STRENGTH RELIABILITY OF TURBINE ROTOR ENSURING BASED ON MULTIDISCIPLINARY OPTIMIZATION

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Abstract

Because of the high stress loading of advanced gas-turbine engine impellers and also engine life and mass high demands, it is necessary to develop new ways of computer-aided design based on using software, realizing modern simulation and multicriterion optimization methods.

This paper is about created software performance capabilities of gas-turbine engine impeller units design-stress optimization. As a computational environment ANSYS has been used. The way suggested allows to take into account structure heat loading during type flight cycle.

Result construction will need minimal design modification and using modern multicriterion optimization methods guarantee, that set engine life and mass demands will meet.

1 Introduction

GTE impeller design optimization requires consideration of multicriteria conflicting requirements. That's why this problem is very difficult and it takes a considerable amount of time. [1] Therefore it is important to automate the process of creating and analyzing the typical design and its optimization using mathematical methods of the minimum / maximum hunting [2]. Modern finite element software packages (ANSYS, MSC.Patran / Nastran, ABAQUS, etc.) have built-in opportunities for the optimization of simple designs. Also, there is a large number of software packages created for the process of multicriteria optimization of structures using various computational environments (IOSO, LMS OPTIMUS etc.). Therefore, optimization of simple structures (beams, membranes, plates, etc.) is not much difficult. [3]

Optimization of complex shape designs, working under difficult loading conditions, requires the development of additional software for computational environments. Created software should automate the process of creating a computational model, the analysis of the design in the required disciplines and analyze the results using the specified geometric parameters and working conditions of construction.

For analysis of impellers GTE several software packages (including non-commercial) are used, each of which analyzes the design in various disciplines (thermal-hydraulic analysis, static and dynamic strength, gas-dynamic analysis, etc.). Each used software package creates its own computational model. Therefore, creating software for the optimization of impellers GTE it is necessary to automate the process of transferring data (boundary conditions, geometry changes, etc.) used between the various computational models and data automatic modification.

Coupled optimization of the whole structure of the impeller is irrational, because it would require a lot of computing power and take a huge amount of time. More rational way is to break design optimization process into several iterations, each of which perform optimization on each GTE element separately from the others, setting other elements influence as the constraints or external loading.

This approach will reduce the time of optimum design obtain and also will make the design process more open to engineers and will take into account changes in the design and configuration changes of operating conditions that always occur during the design of the engine.

2 Statement of optimization problem

HPT impeller design can be divided into several typical blocks. For each block individual software for automation of constructing and analyzing computational models process is created:

- Blade;
- root connection;
- Disk.

Blades optimization requires a complex multidisciplinary approach, in which the problem of strength is only one of many. That's why in this paper only disk and root connection optimization is discussed. The blade design is changeless.

The software used for optimization has been created using programming language APDL [4, 5] of finite element complex ANSYS, which provides to analyze the structural strength. Also automatic interaction with CIAM developed software packages that conduct heat and hydraulic computations is realized.

For optimization a commercial software package IOSO is used, which analyzes the parameter space and hunting of the optimal design. Fig.1 shows the optimization scheme. The optimization process is completed while satisfying set of design requirements with a given accuracy.

Optimization can be performed in both axisymmetric and 3D formulation (impeller sector analysis) at the one mode (usually, most loaded) or with respect to a typical flight cycle (TFC).

To avoid the appearance of degenerate structures in the developed software, additional relations between the variable parameters are set.

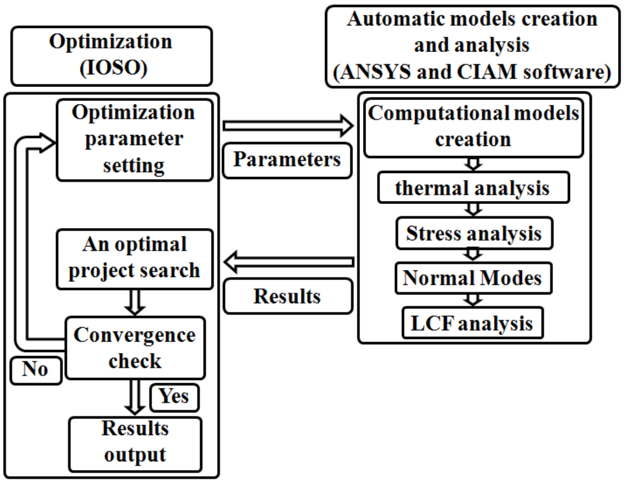

Fig. 1. The scheme of the GTE wheel optimization

Also, additional relations between the parameters that allow to automatically satisfy some of the strength requirements. Some of these relations allow to reduce the number of constraints in the optimization, defining the lower bound of the parameter variation. Another part calculates the value of a parameter, thereby allowing not vary it in the optimization.

