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A Comprehensive Solution of the Problems of Ensuring the Strength of Gas Turbine Engine Compressor at the Design Stage

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Abstract. In this paper we present a complex numerical workflow for analysis of blade flutter and high-amplitude resonant oscillations, impenetrability of casing if the blade is broken off, and the rotor reaction to the blade detachment and following misbalance, with the assessment of a safe flight possibility at the auto-rotation regime. All the methods used are carefully verified by numerical convergence study and correlations with experiments. The use of the workflow developed significantly improves the efficiency of the design process of modern jet engine compressors. It ensures a significant reduction of time and cost of the compressor design with the required level of strength and durability.

1. Introduction

Design of efficient low and high pressure compressors for modern jet engines is one of the most difficult problems in the design of jet engines. Requirements for the reduction of number of stages with the increase of the pressure ratio yields the increase of aerodynamic and structural loading of blades. This needs more refined analysis of possible operating regimes at the engine design stage. First, detailed analysis of blade flutter and forced vibrations in engine wheels, which can result in fast fatigue damage of blades, is needed. However, high-amplitude blade vibrations are not always successfully avoided, and an important problem of consequences of blade detachment arises. Even if a blade is broken off due to fatigue damage caused by high-amplitude vibrations, the engine damage should be localized, and a long safe flight at the auto-rotation regime should be possible.

In this paper we present a complex numerical workflow for analysis of blade flutter and high-amplitude resonant oscillations, impenetrability of casing if the blade is broken off, and the rotor reaction to the blade detachment and following misbalance, with the assessment of a safe flight possibility at the auto-rotation regime. The use of the workflow developed significantly improves the efficiency of the design process of modern jet engine compressors.

2. Blade Flutter Analysis

2.1. Method of Flutter Prediction

The energy method is used for flutter analysis [1]. We assume that the influence of the flow on natural blade modes and frequencies is negligible. Therefore, the airflow can result only in a small additional damping (for stability case) or additional energy inflow (for flutter case) without the change of natural modes and frequencies. Integrating the energy equation for a blade over an oscillation cycle, we obtain the change of the total energy over the cycle:

$$\Delta E = W = \int_{t_o}^{t_0+T} \int_S p(x,y,z,t)\vec{n}(x,y,z,t)\vec{v}(x,y,z,t)dsdt \qquad (1)$$

where $E(t)$ is the total energy, W is the work done by unsteady pressure, T is the blade oscillation period, S is the blade surface, p is the flow pressure, $\vec{n}$ is the blade surface normal, and $\vec{v}$ is the velocity of the blade points. The following inequality is a criterion of flutter: $W > 0$.

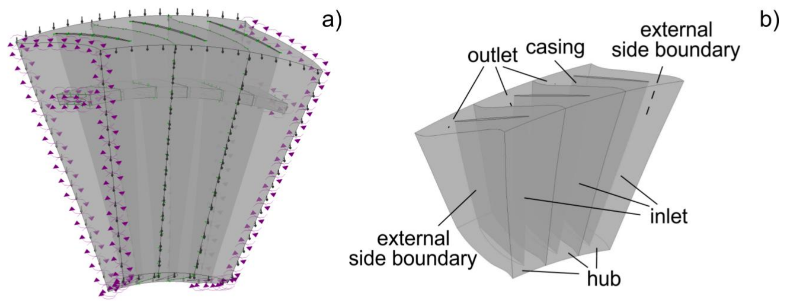

Figure 1. Model of three consecutive blade passages (a), boundary conditions (b).

Finite-volume model of the flow consists of three consecutive blade passages of one stage (Figure 1a). For unsteady fluid flow analysis, initial and boundary conditions (Figure 1b) are extracted from the steady-state flow calculated for the full compressor (where all stages are modelled), verified by full-scale compressor tests.

