# EVOLUTIONARY APPROACH TO STRUCTURAL DESIGN OF WING UNDER STRESS, BUCKLING AND AEROELASTICITY REQUIREMENTS

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**Abstract:** An evolutionary approach to synthesis of optimal aircraft component layouts has been developed. It is based on combined application of topology optimization, an engineering interpretation and optimum sizing of load-bearing structural elements. The developed approach gives possibility to include stress, buckling and aeroelasticity constraints altogether in unified design procedure and to get an optimal wing structure.

## 1 INTRODUCTION

The aircraft structural design is very complicated problem. It is due to that many operating constraints arising from different technical disciplines, determining the performance of the aircraft, should be taken into account. Multidisciplinary design optimization approach is often used to solve this problem involving highly large number of design variables and constraints for the preliminary chosen layout of structure. But the optimization results can be strongly related with the choice of layout. Topology optimization can predict reasonable location of main structural elements.

The aim of this work is to combine the multidisciplinary structural optimization with topology optimization to build an efficient procedure for design of aircraft structures. Topology optimization of continuum structures is a numerical optimization approach aimed at conceptual design. By using topology optimization optimal structural layouts can be found by determining the best locations and geometries of cavities in the design domains. Many numerical methods for topology optimization of continuum structures have been investigated extensively, for example [1–4]. For example, two heuristic methods of structural topology optimization are presented in the paper [3]. They are based on the application of the fully-stressed design criterion, used in practice to determine the structural rational parameters taking into account the strength constraints. In our context, the topology optimization allows to determine the principal load-carrying directions in which structural material should be located. These directions are strongly related with the way of load application and number of load cases. Usually various engineering interpretations of the topology optimization results can be proposed by designer. In this approach, several structural layouts are generated, and the multidisciplinary structural optimization [5] is performed for them.

The approach is demonstrated on the example of design of low-aspect-ratio wing of advanced helicopter.

## 2 METHODOLOGY OF WING STRUCTURAL DESIGN

At the present time use of topology optimization has mostly been confined to the design of individual aircraft components such as wing ribs, spars, attachments and so on [6]. A few papers are devoted to determine structural layouts of wing, for instance [7]. That paper proposes an approach for using topology optimization for developing conceptual designs of wing structural layout with taking into consideration of constraints on local displacements and panel buckling. Note that no aeroelasticity constraints are included in that methodology. The below described approach allows to consider together stress, buckling and aeroelasticity requirements.

The general flow-chart of the developed approach is presented in Figure 1 and it involves the following steps:

1. geometric outlines of a structure are specified as initial data for topology optimization;
2. a set of topology optimization with different control parameters is accomplished to reveal where load-bearing material should be located;
3. engineering interpretation of the obtained topology results to determine several alternative structural layouts;
4. generation of finite element (FE) models of alternative structures using 2D shell elements which include skins, ribs and spars;
5. accomplishment of design optimization for determination of sizes of structural elements with satisfying stress/buckling constraints;
6. computation of aeroelasticity characteristics (flutter, divergence, etc.). If needed, the aeroelastic optimization is performed with minimum gauge constraints arising out of stress/buckling optimization;
7. ranking of structural layouts based on comparison of optimal weights.

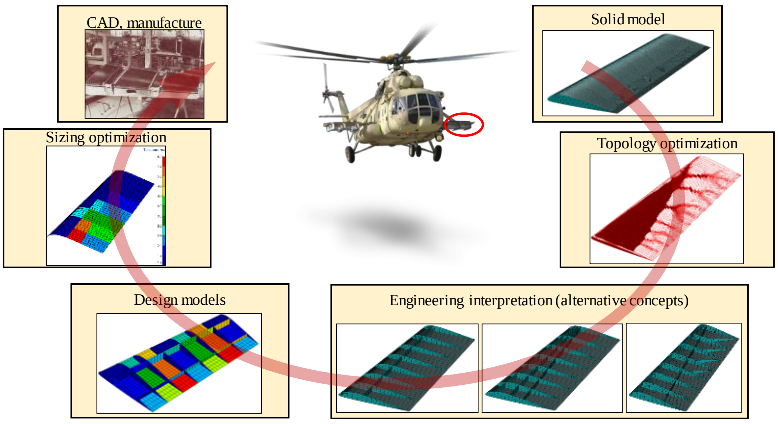

Figure 1: Evolutionary approach cycle

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 subdivided in detail on 3D finite elements for analysis of displacements and stresses.

