Estimation of fatigue margins for composite parts of aircraft engine on the base of vibration tests

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Abstract. During the modernization of the low-pressure compressor of the regional aircraft engine, a flow separator made of polymer composite material was developed, which has less weight, is easier and cheaper to manufacture. However, the separator must undergo a series of tests before being installed on the engine, in particular the endurance tests, necessary to assess the fatigue strength margin. A method for determining the endurance limit of a large part of an aircraft engine is developed in the presented work and consists in replacing the tests of the entire separator with tests of individual structural elements cut from the part. The shape, dimensions and fixation of the elements have been chosen in such a way that their own test frequency was close to the natural frequency of the flow separator on the engine. The natural oscillation frequencies and places of maximum dynamic stresses have been determined before testing on three-dimensional models of the flow separator and elements cut from it. As a result, the structural elements have been tested until appearance of fatigue cracks which allowed to assess the endurance limit and evaluate fatigue strength margin of the separator.

1. Introduction
Currently, a large amount of work is being carried out to study the possibility of using polymer composite materials (PCM) for the manufacture of aircraft engine parts. The main advantage of PCM is a lower density than titanium, as well as lower cost of manufacture, so the use of PCM in aircraft and other engineering industries increases [1].

Use of PCM for the manufacture of parts, which are exposed by high loads and temperatures [2], requires more expensive preliminary investigations. Therefore, with regard to aircraft engines it is advisable to use PCM for the external fan circuit, where main damage could be accumulated due to static and dynamic loading at relatively low external forces and temperatures.

During the modernization of the low-pressure compressor of the SaM146 engine, a flow separator (FS) made of a polymer composite material was developed for the regional aircraft. The location of the flow separator in the low-pressure compressor is shown as figure 1.

However, the separator must pass a series of tests before installation on the engine, including vibration tests, which should evaluate the margin of fatigue strength $K_v$. $K_v$ evaluation is carried out by the results of endurance limit evaluation during fatigue tests and FS strain measurement on the engine.

The problem of fatigue strength of PCM is important for practice and there are many publications on this topic. For example, I K A Widi et al [3] showed that the automotive industry is already utilizing many composite materials for its products and investigated the effect of fiber orientation.
(unidirectional, woven and random) on several resin matrices (epoxy and polypropylene). Fatigue test of the specimens showed the optimum value with the orientation variation of fiber.

![Figure 1](image_url) The separator flows into the low-pressure compressor.

A J Brunner [4] considered fatigue mechanism for fiber-reinforced polymer (FRP) composites and concluded that there is still no full understanding of the effects that require consideration when testing FRP composite materials under cyclic fatigue loads with the aim of using the data for design limits.

A J Brunner et al [5] investigated fracture mechanics tests on carbon fiber composites reinforced with polymer matrix and focused on cyclic fatigue at tensile rupture, plane shift, and mixed loading. The paper analyzes the data using different approaches in an attempt to reduce the spread and determine the parameters for the structural design of carbon fiber. In addition, selected test data comparing load and displacement control in cyclic fatigue tests are discussed.

R C Alderliesten et al [6] discussed various aspects related to the physics of fatigue fracture testing of fiber-reinforced polymers (FRP) composites based on experimental observations. The authors recommended further developing and evaluating approaches that quantify the contribution of fibre bridging unambiguously to use data obtained from unidirectional FRP for structural design with multidirectional lay-ups and interfaces.

L Molent and C Forrester [7] reviewed the cyclic fatigue strength of damaged aircraft composite structures under operating loads and proposed a framework to solve the problem of assessing the damage resistance of these structures based on the slow growth approach.

Yu Kashtalyan and C Soutis [8] reviewed experimental and theoretical studies into the internal-damage mechanisms of cross-polycomposite laminates made within the framework of damage micromechanics and into their effect on the behavior and properties of laminates.

N Lisin et al [9] developed statistical strength theories to describe the results of fatigue tests and to predict the strength of machine components with variable loads. Experiments show that the strength of materials depends significantly on structural defects, and the limiting stress is a statistical quantity.

N S Azikov, A V Zinin [10] performed strength analysis of the structure based on the model of mechanical property degradation for composite material layers taking into account the process of damage accumulation in the course of loading.

T D Karimbaev and D V Matyukhin [11] showed that the variety of forms of fatigue damage in composite materials products and their development are not allowed so far to form a composite material commonly accepted laws such as the law of Paris, the linear summation of Miner and other. They proposed to carry out a fatigue tests of cantilever-fastened specimens at first bending form until vibration frequency decreased to an acceptable value, which is determined from the analysis of the Campbell diagram.
Therefore, the problem of fatigue strength of PCM used for the manufacture of aviation engine parts is also important. However, the most investigations are related to fatigue test of specimens and don’t considered the test of real parts used in aviation engines, especially. Besides, these investigations are studied crack propagations mainly. At the same time, it is not advisable to use crack propagation as criteria for fatigue damage of aviation engine parts, such as flow separator, taking into account higher exciting frequencies in comparison with automotive and aircraft parts. It is better to determine a moment of crack growth until vibration frequency decrease down to acceptable value as criteria of fatigue failure.

