Software package for assessing parameter detuning influence on the durability of impellers of aircraft gas turbine engines

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Abstract. Software package described in the article allows analyzing the durability of impellers of gas-turbine engines (GTE) with parameters detuning. The article presents main provisions of the finite element method used in the analysis of oscillations and durability of elements of GTE rotors. Also, the algorithm for calculating the durability of GTE impellers is presented. Software package is tested on test models. The analysis results of the influence on the durability of parameters detuning introduced by changing the blade stiffness are presented.

1. Introduction

In the near future, tests of the MS-21 aircraft with a PD-14 engine certified by the Federal Air Transport Agency in October 2018 will be conducted. The project implementation to create a basic PD-14 engine, developed by AO “United Engine Manufacturing Corporation” (UEC), for equipping MS-21-300 passenger aircraft with it, is a successful example in the field of Russian engine manufacturing. This project would not have been possible without the use of modern software simulation modeling tools, making it possible in many respects to replace the full-scale experiment with numerical, reducing costs significantly.

Impellers, being the main design elements of GTE rotors, operate in difficult conditions (high rotational speeds, high temperatures, variable pressures, complex aerodynamic loads, etc.). It can be argued that GTE durability is determined by the durability of the most loaded structural elements of its rotor - impellers. One of the many factors that affect durability is parameters detuning, that is, small differences in the geometry, mass, material properties of the impeller individual sectors. The detuning is always present in the actual structure and is the result of errors occurred during its manufacture and assembly. Some authors in their studies have shown that the detuning can have a significant impact on the level of dynamic stresses in rotor blades, which negatively affects the structure durability [1-15].

In this regard, the development of high-precision mathematical models based on the finite element method, efficient algorithms and software for the study of oscillations and durability of GTE impellers is a relevant task. There are a number of works devoted to solving the problems of finite element modeling of impellers of turbomachines [1-7].

2. Equations of natural and forced oscillations of impellers

Natural oscillations equation of an impeller, which is a cyclically symmetric system containing N
sectors, can be represented as:

\[
[K]\{\delta\} = \omega^2 [M]\{\delta\},
\]

The loads acting upon oscillations on the impeller are represented as the sum of harmonics finite number of Fourier series. Each sector of the impeller has a force that differs by a fixed amount from the force acting on a neighboring sector. \(P_{k,j}\) force, acting in the direction of \(k\)-th possible displacement to \(j\)-th sector of the finite element model of the impeller at \(t\) moment of time, is represented as a Fourier series:

\[
P_{k,j}(t) = \sum_{p=1}^{N} A_{pk}(t)e^{i(j-1)\mu},
\]

For each impeller blade, each of the harmonics of this series undergoes a change. As a result, the equation of \(j\)-th sector forced oscillations for a specific Fourier harmonic has the view:

\[
M_p\delta_p^j(t) + C_p\delta_p^j(t) + K_p\delta_p^j(t) = A_p(t),
\]

where \(M_p, C_p, K_p\) - mass matrix, damping and stiffness of the impeller sector, respectively, for \(p\)-th harmonic; \(\delta_p^j\) - displacement vector of the sector.

3. Durability estimation of turbomachine impellers

LCC (level crossing counting or intersection method) and RFCC (rain-flow-cycle counting or “rain method”) methods are most often used to analyze durability from a variety of classification stress classic methods [2]. The choice of a method is not particularly significant. According to these methods, the voltage-time diagram is decomposed into individual values (classes). These voltage classes are subsequently used when applying one or another damage accumulation hypothesis. The difference in LCC and RFCC methods is that LCC method estimates only one parameter - the voltage amplitude, and RFCC method estimates amplitudes and average voltage values in each class. As a result of using one of the classification methods, various groups of static and dynamic voltages with different damage are obtained.

As for the choice of damage accumulation hypothesis, in accordance with which the durability forecast is made, it should be noted that this choice depends on properties of the structure material. In this case, linear hypotheses of damage accumulation are most often used. However, a nonlinear dependence of the damage amount on the number of loading cycles is observed in a number of practical cases. The hypotheses of Palmgren-Miner, Haibach, Corten-Dolan and Sorensen are considered of many hypotheses [3].