The problem statement of topology optimization can be formulated as follows:

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

where **f** is a vector of external load, **U** is a displacement vector, $\rho(\mathbf{x})$ is a material density in the considered design domain, $\Omega$ 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** in each finite element, which relates Young's modulus with the density of each finite element of the structure by means of the following expressions: $\rho(x) = \rho_0 x$ and $E(x) = E_0 x^p$; where $\rho_0$ and $E_0$ are the initial density and Young's modulus of material, and $p$ is a penalty value used in algorithms for selection of the needed and unneeded structural elements [1, 4].

The result of topology optimization is the distribution of densities in elements. The greater value of density shows on necessity material in the place of element and the smaller value shows that no material should be located in that place. It is difficult to see unambiguous solution for structural layout from the topology pattern and an engineering interpretation should be done.

The engineering interpretation of topology results are performed intuitively based on the obtained distribution of material. Usually several alternative layouts can be proposed by studying the obtained topology patterns with different optimization parameters and using of design experience. For example, rib spacing could be defined from buckling consideration for wing panels and manufacturing constraints. Also, note that wing structure usually consists of beam and shell elements.

A choice of reasonable structural layout can be done after structural sizing of alternative configurations. FE models of the wing are created by using 2D shell elements. The models include main load-bearing elements. Design models with design variables as skins, spars, ribs thicknesses are built to provide structural sizing.

Sizes of structural elements are calculated by means of weight optimization under strength and buckling requirements. Generally, mathematical programming methods and/or criteria optimality algorithms are used.

Simultaneous optimization with stress, buckling and aeroelasticity constraints is rather complex. Therefore, at first, verification by analysis of aeroelastic characteristics is done. If all aeroelasticity constraints are satisfied, the structural design procedure finishes. Otherwise, the sensitivity analysis is performed with regard to design variables and aeroelastic optimization starts with minimum values of design variables obtained from stress/buckling optimization.

Finally, the best structural layout is chosen by comparison of the obtained structural masses. Often several optimum structural layouts can be considered as reasonable due to little difference in weight.

## 3 NUMERICAL RESEARCHES

Structural, aerodynamic and aeroelastic analyses are performed by using MSC.Nastran software. Load analysis is fulfilled by means of some possibilities of MSC.FlightLoads. Also, to interpolate the obtained aerodynamic forces to nodal pressures of lower and upper surfaces of solid FE model the Wolfram Mathematica system is used.

### 3.1 Baseline configuration

The finite element model of baseline configuration designed by conventional methods is shown in Figure 2, where main structural elements can be seen. It consists of two spars and eight uniformly spaced ribs that are covered by skins.

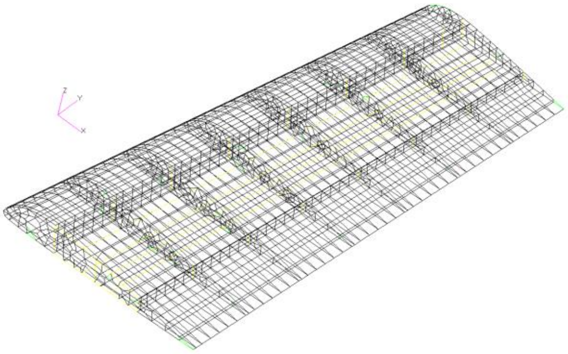

Figure 2: FE model of baseline configuration

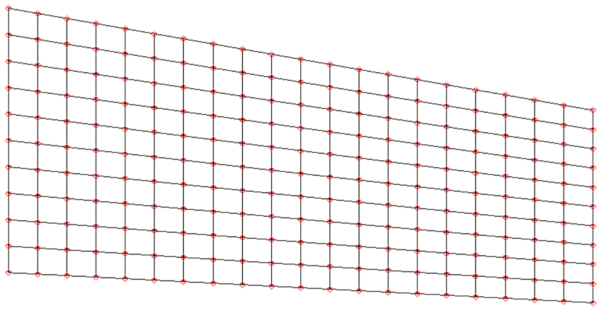

Figure 3: Aerodynamic model

Mean aerodynamic chord of the wing is 1.3 m and the wingspan is 5.7 m. Structural weight is 69.5 kg. One extreme loading case is considered in the investigations. It corresponds to a flight of helicopter at maximum angle of attack of 16 degrees 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 (Figure 3). Aerodynamic surface as plate was subdivided into 200 aerodynamic panels.

