1. Introduction

The implementation of new polymer composite materials (PCM) [1] in the design of an aircraft engine is an important task to improve its efficiency. PCMs are mainly used in the outer air path of aircraft engine fan [2], which are not subjected to high loads, but during operation these structures are exposed to various external factors. Therefore, the problem of assessing the reliability and durability of PCM parts in operation is important. It is necessary to choose the criteria for such. One of the important conditions for the use of PCM in aircraft engines is to maintain operability when sand and dust get into the compressor during take-off and landing.

The issues of assessing the reliability and durability of the PCM internal panel, which is part of the low-pressure compressor of the Sam146 aircraft engine, under the influence of a gas and dust flow, are considered in this paper. Figure 1 shows the location of the panel in the engine.

Dust and gas mixture that is sucked into the engine leads to erosion of parts and deterioration of its characteristics. This effect is inherent in the take-off and landing stages when sand and dust are lifted from the runway by an air stream, which greatly affects the durability of PCM parts.

The erosion resistance of composites depends on many factors. Thus, matrix materials, reinforcement fibers, impact angle and particle velocity have an effect on the solid particle erosion behavior of thermoplastic resins reinforced by short fibers with special attention on an incubation period of erosion [3]. The results of the experiments showed that the mass of an incubation period was strongly dependent on initial surface roughness. The erosion rate at a steady state depended on the matrix material and on the volume content of fibers, regardless of fiber type. Evaluation of composites erosion at different impingement angles and impact velocities of sand particles was done in [4]. Different materials showed...
peak erosion at different impingement angles as well as significant influence on erosion behavior at different impingement velocity and mass of erodent. Then, alumina filling had an effect on the erosion wear performance of glass fiber-reinforced polyester composites [5]. Pure glass-polyester composite without filler showed greater erosion rate whereas a significant improvement in the erosion resistance was observed with alumina fillers. Test of blades with TBC was performed to determine the erosion rates and particle restitution characteristics under different impact conditions [6]. The experimental results show that the erosion rates increase with increased impingement angle, impact velocity, and temperature. In [7] the authors evaluated solid particle erosion behavior of unfilled and graphite particulate filled carbon fabric reinforced epoxy composites. Maximum wear rate was observed at 45° impingement angle. The erosion rates of plain polymers and these composites was studied at various impact angles ($\alpha=15-90^\circ$) and showed that the erosion behavior did not depend on fabric orientation [8]. The authors of [9] studied influence of the concentration, angles of attack and speeds of abrasive particles acting on PCM parts at simulation of the sand and dust throw into the intake of engine fan. A model of the movement of abrasive particles in a compressor of a gas turbine engine was used.

Figure 1. Location of the internal panel on the Sam146 aircraft engine.

Thus, the criteria of the erosion resistance for PCM proposed in the most references is experimental test at injection of air with a concentration of abrasive particles and evaluation of erosion rates by measurements of erosion depth or loss of material weight. The main task of experimental research is to reproduce operating conditions during the test as accurately as possible. Due to the relatively low concentration of abrasive particles in the air during operation, the creation of such a concentration during the experiment will lead to a long test duration. When conducting tests with a high concentration that is several orders of magnitude higher than the concentration in a conventional flow, the reliability of the estimate is reduced due to the need to extrapolate the results to a large resource. Besides, engine operation at different environment condition does not allow to estimate erosion damage in dependence on usual parameters of material erosion but could be done indirectly on the base of assessment of the technical condition of the panel during operation, namely residual thickness of panel.

Therefore, the new indirect criterion of the erosion resistance is proposed for PCM internal panel instead of the usual criteria of erosion rates evaluation. This new criterion is based on estimation of critical thickness when statics and dynamics of panel still satisfy design criteria. When the abrasive flow acts on the panel, the material is carried away and panel thickness is reduced, which changes the strength characteristics of the parts during long operation. Thus, periodical measurement of panel thickness will allow to estimate panel statics and dynamics indirectly if their dependence on thickness is well known.

A dynamic and static calculations of a panels with different thicknesses made of a polymer composite material have been carried out and critical panel thickness when dynamic frequencies and static stress do not exceed the permissible level has been determined.
2. Evaluation method

2.1. Criterion for assessing the erosion resistance of engine parts from PCM

In this paper, we study the PCM internal panel, which is part of the low-pressure compressor of an aircraft engine (figure 2). To increase the accuracy of evaluating the erosion resistance of the panel, it is proposed to periodically measure the thickness $h$ of the panel (figure 3) in operation and then compare it with an acceptable value.

![Figure 2. General view of the studied internal panel from PCM.](image)

![Figure 3. Longitudinal section of panel: $h$ – is panel thickness.](image)

Estimates of the natural frequency of oscillations in the first form and maximum static stresses for panels with different thicknesses after the expected erosion are proposed as criteria for reliable operation.

