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Topology optimization of a gas-turbine engine part

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Abstract. One of the key goals of aerospace industry is a reduction of the gas turbine engine weight. The solution of this task consists in the design of gas turbine engine components with reduced weight retaining their functional capabilities. Topology optimization of the part geometry leads to an efficient weight reduction. A complex geometry can be achieved in a single operation with the Selective Laser Melting technology. It should be noted that the complexity of structural features design does not affect the product cost in this case. Let us consider a step-by-step procedure of topology optimization by an example of a gas turbine engine part.

1. Introduction

For aerospace industry, the reduction in the part weight allows for fuel savings and the pollutant emissions reduction. The reduction in the parts weight and consequently the reduction in the engine weight bring down the cost of its life cycle. Thus, the main task in this industry is designing parts with lower weight while maintaining their utility. Up-to-date software allows for the part geometry to be optimized under known loading conditions, which results in effective weight reductions. However, manufacturing of optimized structures was impractical and often impossible in the past, as it is labour intensive and involves considerable investments in order to provide a complex geometry with conventional production methods of aircraft parts. Subsequent machining further increases a finished part price. The method of selective laser melting (SLM) allows providing a structure (as well as a bionic one) with a complex profile, while the geometry being complex does not influence the prime cost of a finished product. Besides, for SLM, minimum machining is required.

The ideas exchange between biology and engineering is an important trend in development of the optimization methods [1]. Principles of live forms organizations embodied into engineering devices were named biomimetrics. Many mathematical algorithms of topological optimization are now based on the equivalent 'bionic' principles, with these algorithms allowing for the structure topology and shape with the best characteristics to be designed under the given forms of this structure loading. Thus, the 'bionic design' operation will be thought of as parts design based on the methods and algorithms of topological optimization.

2. Topology optimization of a structure

2.1 Target Functions

Optimization shall mean a process of choice of the best option imaginable. The choice of the better decision or comparison of the two alternative decisions is performed with some dependent values (a function) defined by the design data. This value is called a target function. While the optimization task being solved, the values of design data were found at which a target function has a minimum. It worth noting that a target function may not always be formulary. Sometimes it can take only some of the values and be defined in a tabular form, etc. In all the cases, it must be a single function of the design data. There may be several target functions. For example, the aircraft engines design requires that maximum reliability, minimum materials consumption and maximum payload volume (or load-lifting capacity) be provided simultaneously. Some target functions may appear to be incompatible. In such cases, a priority of one target function or another shall be incorporated.

2.2 Essence of the Approach

Topology optimization includes identification of the number, the shape and locations of the cavities in the solid structure, as well as the rules for cohesiveness targeting in a structure. Topological optimization allows finding an optimal material distribution in a given design area under the certain loads and boundary conditions. Loads, boundary conditions, the volume of the created structure and, possibly, some additional restrictions, such as targeted locations, and sizes of cavities and areas full of solid material, are targeted for topological optimization. The topology, the shape and the size of the structure are not expressed in terms of standard parameter functions. For the advantages and capabilities of the additive manufacturing being used in the most efficient way, designing of the parts using topological optimization is necessary [2].

A key property for the task solution by means of methods of topological optimization is material density distribution. If there are some elements left after optimization in a computation region, having the density value equal either to initial density or to zero, this result is then called ‘black-and-white’ topology (or 0-1 topology). However, regions with intermediate density, so-called ‘grey’ material zones, will always appear [3, 4]. One of the ways to eliminate ‘grey’ topology is SIMP-methods (methods involving Solid Isotropic Materials with Penalization), where material density for each element acts as a final element characteristic, with density related to an elastic module with a power-law dependence [5-6]. Under the corresponding values of the index greater than 1, such type of a dependence acts as a penalty function that does not allow the elements with intermediate density to be generated during optimization and results in a ‘black-and-white’ design of the part designed [7].

