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Information model and software architecture for the implementation of the digital twin of the turbine rotor

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Abstract. The manufacturing errors of the turbine rotor lead to the occurrence of vibrations that limit the acceptable modes of operation of aircraft engines. In order to reduce such vibrations, the current manufacturing technology of the rotor contains a complex procedure for balancing it. Creating a digital twin of the turbine rotor will allow to abandon the balancing procedure and reduce the cost of manufacturing parts. This paper presents such stages of creating a digital twin as the determination of typical errors in the manufacture of a turbine rotor, the construction of a digital twin of a part taking into account the errors in manufacture and the determination of its key characteristics. Analysis of the properties of the twin allows to optimize its parameters and to reduce vibration of the entire engine.

1. Introduction

Manufacture and repair of complex science-intensive products has high prime cost, long cycles and significant investments of working capital. The complex science-intensive products, for which quality is a critical indicator, include aircraft engines, power and energy-generating plants, rocket engines, mechatronic systems, etc. [1]. The quality of the mentioned products depends on many factors and, above all, on the geometric accuracy of assembly units and products. Advanced digital technologies can help in solving the task for ensuring quality of complex products, the task for reducing prime cost and manufacture time. Digital twin of the product is an example of similar technologies. The digital twin of the product means its virtual copy which behaves in the same way as a real product.

In manufacturing practice while manufacturing and repairing aircraft engines as well as power plants, there is a problem of quality assurance for the parameter of the rotor vibration state. While manufacturing the parts of the GTE and assembly, there is likely to be geometric deviations [2]. The main parts costs millions of rubles. Manufacturing new parts, if there are a number of deviations, is not economically feasible. Ensemble of deviations, made during manufacturing the parts and assembling, may result in increased vibrations detected during the test phase. Synergies between the probability of increased vibration and deviations is complex and ambiguous. Eliminating all kinds of deviations before the test phase is not economically feasible. However, performance of multiple tests involves significant costs measured in millions of rubles [3]. In order to solve this problem, it is economically feasible to develop and implement digital twins of the products that allow to predict probability of increased vibrations and determine the ways to eliminate them. Using digital twins will also allow to predict failures while operating on the aircraft wing, which is especially important. Using

digital twins while developing new products will allow for optimal choice of technical requirements for the accuracy parameters of the parts and assembly units including the wide range of production experience [4, 5]. This paper considers the task for creating a digital rotor twin of low pressure spool for the gas turbine engine.

2. Information model of the digital turbine rotor twin

Creating a reliable twin involves a solution for a number of tasks to represent the key characteristics of a real product and processes associated with its manufacture in digital form. The actual geometric dimensions of the parts included in the turbine rotor and their relative position in the assembled state have a significant impact on performing the entire aircraft engine, so one of these tasks is to create a model of a valid turbine rotor.

The manufacturing errors of the turbine rotor components and the errors of their assembly to the finished product lead to the emergence of imbalances of rotating parts, which determine the vibration level of the engine as a whole in combination with elastic and inertial characteristics of the components. The procedure for eliminating the imbalance, both individual components of the turbine rotor and the entire product, is used to reduce vibrations. This procedure is performed on special stands, eliminating imbalances is made by adding corrective masses to the turbine rotor parts [6, 7]. Digital representation of this procedure means the development of algorithms for optimizing parameters of turbine component models, leading to reducing distance between the mass center of the model and its rotation axis, which is one of the main causes of imbalance.

After balancing the most important rotor parts and their assembly, the product quality is estimated. This procedure is performed on the basis of the results of bench tests based on the analysis of instrumentation readings. The turbine rotor digital twin shall be able to determine operating parameters of the rotor model, obtaining these parameters will allow to assess the product quality. A large set of tasks associated with the development of a turbine rotor digital twin as well as a diverse set of the data used lead to necessity for structuring tasks and creating information models of the digital twin. Within the framework of this model, it is necessary to organize functional division of tasks between the system modules and to develop interfaces of interaction between them. The work mentioned has been carried out, the resulting information model is presented in Figure 1.

According to the model shown in Figure 1, the task for creating an actual 3D turbine rotor model is divided into a number of subtasks that are solved by individual modules.

The module for determining geometrical parameters for formation of actual 3D rotor models operates with the model of errors in manufacturing the rotor parts and errors of their assembly. Probabilistic characteristics of geometrical errors of the parts and assembly units determined using this module are used for developing a parametric turbine rotor model.

