

Structural design of aircraft wing based on topology and global-local optimization

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1. Abstract

An approach to structural design based on topology and global-local optimization is proposed. It exploits the mathematical models of different fidelity. Solid model is used for topology optimization, shell/beam model – for structural sizing on global level, refined panel model – for detailed sizing on local model, aerodynamic model – for loads and aeroelasticity analysis. Structural design procedure is described. Main features concerning the stated global-local optimization problem is discussed. A numerical example of wing optimization of an advanced helicopter with low aspect ratio is considered.

2. Keywords: Aircraft wing, strength, buckling, topology optimization, global-local approach.

3. 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. This process is very time-consuming and, in practice, it is necessary to simplify the design problem by using mathematical structural models of different levels. In this case, structural optimization should be done both on models of global and local levels. Many technical papers [1–4] are devoted to the development of the multilevel methods for analysis and optimization. In the paper [4] authors presented a global-local approach for structural analysis and optimization with taking into account strength/buckling constraints.

The aim of this work is to combine the structural optimization based on the global-local approach with topology optimization to perform a complete design procedure of aircraft structures. Topology optimization of continuum structures is to find the optimal designs 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 [5–9]. Two heuristic methods of structure topology optimization are presented in the paper [8]. 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 global-local structural optimization is performed for them.

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

4. Structural design procedure

The general process of structural synthesis includes the topology optimization stage directed on search of reasonable structural layouts under action of some extreme loads. Initial data for the topology optimization are geometric outlines of a structure. Flow-chart of structural optimization is shown in Figure 1.

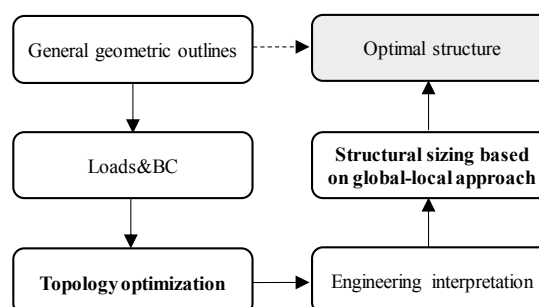


Figure 1: Flow-chart of structural optimization

The topology optimization results are interpreted by design engineers. The second stage is design of structural elements in the interpreted layouts. This stage includes shape optimization and determination of structural element sizes such as shell thicknesses, section dimensions of beam-type elements with taking into account the operative constraints of structure.

We consider that the geometric outlines of mechanical body are specified. They define the place of load-bearing structure (design domain). The structure is supposed to be fixed in some parts and is subjected by external loads of several load cases. The design domain is divided in detail on finite elements for analysis of displacements and stresses by using finite element (FE) method. The main aspects of applied topology optimization methods are discussed in the paper [8].

An engineering interpretation of topology results are performed intuitively based on the obtained distribution of material in solid finite element model. Therefore, several alternative layouts should be generated to make a choice of reasonable structural layout after structural sizing. Structural sizing is fulfilled by means of the global-local approach to optimization described below. The auxiliary optimization algorithms in this approach are based on optimality criteria and mathematical programming methods. Finally, the best structural layout is found by comparison of the obtained structural masses.

4.1. Topology optimization

The most popular approach for determining the optimal structural layout is to minimize the compliance function or the potential strain energy with taking into account a constraint to the given volume (weight) of the structure. Mathematically the statement of the structural optimization problem looks as follows

$$\text{Find } \min \mathbf{f}^T \mathbf{U} \text{ subject to } \int_{\Omega} \rho(x) d\Omega \leq M_0 \quad (1)$$

Here \mathbf{f} is a vector of external load, \mathbf{U} is a displacement vector, $\rho(x)$ 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 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 ρ_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 [6, 9]. Note that the problem statement (1) supposes the only one load case. At the same time, the designed structure of aircraft must bear various loads, and the stresses in its elements must be less than the allowable values. To allow for many load cases the objective function in (1) is replaced by the weighted sum of compliances for all considered load cases.