Vibration tests of the entire separator didn’t allow to get fatigue failure that was associated with limit of existing stand power. A method for determining the endurance limit of a large part of an aircraft engine is developed in the presented work and consists in replacing the tests of the entire separator with tests of individual structural elements cut from the part.

This article describes the procedure of the flow separator endurance limit determination based on:
- calculation of natural frequencies and mode shapes for whole separator,
- unsuccessful fatigue test of separator,
- choice of shape, dimensions and fixation of the elements that could be cut from the separator in such a way that their own test frequency was close to the natural frequency of the flow separator on the engine,
- fatigue tests of elements to determine the endurance limit of separator

2. Calculation of flow separator

2.1. Model
The flow separator is a ring made of polymer composite material with an attached input part made of titanium alloy.

Special attention was paid to the simulation of fastening on the engine, when choosing the design model and boundary conditions [12].

The model of the composite ring and titanium part has been made using three-dimensional hexahedral twenty-node quadratic SOLID186 elements. Number of nodes in the model: 373200; total number of elements: 84597; PCM elements: 50399 (HEX20); titanium part elements: 25499 (HEX20); contact elements: 8699 (QUAD8).

The elements of the composite are connected to the titanium part using contact elements CONTA174/TARGE170, the contact type is bonded.

The model was fixed to the right end by fixing the nodes belonging to the face plane in the three directions in the global coordinate system.

Temperature has not been applied because heating of flow separator is insignificant for dynamics.

Pressure has not been applied because its influence on dynamics is insignificant.

2.2. Material properties
Properties of materials are presented in table 1.

| Properties                  | PCM     | Titanium |
|-----------------------------|---------|----------|
| Modulus of elasticity E11, E22 | 65900 MPa | 114000 MPa |
| Modulus of elasticity E33   | 65900 MPa | 114000 MPa |
| Poisson ratio µ12, µ23, µ13 | 0.3     | 0.3      |
| Shear modulus G12           | 3500 MPa |          |
| Shear modulus G23, G13      | 3200 MPa |          |
| Density                     | 1500 kg/m³ | 4510 kg/m³ |
PCM consists of epoxy polymer matrix and carbon fibers with usual orientation along separator axis (direction 11) and in circumferential direction 22.

2.3. Calculation procedure and results
The calculation has been made in the finite element package ANSYS APDL.

The solver type is SPARSE non-linearity is taken into account large model displacements (nlgeomoption).

Dynamic calculation of the vibration frequencies and mode shapes has been performed when the separator is fixed rigidly around the circle face plane to the right (to the air exit). The titanium part mounted on the PCM is free on the left.

The results are presented as figure 2 and table 2.

![Figure 2: The first 4 vibration mode shapes of the flow separator](image)

| Frequency | Value, Hz  |
|-----------|------------|
| 1         | 308.321    |
| 2         | 333.402    |
| 3         | 416.871    |
| 4         | 448.265    |
| 5         | 604.310    |
| 6         | 665.11     |
| 7         | 780.38     |
| 8         | 965.36     |
| 9         | 1120.9     |
| 10        | 1145.1     |

Table 2. Natural oscillation frequencies of the flow separator.

Calculation showed that one of the modes 1-3 frequencies should be choosen for fatigue test of separator.
3. Fatigue test of the separator

3.1. Test procedure
Fatigue test of separator has been done on the high power electro-dynamic stand Data Physics LE-612/DSA10-40K (USA) in fatigue test laboratory of PJSC UEC-Saturn, Rybinsk.

A special tool has been developed to fix the separator on the electro-dynamic stand, simulating its fastening on the engine (figure 3).

![Figure 3. Installation device for FS on the vibration table.](image)

Strain gauges, accelerometers and laser vibrometer have been installed on the separator and table of stand to measure dynamic frequencies, relative strains, vibrospeeds and displacements.

First of all, calibration test has been done to choose vibration mode with the best excitation.

The best excitation has been measured by strain gauges, accelerometers and laser vibrometer at mode 3 with three nodal diameters that are minimum from the first 5 modes.

Excitation at mode 6 with 2 nodal diameters was worse than excitation at 3rd mode due to higher frequency.

3.2. Test results
Tests at 3rd mode frequency were conducted by stepwise increase of the exciting force beginning with maximum stress level of 0.7 of the expected endurance limit $\sigma_{E}$ that is determined as 30-40% of material yield limit. After test at this level during base number of $10^7$ cycles the level of maximum stress/displacement measured by strain gauges/laser vibrometer was increased and test during $10^7$ cycles were repeated again.

After some tests with increased level of stresses during the resonance trials failed to achieve the required for the appearance of the fatigue damage the stress level in the separator flows, which was associated with limit of existing stand power. Therefore, the separator passed a base number of $10^7$ cycles without cracking at a stress level below its real endurance limit.