2.3 Schematic Usage of the Bionic Design Concept

The technology for the design of reduced-weight parts for gas-turbine engines using the bionic design concept includes the following stages:

- Importing of the part geometric model into the developed software package. The input data for the bionic design operation are 3D electronic solid-body geometric models of gas-turbine engine parts generated with common design CAD-means;
- Assigning of physical and mechanical material properties of the part;
- Formalization of the physical-and-mechanical and operational requirements to a redesigned part; strength, reliability, definition of a loading diagram and load variation range, dynamic characteristics of the part, etc. (dependent upon the redesigned part type);
- Formalization of the technology requirements for a redesigned part; identification of the areas and surfaces staying unchanged during redesign; formalization of the part topology taking into account its location within a finished product (the size and the location of the fasteners, part dimensions, etc.), as well as capabilities and characteristics of the SLM process being taken into account;
- Widening of the calculated area within the given dimensions, simplification of the initial topology of the designed part;

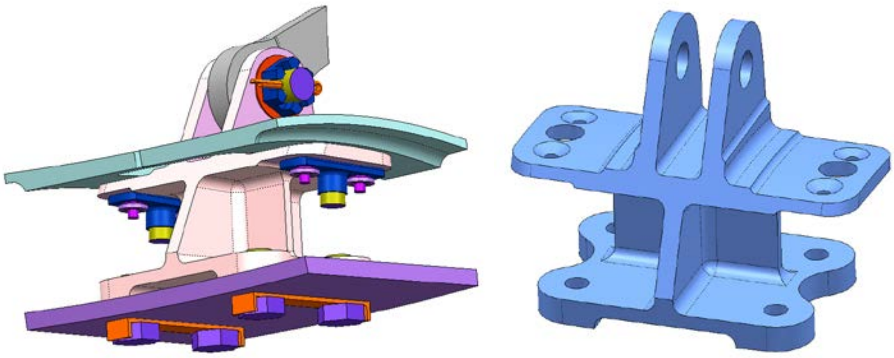
- Generation of a finite element representation of the part which is acceptable for topological optimization performance;
- Performance of the part topological optimization using up-to-date software;
- Smoothing of the redesigned part surface. Creation and rework of the 3D solid-body geometric model of the part after topological optimization being performed;
- Generation of detailed finite element representations of the parts, which are acceptable for performance of verifying engineering analysis on using up-to-date software packages;
- Performance of computing experiments in order to verify compliance of properties of the part with a new topology with initially targeted physical-and-mechanical and operational specifications. In case the redesigned part is incompatible with given specifications, a repeated redesign of the part is necessary with changed input parameters of the topological optimization algorithm;

For a part with a new shape and topology, compatible with the given requirements, a standard procedure of the part design is to be performed with the necessary design documents being issued.

3. Practical usage of the bionic design concept for gas-turbine engine parts

3.1 Task Setting

A bracket for drawing bars of a reverse device, manufactured in Aviadvigatel JCS, was selected as a modelling task to test the topological optimization procedure, Figure 1.



a b

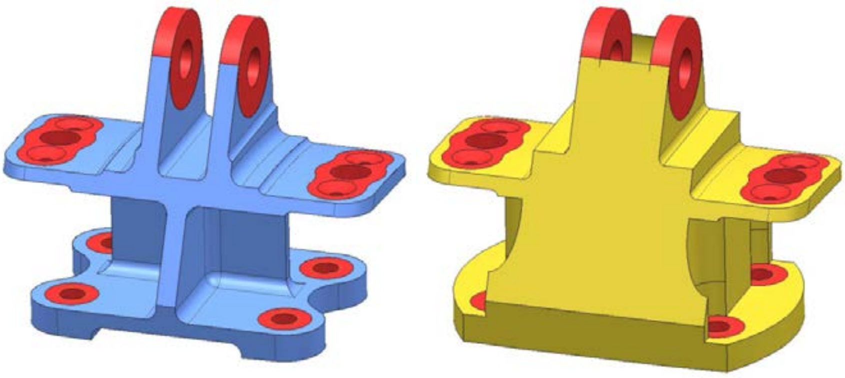
Figure 1. The geometry of a source model of the part under investigation: a – assembly; b – single.

This part takes up an aggregate complex of loadings in the different modes. The full load set was provided by the Engineering Department. The approach included two load steps.

The maximum stiffness was selected as a target function, namely minimization of the strain energy sum in the model to combine two selected static load sets. The decrease in the weight of the bracket simplified structure up to 35% was chosen as a limit. Thus, it results in a new bracket with an optimal geometry, with its weight being equal to 80% of that of the initially designed part. As a result, stresses at the selected load steps are expected to decrease in the optimized version of the bracket in comparison with the initially designed part.