Static and buckling analysis showed that strength and buckling constraints are satisfied. Allowable stresses for flight loads are assumed equal to 240 MPa (24 kgf/mm$^2$). The largest stresses are observed around the wing root in the region of the front spar. Maximum stress of 17.7 kgf/mm$^2$ is achieved in the front spar web and it is about 16.2 kgf/mm$^2$ in the upper skin (Figure 4).

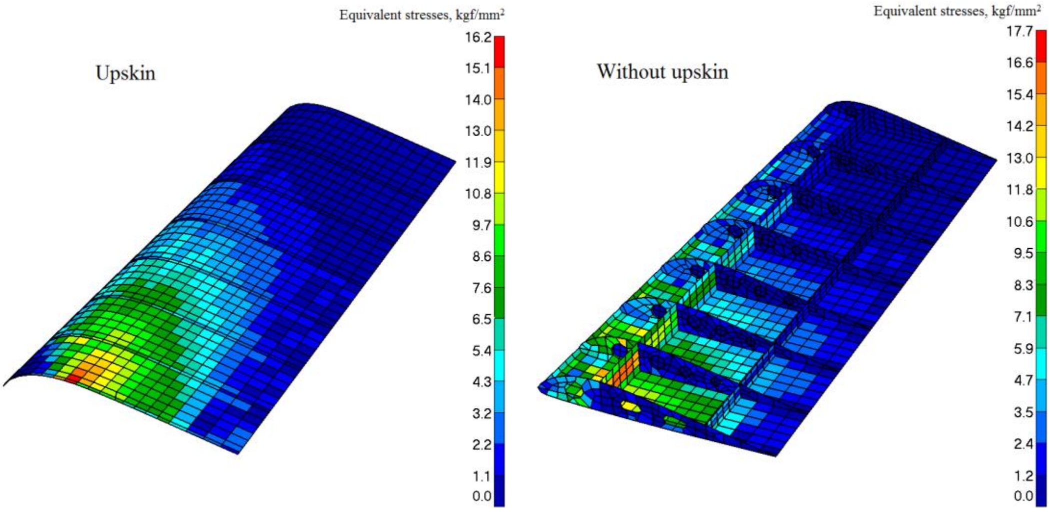

Figure 4: Von Mises stresses

The buckling load parameter is equal to 1.05 and it corresponds to buckling shape of the wing panel in the trailing part at the wing root. Flutter and divergence analysis shows that the divergence speed of 283 m/s satisfies the aeroelastic requirements. It is significantly higher than 145.2 m/s, which is in accordance with the airworthiness requirements. Flutter speed is beyond the speed range of interest.

Multidisciplinary sizing optimization was performed to minimize structural weight. Optimal thicknesses of upper and lower panels, ribs and spars webs are shown in Figure 5.

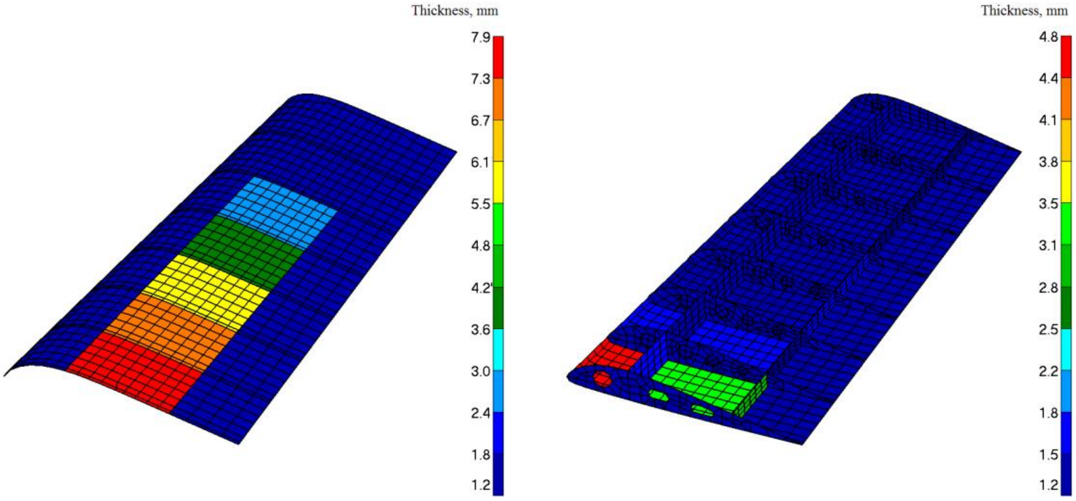

Figure 5: Optimal thicknesses

The weight after optimization is 47.2 kg. Note that the obtained weight is significantly less than the weight for initial structure. Critical flutter and divergence speeds are much greater than the maximum flight speed, so aeroelasticity constraints are satisfied.

