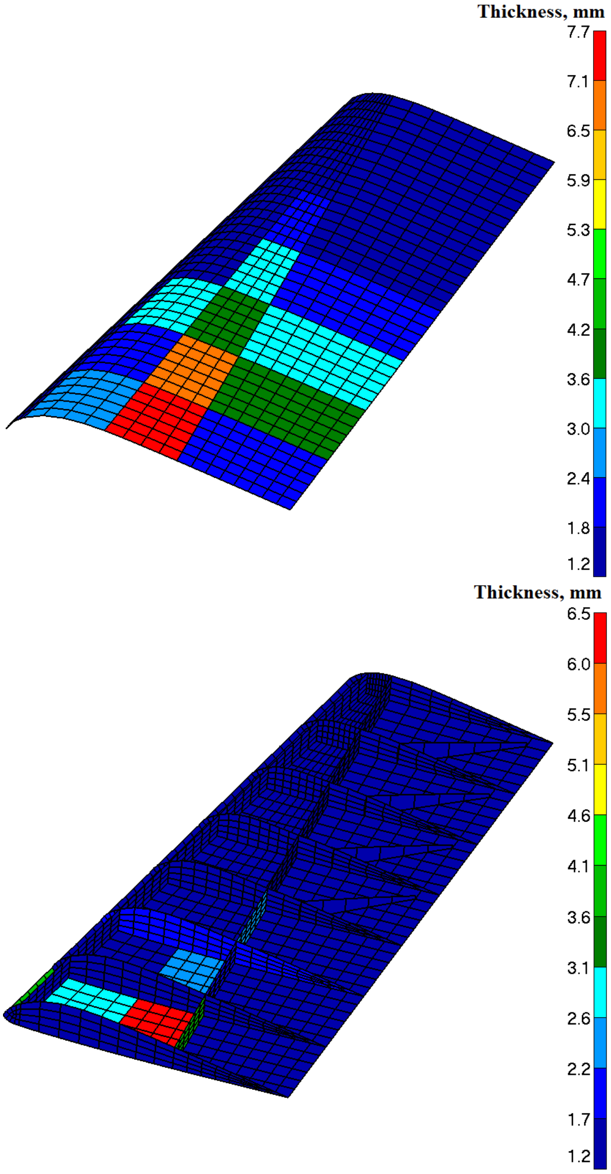


Fig. 6. Optimum thicknesses after strength/buckling optimization

Aeroelasticity analysis was performed for these two layouts. The constraint on the divergence speed was satisfied for all flight regimes. The obtained optimum parameters after structural optimization do not provide flutter requirements. Note that change of panel skin thicknesses for taking into account flutter constraints in optimization process leads to the increase in weight only by 0.8 kg. Comparison of all considered structural layouts with optimal distribution of material showed that the weight benefit was about 10 percent owing to the choice of location of the primary elements. Traditional wing structure designed without the use of topology optimization stage is about 60 percent heavier than the obtained optimal structure.

4.2 Aero-structural shape/sizing optimization

In this design study only extreme cases of symmetrical loading were considered. Therefore, we used only half of the aircraft, including all major parts: fuselage, wing, horizontal tail, vertical tail, engine on the pylon and etc. Only one control surface on the wing (outer aileron) was modeled.