Mesh displacement in the form travelling wave corresponding to the wheel natural mode with a specified number of nodal diameters is applied to each blade surface:

$$\vec{u}(x,y,z,t) = A \cdot \left[\sin \omega t \cdot L_1(x,z) - \cos \omega t \cdot L_2(x,z)\right] \qquad (2)$$

where A and $\underline{\omega}$ are the blade oscillation amplitude and circular frequency, and $L_1(x,z)$, $L_2(x,z)$ are functions interpolating blade mode shapes corresponding to the node and antinodes of the wheel. The aerodynamic mesh deforms in accordance with the specified displacement of the boundary.

For modelling a forward (or backward) traveling wave, a phase lag $\omega t - \varphi$ and lead $\omega t + \varphi$ with respect to the middle blade are specified for neighbouring blades, where the phase shift $\varphi = 2\pi m/N$ corresponds to the number of nodal diameters m (N is the number of blades).

2.2. Examples

As an example, we analysed the influence of various design parameters on flutter boundary, namely, radial and axial clearance, closure and opening of the inlet guide vane, radial flow irregularity, inter-blade tension in the mid-span shroud. The work done by pressure is calculated for the second and third natural modes of first-stage shrouded blades of a low-pressure compressor. A series of computational models, representing the change of one of the design parameters, was considered. The following configurations were studied:

1. Increased radial clearance by 0.5 mm
2. Increased radial clearance by 0.5 mm and shut by 1.5° inlet guide vane
3. Increased radial clearance by 0.5 mm and opened by 2° inlet guide vane
4. Increased radial clearance by 1 mm
5. Specified radial non-uniformity of the flow at the inlet

6. Decreased tension force in the mid-span shroud (simulation of the wear in shroud contact pairs)

Each mode was analysed in a full range of possible nodal diameters. Results for one flow regimes are presented here.

For the baseline mode, as well as for cases 1-5, calculation results predict the occurrence of flutter for the second mode at m=5 (Figure 2). It is seen that the change of the design parameters considered in cases 1-5, does not result in significant change of the work done by pressure over the oscillation cycle. In the case 6 the results show that the wear of the mid-span shroud contact pairs stabilises the blade, as the work for both modes becomes negative for all nodal diameters.

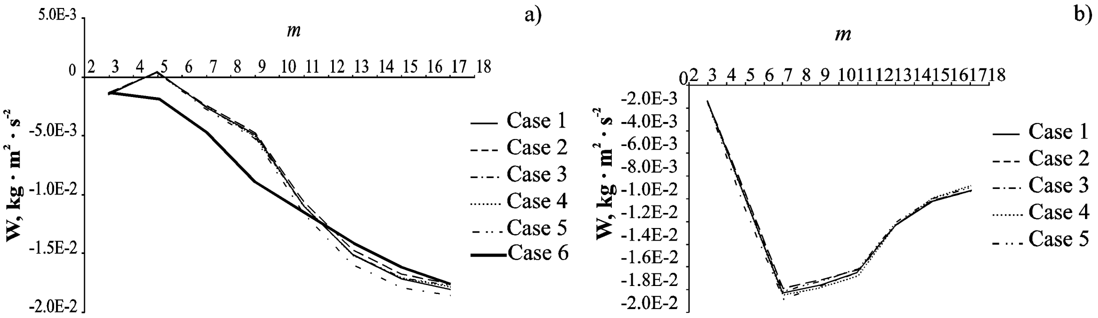

Figure 2. Work done by unsteady pressure vs nodal diameter. Mode 2 (a), 3 (b).

Comparison of calculation results with flutter test data shows a good agreement both in overall prediction (stability or flutter), and, for the flutter case, in the fastest growing mode.

3. Forced vibrations

When the engine is operating, the compressor blades are subject to periodically changing forces caused by the circumferential non-uniformity of the flow due to wakes of guide vanes and blades of preceding stages. When the frequency of these forces coincides with the natural frequency of the blade, resonance occurs. Possible resonance regimes can be found through Campbell diagram.