Digital imaging of the balancing process is realized by the virtual balancing module of 3D low-pressure turbine rotor models. This module uses an actual turbine rotor model together with assembly parameter calculation procedures in order to determine the parameters of balancing elements that allow to minimize the rotor model imbalance.

The task for determining the operational turbine calculation parameters is solved by the same-name module. This module calculates such parameters as deformation of the parts of the assembly unit, its own frequencies, radial and end beating of control surfaces. Based on the analysis results of the obtained data, the product quality is estimated.

The calculation management module is used for coordinating the work of all working modules. The task of this module is to create tasks for calculation and consolidation of numerical simulation results.

Let's consider the tasks and the structure of the described modules.

3. Software architecture of the digital turbine rotor twin

3.1. Module of geometric parameters for forming actual 3D turbine rotor models

Imperfection of machining equipment and technological processes for manufacturing turbine rotor parts lead to the fact that their geometrical parameters differ from the specified nominal values. Using various manufacturing processes of the component leads to formation of specific manufacturing

errors. In order to create a reliable digital turbine rotor twin, it is necessary to determine probabilistic characteristics of various geometric parameters of the parts and assembly units [8, 9]. The module for determining probabilistic characteristics of geometric parameters of parts is designed to prepare data for formation of a parametric 3D low-pressure rotor model. The module concerned is implemented by a set of scripts of Matlab system and solves the following tasks:

    1) obtaining information on manufacturing errors and assembly of parts;

    2) generalization of errors in manufacturing and assembly of parts;

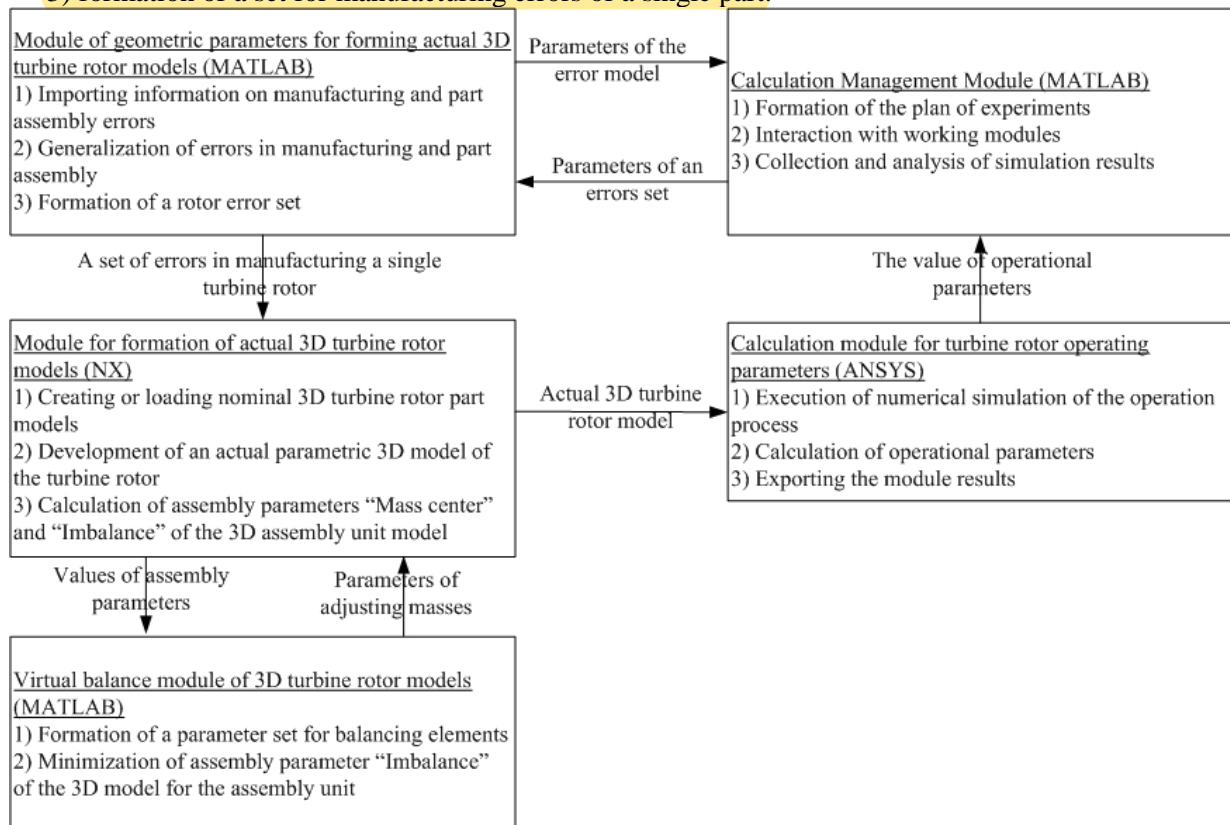   3) formation of a set for manufacturing errors of a single part.

