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Finite Element Modeling of Contact Heat Transfer in the Turbine Rotor Design of an Aircraft Gas Turbine Engine

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***Abstract* — On the basis of the finite element method (FEM) a mathematical model of the modular structure of the turbomachine exemplified by the aircraft gas turbine engine, AL-31F, is developed. It is notable for describing the solution of interdependent problems of the theory of elasticity and thermal conductivity, taking into account the changes in the parameters of the contact interaction of the turbomachine parts. A technique allowing obtaining updated values of stress and temperature fields in the modular structure of turbomachines, operating in a complicated complex of structural-force and thermal effects, is proposed with the identification of the influence of contact thermal resistance on the temperature field.**

Key words — finite element method, contact problem, contact heat transfer, contact thermal resistance.

I. INTRODUCTION

The work of the prefabricated modern thermal turbomachinery is associated with high-intensity force and temperature effects. Under these conditions, when changing the level of mechanical contact pressure on the mating surfaces, there is a change in the nature of the heat flow passing through the joints of parts. The resulting additional contact resistance to the heat flow leads to local overheating and, accordingly, to the change in the properties of the material, which produces the appearance of plastic deformations. The latter circumstance, in combination with working mechanical loads, can lead to a decrease in the efficiency of the modular structure as a whole. In particular, the presented circumstance is relevant to heavy-loaded thermal machines, such as turbines of aircraft gas turbine engines (GTE). The use of approximate values of the characteristics of contact interaction of the parts of the prefabricated heat-loaded structures is associated with the risk of making erroneous decisions in the development of reliable and resource-intensive thermal machines.

For a GTE of a highly maneuverable aircraft it is typical to have frequent changes in operating modes, marked by a significant change in the parameters of the working processes. One example of such engines is the AL-31F, installed on the Su-27 and its modifications. Among the temperature parameters of the working processes, not only the absolute temperature values are important, but also the gradients of the temperature fields in the engine design. A change in the temperature gradient results in a change in the matching conditions, that is, a change in the contact pressure level and a change in the temperature gradient on the mating surfaces are interdependent processes. Thus, the state of the heat-stressed deformable modular structure is characterized by two interdependent physical aspects of its mathematical modeling. On the one hand, it is a simulation of the temperature state of the structure. On the other hand, it is a simulation of the stress-strain state (SSS) under the influence of external loads, including thermal expansion forces.

II. MAIN ASPECTS OF FINITE ELEMENT SIMULATION OF CONTACT HEAT TRANSFER

Over the past few decades, a large number of domestic and foreign works have been devoted to the problems of contact heat transfer. Many of them are the attempts to determine the dependence of the contact thermal resistance on the actual contact area, modeling the influence of the interacting surfaces micro-irregularities [1]. There are works connected with a three-dimensional modeling of the roughness of the contacting surfaces using the FEM [2]. In general, the FEM undergoes numerous developments of new approaches to modeling of contact interactions concerning the problems of thermal conductivity and elasticity theory [3–6]. However, there is still no concept that would have an undeniable advantage over other ideas and be widely used in the design work on the creation of GTEs and other models of equipment, the functioning of which is characterized by high temperatures.

Despite the fact that the heat flow goes through the contact zone in several ways (thermal conductivity through the metal contact, radiation through the medium layer), and quite apart from the fact that the thermal contact resistance is very much dependent on the purity of the treatment and the degree of the breaking-in of the mating areas and the thermal conductivity of the medium between the mating bodies, for many cases, the nature of the dependence of the contact thermal resistance on the contact force pressure is common. Many experimental works [7] show that the dependence of the contact thermal resistance on the contact pressure for a variety of pairs of mating materials has the form shown in Fig. 1.