## 3.2 Alternative layouts

The minimum of structural weight corresponds to some reasonable layout that can be found by topology optimization. It is assumed that the design domain of the wing is fixed at root part and aerodynamic pressures for a load case are applied to upper and lower surfaces that are the outer edges of solid elements.

To determine aerodynamic forces in extreme load cases and to perform aeroelasticity analyses the aerodynamic model of the wing shown in Figure 3 is used. The wing outlines serve for generation of a solid FE model which is used in topology optimization (Figure 6, top). It is important for this problem to correctly transfer pressure loads from aerodynamic model to FE model. It was performed by interpolation of the obtained pressures with using polynomial function of nodal coordinates on outer surfaces of the FE model. Topology optimization was accomplished with the aim to minimize compliance at saving 50 percent of initial solid model weight in the final design. The obtained pattern where the load-bearing material should be distributed is shown in Figure 6 (bottom, left). Also, an extrusion manufacturing constraint is included which forces all structure to remain uniform through the thickness of the wing (Figure 6, bottom, right). In this case the zone with more concentrated distribution of material can be seen. In the patterns the cyan colored regions correspond to low material densities and the red colored regions – to high material densities which define the load-carrying regions. 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. According to the left pattern, we should choose a wider wing-box. On the other hand, the right pattern offers a narrower wing-box with spars locating along the maximum wing depth. Ribs are suggested to be located at the same places as in the baseline configuration. As it can be seen from the pattern, additional ribs could be needed at the end part of the wing.

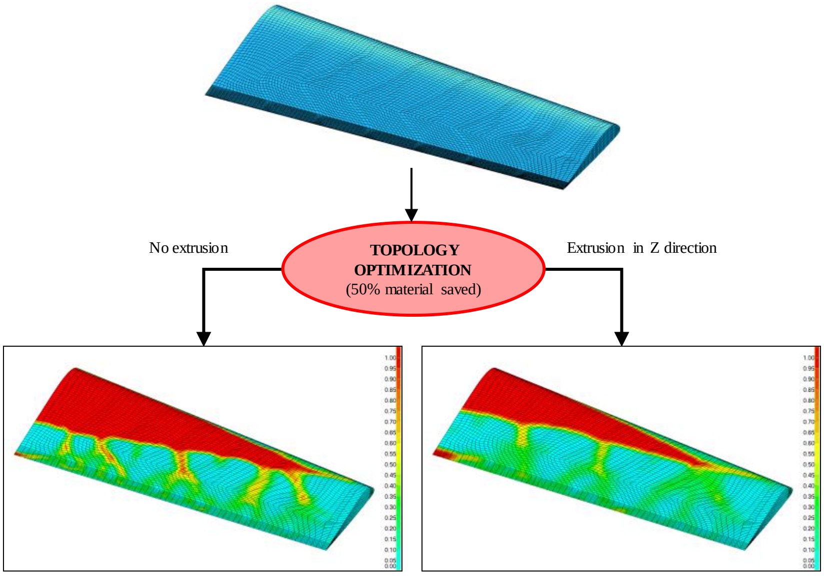

Figure 6: Initial solid FE model (top), topology results (bottom)

The following seven structural layouts based on engineering intuition were proposed. They are shown in Figure 7 with hidden upper skin of the wing. Their description is given in the Table 1.

| | |
|---|---|
| 1 | Single-spar layout in which the spar is in the centre of the maximum material concentration zone. |
| 2 | Two-spar layout in which spars are at the bounds of the maximum material concentration zone. |
| 3 | The same as *Layout 2* but the wing-box width is narrowed (front spar is along the maximum structural depths). |
| 4 | Three-spar layout with spars corresponding to *Layout 1* and *Layout 2*. |
| 5 | Three-spar layout with spars corresponding to *Layout 1* and *Layout 3*. |
| 6 | The same as *Layout 2* with additional ribs at the end part of the wing. |
| 7 | The same as *Layout 4* with additional ribs at the end part of the wing. |