![Figure 1. Block diagram of the software package](image-url)
Figure 2. Block diagram of the algorithm for calculating the durability of GTE impellers.
4. **Software package description for estimating the influence of parameters detuning on the impellers durability of GTE aviation**

Using the above provisions, a software package for analyzing the durability of turbomachine impellers with parameters detuning was developed. The software package is written in the programming language of MATLAB package, which is currently used to solve engineering and scientific problems. The application areas of the developed software package are: design, manufacture (assembly) of aviation GTE and their operation.

Minimum requirements for system software and a computer when using a software package are determined by minimum requirements of MATLAB package. These are 32 or 64 bit Microsoft Windows operating system, a Pentium processor, at least 1 GB of RAM, a monitor of at least 256 colors, a graphics adapter (at least 16 bits), a hard disk of at least 5 Gbytes.

The software package includes a number of modules with various purposes (Fig. 1). These are such modules as:

- **Preprocessor** – module for input of initial data and structure of a finite element net;
- **Osc_Rotor** – module for calculating free oscillations of the structure;
- **Resp_Rotor** – module for calculating forced oscillations of the structure;
- **Stress_Rotor** – module for calculating dynamic voltages in the structure;
- **Durability_Rotor** – durability calculation module;
- **Postprocessor** – module of the results output in the form of isolines, graphs, diagrams or tables.

Figure 2 shows block diagram of the algorithm for calculating the durability of GTE impellers.

5. **Software package testing**

Testing of the above algorithm was carried out on two models: a single disk model and an impeller model, which consisted of 24 blades.

The disk model had the following parameters:

- geometry: inner radius - 0.1 m, outer radius - 0.2 m, disk thickness - 0.001 m.
- material characteristics: module of elasticity $E = 215$ GPa, density - 8200 kg/m$^3$, Poisson ratio - 0.29.

The condition of fixing the disk is on the internal contour. Figure 2 shows oscillation patterns that differ in the number of node diameters $n$ and node circles $m$. Calculation results showed good accuracy in comparison with the results of the experiment [3] and the results obtained using ANSYS software package. (Table I).

![Forms of free oscillations of the test disk](image_url)

**Figure 3.** Forms of free oscillations of the test disk
Table 1. Frequencies of free oscillations of the test disk, Hz

| m | n = 0      |     |     | n = 1      |     |     |
|---|------------|-----|-----|------------|-----|-----|
|   | FEM        | ANSYS | Exp. | FEM        | ANSYS | Exp. |
| 0 | 79.04      | 78.74| 79.2 | 80.81      | 80.38| 81.2 |
| 1 | 517.2      | 522.58| 515.8| 527.3      | 532.09| 526.3|
| 2 | 1483       | 1543.9| -    | 1494       | 1543.9| -    |

The impeller model contained 24 blades and had the following parameters:
- geometry: inner radius - 0.014 m, outer radius - 0.06 m, disk and blade thickness - 0.002 m, blade length – 0.036 m, blade width - 0.012 m;
- material characteristics: module of elasticity E – 210 GPa, density - 7850 kg/m³, Poisson ratio - 0.3.

![Figure 4. Impeller model](image)

Forms of free oscillations of the impeller model are shown in Fig. 5. Calculation results of free oscillations frequencies in comparison with the experiment and calculations in ANSYS software package are given in Table 2.

![Figure 6. Forms of free oscillations of the impeller model](image)

Table 2 shows the obtained results being in good agreement with calculations in ANSYS program, as well as with the experimental data, which indicates the efficiency of the developed algorithms and software.

6. Analysis of Rolls-Royce durability
After testing the program, a Rolls-Royce impeller durability calculation was carried out, including 29 blades.
The impeller, made of titanium, had the following material characteristics: module of elasticity $E = 120100 \text{ H/mm}^2$, density - 4637 kg/m$^3$, Poisson ratio - 0.26.