Figure 1. Information model of the digital turbine rotor twin.
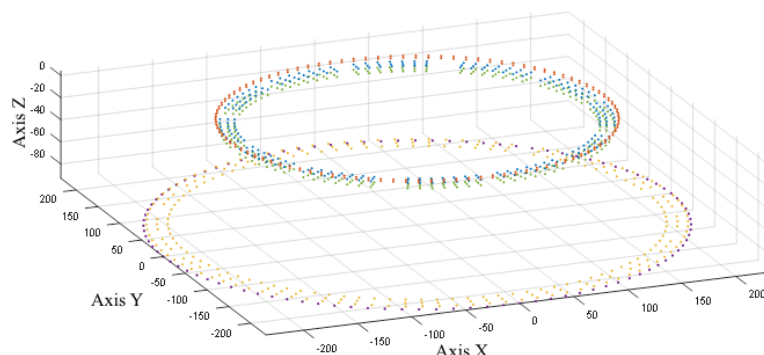

Figure 2. Importing the measurement results of the part "retainer" into the Matlab system.

Geometrical parameters of the manufactured parts as well as assembly parameters of the turbine rotor are measured on coordinate measuring machines. Control of the measurement process and accumulation of measurement results takes place in a specialized software. This software has limited tools for processing measurement results, so its use for generalized manufacturing and assembly errors is inefficient. The developed software allows to export measurement results from the PCDMIS project (a specialized software for working with coordinate measuring machines) to text files for further

processing by third-party applications. The results of importing measurement data into Matlab system are shown in Figure 2.

Based on the downloaded information, statistical and probabilistic analysis of the resulting errors is carried out, as a result of which probabilistic distribution parameters of errors are determined. Probabilistic parameters, characterizing the mutual arrangement of the rotor parts relative to each other, can be determined based on probabilistic parameters for distribution of the concerned errors of the parts and assembly units. The parametric of the low-pressure turbine rotor model takes into account the probabilistic parameters characterizing the mutual arrangement of the rotor parts relative to each other. Formation of a parametric low-pressure turbine rotor model is performed in the module for construction of actual 3D models.

3.2. Module for formation of actual 3D turbine rotor models
The module for construction of actual 3D part model solves the task for creating a parametric 3D turbine rotor model, which is an integral part of the digital twin of the specified product. In order to solve this problem, the module implements the following subtasks in the Siemens NX system:

1) Creating or loading nominal 3D models of the parts;
2) Constructing actual 3D models of the parts;
3) Calculation of assembly parameters "Mass center" and "Imbalance" of the 3D assembly unit model.

Information on deviations of the geometric parameters of the turbine rotor parts and information on their assembly errors is used to change its nominal 3D model. The nominal model of the parts and rotor assembly can be obtained either by importing the model from a CAD file created by the designer or by using the design documentation.

Siemens NX has a large range of tools to evaluate the parameters for 3D models of the parts but manual use of these tools is not suitable for automatic calculations, so for automation of parameters change and calculation of the assembly mass center, software applications in the NX/Open API module has been developed in Visual Basic programming language. The software application is implemented in the form of a calculation server allowing its use by third-party applications (Fig. 3).
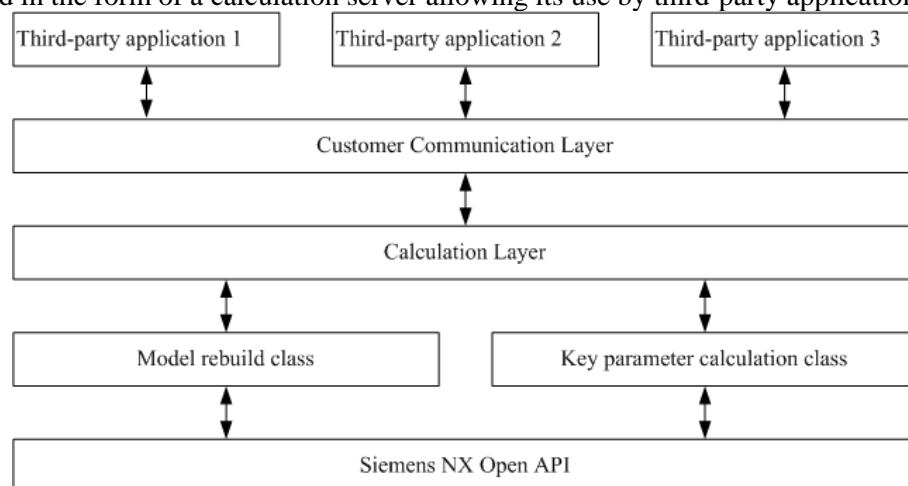

Figure 3. Structure of the calculation server.