Table 1: Description of structural layouts

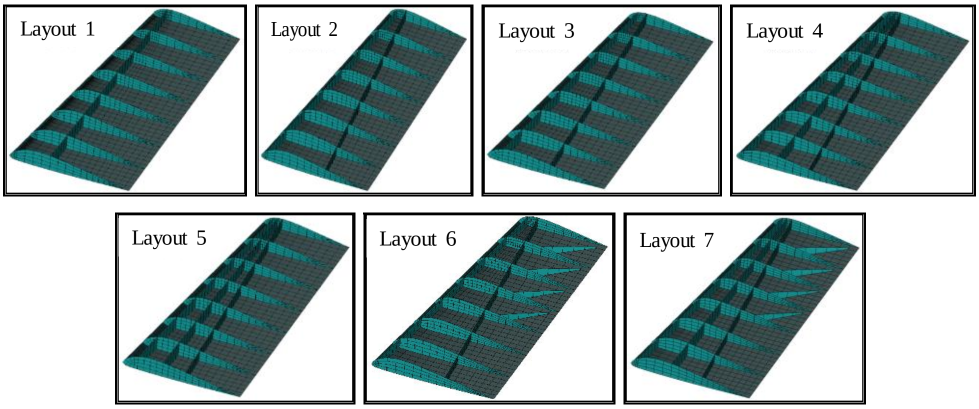

Figure 7: Alternative structural layouts

### 3.3 Sizing optimization

In the sizing optimization, the thicknesses of the panel skins, ribs and spars are considered as design variables. Minimum thickness for all of them is 1.2 mm. The allowable stress in design researches chosen from strength and fatigue conditions is equal 240 MPa. The number of design variables in layouts varies from 71 to 89. This difference is due to the number of spars and additional ribs in these layouts.

The structural optimization under strength/buckling/aeroelasticity requirements for the layouts leads to the following optimal weight values that are presented in Table 2. The optimal structural layouts from the viewpoint of strength are two-spar configurations. However, buckling analysis showed that none of the considered layouts satisfies to buckling requirements.

| Layout # | Only stress constraints | Stress/buckling constraints | Stress/buckling/aeroelasticity constraints |
|---|---|---|---|
| 1 | 35.5 | 47.8 | - |
| 2 | **31.6** | 45.2 | - |
| 3 | **31.7** | 49.8 | - |
| 4 | 32.2 | 44.2 | - |
| 5 | 32.3 | 46.7 | - |
| 6 | 32.0 | **43.2** | **43.9** |
| 7 | 32.5 | **42.4** | **43.2** |

Table 2: Optimal masses (kg)

Then the structural optimization with stress and buckling requirements shows that the best layout here is the three-spar wing with additional ribs (weight 42.4 kg). The second layout in weight rank is two-spar wing with additional ribs (weight 43.2 kg). Optimum thicknesses for the two-spar wing layout are shown in Figure 8. It is worth to mention that thicknesses in wing-box root part significantly change both in spanwise and chordwise directions.

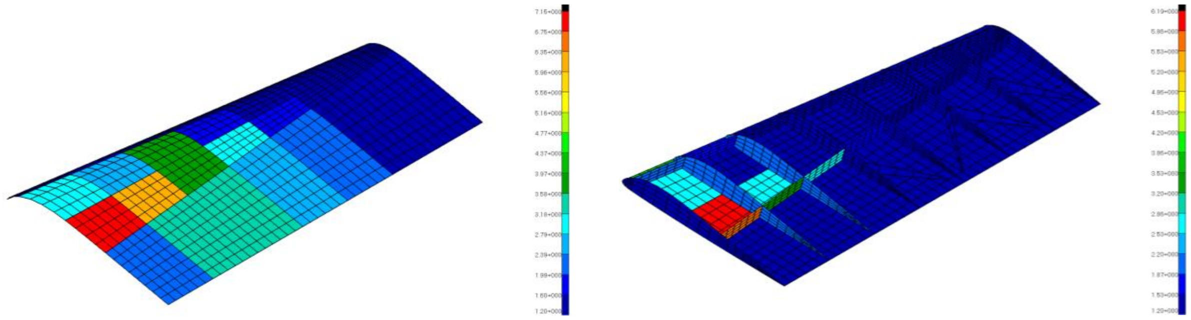

Figure 8: Optimum thicknesses after strength/buckling optimization

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. Flutter analysis observed three flutter points with shell shape vibration of lower skin at trailing part of wing. It could be explained that in this place the obtained thicknesses are close to minimum value after the stress/buckling optimization. The lowest flutter speeds for two- and three-spar wings were 124 m/s and 121.5 m/s, respectively. The sensitivity analysis of flutter speeds versus design variables confirmed that thicknesses of lower panels at the trailing part have greater influence on flutter constraints.