3 Choice of parameters design optimization

To improve the quality of design, for reducing the total time of the final design obtaining, and also for reducing time structural modification after optimizing, it is very important to simplify the typical design and to choose the partitioning scheme into specific geometric parameters.

This section describes the scheme of partitioning into optimization parameters of “fir-tree-type” lock and HPT impellers.

Some parameters can be not varied and can be determined from structural or other reasons. Parameters of lock and disk, which usually vary are marked in Figures 2-3 with red. Black marker is used for parameters that usually are not vary.

3.1 Parameterization scheme of the " fir-tree-type " root connection

Partition version of "fir-tree-type" lock is shown in Figure 2. While optimizing the number of teeth is also varying parameter. The model used allows to take into account the cooling holes in the root, if any.

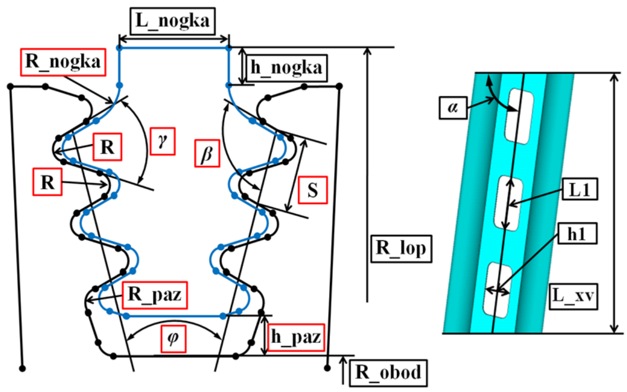

Fig. 2. Partitioning scheme for the optimization of the "fir-tree-type" root connection

3.2. Parameterization scheme of disk

One of the ways of partitioning into parameters of asymmetric disk with one hub is shown in Figure 5. This scheme can be complicated by adding a few extra dimensions to the web and the hub of the disc. But experience shows that the complication is not necessary. If we equate the corresponding dimensions of the left disc side to the size of the right disc side, you'll get a partitioning scheme for symmetric disk.

Most of rotor discs have similar construction. That's why this partition may be used for optimization of the impellers of HPC, HPT and LPT.

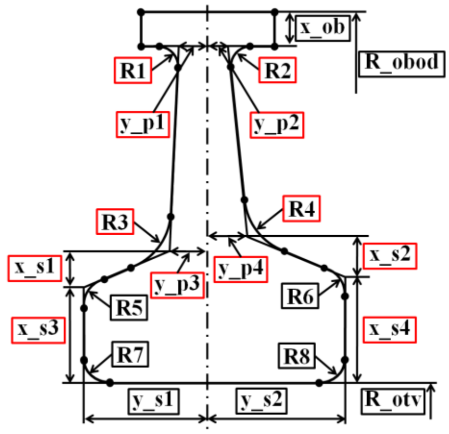

Fig. 3. Partitioning scheme of the disk with one hub

4 Automation the process of thermal analysis

Correct assessment of the thermal state of the structure is very important for strength design. Software developed allows to perform the thermal analysis of the structure by several ways (depending on the design phase, the presence of the initial data and the required degree of accuracy of thermal fields):

1) Identification of the thermal state of the temperatures specified in several specified radial sections of the disc. This way is used in the early stages of design when the design is not defined yet, and thermal state is defined approximately.

2) Transfer of the thermal state from some initial model to the model that is created for each iteration of optimization. This way is used in cases where the design is already defined, and there is some initial thermal state.

3) Full heat analysis of generated at each optimization iteration finite element model of the projected impeller element. This method is used in the final stages of designing the impeller when thermal analysis already conducted some initial design and heat transfer boundary conditions are defined on the specified surfaces of the lock and disc (heat transfer coefficient and ambient temperature).

