Development of a mathematical model to demonstrate the impact on the fan blades of a high dual-circuit turbofan engine

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Abstract. A mathematical model describing the impact of a foreign object (bird) on the fan blades of a turbofan engine with a high degree of dual circuitry was developed. The validation of the calculation studies was evaluated based on the examination on the prototype engine. Considering the increasing application of composite materials in the designs of prospective aviation gas-turbine engines and assuming the importance of the issue related to providing a sufficient level of airworthiness special attention is paid to the modeling and assessment of the condition of composite fan blades. In this connection the developed model allows to investigate the stress-strain state of the blades made of different, including composite materials, of the fan under the influence of foreign objects and birds on them.

1. Introduction
Preventing the consequences of airplanes and helicopters colliding with birds is an extremely urgent task. Every year birds are responsible for 5-7 accidents and disasters of aviation equipment, as well as premature removal of engines in operation and their repair [1].

The use of mathematical modeling to solve this problem is the most preferable approach at the present time, since conducting a full-scale experiment and assessing the consequences of hitting a bird is a rather expensive test and requires the involvement of significant human and material resources.

Previously, specialists of MSTUCA conducted a wide range of works related to computational studies of bird ingress into a gas turbine engine with further validation of this model by comparing the calculation results with field tests of the engine [2]. In [2], calculated and experimental data reflecting the accuracy, reproducibility, and sensitivity of the mathematical model are given.

The validation stage of the computational model of bird throwing was preceded by verification of its components, during which the characteristics of the constituent elements of the computational model were determined to meet predetermined requirements:

- bird model;
- model of fan blade material destruction;
- model of the first stage of a low-pressure compressor with an inlet guide apparatus.
The requirements for the poultry model and the fan blade material failure model were determined on the basis of full-scale sample tests.

Verification of the bird model was performed using James Wilbeck's experiments with high-speed hitting of the bird into a rigid plate [3]. Thus, the numerical simulation of the impact behavior of the bird is largely based on the results of James Wilbeck's studies of the behavior of the bird material and its substitute when it collides with a rigid plate at speeds sufficient for severe deformation and hydrodynamic behavior of the experimental bird (100 - 300 m/s).

The main conclusion from his research: poultry substitute can be homogeneous. This allows in-situ and numerical tests to use a homogeneous poultry structure with uniform properties. The second conclusion from the obtained hydrodynamic model of the bird material and its experimental verification is that the bird can be described as a low-strength material with the equation of state of water with an average density of 950 kg/m3.

The geometry of the bird is also an important factor [4]. The most suitable shape is a cylinder with hemispheres.

James Wilbeck developed a non-stationary hydrodynamic model of the bird. In this case, when the stresses arising from the impact are much higher than the yield strength of the material, the problem can be approximated as a hydrodynamic one, neglecting the strength properties of the bird material, because in this case, the impact is dominated by the density of the bird model material [5].

As a result of the work performed [2], the authors demonstrated good convergence of the numerical simulation of the bird impact and test results. The damage to the blade material for the numerical simulation is similar to that obtained in the bench tests.

However, this technique provides good applicability when using traditional metal alloys with a crystalline structure and providing isotropic characteristics in fan blade design. Nevertheless, considering the growth of the volume of composite materials application in the fan blade production and considering the advantages of their use, it is necessary to consider the anisotropic characteristics of the products.

In the present study, the authors developed appropriate mathematical models to track in detail the interaction between fan blades and birds at the moment of impact. The developed models are high level 3-dimensional models, which with acceptable accuracy consider the dynamics and nonlinearity of the process of impact of the fan impeller with the bird. At the same time, the developed models are highly efficient and resource-saving when performing calculations.

2. Modeling problem statement and boundary conditions

Dynamic interaction of the fan impeller with foreign objects is a multidisciplinary process, which combines high-speed changes of large dynamic motions and deformations, including plastic, with local damage, partial or complete destruction of interacting bodies. Thus, a highly nonlinear dynamic nonstationary physical phenomenon of extreme complexity is supposed to be investigated. A detailed study of this phenomenon can be carried out on the basis of effective numerical methods using high-speed computing technology. Analysis of existing software shows that the most suitable for this purpose, to date, is a combination of the software package LS-DYNA, which uses an explicit finite-difference method for integration of equations of nonlinear dynamic processes in deformable media in time, and integration with spatial coordinates by the finite element method, and based on the use of finite elements program complex ANSYS. It should be noted that the above software products provide the opportunity to apply many mathematical models of materials, including layered anisotropic composite materials to simulate the characteristics of fan blades made of composite materials, considering their anisotropic properties.