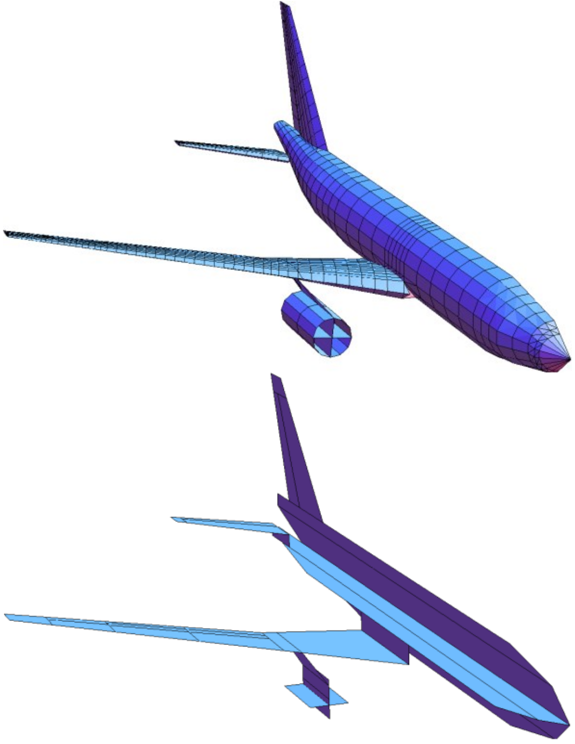


Fig. 7. Structural and aerodynamic model

The main parameters of airplane have been defined from preliminary researches and studies of prototypes. They are given in Table 1.

Table 1. Main parameters of aircraft

Maximum take-off weight	76.5 ton
Airplane length	42 m
Wing area	128 m^2
Wing span	40 m
Aspect ratio	12.5
Mean aerodynamic chord	3.58 m
Wing sweep angle of ¼ chord line	29°

For optimization purposes the design model of the airplane wing was prepared. It consists of 174 design variables that include domains of skins, stringers, ribs and spars. The sweep angle of the wing tip part was a geometric design variable in this research.

Three most dominant cases were considered and they are presented in Table 2. Aluminium alloy with allowable stress of 400 MPa was taken as structural material. Structural elasticity was also considered at loads calculation. The analyses were performed for flight loads, so the allowable stresses were chosen to be equal 266 MPa that corresponds to 400 MPa for design loads.

Table 2. Load case parameters

Description of load case	M	q, kPa	H, m
Max. lift coefficient and max. load factor	0.37	9.57	300
Max. load factor on cruise	0.82	15.9	8500
Max. load factor at maximum speed V_D	0.89	21.2	7640

The flutter requirements were applied only to the specified modes which were obtained during preliminary flutter analysis. 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.

Changing the geometry of the wing end part was done by applying the affine transformation to the coordinates of defined area (dashed rectangle) shown in Figure 8.

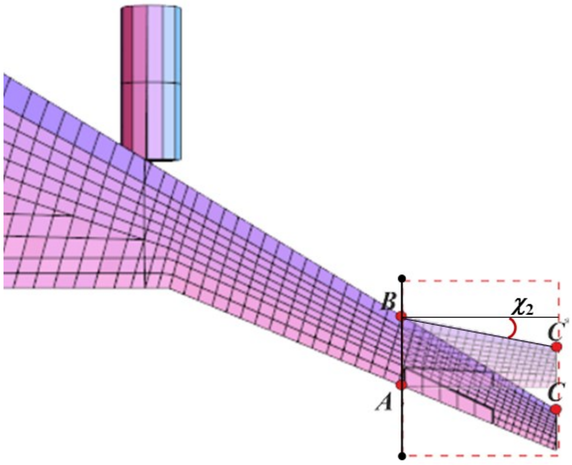


Fig. 8. Generation of new wing geometry

It is essential that this transformation allows to save the wing area and aspect ratio. This transformation procedure was also applied to the appropriate aerodynamic and mass-inertia models. The above-described algorithm for generation of computational models was used to create 16 airplane models with sweep angles from -20° to +50° with the step of 5°.

Below Figure 9 shows two configurations with the maximum change of the sweep angle of wing tip part.

