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Computer technology of the thermal stress state and fatigue life analysis of turbine engine exhaust support frames

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Abstract: An advanced computer technology of the thermal stress state and fatigue life analysis of turbine engine exhaust support frames based on the use of licensed engineering analysis software, as well as some specialized home codes are presented in the paper. The developed technology allows perform simulations for the full model of the structure, not only for the typical fragments models, and increase an accuracy of calculations and significantly reduce a design time.

Keywords: Exhaust support frame (ESF), computer technology, finite element method, finite volume method; numerical simulation, *pro-FE*, *STAR-CCM+*, *ABAQUS*, *ANSYS*.

1 Introduction

ESF (exhaust support frame) are one of the critical and most loaded part of the gas-turbine engines. During operation, these units are exposed by a complex combination of thermal stress due to the high-temperature flow of the fuel combustion products and mechanical loads. Interaction with high-temperature flow leads to uneven heating of the structure, which causes temperature stresses acting in conjunction with stresses from mechanical loads. The ESF structure must be deformed elastically and meet the specified requirements for the fatigue life. Due to the complex geometry and the high cost of manufacturing experimental studies of ESF strength under normal operating conditions are very difficult and much expensive. Therefore, the numerical studies of thermal state, strength and fatigue life are an integral part of a design process and certifica-

tion of the ESF construction [1]. At the stage of the ESF design considerable attention should be paid also to reduction of its metal content (weight optimization). In the process of construction optimization a number of design versions are examined, which requires large labor expenses for the development of corresponding grids and conducting of numerical calculations. This stimulates progress of numerical methods and computer technologies able to essentially increase an accuracy of numerical modeling of thermal and stress states of gas-turbine units and to reduce design time [2–11].

A description of computer technology of the thermal stress state analysis of turbine engine ESF is presented in [4]. A main feature of the technology is a simulation of the thermal state for certain typical fragments of the ESF, and then on a basis of the obtained results automatically formed a full temperature field. This approach to the solution of a problem was applied mainly due to the functional limitations of the software in terms of radiant heat transfer. In this paper, an improved technology is presented with an ability to perform calculations on the full model of a structure. This technology is based on the combined use of the following software:

- *pro-FE* – to build finite element models (FEM) with application of special panels and macros, developed using internal parametric language [4, 12];
- some home codes for automation of boundary conditions formation and setting of loads, calculation of fatigue life, processing of results of calculations [4, 6];
- *STAR-CCM+* – to create of FVM, FEM and calculation of thermal and stress states by the finite element and finite volume methods [5];
- *ABAQUS / ANSYS* – to calculate of the thermal stress state by the finite element method.

It is important to note that, if it's necessary to optimize individual zones of the structure or a comparative analysis of the thermal stress for several variants, it is effective to use only *STAR-CCM+* in accordance with the calculation algorithm shown schematically in Figure 1. Given the high efficiency of grid generation in *STAR-CCM+*, the proposed

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approach can significantly reduce the overall time to conduct the calculated optimization [3].

Figure 1: A block diagram of the calculation process using the presented technology

Below is a description of the main stages of the presented computer technology.

2 Generation of Discrete Models

The development of computational models is a responsible and one of the most important stages of the numerical simulation. An accuracy of the solution depends on the quality of the constructed models, so in the presented technology is paid special attention to this stage of work.

Automatic FVM and FEM generation is performed in parallel mode in STAR-CCM+ (Siemens PLM Software). The time required for automatic generation of mixed-type FE-grids and FV-grids in STAR-CCM+ is about two orders of magnitude lower than for the development of a higher-quality FE-grids consisting of 100% hexahedrons in other software packages [3–5].

To build a high-quality FE-grids preprocessor pro-FE is used. The use of pro-FE makes it possible to effectively generate the grids, especially in areas with complex geometric features, and to ensure a good quality due to the possibilities of parametric rearrangement and efficient smoothing algorithms. To reduce the time of grid generation, automate the execution of repetitive blocks of commands, as well as the effective formation of BC on large-

dimensional grids, the "adaptation" of pro-FE capabilities is performed to the construction of complex models through the development of special "panels", macros and programs [8]. Fig. 1 shows a block diagram of the FEM generation algorithm based on these software tools.

Figure 2: General block diagram of the algorithm for generation of FEM

Figure 3: The curves of results convergence by refining mesh

The optimal density of the FE-grids is revealed on a basis of the convergence research of the different grids, prepared by the path of successive automatic thickening in local areas with a change of element sizes (Figure 3). Numerical attempts show that an optimal FEM should be at least ~1.6 million isoparametric elements, and the FVM for thermal state analysis - at least ~4÷5 millions cells (Figure 4).