Implementation of the application in the mentioned form allowed to use the capabilities of the Siemens NX system to the full extent when creating a turbine rotor digital twin [10]. Interaction of third-party applications with calculation server occurs via TCP protocol, tasks fpr calculations are sent in the form of simple text messages.

3.3. Module for formation of actual 3D turbine rotor models
The digital representation of the turbine rotor balancing procedure is implemented in the virtual balancing module of the 3D model of the assembly unit. During operating this module, the parameters

of balancing loads are calculated allowing to minimize the imbalance of the turbine rotor model. The module is implemented in the Matlab system and uses the calculation server described above. The structure of the module is shown in Figure 4.
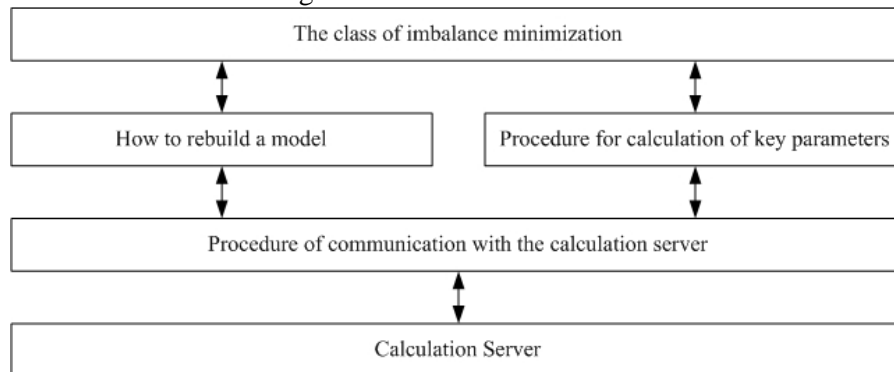

Figure 4. Virtual balancing module structure.

The imbalance minimization class is capable of working in batch mode when the user specifies several sets of parameters for constructing an actual model and for each of them, the application defines parameters of balancing loads. In its work, the object of the specified class uses the procedure of reconstructing the model and the procedure for calculation of key parameters. These procedures are wrappers calling the corresponding calculation server methods.

3.4. Module for calculation of operational parameters
One of the goals for creating a turbine rotor digital twin is to estimate the product quality. In order to estimate the manufacture quality, it is necessary to determine the resulting parameters of operation of the created rotor model. The solution for this task is the calculation module of operational parameters. This module is implemented in the form of sets of Matlab system scripts and finite-element model of the product in the ANSYS system. The module block diagram is shown in Figure 5.
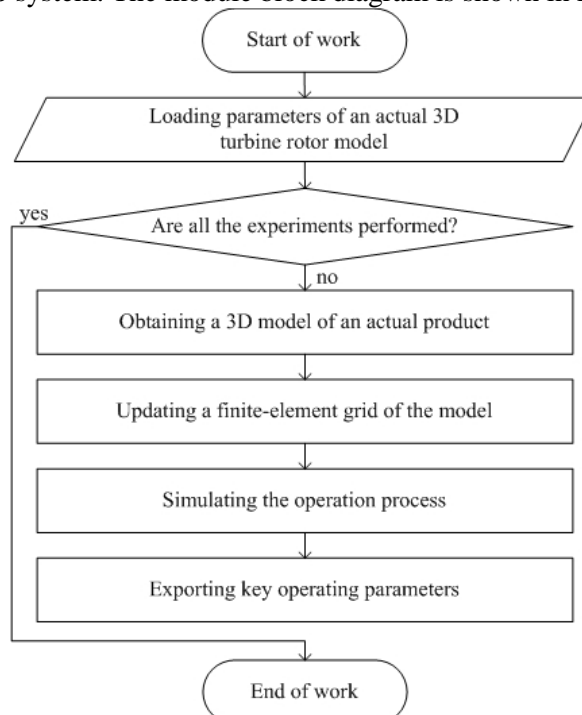

Figure 5. Block diagram for operating the module for calculating operational parameters.