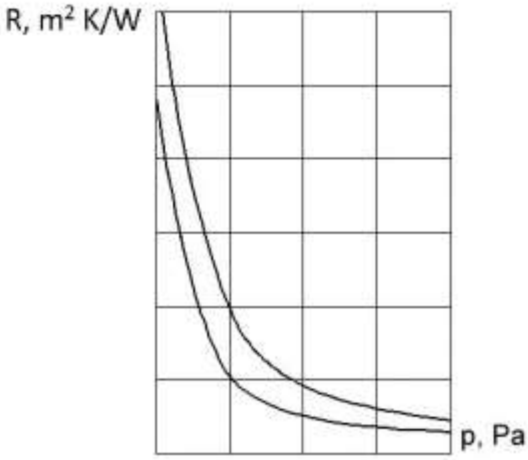

Fig. 1. Experimental curves of contact thermal resistance dependence on contact pressure

This kind of curves allows us to approximate such a dependence with the help of the piecewise linear (bilinear) function that opens convenient possibilities in the finite element modeling of the contact heat transfer using a special linear contact finite element of a one-dimensional type. This finite element has a parameter that takes one of two possible values depending on the state of the contact. The approach with the use of such element is described in [6, 8], where it is called the CECS (contact element of structures conjugation). The parameter of the element here is the so-called initial clearance, which determines the point moving from the state of tension to the state of the gap. The main advantage of the CECS is its simplicity in the implementation of the finite element solution of the contact problem of the mechanics of a deformable rigid body.

By analogy with the CECS, a contact thermal element (CTE) [9] was developed, designed to simulate the contact heat transfer. The CTE also has a parameter that takes one of two possible values depending on the intensity of the heat flow passing through the joint. This property of the contact element determines the approximation of the above-mentioned experimental curves by the bilinear function (Fig. 2).

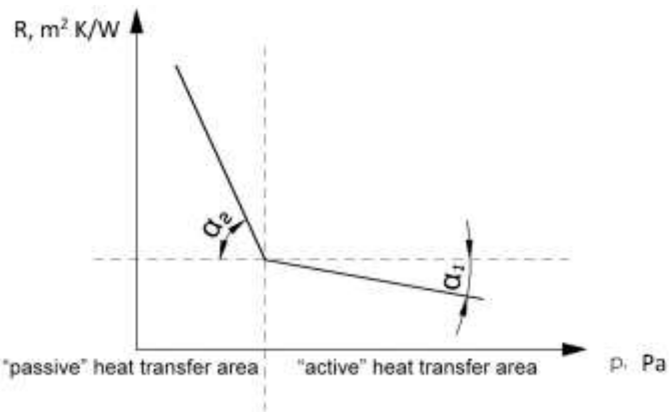

Fig. 2. Bilinear approximation of experimental curves of the dependence of thermal contact resistance on the contact pressure

Since the value of the contact pressure is directly proportional to the value of the field residual of contact displacements (in the elastic formulation of the problem), the graph shown in Fig. 2 is converted to the view given in Fig. 3.

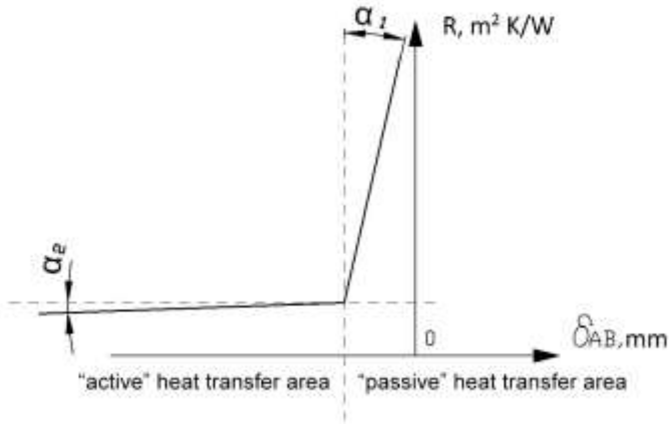

Fig. 3. Bilinear approximation transformation

Here, along the abscissa axis, the value of the coordinates (displacements) residual δ_{AB} between the mating nodes of the finite element grid of the contacting surfaces is used. In turn, the surfaces determine the value of the contact nodal forces between them and, thereby, the level of the contact heat exchange. The fracture point of the graph defines the phase of qualitative changes in the nature of the dependence of thermal resistance on the contact pressure. According to the experimental data, this phase begins not with the zero mark of the distance between the bodies, but with a certain value of the contact pressure corresponding to a certain value of the negative residual coordinates (fitting with tension). It is obvious that with an increase in the class of roughness of mating surfaces, as well as the level of breaking-in (aging) between them, the absolute value of this residual decreases. This is confirmed by the nature of the experimental curves presented in [3].