The computer model includes ESF, as well as the adjacent additional elements, which allows:

- to avoid the need to form additional BC in the model

at the places of parts connection;

- to improve the accuracy of stress state calculation due to accurate simulation of conditions of fixing and taking into account the compliance of additional elements;
- to improve the accuracy of the thermal state simulation by taking into account the radiant heat exchange with the surrounding parts.

Special macros and programs are used to efficiently form boundary conditions and loads on high-dimensional computational models [4, 8].

Figure 4: Fragments of Discrete Models

3 Thermal Analysis

Typically, the simulation of a thermal state of ESF is carried out for the most "heavy" stationary thermal modes of an engine and for the conditions of unsteady loading on the flight cycle. STAR-CCM+ allows to simulate the thermal state of the ESF taking into account the radiant heat transfer on the whole model, if there are enough computational resources. For example, to perform unsteady calculations on FVM ~ 10 million polyhedral cells at an acceptable time, 70-80 IBM cluster cores with the following parameters of counting nodes are required: 3 GHz, 64 GB.

The boundary conditions of convective heat transfer with the external environment are formed in the form of:

- Model surface distributions over a set of regions with their boundaries and dimensions;
- Tables and text files with heat transfer coefficients and ambient temperatures for regions.

The formation of boundary conditions is performed automatically by special macros.

The results of calculations for stationary modes are presented in a form of temperature distribution and temperature change curves for a height of an inner surface of typical racks. For unsteady modes the temperature fields in the given time sections of a flight cycle and the graphs

of temperature versus time in the control points or individual fragments of the structure are determined (Figure 5).

Figure 5: The graphs of temperature versus time in the individual fragments of the structure

The temperature distribution is automatically interpolated to all FEM nodes in STAR-CCM+ and written to the special format files for transfer to ABAQUS / ANSYS.

The acceptability of this technology has been confirmed experimentally.

4 Thermal Stress Analysis

The analysis of the ESF fatigue life under conditions of unsteady loading on the flight cycle determines a detailed study of the stress state kinetics in their most stressed zones. Such calculations can be performed in ABAQUS or ANSYS, which have all the necessary functionality [3, 4]. For example, in some cases, the calculations are carried out taking into account the nonlinearity of the material in accordance with any theory of plasticity [13, 14]. A plasticity model with isotropic hardening of the material is used often and dependence of material properties via temperature is also taken into account.

Different methods of solving of algebraic equations systems are used for calculations on different computing platforms. The choice of the solution method is determined, first of all, by the dimensionality of the computational model and the RAM [4]. Running tasks on the solution is performed by macros.

Simulation of thermal stress state of the structure is performed in the given time points of the flight cycle to determine the most stressed areas, getting the dependences of stresses and strains via time to analyze safety factors of the structure. In addition, the values of radial and axial displacements averaged values of radial forces are deter-

mined in control points and cross sections on the flanges. Special macros are used to automate the results processing [4].

The results are presented as a distribution of equivalent stresses, total and plastic deformations, as well as tables with the values of the components of equivalent stress and total strain tensors in the critical zones for the selected time sections. The changes in the values of the components of the total strain and stress tensors, the main deformations in the critical zones are analyzed (Figure 6).

Figure 6: The dependence of the intensity of total deformations in the critical zones of one of the EF on the flight cycle

As previously noted, if it is necessary to perform calculations for several design options, calculations are performed in STAR-CCM+. For efficient application of STAR-CCM+ it seems to be reasonable to use two-stage technique for every design option. At the first stage, stress-strain analysis is performed on the base of a coarse mesh of relatively low dimensionality (approximately 2 million cells) in order to define the most stressed areas. At the second stage, series of local mesh refinements is performed in these areas (the refined mesh includes about 8 million cells) up to the series convergence (Figure 7). In this case, the iterative solution of the system of equations can be accelerated in several times, using as an initial approximation the solution obtained on the "coarse" grid.

Figure 7: The convergence of the calculation results in STAR-CCM+ during the local mesh refinements

5 Fatigue Life Calculation

When the engine is operated in critical areas of the ESF fatigue damage will accumulate. Reaching of the critical damage values leads to the emergence of macro-cracks, as the limit state at the first stage of fatigue failure.