Specified surfaces of the original model, which already has the necessary thermal boundary conditions, automatically are assigned to specific model surfaces generated for each iteration of optimization. These surfaces are applied the same boundary conditions as in the initial model. After the transfer of thermal boundary conditions thermal analysis is performed.

Such a method of obtaining the thermal state can be used for calculations at one mode, and also taking into account a typical flight cycle.

In most cases, a combined approach is used, i.e., for different parts of the structure different ways to determine the thermal state are used.

5 Automation the process of LCF analysis

When optimizing the elements of modern rotors GTE as one of the criteria acts requirement to ensure the allowable number of loading cycles. Software developed allows for the existing stress state and thermal state of the design to determine LCF automatically at each iteration of optimization. Also, you must specify material properties in the range of operating temperatures required for the analysis of LCF. Analysis LCF algorithm for TFC is shown in Figure 4.

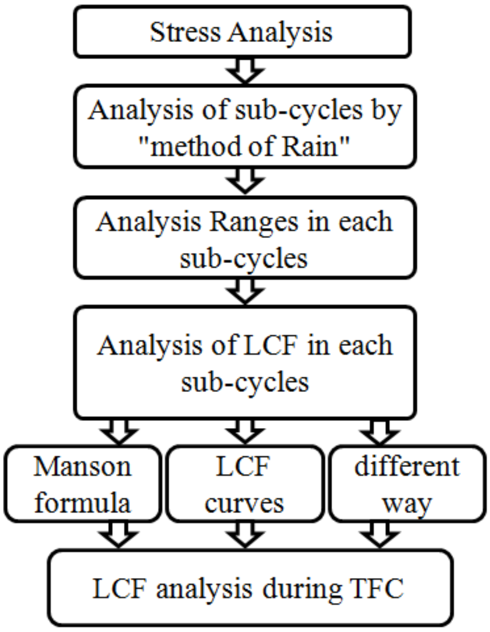

Fig. 4. Algorithm for calculating LCF

LCF computation can be conducted for the mode 0-MAX-0, and for a typical flight cycle. Allocation of subcycles held by the "method of rain." Value of LCF can be determined using the experimental curves of LCF, the Manson formula or other specified functional or tabular dependence of components of the stress state on number of cycles. Overall LCF taking into account TFC determined from the formula of linear damage summation.

6 Examples of the impellers optimization

This section provides examples of structurally-mechanical optimization of impeller lock and disk of high pressure turbine. This approach is applied for the design of other rotors impellers elements.

6.1 Optimization of "fir-tree-type" root connection

When optimizing "fir-tree-type" lock impeller sector is analyzed at each iteration. Partitioning scheme of the lock and the disc is given in sections 3.1 and 3.2. Parameters vary randomly within the specified bounds. According to the presented scheme the optimization of model HPT disk is performed. In this example, the parameters of lock and disc are varying together [6].

Before starting the optimization it is necessary to create a finite element model of the blade, which can be relatively coarse, as it is only required for more accurate modeling of loading of the lock . At each iteration of optimization present model is automatically being completed with finite element model of the root and disk using specified parameters, then stress analysis is performed and LCF factors considering contact interaction in the root are determined.

In this example, the goal of optimization was design of HPT impeller root and disc of minimum mass for 20,000 operation hours and 10,000 loading cycles. Estimated value of LCF determined using Manson formula [1] with a safety factor K_N = 5.

Disk rotation speed is 14500 rev / min.

To determine the thermal state of the disk at each iteration of the optimization thermal analysis is carried out, in which the temperatures at three radii are used as the boundary conditions:

- The central hole of the disc - 260 ° C;
- Disk rim - 570 ° C;
- Air-gas channel - 600 ° C;

The temperature distribution in the root is assumed constant and equal to 720 ° C.

Calculation is carried out in three phases: design load, unloading and analysis of LCF.

To evaluate the efficiency of the proposed method the results of the development of the same HPT lock and disk obtained using the standard method based on one-dimensional models are performed.