2.2. Model

To study the effect of erosion on the panel strength, several design models with different thicknesses were created. Static and dynamic calculation of models was carried out in the ANSYS software package. An example of a model is shown in figures 4a and 4b.

![Figure 4. Finite element model of the interior panel of the PCM: general view (a) and attachment parts (b).](image)

Detailed mathematical modeling of all factors affecting the product during operation, allows to achieve high reliability of the calculation results. An important issue is the modeling of the boundary conditions, on which the accuracy of the obtained results depends significantly [10]. Modeling of contacts and panel assembly on the engine are shown below.

Figure 5 shows all types of contacts simulating real operating conditions. The tightening of the screws was set to 5.25 N·m. A tension of 0.1 mm was set between the bushing and the seal washer.
Figure 5. Types of contacts in assembling of panel.

Figure 6 shows the model fixing areas corresponding to the product fixing areas on the engine. The screws and bushings were secured at all degrees of freedom. Friction contacts is simulated with a coefficient of friction of 0.15. The first stage of the calculation is to check the static strength of the installation of the product, for this, the bolt tightening is calculated, shown in the figure 7.

Figure 6. Fixing of panel.  
Figure 7. Tightening of screw-bolts.

From the previously performed aerodynamic calculations of the engine under study, pressure distributions (figures 8 and 9) and temperatures (figure 10) over the panel surface were obtained.

Figure 8. Distribution of pressure on the inner side of panel.  
Figure 9. Distribution of pressure on the outer side of panel.
2.3. Material properties
Toho TENAX material has been used as panel material with transversely isotropic properties. Titanium alloy VT6 has been used for support and washer (figure 4b). The screw was made of EP99 material. VITONE material was used for laying between the panel and support (table 1).

Table 1. Properties of materials.

| Properties                        | PCM     | Titanium | EP99    | VITONE |
|-----------------------------------|---------|----------|---------|--------|
| Modulus of elasticity E11, E22, MPa | 59,400  | 114,000  | 190,300 | 50     |
| Modulus of elasticity E33, MPa    | 5714    | 114,000  | 190,300 | 50     |
| Poisson ratio µ12                 | 0.07    | 0.3      | 0.3     | 0.45   |
| Poisson ratio µ23, µ13            | 0.15    |          |         |        |
| Shear modulus G12, MPa            | 4,500   | 472      | 732     |        |
| Shear modulus G23, G13, MPa       | 4,100   |          |         |        |
| Density, kg/m³                    | 1,530   | 4,510    | 8,440   | 1,500  |

2.4. Calculation results and discussion
An example of the calculation results of the first three forms of vibration and static stresses for the ready panel with a thickness of 1.2 mm is shown in figures 11a-c, 12a, and 12b.

Figure 10. Distribution of temperature on a panel.

Figure 11. Example of results of calculation of three first forms of vibrations: first (a). second (b), and third (c) forms.
Figure 12. Example of results of calculation of static stresses at inner (a) and outer (b) sides.

The results of calculating the panel natural frequencies are shown in the table 2. The obtained frequencies are compared with the frequencies of the harmonics of the engine rotor under study. The critical thickness in our calculations is the interval between 0.9-0.8 mm, with this change, the natural frequency of the oscillations of the panel drops from 442 to 371 Hz, which crosses the 4th harmonic value of the engine rotor.

Table 2. Results of calculation of eigenfrequencies and vibration modes of the internal panel.

| Forms of vibrations | Panel thickness, mm | Frequency of vibrations, Hz |
|---------------------|---------------------|-----------------------------|
|                     | 1.2 | 1.1 | 1.0 | 0.9 | 0.8 |
| 1                   | 517 | 498 | 475 | 442 | 371 |
| 2                   | 575 | 552 | 526 | 496 | 457 |
| 3                   | 602 | 578 | 548 | 514 | 458 |

Table 3. Results of calculating the static stresses of the internal panel.

| Stress component | Panel thickness, mm | Maximum stresses, MPa |
|------------------|---------------------|------------------------|
|                  | 1.2 | 1.1 | 1.0 | 0.9 | 0.8 |
| \( \sigma_{x+} \) | 61.4 | 66.0 | 64.6 | 64.3 | 67.1 |
| \( \sigma_{x-} \) | -83.0 | -83.4 | -83.6 | -83.6 | -87.4 |
| \( \sigma_{y+} \) | 78.1 | 80.9 | 83.4 | 85.8 | 108.1 |
| \( \sigma_{y-} \) | -101.7 | -103.6 | -105.2 | -106.7 | -106.2 |
| \( \sigma_{z+} \) | 6.4 | 6.8 | 7.2 | 7.6 | 8.7 |
| \( \sigma_{z-} \) | -57.2 | -57.0 | -57.0 | -56.8 | -56.4 |
| \( \tau_{xy} \) | 19.8 | 20.3 | 20.8 | 21.2 | 22.0 |
| \( \tau_{yz} \) | 30.3 | 30.1 | 30.4 | 30.6 | 30.7 |
| \( \tau_{xz} \) | 23.0 | 23.0 | 22.9 | 22.8 | 22.7 |
The results of the static stress calculation are shown in the table 3. Static stresses at the selected thicknesses are increased up to 40% maximum and do not exceed the permissible level. Maximum radial displacements do not exceed 1 mm that is also acceptable from aerodynamics point of view. Therefore, allowable reduction of panel thickness due to erosion can be down to 1 mm on the base of dynamic and static calculations and taking into account accuracy of measurement during inspection in field.