The solution to the described problem is constructed as a superposition of solutions to the static and dynamic problems.

The static problem is formulated as the determination of the initial stress-strain state of the impeller blades from stationary loads - centrifugal load from rotor rotation, differential pressure, temperature.

The dynamic problem is formulated as follows:
3. **Models and methods for solving the problem**

Each of the tasks formulated above is quite complex and may be of independent interest. The solution of the problem in a general statement requires the development of both a strategy of approach and step-by-step implementation, allowing to implement a gradual approach to the goal. Each of the intermediate stages can be implemented under its own assumptions and with its own methods, ultimately leading to the solution of the main problem.

The ANSYS software package was proposed to solve the static problem. The definition of displacement and stress fields in this case can be performed with a high degree of accuracy.

The dynamic problem of the impact of the blade and a foreign object is solved using the LS-DYNA software package. In this case the ways of blade representation by finite elements in both systems are identical and the calculated static fields of displacements and deformations in nodes of 3-dimensional finite-element model are used as initial data for determination of additional dynamic components.

For the initial study and debugging of the model, a generalized fan impeller of a promising engine was selected.

The appearance of the impeller is shown in figure 1. The blades have a complex spatial shape and are fastened at the base by dovetail shanks in the corresponding grooves of the disk.

![Figure 1. Model of the fan impeller of the prospective engine.](image)

The geometric model of the bird is shown in figure 2. The bird is modeled as a three-dimensional ellipsoid of rotation.
The material model of blades was chosen depending on the material from which it is planned to produce them. The analysis of material models in the LS-DYNA software package showed that the COMPOSITE DAMAGE model can be used for this purpose. The selected COMPOSITE DAMAGE material model implements a mathematical Chang fracture model. This fracture model uses five independent parameters. These parameters are:

- tensile strength in the longitudinal direction $\sigma_{1b}^+$,
- transverse tensile strength $\sigma_{2b}^+$,
- shear strength $\tau_b$,
- compressive strength in transverse direction $\sigma_{2b}^-$,
- nonlinear shear stress parameter $\alpha$.

At the same time, the characteristics $\sigma_{1b}^+$, $\sigma_{2b}^+$, $\tau_b$ and $\sigma_{2b}^-$ should be determined from experiments. The parameter $\alpha$, called the nonlinearity parameter of shear strain, is determined from the experimental curve of the dependence of shear strain on shear stress, which is approximated by the relation.

$$\varepsilon_{12} = \sigma_{12} / G_{12} + \alpha \sigma_{123}$$  \hspace{1cm} (1)

Where $G_{12}$ – shear modulus.

Ratio $\tau_b^*$ of shear stresses to shear strength

$$\tau_b^* = \left[ (\sigma_{12})^2 / G_{12} + 1.5\alpha (\sigma_{12})^2 \right] / \left[ (\tau_b)^2 / G_{12} + 1.5\alpha (\sigma_{12})^2 \right]$$  \hspace{1cm} (2)

is used in all fracture criteria.

The matrix cracking criterion is taken in the form

$$F_{\text{matrix}} = (\sigma_{22} / \sigma_{2b}^+)^2 + \tau_b^* > 1$$  \hspace{1cm} (3)

When the condition $F_{\text{matrix}} > 1$ in the element is fulfilled, the elastic characteristics of the material $E_2$, $v_{12}$ and $v_{23}$ is zeroed.

The compression fracture criterion is taken in the form

$$F_{\text{comp}} = \left( \sigma_{22} / 2\tau_b \right)^2 + \left( [\sigma_{22}^2 / 2\tau_b] - 1 \right) (\sigma_{22} / \sigma_{2b}^-)^2 + \tau_b^* > 1$$  \hspace{1cm} (4)

When the condition $F_{\text{comp}} > 1$ in the element is fulfilled, the elastic characteristics of the material $E_2$, $v_{12}$ and $v_{23}$ is zeroed.

The criterion of total failure is taken in the form
When the condition $F_{\text{fiber}}>1$ is satisfied in the element, all elastic material characteristics $E_1, E_2, G_12, \nu_12$ and $\nu_23$ is zeroed, thus, the finite element is considered to have collapsed.

Thus, Chang’s mathematical model uses five parameters in three fracture criteria. The matrix cracking and compression fracture criteria condition the local failure of the material. When the fiber fracture condition is reached, it is assumed that the element has completely failed.