Thus, the application of the bilinear function allows us to use two states of the CTE: the state of active heat exchange and the state of passive heat exchange.

III. DEVELOPMENT AND ANALYSIS OF FINITE ELEMENT MODELS OF THE UNITIZED ROTOR OF THE TURBINE ENGINE AL-31F

The presented theoretical approach was tested on a fragment of the turbine design of the aircraft turbine engine. The finite element building was carried out in the system of the engineering analysis FEMAP. The finite element model (Fig. 4) was constructed using cyclic symmetry of the rotor with respect to the axis of rotation. The presented model consists of four bodies (a disc or impeller, a compressor shaft, a rear shaft, a tie bolt with a nut) on the mating surfaces of which the same (equidistant) finite element grids are simulated. This is necessary to establish the contact finite elements between the corresponding nodes of the mating surfaces of the parts.

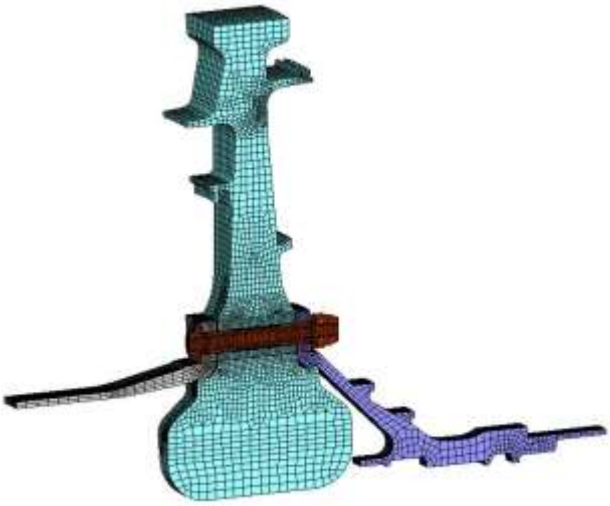

Fig. 4. Model of modular rotor of the turbine engine AL-31

With the maximum reliability of the geometry of the object under study relative to the drawings (electronic models) of the considered finite element model of the rotor certain idealization was made. This is relevant to the simulation of threaded connections. In particular, the connection of the nut and the clamping bolt (a coupling, fitter bolt) is made solid.

The shaft of the turbine impeller connection with the compressor is modeled in the area of the flange participating in the connection of the shaft with the turbine working disc. Here, the finite element mesh on the flange surfaces that are mated to other parts has the same shape and size as the mesh of the mating surfaces of the parts. This applies to the connection surfaces of the flange with the bolt head, with the fitting surface of the bolt body, the front surface of the disk, as well as the surface of the centering spigot of the disk, which ensures the alignment of the rotor assembly with respect to the axis of rotation. The rear shaft is also partially modeled in the flange area of the coupling with the turbine working disc.

The idealization took place in the rim of the disk. Here, the pull ends and the blades are replaced by an external temperature load acting from them (boundary conditions of the first kind of the temperature problem). The mechanical load in the form of centrifugal and gas forces from the blades was not taken into account. In addition, there are no simulated holes in the rim of the disc designed to supply cooled air through the disc body into the rotor blades.

Fig. 5 shows a fragment of the discussed structure, in which several pairs of contact surfaces are concentrated. This unit is of the greatest interest in the study of the contact heat transfer. The contact elements are shown in red.

The following effects were used as a mechanical load:

1) centrifugal load caused by the rotation of the rotor at a frequency of n = 13300 r./min (distributed throughout the volume of the rotor parts according to their mass density);

2) gravitational load corresponding to the acceleration g = 9.81 m/s^2 (distributed throughout the volume of the rotor parts according to their mass density);

3) thermal expansion forces due to the change in the temperature from the initial value T_0 = 293 K (determined for each finite element).