Taking into account that maximum calculated stresses are a few times lower that minimum yield limit of panel material, an influence of reduction of panel thickness due to erosion is less significant than it influences on dynamics. Therefore, allowable reduction of panel thickness down to 1 mm is also acceptable from static loading point of view.

3. Conclusion
The new indirect criterion of the erosion resistance is proposed for polymer composite materials internal panel instead of the usual criteria of erosion rates evaluation. This new criterion is based on estimation of critical thickness when statics and dynamics of panel still satisfy design criteria.

Series of dynamic and static calculations of a panels with different thicknesses have been carried. Critical panel thickness of 0.9 mm was revealed at which the vibration frequency in the first form decreases to 442 Hz and approaches the dangerous rotor harmonics of the engine, at which the probability of the work of the part in the critical region increases.

Static stresses at the selected thicknesses are increased up to 40% maximum and do not exceed the permissible level. Maximum radial displacements do not exceed 1 mm that is also acceptable from aerodynamics point of view. Allowable reduction of panel thickness can be down to 1 mm on the base of dynamic and static calculations and taking into account accuracy of measurement during inspection of aviation engine in field. Proposed criterion can be used by aviation companies for assessing the reliability of parts made of polymer composite materials in the event of sand and dust entering the compressor during take-off and landing.

Acknowledgement
The work was carried out with the financial support of the Ministry of Education and Science of the Russian Federation as part of the comprehensive project No. 2017-218-09-172. The authors thank the staff of PJSC UEC-Saturn, Rybinsk for their help and support with carrying out this work.

References
[1] Jones R M 1999 Mechanics of Composite Materials. 2nd ed. (Boca Raton: Tailor & Francis Group), p 538 https://doi.org/10.1201/9781498711067
[2] Anoshkin A N, Zuiko V Yu, Shipunov G S and Tretyakov A A 2014 Technologies and problems of composite materials mechanics for production of outlet guide vane for aircraft jet engine. PNRPU Mechanics Bulletin. 4 5 doi: 10.15593/perm.mech/2014.4.01
[3] Miyazaki N and Hamao T 1994 Solid particle erosion of thermoplastic resins reinforced by short fibers. J. Compos. Mater. 28 320 https://doi.org/10.1177/002199839402800905
[4] Harsha A P, Tewari U S and Venkataraman B 2003 Solid particle erosion behavior of various polyaryletherketone composites. Wear 254 453 https://doi.org/10.1016/S0043-1648(03)00143-1
[5] Patnaik A, Satapathy A, Mahapatra S S and Dash R R 2008 Parametric optimization of erosion wear of polyester-GF-alumina hybrid composites using Taguchi method. Journal of Reinforced Plastics and Composites. 27 1039 https://doi.org/10.1177/0731684407086867
[6] Swar R, Hamed A, Tabakoff W and Miller R A 2012 Surface deterioration of thermal barrier coated turbine blades by erosion. International Journal of Rotating Machinery. 2012 601837 https://doi.org/10.1155/2012/601837
[7] Sudarshan Rao K, Varadarajan Y S and Rajendra N 2015 Erosive wear behaviour of carbon fiber-reinforced epoxy composite. Materialtoday Proceedings. 2 2975 doi: 10.1016/j.matpr.2015.07.280
[8] Liu B, Bao L and Xu A 2016 Effect of fabric orientation and impact angle on the erosion behavior of high-performance thermoplastic composites reinforced with ductile fabric. *Wear*, **352–353** 24 https://doi.org/10.1016/j.wear.2016.01.016

[9] Zinin A V, Dobrovolsky S V, Lebedev A K, Krupennikov V A and Shevyakov A O 2019 Wear and erosion resistance in a gas-abrasive stream of composite elements of an aircraft engine. *Russian Aeronautics* **62** 696 https://doi.org/10.3103/S1068799819040226

[10] Arkhipov A N, Volgina M V, Matushkin A A, Ravikovich Ya A and Kholobtsev D P 2018 Effect of a model and boundary conditions on the results of analyzing the stress-strain state of a low-pressure compressor rotor. *Russian Aeronautics* **61** 509 https://doi.org/10.3103/S1068799818040025