3.2. Topological Optimization Performance

In order to solve the optimization task, the part geometry was maximally simplified by building it up with the additional material. The limiting condition was the capability to install the simplified part into the attaching lug. The fastening elements which must be targeted unchanged were kept as separate bodies, as boundary conditions are applied to them. As the result, the part weight increased five times, Figure 2.



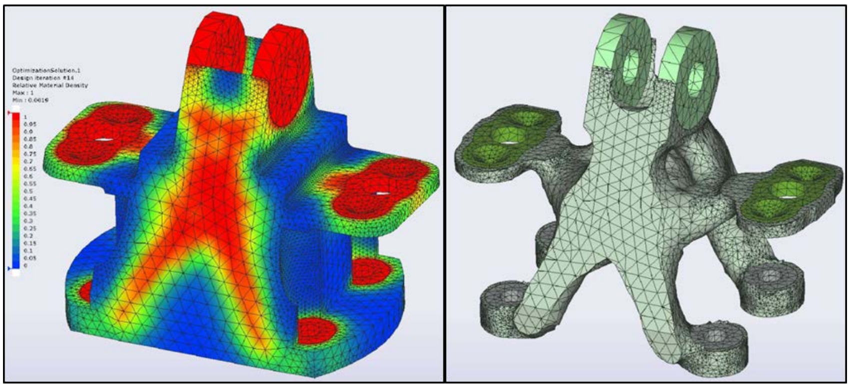
a b

Figure 2. Simplification of the part geometry: a – selection of unchanged fastening elements; b – simplified part.

The independent CATOPO software was selected as a basis for introduction of the topological optimization method. It permits to perform analysis of the stress-strain state of the part caused by application of the loads in the form of concentrated and distributed loads, thermal effects as well as its own natural oscillation.

3.3. Optimization Results

Figure 3 shows the geometry which was identified as the result of topological optimization of the selected part of a gas turbine engine. The results of the topological optimization are summarized in Table 1.



a b

Figure 3. The studied part with the optimized topology: a – density distribution; b – optimised part.

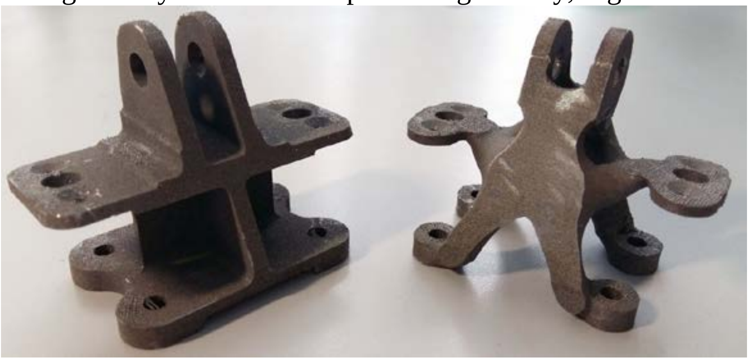
Table 1. Topological optimization results.

Version	Weight, kg	von Mises stress (step No. 1), MPa	von Mises stress (step No. 2), MPa
Initial	0.138	77	44
Simplified	0.687	34	22
Optimized	0.111	30	28

Accordingly, the use of the bionic design technology allowed not only for weight reduction of the fastening element under investigation, but also allowed for the significant reduction in the stresses at the investigated load steps. At that, strain-stress state calculations for the part showed that when the bracket weight reduced by 20%, the main von Mises stresses in it decreased by 48% on the average in comparison with the initial model.

3.4. Practical Use

The part under investigation was manufactured from steel powder by the SLM method in two versions: with the initial geometry and with the optimized geometry, Figure 4.



a b

Figure 4. The parts produced with the SLM method by Aviadvigatel JCS: a – initial geometry; b – optimal geometry.

The weight of the part decreased by 20%. The parts are now ready for the mechanical tests.

4. Conclusion

The use of the bionic design technology and topological optimization for the weight reduction of the engine parts allows for the final weight of the engine to be reduced with all other properties being maintained. The weight reduction for some parts can reach 50%.

The use of the bionic design technology is essentially related to the additive manufacturing methods due to the geometric shapes being complex. The similar technologies have been successfully introduced by the leading engines corporations, and more recently, they have been developed at Aviadvigatel’s facility. The bionic design of aero engines offers vast prospects for the aerospace industry.

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