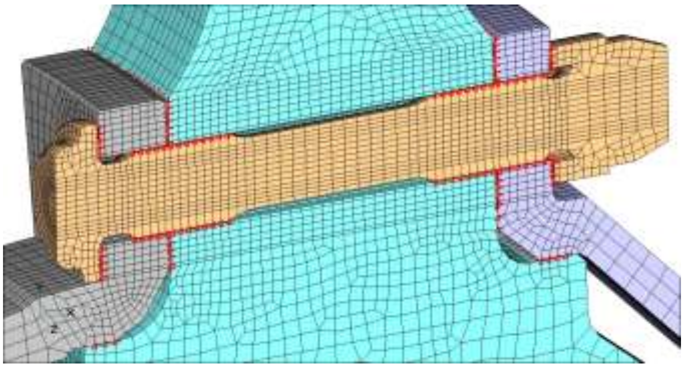

Fig. 5. Investigated unit of the modular rotor of the turbine engine AL-31

The thermal expansion forces were taken into account after obtaining the results of the solution of the temperature problem, i.e. after obtaining the temperature field over the entire volume of the prefabricated structure. To solve this temperature problem, the boundary conditions of the thermal conductivity process of the first and third kind were set, corresponding to the maximum steady-state operation of the engine. The calculation of the finite element model was carried out in a separate program, which was developed with the implementation of the idea of bilinear approximation of the experimental curves of the dependence of the contact thermal resistance on the contact pressure. For the convenient display of the calculation results, the program output has been imported into the FEMAP system. The temperature field is shown in Fig. 6.

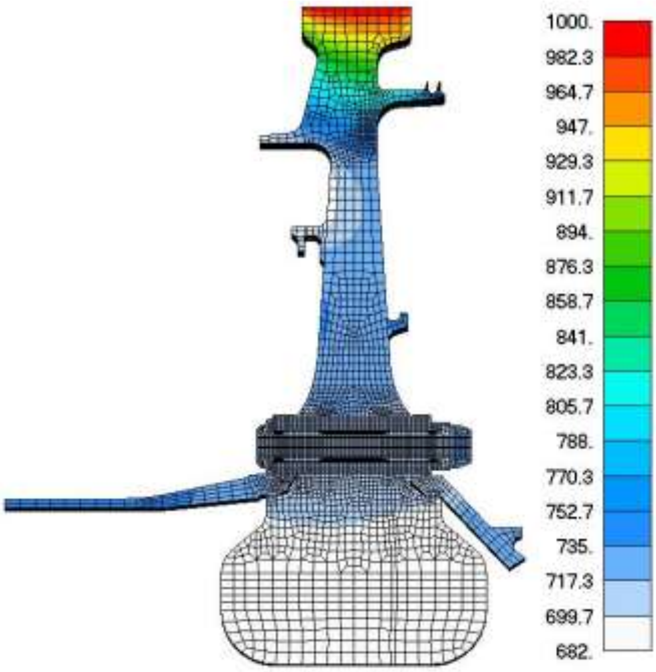

Fig. 6. Temperature field in the model (maximum steady state), K

The resulting temperature field was used as input data for the SSS calculation. This calculation was also performed in the author's program, allowing us to calculate the "initial clearance" of the contact finite element when changing the interface conditions, caused by the changes in temperature fields. In this case, the mechanical and temperature problems are solved in turn in several iterations. Below, in particular, there are the calculation results of the fields of contact forces on the mating surfaces.

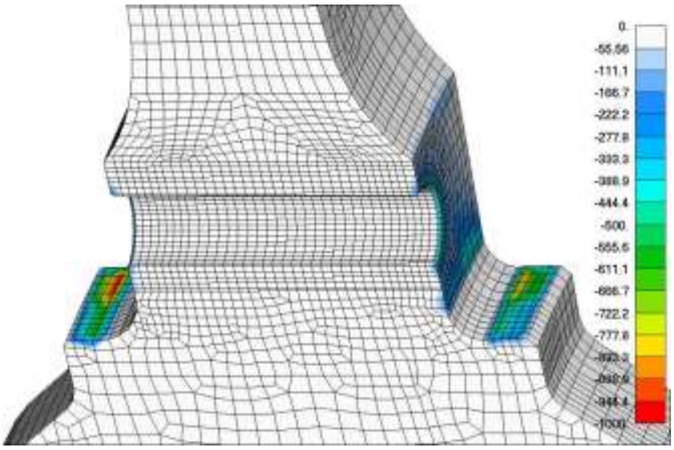

Fig. 7. Contact forces field. The details are only loaded by the forces of the contact interaction, N