In order to be able to carry out a sequence of experiments, the entry point to the module, the CalcBalance script generates a control task for each stage of the work and a summary task to perform simulation of the operation process for each experiment.

After formation of all control scripts, the ANSYS system is started, the project of finite-element rotor model is opened, and the main control script is transferred to the system. The ANSYS system performs numerical simulation of the operation process and exports the key parameters of this calculation to text files for further analysis.

At the final stage of the work, the ExtractResults script parses the obtained files and saves the resulting tables to a *.mat file for further analysis.

3.5. Calculation management module

The described modules solve the tasks associated with creating a turbine rotor digital twin. In order to coordinate the work of the created modules and to provide one entry point to this system, a module for controlling the conduct of theoretical experiments has been developed. The specified module is designed to solve the following tasks:

1) Formation of a plan for experiments;
2) Interaction with working modules;
3) Collection and analysis of simulation results.

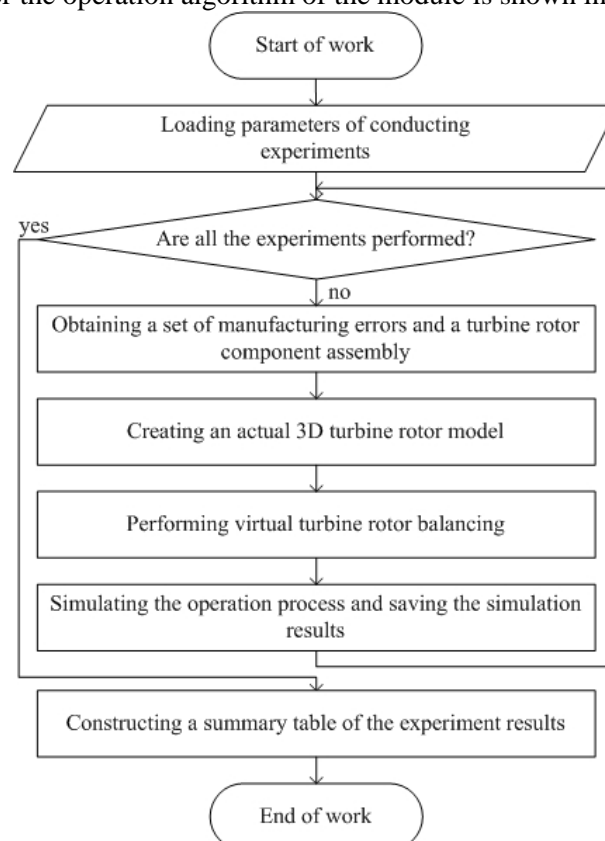The block diagram for the operation algorithm of the module is shown in Figure 6.

Figure 6. Block diagram for the operation algorithm of the control module.

At the first stage, the user creates an experiment plan and saves it to an Excel file.

While starting the control module, the file of the experiments and their numbers are specified. The application loads the file and starts working with the specified experiments. In order to create an actual turbine rotor model, a parameter definition module for actual 3D parts models is called, and a set of manufacturing and assembling errors of the rotor component is generated.

At the next stage, the task is formed to generate an actual 3D turbine rotor model and to balance it, and the modules responsible for solving these tasks are started.

After virtual turbine rotor balancing, the task for simulating the operation process and for saving the results is created. The results of each experiment are stored in separate catalogs, so to obtain generalized data, the application scans the catalogs data and loads the found results of the experiments.

4. Results of experimental studies

The developed software system of the turbine rotor digital twin has been used to assess the operating modes of the turbine rotor and to determine the dependence of imbalance on the rotor speed [11, 12] . According to the calculation, the values of coordinates of the mass center have been obtained and the imbalance of the product has been determined. The values obtained are listed in Table 1.

Table 1. Center mass coordinates values and imbalance numbers.

Frequency, Hz	x, mm	y, mm	z, mm	r, mm	D, g*mm
5	1799.4	1.70E-03	1.60E-03	2.33E-03	330.218
25	1799.4	-2.04E-04	-2.41E-04	3.16E-04	44.722
54.81	1799.4	5.80E-03	-5.40E-03	7.92E-03	1120.941
83.33	1799.4	4.22E-04	2.33E-05	4.24E-04	59.915
100	1799.4	-1.54E-04	-1.79E-04	2.37E-04	33.465

Table 1 shows that the critical speed frequency is 54,81 Hz, at the same time an imbalance of 1120.941 g*mm arises. At the operating speed (5000 rpm), the imbalance amounts to 59,915 g*mm.