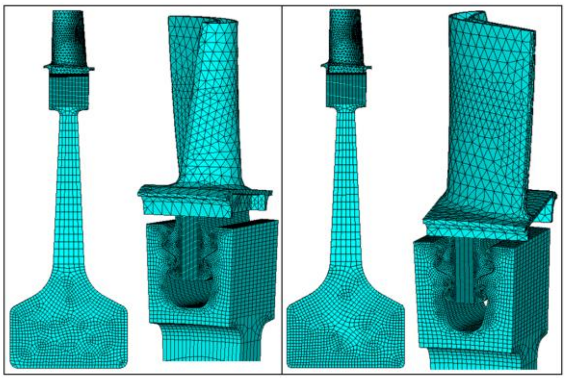

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Fig. 5. Finite-element models of structures: a) initial; b) optimized

Results of the analysis of the original design and the optimization results are shown in Table 1. Table 2 shows the values of variable lock parameters of original and optimized designs. The finite-element models of the original and optimized structures are shown in Figure 5.

As can be seen from the data obtained, the original design needs further refinement, because lock cyclic life almost 2 times lower than required. And though time getting the basic parameters of the lock is not more than a minute, further refinement of the design in 3D setting may take a few days of work of the designer.

Table 1

The results of "fir-tree-type" root connection optimization "

	initial design	optimized design
Blade mass, kg (one / all)	0.071/5.04	0.071/5.04
Root mass, kg (one / all)	0.037/2.65	0.033/2.34
Disc mass, kg	61.2	59.9
Impeller mass kg	68.9	67.3
Root LCF, K_N = 5	9200	11740
Disc root connection LCF, K_N = 5	6800	10000
Disc hub LCF, K_N = 5	10000	10000

The resulting 3D optimization design satisfies all the requirements and also has less mass than the original. Optimization is performed on the same computes as in the previous section. Time for optimum design is about 2 - 3 days of automatic calculations.

Table 2

Values of lock variable parameters of initial and optimized designs

	initial design	optimized design
R_nogka, мм	5.2	4.2
S, мм	7.08	7.1
R, мм	1.3	1.44
R_paz, мм	2.3	2.26
φ	25.8°	31.9°
β	117.3°	114.7°
γ	70.5°	62.3°

6.2 Disk optimization during TFC

Analysis of design by TFC at each optimization iteration allows to consider the impact of primary and secondary sub-cycles to low-cycle fatigue design, whose contribution to the defect can sometimes be significant (up to 40%) [7].

Since the analysis of the kinetics and low-cycle fatigue and stress state of impeller during TFC requires large computational resources and takes a lot of time, the optimization of the design using TFC is held in axisymmetric formulation.

For optimization the changes of the thermal state parameters, heat transfer coefficients and temperature in the cavities for the original design of the disc must be set within the TFC.

In this example, the dimensions of the web and hub of the disc has been optimized. The geometry of the rest of the structure has not been varying. Before starting the optimization it was necessary to create a finite element model of the non-optimized structure and to set zones of contact interaction in the right places. Figure 6 shows the used finite element model of the non-varying part and partitioning scheme.

For determining the thermal state at each iteration of optimization a combined approach is used. For non-optimized part of the structure the transfer of the thermal state of the nodes of the original model is carry out to the nodes of the finite element model, obtained at each time of TFC (Figure 7).

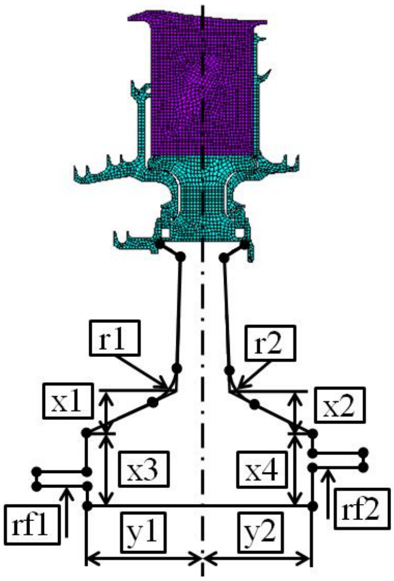

Fig 6. Finite element model of the structure is not optimized

To determine the thermal state of the design to be optimized (web, hub) surfaces of the web and the hub of the original model are divided into five specific areas (Figure 7). In each border zone tabular dependence of heat transfer coefficient and ambient temperature on the axial coordinate (hub bottom) or radius (rest areas) and on the time. Optimized surfaces of the model created for each iteration of optimization, are also divides into five respective zones. The values of thermal boundary conditions on the surface elements of the model are obtained by their approximation according to created table of the dependencies of the border zone in which they are located. Scheme of transferring the heat transfer coefficients from the original design to design to be optimized on is shown in Figure 7. Temperature is transferred in a similar manner.