The increase of minimum thicknesses of the lower panel skin up to 1.3 mm and, in addition, the increase thickness of lower panel skin in the root part in the trailing edge up to 1.5 mm leads to satisfaction of flutter requirements. The damping coefficients versus flight speed are shown in Figure 9.

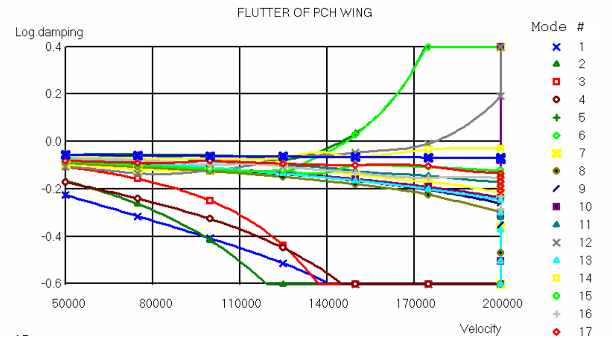

Figure 9: Damping coefficients versus flight speed

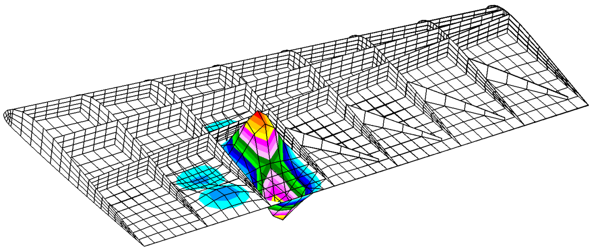

Figure 10: Flutter shape

There are three flutter forms with speeds 145.2 m/s, 147 m/s and 177 m/s for optimum three-spar layout with weight of 43.2 kg. Note that change of panel skin thicknesses for taking into account flutter constraints leads to the increase in weight by 0.8 kg. In Figure 10, the shell flutter vibration is shown.

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 use of optimization methods is about 60 percent heavier than the obtained optimal structure. As buckling constraints are active for the most part of upper skin, application of stiffened panels can lead to significantly less weight.

## 4 CONCLUSION

The proposed approach to structural design is based on topology and multidisciplinary sizing optimization. It was demonstrated on the example of the low aspect-ratio wing. Topology optimization with different constraints gave possibility to determine several alternative layouts. Comparison of the chosen alternative 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. It is concluded that the best structural layout from the viewpoint of strength, buckling and aeroelasticity is the three-spar wing with additional ribs at the end part. The developed approach is a very useful tool for the design process of complex aerospace structures. In future work the optimization of stiffened panel parameters will be included in the proposed approach that can allow additional weight reduction. Some aspects of this problem are involved in the paper [8].

## 5 REFERENCES

[1] Bendsoe M.P. and Sigmund O., *Topology Optimization: Theory, Methods and Applications,* Springer-Verlag, Berlin, 2003.

[2] Xie Y.M., Huang X., Evolutionary topology optimization of continuum structures: methods and applications, Wiley, 2010.

[3] Sysoeva V.V., Chedrik V.V., Algorithms for structural topology optimization, *TsAGI Science Journal*, 2011, 42 (2), pp. 259-274.

[4] Uskov V.M., Balunov K.A., Method for topology optimization with clear boundary shape of structure, *International Conference on Engineering and Applied Sciences Optimization* (*OPT-i*), Greece, 2014 (ISBN:978-960-99994-5-8).

[5] Kuzmina S.I., Chedrik V.V., Ishmuratov F.Z. Strength and aeroelastic structural optimization of aircraft lifting surfaces using two-level approach, *6th World Congress of Structural and Multidisciplinary Optimization* (*WCSMO-6*), 30 May – 03 June, Rio de Janeiro, Brazil, 2005.

[6] Krog L., Tucker A., Kemp M. and Boyd R., Topology optimization of aircraft wing box ribs, *10th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, Albany, New York, USA, 2004.

[7] Eves J., Toropov V.V., Thompson H.M., Gaskell P.H., Doherty J.J., Harris J.C., Topology Optimization of Aircraft with Non-Conventional Configurations, *8th World Congress on Structural and Multidisciplinary Optimization* (*WCSMO-8*), June 1–5, Lisbon, Portugal, 2009.

[8] Chedrik V.V., Tuktarov S.A., Structural design of aircraft wing based on topology and global-local optimization, *11th World Congress on Structural and Multidisciplinary Optimization* (*WCSMO-11*), June 7 – 12, Sydney, Australia, 2015.

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