If the blades are made of titanium alloy-based material and the task is to study the possibility of their fracture, the analysis of material models in the LS-DYNA software package showed that the BILINEAR IZOTROPIK model can be used for this purpose [6]. This mathematical model of deformation is based on the application of the laws of plastic flow with isotropic Mises’s yield surface hardening. The fracture criterion is when the accumulated plastic strain $\varepsilon_{\text{eff}}^p$ reaches a given limit value $\varepsilon_{\text{max}}^p$.

$$\varepsilon_{\text{eff}}^p = \int_0^1 d\varepsilon_{\text{eff}}^p = \varepsilon_{\text{max}}^p, \varepsilon_{\text{eff}}^p = (2d\varepsilon_{ij}^p\varepsilon_{ij}^p / 3)^{0.5}$$  

In addition, this model provides for the possibility of fracture of the material under all-round stretching

$$\sigma = \sigma_{ij} / \sigma_{ij} = \sigma_{\text{max}}$$

here $\sigma_{ij}$ – are the components of the stress tensor, and $\delta_{ij}$ – is the Kronecker symbol.

The PLASTIK KINEMATIK model was used to describe the nature of nonlinear deformation of the bird and its fracture. This mathematical model of deformation is based on the application of the laws of plastic flow with kinematic hardening of the Mises yield surface. The fracture criterion is when the accumulated plastic strain $\varepsilon_{\text{eff}}^p$ reaches a given limit value $\varepsilon_{\text{max}}^p$.

$$\varepsilon_{\text{eff}}^p = \int_0^1 d\varepsilon_{\text{eff}}^p = \varepsilon_{\text{max}}^p, \varepsilon_{\text{eff}}^p = (2d\varepsilon_{ij}^p\varepsilon_{ij}^p / 3)^{0.5}$$

As already noted in the formulation of the problem to study the impact of a foreign object on the fan blades it is necessary to carry out two calculations:

- static one for determination of blades prestressing in the field of acting static loads (centrifugal forces, etc.)
- dynamic to determine the impact effect on the pre-stressed blades.

When calculating the stress-strain state in the field of centrifugal forces in the ANSYS package, the following boundary conditions were applied. All nodes of disk and bird were rigidly fixed from all displacements. In general, these conditions are consistent with the RIGID BODY model. In this way the pre-stressed state in the fan vane was obtained.

Further, the following boundary conditions were used to solve the dynamic impact problem in the LS-DYNA package [7]. All nodes of an absolutely rigid disk body were given the law of motion (see figure 3). According to this law, all nodes of a perfectly rigid disk (an absolutely solid body) make a rotary motion around the fan axis with the same and constant velocity equal to the rotor speed of the engine fan at the cruising mode.

When solving the static problem, all nodes in the bird model were fixed rigidly.

When solving the dynamic problem, all nodes in the bird model were moved. The initial velocity of their axial movement in the calculations was assumed to be 100 m/s.
The developed methodology was used to estimate the stress-strain state of the fan impeller in the cruising flight mode when a large bird weighing 6.8 kg falls into its tract. The calculation has been carried out for the blades made of titanium alloy and carbon plastic.

Figure 4 and figure 5 show the behavior of the impact of the bird with titanium and carbon fiber blades at different moments of time.

**Figure 3.** Law of displacement of the disk.

**Figure 4.** Movements of 5 points of 5 titanium blades at the start of impact interaction.
For blades made of titanium alloy, the greatest stresses are realized on the second and third blades in the area of their impact with the bird. The levels of static and dynamic stresses at points distant from the area of interaction between the blades and the bird in the time interval under consideration are lower than their limit values. This fact allows us to conclude that under the conditions of the considered problem, local fractures of the first, second and third blades are possible.

For blades made of carbon fiber reinforced plastic the levels of static and dynamic shear stresses at different moments of time in the area of interaction of the blades with the bird, as well as in the root section at the leading edge of the first and second blades exceed the limit values of interlayer stresses. This circumstance allows us to conclude that under the conditions of the considered problem, local delamination of the blade material is possible without general destruction of the carbon fiber reinforced plastic blade.

4. Conclusions
A mathematical model describing the impact of a foreign object on the fan blades of a large double-circuit turbofan engine has been developed.

The proposed model allows to investigate the stress-strain state of fan blades made of different, including composite materials, under the influence of foreign objects and birds on them.

The proposed mathematical model allows considering the anisotropic properties of the composite material.

According to the developed methodology, a computational study of the impact of a bird weighing 6.8 kg on the fan of a promising engine was carried out.

The analysis of the calculation shows that within the studied cases and time intervals, it is possible:

- local destruction of titanium blades in the area of impact of the bird with the blade,
- local delamination of carbon fiber reinforced plastic blades in the area of the impact of the blade with the bird without general destruction of the blade.

As part of further research, it is necessary to verify the proposed mathematical model on the basis of full-scale tests on throwing birds in the fan, made with the use of composite materials.

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