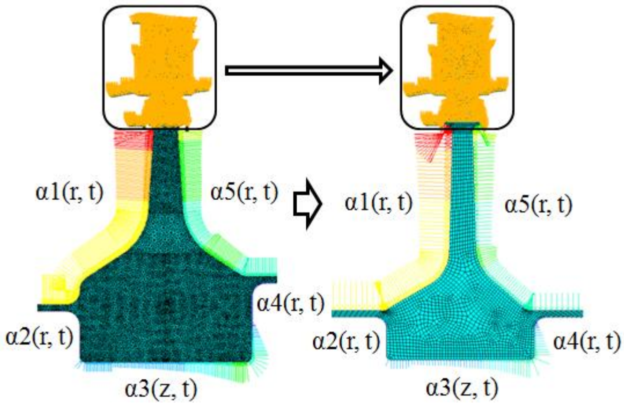

Fig. 7. Thermal boundary conditions scheme transfer from the original design (left) to design to be optimized (right) at each point of TFC

Heat transfer boundary conditions and analysis of the thermal state is repeated at each point of a typical flight cycle. At the same time a thermal analysis at current point of TFC takes into account previous thermal state.

Each iteration of the optimization is divided into several stages:

1) the purpose of the design;

2) the creation of heat and strength FEM;

3)the transfer of thermal boundary conditions and thermal analysis at each point of TFC;

4) analysis of the kinetics of stress state using the resulting thermal state;

5) analysis of LCF for TFC.

Thermal and strength finite element models are obtained by completing of nonvarying part of the disc bottom (blade and hub) with specified parameters.

According to the presented scheme HPT disk model for TFC has been optimized. Required to design the HPT disk of minimum mass for 7000 loading cycles. Estimated value of the LCF was determined by the LCF curves with a safety factor K_N = 3. And typical flight cycle includes 465 calculated points.

To evaluate the efficiency of the method proposed the results of the development of the same design HPT disk are represented, but only at the most loaded mode. Results of the original design analysis and the optimization results are shown in Table 5.

Table 5

HPT disk optimization results based on TFC

	Optimization on one mode	Optimization based on TFC
Disc Weight, kg	53.32	46.36
LCF KN = 3	7000	7000

As a result of optimization the increasing of hub heating was obtained by reducing the size of the hub. The temperature of hub increases to 33 °C. Thus, increasing the centrifugal forces stress by reducing of the hub is balanced by reduction of thermal stresses, as the temperature difference between the rim and the hub is reduced (Fig. 8). Maximum stress does not change, but reduced the weight of construction.

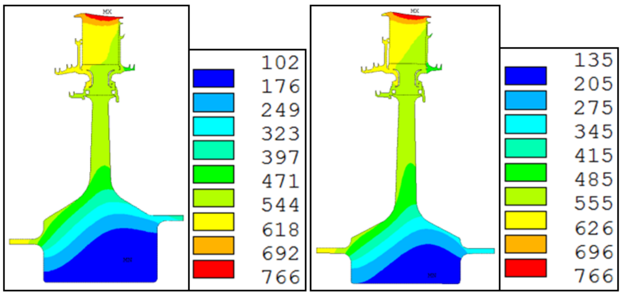

Fig. 8. Thermal state of the original and optimized designs at the most dangerous moment TFC (780 seconds)

Optimum design obtain time is about 4 days of automatic calculations. The optimization time may be significantly reduced by replacing non-variable model parts with their result factors, and also taking into account, that the main contribution to LCF is introduced only in the most intense modes of TFC. Therefore, instead of analyzing all points of TFC, only a part of them may be analyzed.

7. Conclusion

The approach of the GTE impellers elements design described in this paper, is based on elements design-strength multicriteria optimization with taking into account strength and design constraints, and allows:

1. Significantly reduce the complexity and design time
2. Reduce the weight of the wheels while providing resource
3. Carry out design on the selected mode, or taking into account all modes of aircraft engine typical flight cycle.

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