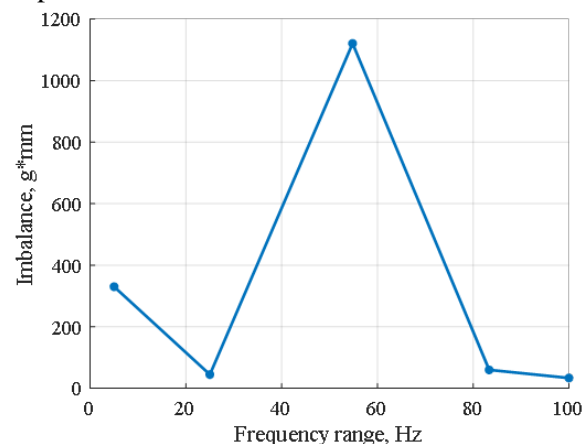The resulting graph for dependence of the imbalance value on the rotor speed is shown in Figure 7.

Figure 7. Dependence of the imbalance value on the rotation speed.

In order to assess the information system reliability, a rotor simulator has been manufactured, and laboratory tests have been carried out. Verification of the model has been carried out using the stand including balancing machine DB-51 and device for balancing BALKOM-4M. Verification has been performed at a speed of 3000 rpm which corresponds to an angular rotation frequency of 50 Hz. The existing laboratory stand provides a limited set of information, so for research at higher speeds and advanced functionality now, the team of authors is developing a specialized stand.

In the manufacture of real parts, there are many errors which may be divided into the following groups of deviations: forms and location of surfaces, and dimensions between them. Deviations from flatness and cylindricality, which are 0.03 mm, are considered as deviations of the forms of surfaces relative to their nominally defined geometry. Deviations from the nominal position of surfaces are represented by face and radial beats that do not exceed 0.03 mm. Deviations of dimensions between surfaces are not more than 0.05 mm. Radial and end beating of surfaces with a value of not more than 0.02 mm is allowed during assembly of the parts.

The developed rotor simulator model has been used in the numerical simulation of the rotor operation process and determination of the magnitude of the resulting imbalance. Comparison of

laboratory results and numerical simulation shows satisfactory convergence within 20%. A detailed description of the verification process is not given due to the limitation on the volume of the article. Differences between the parameters of the actual operation of the turbine rotor and the results of numerical simulation arise both from the manufacturing and assembly errors of the rotor as well as from the use of model methods.

The reliability of computational results using computation methods depends on accuracy of reproduction of the actual part geometry and the rotor assembly, on the assumptions made in the model design, and neglect of a number of forces acting in the process of the rotor operation having relatively small values. Also, computational simulation significantly depends on the features of the finite-element methods used, consisting in simplification of the process and dependence of the calculation accuracy on the parameters of the finite-element grid.

5. Conclusions

Information technologies allow to improve the quality of manufactured products and to reduce the costs of its manufacture. The digital twin of the product allows to refuse a large number of field tests and to determine the future performance characteristics of the product with numerical methods. This article presents one of the aspects for creating a digital twin — creating an information model and software architecture that implements the twin.

The presented information model defines the range of tasks that need to be solved when creating a twin, the sequence of their solution and the division between the modules of the system. The software architecture is very flexible, increasing the amount of retrieved information will not require significant restructuring of the software.

The developed model can be used to predict the considered operating parameters of the rotor of a low-pressure turbine of an NK product under the technological conditions of its manufacture. The dimensions of the rotor of the low pressure turbine are 2 meters long, diameter 1 m, weight up to 400 kg. The rotor assembly errors are not more than 0.3 mm, the balancing errors are not more than 500 g*mm. The developed model with its modification can be used to predict the operating parameters of rotors having other sizes, weight, and characterized by different accuracy of assembly and balancing.

Creating parametric and computational rotor models requires time outlays (1-3 working days) and personnel qualification. The created models may be used to perform calculations for a specific rotor designation available in manufacturing. The number of rotor designations in manufacture is often not large, the time outlays to create models for a certain rotor are single. The computation time depends on the accuracy required and extent of the information retrieved from the experiments. For aircraft engine rotors, the calculation time may range from 30 minutes to several days. Calculation time may be significantly reduced by using computational clusters. In order to obtain the results in the current work, the computation time was no longer than 3 hours while using a four-base Intel i7 processor.

The experimental studies show that the information model and the software architecture are functionally operative and may be used to determine a large number of operational parameters of the turbine rotor.

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