STRUCTURAL OPTIMIZATION BY USING DIFFERENT LEVEL MODELS

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Summary A two-level flowchart for solving design optimization problems of aircraft structures under stress, buckling and aeroelasticity constraints is presented. The proposed approach is based both on using of different level models for calculation of design constraints and on two-level optimization scheme. A set of test problems has been solved and the approach has been used in design studies of advanced aircraft structures. The airplane wing design problem is discussed to demonstrate the application of the method.

The structural optimization methods have advanced essentially over the last decades and now they are intensively used to improve design process in aviation industry. They have a key role in the developed programs of automated structural design of aircraft. The different design stages are characterized by different fidelity of structural and aerodynamic models and correspondingly by different methods of optimization. Practical optimization problems can have from hundreds to thousands design variables and thousands of highly nonlinear and implicit constraints from various disciplines (linear static analysis, buckling, modal analysis, aeroelasticity, etc.). The best way to solve such complex problem is to consider all these constraints and design variables simultaneously in one design optimization process. However, there is no possibility at present time to do this due to different reasons such as organizational problems in a design company and very large dimension of the optimization task. Unfortunately, the developed design software cannot be utilized to the full extent and often step-by-step procedures with only several types of constraints are used at aircraft design. Therefore, different methods of structural optimization are useful to have in multidisciplinary design system. Optimality criteria and mathematical programming methods are two major numerical approaches to solve structural optimization problems. Both these approaches generate a set of design points in the space of design variables that can converge to the optimum.

The widespread approach to structural analysis in the design software is finite element (FE) method. At different design stages the fidelity level of FE idealization of structural model is of different complexity. Furthermore, experts in different disciplines (for example, in stress analysis and aeroelasticity analysis) typically tailor FE models according to their individual requirements. Very refined meshes which are necessary for stress and panel buckling analysis can often be impractical in the optimal design with aeroelasticity requirements. The problems of aeroelasticity and loads analysis could be solved by using the discrete-continual model such as equivalent plate/beam model. Therefore it is necessary to use different level models in multidisciplinary design optimization procedures. The paper describes the developed approach of multilevel optimization which include both calculation of design constraints in different level models and two-level optimization scheme. The design of practical aviation structures involving a large number of elements with multiple load cases involves excessive number of design variables and constraints. The optimization problem becomes very large, and the solution process becomes too costly. In this case the optimization problem can be reformulated as a series of smaller problems for separated subsystems of structure. To coordinate coupling between the subsystems a coordination problem is added. Such decomposition of the initial problem can be multilevel [1]. We consider a two-level approach in which the optimization problem is decomposed into a number of smaller subproblems. Each subproblem having own goal function and constraints is solved independently in the first level. The coordination problem is solved in the second level.

As an example, in the paper the two-level approach to structural optimization with stress and panel buckling constraints is considered in details. The design constraints are written for a stiffened panel. Shell finite elements to simulate skin of the panel and beam/rod elements to simulate the panel stringers are used in the global FE model. Local FE model of a separate panel includes only shell elements and has very detailed mesh to correctly describe the buckling shapes of all panel elements. Also the stiffened panel can be modeled by equivalent rectangular stiffened plate. In this case the Ritz-Timoshenko method can be used to calculate critical stresses for global buckling of panel, local buckling of skin between stringers and local buckling of stringer elements. The approximate equations of interaction of different load components are used to compute critical load parameter of buckling. Main relationships for stress and buckling constraints are given.

We divide a vector of design variables on two subvectors $\mathbf{Y}=\{\mathbf{t}, \mathbf{F_e}\}^T$ and $\mathbf{Z}=\{\mathbf{Z_1}, \mathbf{Z_2},\ldots, \mathbf{Z_K}\}^T$, where $\mathbf{Z_k}$ are variables of *k*-th panel, $\mathbf{t}$, $\mathbf{F_e}$ are row vectors of design variables in FE model (thicknesses and cross section areas of elements). The first level optimization problems can be formulated for each panel as:

Find $\min m_k(\mathbf{Y}^*, \mathbf{Z}_k)$ at satisfying to $\varphi_i \le 1, \quad i=1,2,\cdots,8$, $\mathbf{Z}_k^{(l)} \le \mathbf{Z}_k \le \mathbf{Z}_k^{(u)}, \quad k=1,2,\ldots K$, where m_k is mass of *k*-th panel, K is number of panels, φ_i are stress and buckling constraints in panel elements, $\mathbf{Y}^*$ is vector with fixed

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components. The vector of design variable includes panel parameters such as skin thickness, stringer element thicknesses and widths. Also the distance between stringers can be considered as design variable. Eight stress and buckling constraints are calculated after FE analysis and determination of critical stresses by using rectangular plate model.