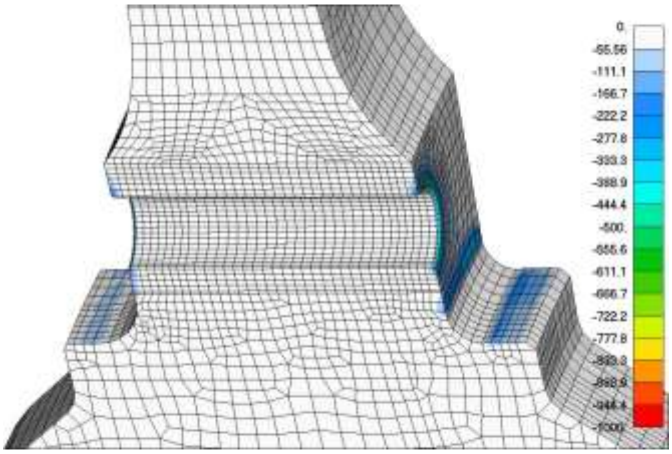

Fig. 8. Contact forces field; the details are loaded by the forces of the contact interaction and the centrifugal force, H

Analyzing the results shown in Fig. 7, 8 and 9, it can be concluded that the centrifugal forces weaken the tension on the radial surfaces, i.e. on the centering spigots of the disk and shafts. This can be explained by stretching the entire structure in the radial direction in the field of centrifugal forces. The effect of thermal expansion forces exacerbates the attenuation effect. This can lead to an increase in the contact thermal resistance in these joints, which, in turn, can cause temperature jumps in them.

In the next series of calculations, the heat transfer conditions were made to provide the greatest possible temperature gradient in the areas of the parts joints. This design case may correspond to the initial stage of the maximum operating mode of the engine, when the rim of the disc has already warmed up to the operating temperature, and the disk hub, due to its greater thermal inertia, remains cold. The temperature field obtained for this calculation case is shown in Fig. 10.

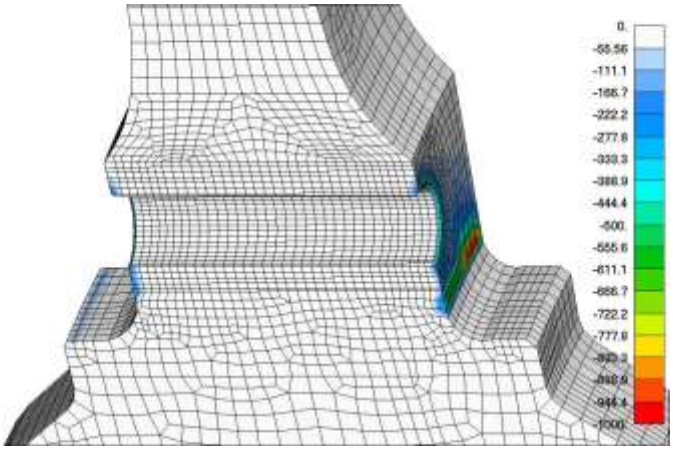

Fig. 9. Contact forces field; parts are loaded by contact interaction forces, centrifugal and thermal expansion forces, N