In the simplest case, the calculation of the fatigue life of the ESF is performed using only the low-cycle fatigue curves, obtained at different temperatures and types of stress state. In this case, it is impossible to take into account the quasi-static damage of the material in the most loaded areas. In general, the cyclic deformation diagrams and long-term strength curves with the corresponding loading regime should be known [15–17].

To perform a more accurate calculation of fatigue life, the shape of the deformation cycle in the critical zones must be taken into account. For this purpose, a mode of material loading in the most stressed zones, obtained as a result of calculations, is schematized. After schematization, the amplitudes of deformations in the cycle are distinguished, which have the main influence on the accumulation of fatigue damage. As a result of schematization, we obtain data on the repeatability of the amplitudes of the full deformations of different levels in the cycle, as well as the accumulated number of sub-cycles. Schematization of the cycle is carried out by the method of "full cycles" [20, 21]. A calculation of fatigue life material in critical zones is based on the corrected hypothesis of linear summation of fatigue damage, which has the strength con-

dition in form [18, 19]:

$$\sum_{i=1}^{m_{ij}^k} \frac{N_i^*}{N_i} = 1 \quad (\sigma_{ai} \geq \sigma_{-1d}),$$

where N_i^* - the number of cycles of repetition of the amplitude σ_{ai} for the entire service life;

N_i - the number of cycles on the fatigue curve, corresponding to the amplitude σ_{ai} ;

m_{ij}^k - number of different levels of stress amplitudes (sub-cycles).

σ_{-1d} - the fatigue limit of the material of the part.

The summands corresponding to the amplitudes of conditionally elastic stresses $\sigma_{ai} < \sigma_{-1d}$ should not be included in the sum, since for them the fatigue life N_i is equal to infinity ∞ .

Instead of the fatigue limit of the sample material σ_{-1} , the fatigue limit of the part σ_{-1d} defined is considered.

$$\sigma_{-1d} = D \cdot \sigma_{-1}.$$

In engineering practice, the following formula is widely used to determine the coefficient K_D :

$$K_D = \frac{1}{(K_\sigma / K_{d\sigma+1/K_F-1}) / K_v}$$

where $K_{d\sigma}$ - scale factor; K_F - factor affecting the quality of surface treatment; K_σ - stress concentration factor:

It is obvious that

$$N_i^* = \lambda \cdot v_{ic}^k,$$

where λ - the number of flight cycles that the material is able to withstand in the area under consideration until the formation of macroscopic cracks. Then the strength condition can be represented as

$$\sum_{i=1}^{m_c^k} \frac{\lambda \cdot v_{ic}^k}{N_i} = 1 \quad (\sigma_{ai} \geq \sigma_{-1d}).$$

Thus, the solution of the problem of determining the EF fatigue life is reduced to the calculation of a number of flight cycles to the formation of macroscopic cracks for each of most loaded zones.

The automate and improve an accuracy of calculations, the described calculation algorithm is implemented in the program FAN. The block diagram of the calculation algorithm is shown in Figure 8. The program provides the user with an ability to select property values for many of the most common materials from database or to set values manually.

After the program operation, a table is displayed, in which the specified numbers of the nodes of the computational model, the values of the corresponding temperature

Figure 8: The block diagram of the calculation algorithm

and the results of calculations are specified – the durability value for the critical zones in flight cycles.

Fatigue analysis and fatigue damage models (and failure criteria) could also be implemented in simple fiber-based finite element platforms (see e.g. [22]). This would speed up the process and make approaches such as those applicable to large-scale oriented analysis.

It should be noted that the total number of cycles before the failure of the ESF under cyclic thermal loading is defined as the sum of the number of cycles at the stage of fatigue crack nucleation calculated using the above approaches, and the number of cycles at the stage of crack propagation to critical dimensions determined by the Paris-Makhutov equation. In accordance with the described technology, the durability of the ESF is determined only by the moment of formation of macroscopic cracks within the most stressed zones.

6 Conclusions

1. A new technology is developed for simulating the thermal stress state and fatigue life analysis of ESF based on the use of modern licensed software and allows carry out calculations for all complex structures, improve the accuracy of the calculations and significantly reduce the effort in designing and optimizing. Targets to define accuracy calculations could be identified with experimental

testing, if or when results are available.

2. Numerical attempts carried out on the basis of the developed technology show that the optimal finite element model for stress state analysis should be at least ~1.6 million elements, and the finite volume model for thermal state analysis - at least ~ 4 - 5 million cells.

3. The developed technology was used to calculate the thermal stress state and fatigue life of the ESF for new engines and is currently used in similar calculations for other complex components of engines.

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