Two heuristic methods of topology optimization which consider stress constraints for many load cases are presented in the paper [8]. The developed algorithms based on the use of a simple fully-stressed design criterion. They allow obtaining reasonable structural layouts with taking into consideration of many load cases and different allowable stresses in the structural elements. The comparison of the resulting structures with the optimal topology, obtained by two approaches showed that they are in good agreement. Both these methods can be used in the structural design of aircraft wing based on topology and global-local optimization.

4.2. Global-local structural optimization method

Generally the finite element method is used for static and buckling analysis. These problems are usually solved with using different fidelity meshes. The high fidelity grid is not mandatory to perform stress analysis of regular aircraft structure but it is significantly required for computation of buckling load and shape of panels. Design engineers prepare several mathematical models which include both the full-scale structure under research and its separate parts. The global full-scale model includes only global structural parameters. The local model of a separate aircraft component should be created with more details to take into account the stress irregularities and to determine buckling loads and shapes if compressing forces are available.

Problems of interaction between the global and local models are discussed in [4]. The main idea is to interpolate the internal nodal forces computed on the global model into the nodal forces of the local model. In the optimization process on local model applied forces are considered as fixed. The initial elastic parameters of the local FE model have to be close to the elastic parameters of the global one. The possible difference between them is due to the holes and the stiffening structural elements. The accordance of the elastic material characteristics and the loads on the models is performed by their recalculations at the global and local levels of the approach.

The general optimization problem with using global and local models can be solved by using two-level approach described in [2, 3]. In this approach the initial optimization problem is decomposed into separate optimization problems of two levels. Consider such two-level approach when system problem is divided into a set of smaller subproblems with their own goal functions and constraints. The individual optimization of subsystem is performed independently on the first level and coordinate problem is solved on the second (system) level. Generally, the nonlinear programming problem is formulated by the following way:

Minimize $f(\mathbf{X})$ subject to constraints

$$\mathbf{g}_j(\mathbf{X}) \leq 0, \quad j=1,2,\dots,m; \quad \mathbf{h}_k(\mathbf{X}) = 0, \quad k=1,2,\dots,p; \quad x_i^l \leq x_i \leq x_i^u, \quad i=1,2,\dots,n, \quad (1)$$

where x_i^l и x_i^u denotes upper and lower limits of x_i , which are components of the vector of design variables

$\mathbf{X} = \{x_1, x_2, \dots, x_n\}^T$. The vector \mathbf{X} is subdivided into two subvectors \mathbf{Y} and \mathbf{Z} : $\mathbf{X} = \{\mathbf{Y}, \mathbf{Z}\}^T$. The vector \mathbf{Y} includes the interaction variables between subsystems and the vector \mathbf{Z} has the variables belonging only to subsystems. The vector \mathbf{Z} can be partitioned by following way: $\mathbf{Z} = \{\mathbf{Z}_1, \mathbf{Z}_2, \dots, \mathbf{Z}_k, \dots, \mathbf{Z}_K\}^T$, where \mathbf{Z}_k are the vectors with variables related with only k -th subsystem and K is number of subsystems.

The vector \mathbf{Y} may appear in all constraint functions while the vectors \mathbf{Z}_k appear only in the constraint sets: $\mathbf{g}^{(k)} \leq 0, \quad \mathbf{h}^{(k)} = 0$. The bound constraints can be written as $\mathbf{Y}^{(l)} \leq \mathbf{Y} \leq \mathbf{Y}^{(u)}, \quad \mathbf{Z}_k^{(l)} \leq \mathbf{Z}_k \leq \mathbf{Z}_k^{(u)}, \quad k=1, 2, \dots, K$.

The goal function can be expressed as $f(\mathbf{X}) = \sum_{k=1}^K f^{(k)}(\mathbf{Y}, \mathbf{Z}_k)$, where $f^{(k)}(\mathbf{Y}, \mathbf{Z}_k)$ is the contribution of the k -th subsystem to the general goal function. The two-level method can be formulated as follows.