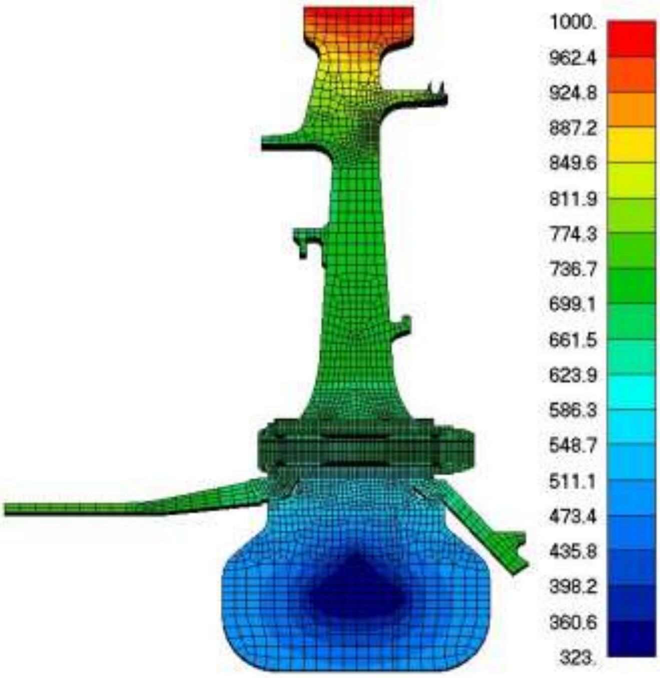

Fig. 10. Temperature field in the model (the initial stage of the maximum mode), K

The temperature field shown in Fig. 10 was obtained taking into account the contact thermal resistance calculated using the bilinear approximation depending on the coupling conditions. It should be noted that the conditions of conjugation of parts of this design in the model under study remain in a state of tension under the influence of all external load factors. This is due to the large initial tightening force of the tie bolts. In the state of tightness, the value of the contact thermal resistance is usually negligible. Nevertheless, in the picture of the temperature field there are sharp temperature changes in the mating surfaces (Fig. 11).

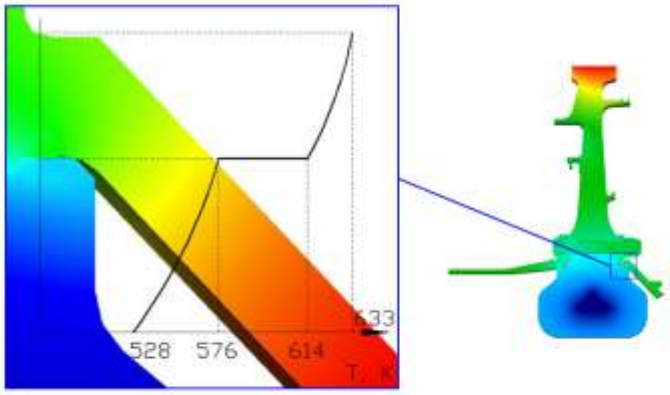

Fig. 11. Temperature difference between centering spigots and rear shaft, K

As shown in Fig. 11 the temperature difference is 38 K. This is the highest value obtained in the analysis of this design. It is difficult to say how significant this value of the temperature difference is. The presented calculations were carried out for the conditions of stationary heat exchange. In the case of a steady-state operation of the engine the concept of stationary heat transfer is quite adequate. Moreover, at unsteady modes it can give significant deviations in the results of the temperature fields. In particular, the temperature field in Fig. 10 is got with the accepted assumption of replacement of the non-stationary heat transfer by the stationary one. It can be assumed that this affected the decrease in temperature jumps in the joints, i.e. when calculating the temperature fields of the non-stationary heat transfer, the temperature jumps in the joints may be higher.

One important circumstance should be noted here. After the assembly the turbine rotor parts are immediately in a high-stress state close to the yield point of the material. Because of the complex workloads in some of the most stressed areas, there are plastic deformations. This occurs mainly on the mating surfaces and leads to a decrease in the tightening force of the bolts, which, in turn, changes the structural rigidity of the rotor, being one of the conditions that determine the values of the natural frequencies of the rotor. Thus, the contact problem of determining the most accurate picture of the SSS with the prediction of plastic deformations is important in the dynamics of the modular rotor [10]. At the same time, the temperature factor has a bilateral effect on the occurrence of plastic deformations, since, firstly, it determines the thermal expansion forces, and, secondly, it defines the values of physical and mechanical characteristics, depending on the temperature, in particular, such as the modulus of elasticity. In this regard, the problem of finding the most accurate temperature field in the modular design of the turbine of the aircraft GTE is of practical interest for researches and cannot be considered without taking into account the contact heat exchange.

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