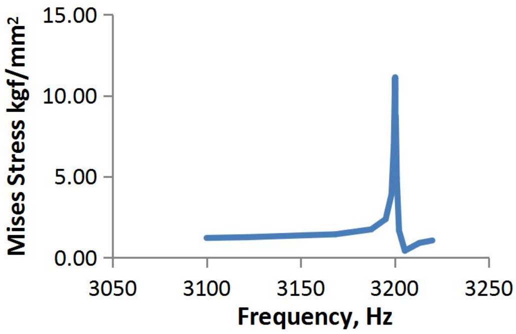

Figure 3. Frequency response at resonance regime.

The algorithm for calculating the amplitude of resonant oscillations consists in the following:

1. Calculation of the steady flow of air in the compressor with averaging of the parameters in the axial stator-rotor clearance;
2. Extraction of the model of the rotating wheel and guide vanes under consideration;
3. Calculation of the unsteady air flow in the selected stage without averaging of the parameters in the axial clearance, to obtain the unsteady pressure over the blade.
4. Transferring of the unsteady pressure field over the blade from CFD and CSD code.
5. Calculation of the amplitude of the resonant oscillations in the frequency domain (Figure 3).

4. Investigation of the impenetrability of engine cases due to blade breaking off.

Reliable computational methodology of impenetrability of the GTE cases after rotor blade breakage is a significant tool at the stage of design of a new product. Over the past several decades, the computational methods for assessing the impenetrability have undergone a significant evolution: from relatively simple semi-empirical techniques based on conservative energy criteria up to modern approaches to the analysis of supercritical behavior of structures using direct computer modeling in combination with a set of full-scale and virtual experiments needed for identification parameters of the calculation scheme. The main disadvantage of most of such calculation methods based on computer simulation is the low level of reliability of the results obtained. We present an original computational technique for assessing the impenetrability of GTE cases due to a blade breaking off, which has a higher predictive accuracy than existing ones [2-3].

4.1. The computational method for estimation the impenetrability of the GTE cases
The method is based on the experimental and computational procedure for solving the initial-boundary value problem by the finite element method in combination with the system of full-scale and virtual verification experiments used to adjust the calculation scheme (Figure 4). Verification of the calculation scheme consists in the classification of thermomechanical processes realized in the computational domain based on the characteristic values of deformations, strain rates, temperatures and parameters of the type of stress-strain state with subsequent reproduction of representative thermomechanical processes in verification experiments. The correction of the calculation scheme, which consists in the refinement of the parameters of the mathematical model (the parameters of the constitutive relations and the failure criteria for the materials used, the parameters of the contact interaction, etc.) is performed by reconciling the results of full-scale and virtual verification tests.

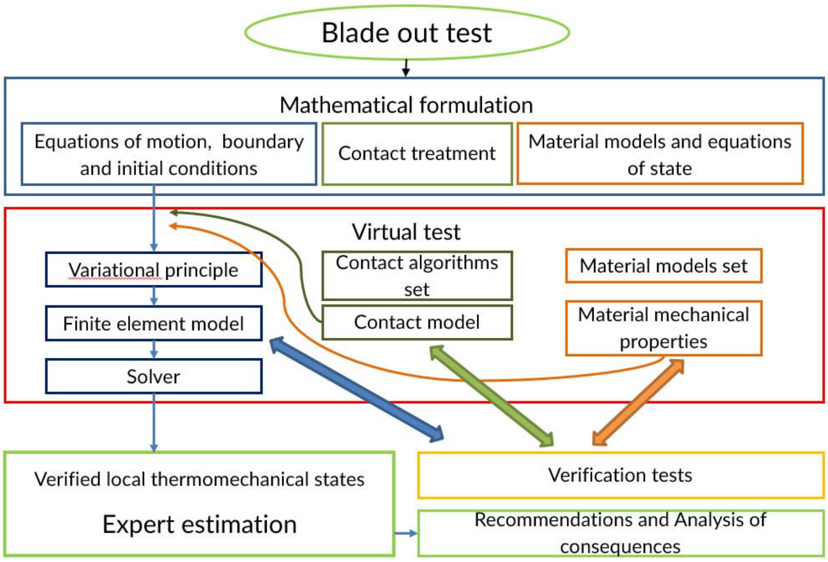

Figure 4. General scheme for the solution of the problem.