In the first level problem we tentatively fix the values of the vector \mathbf{Y} at values of vector \mathbf{Y}^* . The problem Eq.(1) is reformulated as K independent optimization problems as follows:

Find the vector \mathbf{Z}_k which minimizes function $f^{(k)}(\mathbf{Y}, \mathbf{Z}_k)$ at satisfying the constraints:

$$\mathbf{g}^{(k)}(\mathbf{Y}, \mathbf{Z}_k) \leq 0, \quad \mathbf{h}^{(k)}(\mathbf{Y}, \mathbf{Z}_k) = 0, \quad \mathbf{Z}_k^{(l)} \leq \mathbf{Z}_k \leq \mathbf{Z}_k^{(u)}, \quad k=1, 2, \dots, K. \quad (2)$$

In the second level problem the following problem is solved:

Find new vector \mathbf{Y}^* which minimizes the function

$$f(\mathbf{Y}) = \sum_{k=1}^K f^{(k)}(\mathbf{Y}, \mathbf{Z}_k^*), \quad (3)$$

at satisfying the constraints $\mathbf{Y}^{(l)} \leq \mathbf{Y} \leq \mathbf{Y}^{(u)}$. Here \mathbf{Z}_k^* are the vectors of variables which are the optimal solution of the first level problems. The constraint on bounds of the vector \mathbf{Y} is added into the problem to provide a finite value of the goal function $f(\mathbf{Y}^*)$ at solving the second level problem.

The iterative algorithm can be represented in the following steps:

- 1) Start with an initial coordination vector \mathbf{Y}^* .
- 2) Solve the K first level problems Eq.(2) and find the optimal vectors $\mathbf{Z}_k, k=1, 2, \dots, K$.
- 3) Solve the first level problem Eq.(3) and find new vector \mathbf{Y}^* .
- 4) Check for the convergence of goal function f and the vector \mathbf{Y}^* by comparison their values with those obtained earlier in iteration process.
- 5) If the process has not converged, go to step 2 and repeat the process until convergence.

Satisfying to buckling constraints at structural optimization is important requirement at aircraft design. Such constraints are prescribed to structural panel which generally consists of plate elements modeling a skin of the aircraft lifting surface and bar elements modeling stiffening stringers. Different buckling shapes can be encountered for the panel under compression/tension and shear loads. Stress constraints in panel and gauge constraints on panel design variables are also imposed. The design variables for local level (in the panel) are skin thickness, sizes of stringer elements and panel stringer step.

5. Numerical optimization example

A wing of an advanced helicopter with low aspect ratio is considered as an example for approval of the developed method. The research purpose is to find optimal wing structural parameters which provide minimum weight at satisfying to strength, buckling and aeroelasticity constraints. Obviously, the minimum of structural weight corresponds to some reasonable layout which can be found by topology optimization.

To determine aerodynamic forces in extreme load cases and to perform aeroelasticity analyses an aerodynamic model of the wing has been created. Also the wing outlines serve for generation of a solid finite element model which is used in topology optimization (Figure 2, left). It is important to correctly transfer pressure loads from aerodynamic to FE model. It was performed by interpolation of the obtained pressures with using polynomial function of nodal coordinates in outer surfaces of the FE model. Topology optimization was accomplished to minimize compliance at saving 30 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 2, right.

In the pattern the lighter regions corresponds to low material densities and the darker regions – to high material densities which define the load-carrying regions. It is seen that some wing-box can be considered as structural layout together with a set of cross rib elements in the trailing part of the wing. However, it is difficult to choose explicitly one layout corresponding to this pattern. That is why it is worth to consider several possible layouts. The

following seven ones were proposed based on intuition. They are shown in Figure 3 with hidden upper skin of wing.

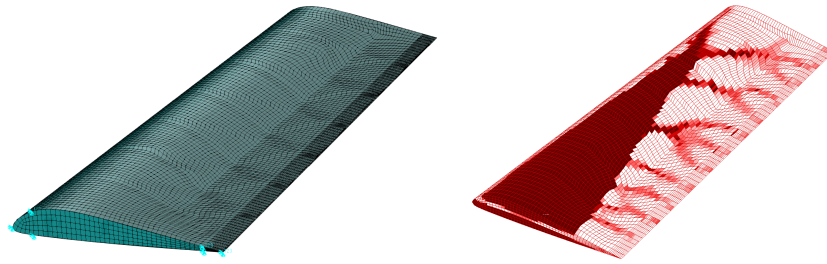


Figure 2: Initial solid FE model (left), topology result (right)