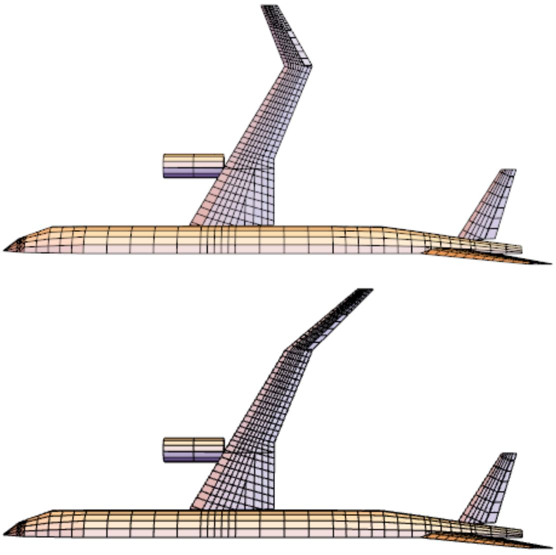


Fig. 9. Configurations with limit sweep angles in optimization process

Multidisciplinary aero-structural optimization to determine preferable wing shape was done in two stages. Firstly, structural optimization was accomplished only with stress constraints for the considered sweep angles. Flutter analysis of these optimal structures showed that none of them satisfy flutter requirements. Flutter speed versus sweep angle of the wing tip part is given in Figure 10.

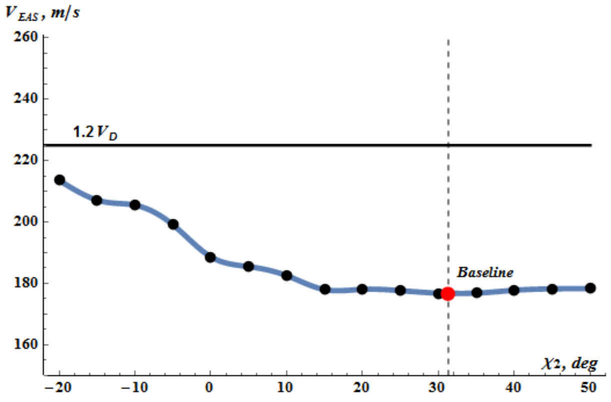


Fig. 10. Flutter speed versus sweep angle of wing tip part

Then structural optimization was fulfilled with flutter constraints and gauge constraints with minimum values of structural sizes taken from previous stress optimization. The obtained structural weight for both optimization procedures are drawn by two curves in Figure 11.

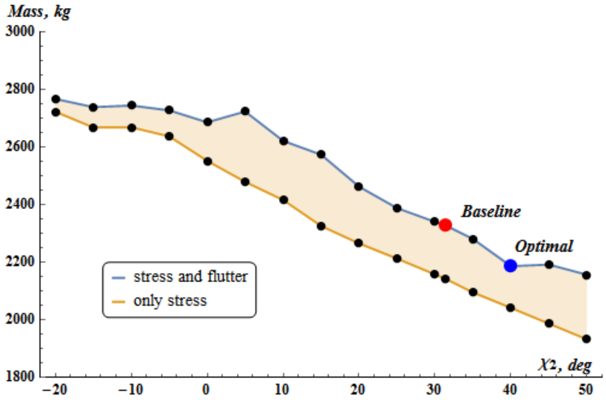


Fig. 11. Dependence of optimal weight on sweep angle of wing tip part

As it can be seen for the negative sweep angles the difference in the structural weights for two optimizations is little and it significantly increases when the angles of wing tip part become positive. Finally, to understand what influence on outer aileron effectiveness has the sweep angle we perform analysis of static aeroelasticity of the obtained optimized wing configurations. Aileron reversal is observed for wing when sweep angle is larger than 45° at low flight speeds (M=0.37). At higher speeds effectiveness of outer aileron is not sufficient for the wing shape with sweep angle of 40°, but in these flight regimes the roll control can be provided by inner aileron.

Therefore, the most preferable configurations from loads, strength, flutter and structural weight point of view is configuration with sweep angle of 40°. Weight of optimal structure is 2186.6 kg and it is lighter by 6.3% than the baseline configuration. Thicknesses of upper/lower skins and spar/rib webs and stress distribution in them for the optimal configuration are presented in Figures 12-15.

Only first investigations on aerodynamic performance were done by using CFD software. The preliminary results showed that changing sweep angle of the wing tip part in backward direction slightly increase lift-to-drag ratio. To understand cross-discipline aerodynamic-structural effects an additional extensive further work is still required.