### Table 2. Frequencies of the impeller free oscillations, Hz

| $n$ | $m = 0$ |  |  | $m = 1$ |  |  |
|-----|---------|---|---|---------|---|---|
|     | ANSYS   | FEM | Exp. | ANSYS   | FEM | Exp. |
| 0   | 263.4   | 260.1 | 265 | 1470 | 1461 | 1386 |
| 1   | 280     | 251.1 | 210 | 1515.2 | 1522 | 1361 |
| 2   | 314.1   | 320.7 | 340 | 1730.7 | 1737 | 1723 |
| 3   | 485     | 492   | 501 | 2184 | 2147 | 2109 |
| 4   | 651.22  | 669   | 681 | 2785 | 2714 | 2714 |
| 5   | 778.1   | 808   | 803 | 3323.3 | 3354 | 3452 |
| 6   | 858     | 912   | 922 | 4030 | 4002 | 4102 |
| 7   | 980.5   | 987   | 938 | 4574.9 | 4613 | 4738 |
| 8   | 1041    | 1042  | 961 | 5048.1 | 5155 | 5112 |
| 9   | 1054.5  | 1080  | 1008 | 5430 | 5605 | 5513 |
| 10  | 1089    | 1105  | 1027 | 5742 | 5947 | 5983 |
| 11  | 1106.5  | 1119  | 1030 | 6140.7 | 6166 | 6212 |
| 12  | 1118.6  | 1124  | 1032 | 6354.9 | 6243 | 6221 |

General view of the impeller is shown in Figure 7.

**Figure 7.** Rolls-Royce impeller

An analysis of the effect on the detuning durability introduced into the system by changing the stiffness of the blade materials was carried out in the studies. Two options for changing the stiffness of the impeller blades were investigated.

In the first case, Young's modulus value of the blades material was changed by no more than 10%. Young's modulus for $n$-th blade ($E_n$) was determined as:

$$E_n = E_0 (1 + \Delta f_n^E) ,$$

where $E_0$ - nominal value of Young's modulus; $\Delta f_n^E$ - change of Young's modulus value for $n$-th blade.

Change of blade areas Young's modulus is on Fig. 8. Natural frequencies of the blades changed in proportion to the change in Young's modulus and oscillation forms remained unchanged.

In the second case, each blade was divided into 4 parts with different values of the module of elasticity (Fig. 7). The detuning was introduced by changing values of module of elasticity (not more than 10 percent) for different parts of the blade: $E_n,1$ for the lower left and upper right side, $E_n,2$ for the lower right and upper left side of the blade.

Schematization of voltages arising in the material during oscillations with the “rain method” was used to calculate the durability [4,6]. In addition, a comparison of the results obtained using various hypotheses of damage accumulation was made (Sorensen, Corten–Dolan, Palmgren–Miner).
Table III presents the results of calculating the impeller durability with detuning and without detuning when using various hypotheses of fatigue damage accumulation.

| Linear hypotheses of fatigue damage accumulation | Durability (cycle) | Variant 1 | Variant 2 |
|-------------------------------------------------|--------------------|-----------|-----------|
|                                                  | System tuning      | System detuning | System tuning |
| Palmgren - Miner                                 | 1.2860 E+5         | 1.1890 E+5     | 1.1675 E+5  |
| Haibach                                          | 1.1390 E+5         | 1.0087 E+5     | 0.9873 E+5  |
| Corten - Dolan                                   | 1.0594 E+5         | 0.8907 E+5     | 0.8985 E+5  |
| Sorensen                                         | 0.8908 E+5         | 0.7896 E+5     | 0.7974 E+5  |

7. Conclusion
The developed software package for the study of parameters detuning influence on the impellers durability of aviation GTE was tested on test models. Using this package, a study of the effect on detuning durability implemented into the system by changing blade stiffness was conducted. The calculation results allow us to conclude that even a small detuning can have a noticeable effect on the impeller durability.

This package can be used as a separate model in computer-aided design systems for such objects as impellers of GTE rotor. Also, its use is possible at manufacturing stage (assembly) of rotors and during diagnostic control at the stage of aviation GTE operation.

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