The second level optimization task is to find structural parameters **Y** minimizing mass of FE model when stringer parameter $\mathbf{Z}_k^*$ obtained from the first level are fixed. It can be formulated as follows:

Find $\min f(\mathbf{Y}) = \sum_{k=1}^{K} f^{(k)}(\mathbf{Y}, \mathbf{Z}_k^*)$ at satisfying to $\varphi_4(\mathbf{Y}, \mathbf{Z}_k^*) \le 0, \quad \mathbf{Y}^{(l)} \le \mathbf{Y} \le \mathbf{Y}^{(u)}$. Here φ_4 is function comprising only stress constraints. The coordination optimization problem is solved by using only results from FE analysis.

Solution of the problems of two levels should be performed iteratively until convergence. Therefore it is unnecessary to solve the coordination problem with large accuracy and it is enough to do only several iterations for determination of vector $\mathbf{Y}^*$ in intermediate iterations. This can considerably increase performance of optimization process at design of large-scale structures.

Different similar multilevel structural optimization schemes are also implemented in multidisciplinary design software ARGON to treat aeroelasticity constraints together with strength and buckling constraints [2, 3]. The design optimization problem of supersonic airplane wing is presented to demonstrate the application of the method. The important parameters determined by using the proposed two-level are number of stringers in panels and sizes of panel. Many optimization runs to design wing have been done at parametric changes of these parameters. It was obtained that optimum value of stringer step in titanium wing-box is about 80 mm. Preliminary analysis of composite tip part of wing showed that initial structural layout has unlucky location of ribs and spars and the needed thicknesses to compensate buckling constraints achieved to 20-25 mm. It was due to relatively little structural depth, low elasticity modulus of composite laminate, using of unstiffened panel and large ribs step. Thus the problem of determination of optimal ribs step in the tip part of wing was considered. The optimization runs were done for models with different additional partitioning of panels. The obtained optimal rib step is 250 mm. In this case the thickness of composite skin can be reduced more than two times in comparison with initial structural layout. The equivalent von Mises stresses in upper wing skin for optimized structures are shown in Fig. 1 for extreme load case. Maximum stresses are observed practically in all titanium part of wing-box in the case of account of only stress constraints. Meanwhile, in the case of satisfying both stress and buckling constraints the maximum stresses take place only in central part of wing-box.

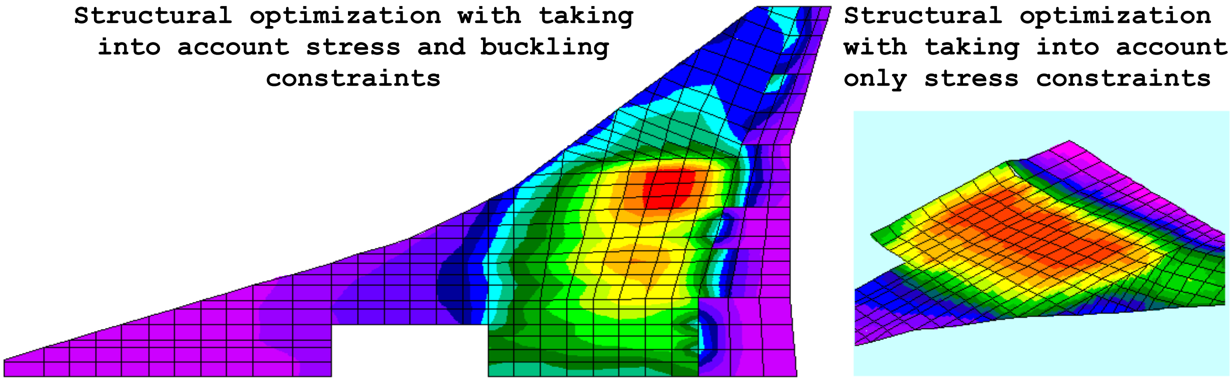

Fig. 1 – Von Mises stress distribution in upper skin for optimized structures

To perform aeroelastic analysis of airplane the FE stiffness and mass matrices of optimized wing were reduced to ones of equivalent plate model. The first analysis showed that aeroelasticity constraints were not satisfied: poor effectiveness of elevons and low value of flutter speed. Sensitivity analysis showed that aeroelasticity characteristics are mainly defined by stiffness of root and middle sections. Structural optimization procedure with using equivalent plate model allows finding optimal increase of skin thicknesses in metallic part of wing. The increase in mass was less than 5 percent.

References

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