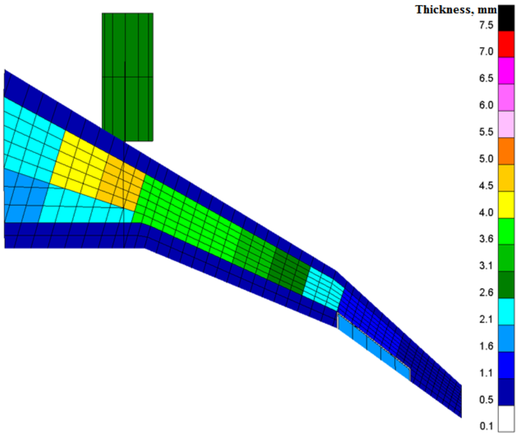


Fig. 12. Thicknesses of upper skin

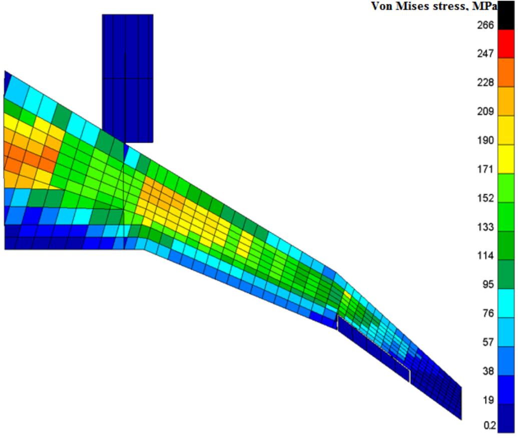


Fig. 13. Von Mises stresses in upper skin

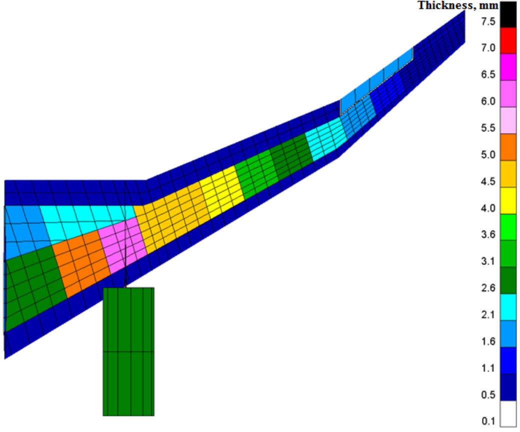


Fig. 14. Thicknesses of lower skin

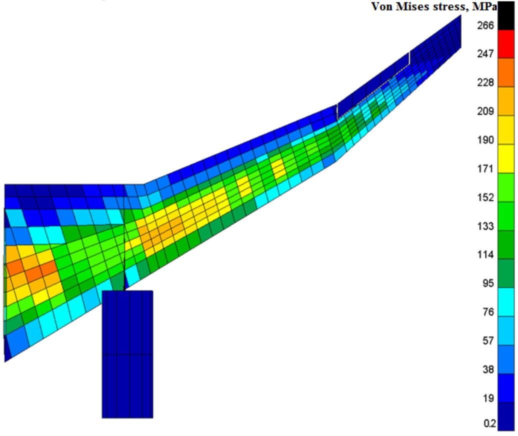


Fig. 15. Von Mises stresses in lower skin

5 Conclusion

The paper has proposed multidisciplinary approach of structural design based on topology and sizing/shape optimization. The approach was demonstrated on examples of the low aspect-ratio wing and wing of middle range aircraft.

Application of topology optimization helped to determine several alternative layouts. By means of structural optimization under strength/buckling requirements two reasonable layouts were obtained: three-spar and two-spar wings with additional ribs at the end part. The weight benefit is about 37.5 percent.

Multidisciplinary structural optimization with stress and flutter constraints has been performed for wing with swept wing tip. The most preferable structural layout from point of view of loads, strength, flutter and structural weight was found. The optimal sweep angle of wing tip part is in backward direction of about +10° with respect to the baseline wing. The structural weight for the obtained optimal wing at satisfying strength and aeroelasticity constraints is about 6.3% less than one for optimized baseline configuration.

The developed multidisciplinary approach shows its efficiency and usefulness in design process of complex aerospace structures and can be used in modern design practice.

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