4.2. System of verification tests.
In this calculation technique, a set of verification tests consists of static and dynamic experiments (at normal and elevated temperatures) realizing thermomechanical states from a limited number of classes obtained as a result of solving the initial boundary value problem. A minimum set of verification tests for each material should include the following experiments: static uniaxial compression, tension and torsion (till failure) tests, dynamic uniaxial compression, tension and shear tests by the Kolsky method and its modifications, and ballistic impact tests.

4.3. Estimation of the quality of the methodology for assessing the impenetrability of the GTE cases
As an illustration of the efficiency of the calculation scheme used, the results of verification experiments using the Kolsky method for uniaxial compression and tension of metal samples, ballistic impact tests for metal and woven barriers (Figure 5), and bench tests for assessing the impenetrability

of the metal casing GTE are shown (Figure 6). Quantitative and qualitative agreement of the obtained results shows the efficiency and reliability of the presented calculation technique at all stages of design and subsequent operation of the gas turbine engine (Figure 7).

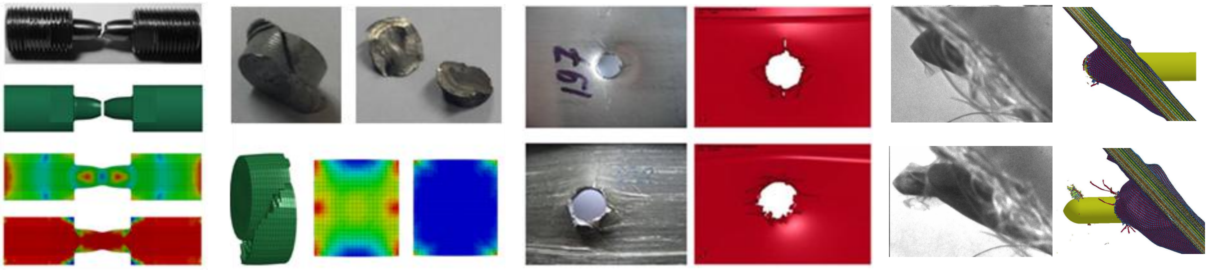

Figure 5. Comparison of results of full-scale and virtual verification tests .

Figure 6. Comparison of the results obtained using the presented methodology with the data of bench tests.

Figure 7. Investigation of the composite case impenetrability.

5. Analysis of the rotor misbalance and bearing loading due to blade breaking off

In this section we consider the modeling of the rotor dynamics (Figure 8) in the case of a blade breakage [4-5]. Figure 9 shows the program of rotation frequency change of low-pressure rotor, starting from the standard spinning mode, first stage blade breakage and the autorotation mode.

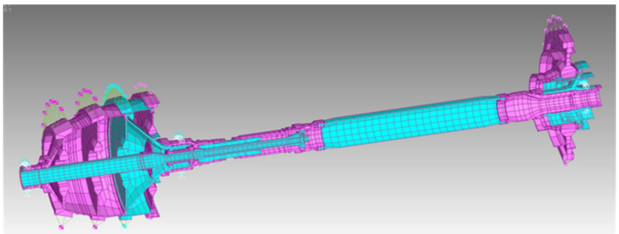

Figure 8. Finite element model of a low pressure rotor.