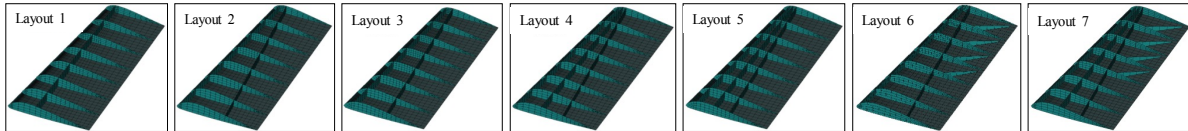


Figure 3: Alternative structural layouts

Description of these seven layouts is given in Table 1.

Table 1: Description of structural layouts

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 <i>Layout 2</i> but the wing-box width is narrowed (front spar is along the maximum structural depths).
4	Three-spar layout with spars corresponding to <i>Layout 1</i> and <i>Layout 2</i> .
5	Three-spar layout with spars corresponding to <i>Layout 1</i> and <i>Layout 3</i> .
6	The same as <i>Layout 2</i> with additional ribs at the end part of the wing.
7	The same as <i>Layout 4</i> with additional ribs at the end part of the wing.

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

The structural optimization under strength requirements for these seven layouts leads to the following optimal weight values: 35.5 kg, 31.6 kg, 31.7 kg, 32.2 kg, 32.3 kg, 32 kg and 32.5 kg, respectively. Therefore, the optimal structural layouts from the viewpoint of strength are two-spar configurations. However, buckling analysis showed that all of the considered layouts do not satisfy to buckling requirements.

Then the structural optimization with stress and buckling requirements were accomplished. The best layout here is 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). They are slightly different in weight so these both are studied in further investigations. Comparison of all 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.

Optimum thicknesses for design variables are shown in Figure 4. It is worth to mention that thicknesses in wing-box root part significantly change both in spanwise and chordwise directions.

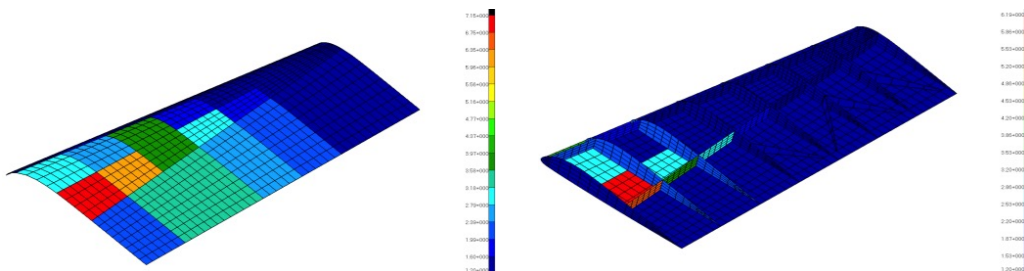


Figure 4: Optimum thicknesses after strength/buckling optimization on global level

For some wing upper panels the buckling constraints become active. This is due to the fact that upper panels have smooth skin (no stringers). Buckling shape for optimal wing is shown in Figure 5. The buckling load factor is equal 1. It is obvious that the stiffened panel is more effective to resist buckling. So addition of stringer elements is necessary to include. Addition of such elements in global finite element significantly increases both the number of degrees of freedom and the number of DV. Some of new design variables related with stringer elements are geometric and they define stringer shape. Therefore it is necessary to consider the design problem with using local models of panels. In the local optimization problem the design variables are the number of stringers, thicknesses of stringer elements, the stringer depth and skin thickness. In this research the shape of stringer section is rectangular, and we have four DV for each panel. Only upper wing panels are considered because they are under the action of compression loads. Figure 6 shows relation between global FE model and local one for a separate panel.

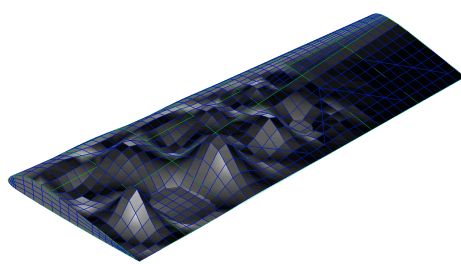


Figure 5: Buckling shape

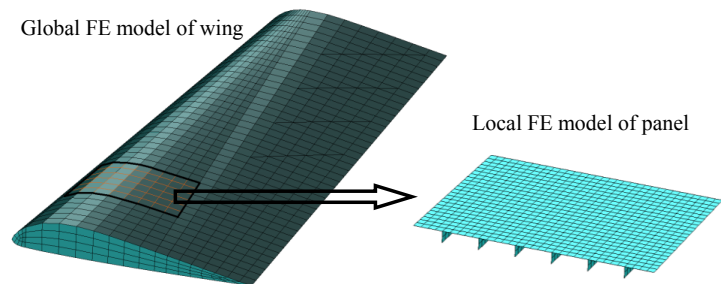


Figure 6: Extraction of local model from global model

Iterative global-local optimization was performed. The two-spar wing had the least weight (36.3 kg) while weight of three-spar wing was 38.1 kg. Note that panel smeared thicknesses are significantly reduced if compared with the results obtained for smooth thickness with optimization on global model. For example, thickness of root upper panel was 7.4 mm and after global-local optimization it became 3.14 mm. Optimum stringer parameters of this panels are following ones: the number of stringers is 6, its depth is 30 mm and its thickness is 1.86 mm. Note that different optimal solutions can be obtained during the optimization process at parametric change of stringer step and depth. More technological root panel structure was obtained with the stringer depth of 45 mm. In this case the skin thickness is 2.01 mm and stringer thickness is 3.45 mm. The global-local approach to optimization of wing with stiffened panels allowed reducing of structural weight by 16.8 percent.

Aeroelasticity analysis was performed for the chosen two-spar layout with additional ribs at the end part of wing. Note that the constraint on the divergence speed was satisfied. The obtained optimum parameters after global-local optimization do not provide flutter requirements. The flutter speed after analysis was 112 m/s but it must be greater than 145.2 m/s. The sensitivity analysis showed that it was necessary to increase minimum thicknesses of the lower panel skin up to 1.3 mm. In addition, the needed thickness of lower panel skin in the root part in the trailing edge was 1.5 mm. The damping coefficients versus flight speed are shown in Figure 7.

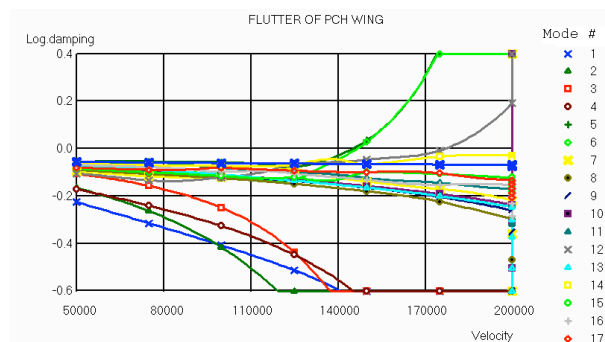


Figure 7: Damping coefficients versus flight speed

There three flutter forms with speeds 146 m/s, 147 m/s and 177 m/s. Note that change of panel skin thicknesses for taking into account flutter constraints leads to the increase in weight by 0.8 kg. Weight of optimum wing structure with satisfying all imposed constrains is 37.1 kg.

5. Conclusions

The paper has proposed an approach to structural design based on topology and global-local optimization. The approach was demonstrated on an example of the low aspect-ratio wing. Application of topology optimization

helped 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. By means of structural optimization under strength/buckling requirements two reasonable layouts were obtained: the three-spar and the two-spar wing with additional ribs at the end part. It was shown that the additional significant reduction of weight could be reached by use of global-local optimization. This approach to optimization of wing with stiffened panels allowed additionally reducing of structural weight by 16.8 percent. It is concluded that the best structural layout from the viewpoint of strength, buckling and aeroelasticity is two-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. It gives reliable results and reduces computational costs compared to a traditional approach to optimization.

6. References

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