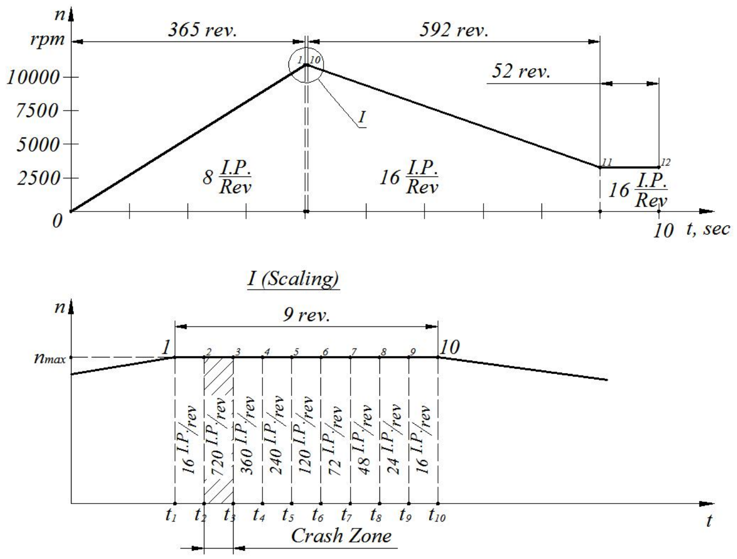

Figure 9. Rotation frequency change during the simulation of the blade breakage.

The total running time consists of four periods (Figure 9): starting from zero to the maximum speed; operation at maximum speed, at which the blade breakage is simulated; deceleration of the rotation speed; operation at autorotation mode (30% of the maximum speed).

To simulate the process of the blade breakage, the data obtained in the full-scale experiment are used in the form of measured location of the 1st stage wheel gravity center after the blade breakage. The results of the calculation (Figure 10) show a significant drop in the oscillations amplitude when switching to the autorotation mode, comparing to the blade breakage moment.

With calculated displacements of the low-pressure rotor supports (Figure 10) and rotor stress at the blade breakage and autorotation regimes, we estimate bending strength of the rotor shaft, fatigue strength of the rotor, bearing loads and durability, and finally, the safety of the engine operating at the autorotation regime.

The results of the rotor dynamics analysis during the blade breakage show the effectiveness of the experimental-theoretical approach described.

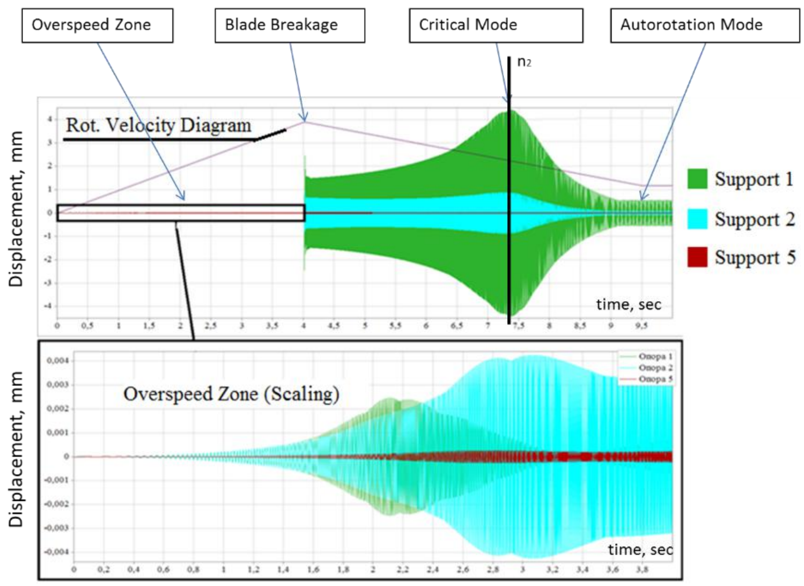

Figure 10. Displacement of low-pressure rotor supports during the simulation.

6. Conclusions

The numerical approach developed is an efficient tool for modeling the most dangerous regimes of compressor blades, rotor shaft and bearings. It ensures a significant reduction of time and cost of the compressor design for modern jet engines with the required level of strength and durability.

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