In order to achieve an endurance limit of separator it was proposed to replace the tests of the entire separator with fatigue tests of individual structural elements cut from the part, which require energy to excite to a destructive level of stress within the capabilities of existing vibration stands in the industry.

4. Fatigue testing of structural elements

4.1. Models and calculations
The scheme of the structural elements (SE) cutting from the flow separator is shown as figure 4.

Width and length of SE models were varied in the ranges 20-40 mm and 150-250 mm. Thickness of SE has not been changed.

Fastening the structural element on the table of low power vibration stand ETS Solutions L215M (China) is carried out in Moscow Aviation Institute (National Research University) laboratory using the original fastener of separator on the engine so that the maximum dynamic stress of structural
elements coincide with the location of maximum stress in the separator. The use of this approach makes it possible to obtain the values of the endurance limit of the separator taking into account its manufacturing technology and design features.

Figure 4. The scheme of the SE cutting from the flow separator.

For this purpose, a number of 3D finite element models were made and a series of their dynamic calculations was carried out. Finite-element meshes, fixation and calculation procedure are similar to ones for separator (subsections 2.1, 2.2).

The final shape and dimensions of the structural elements were chosen 170×22 mm in such a way that their natural frequency of testing 253 Hz is slight lower then 1st mode frequency of the flow separator, taking into account a necessity of element failure. An example of the results of the calculation of dynamic displacements and stresses is shown as figure 5.

Figure 5. Dynamic displacements and stresses in SE.

4.2. Calibration
The SE of the flow separator is cut according to the size determined as a result of the calculation, and strain gauges are installed in the area of calculated maximum dynamic stresses.

Then the specimen is fixed on the table of the vibration stand with the help of a specially designed device that simulates the fastening of the flow separator on the engine using a standard fastener (figure 6), and its calibration is carried out by strain gauges. The excitation mode at the resonant frequency is set by means of a triangulation laser, which measures the amplitude of the SE tip displacement, and the relative strain corresponding to the obtained value of the amplitude is determined using the values measured by the strain gauge. The excitation is changed stepwise with a relative strain step of \(20 \times 10^{-5}\) to a maximum relative strain of \(70 \times 10^{-5}\) in order to avoid fatigue damage of strain gauge during calibration. The data are entered in the table and a calibration graph is built on them (figure 7), which is used in the fatigue test to assess the stress level using amplitude of specimen vibration.
4.3. Test procedure and results
Fatigue tests for the elements of flow separator were carried out using the ‘staircase’ method, the essence of which is a stepwise change in the load on the next tested element after test of previous one during $10^7$ load cycles. SE are tested starting from the stress level exceeding the expected endurance limit $\sigma_{\text{end}}$ by at least 20%. At destruction of SE before life $10^7$ cycles, the following element is tested at the level of stresses on a step below (-20 MPa). The criterion of failure in determining the limits of endurance is a drop in the resonant frequency of more than 10%. If after operating time $10^7$ cycles SE has not reached the state of destruction, the next element is tested at a step higher (+20 MPa). For the endurance limit of the flow separator, a stress of 80% of the minimum alternating stress at which the tested elements have passed the test base $10^7$ cycles without failure is accepted. The test results are presented in table 3.

![Device for fixing the SE on the vibration stand table.](image)

**Figure 6.** Device for fixing the SE on the vibration stand table.

![Calibration graph of the dependence of the SE displacement range on the relative strain.](image)

**Figure 7.** Calibration graph of the dependence of the SE displacement range on the relative strain.
Table 3. The results of the fatigue tests.

| Number SE | Stress   | Notice    |
|-----------|----------|-----------|
| SE No.1   | 1.2σ\textsuperscript{*}₁ | Not cracked |
| SE No.2   | 1.4σ\textsuperscript{*}₁ | Cracked    |
| SE No.3   | 1.2σ\textsuperscript{*}₁ | Not cracked |

The destroyed element No.2 was examined using optical and electron microscopes to determine the location and nature of the damage. The results are shown as figure 8.

Figure 8. Examination of destroyed samples with a microscope.

The main cracks are located on the lateral sides near the hole for element fixation (see white arrows). Cracks are propagated in the epoxy polymer matrix in the axial direction. Some additional cracks are visible in parallel with the main crack (dash arrows). The broken carbon fibers available on the lateral sides (see right bottom photo) appeared due to the cutting of the element from the separator.

Presented photos show that real stresses on the location of crack initiation and propagation don’t correspond to location of calculated maximum stress. More complex finite-element model is necessary for calculation of real stress. However, this academic task is not important for applied task of endurance limit and fatigue strength margin estimation. It is possible to use proposed procedure of calculation and test taking into account that both the flow separator and structural element are calculated using similar anisotropic finite-element models and stresses are measured using similar strain gauges.

The obtained values of the endurance limits were compared with the dynamic stresses measured during the strain gauging of the flow separator during the preliminary tests of the engine, and the fatigue strength margin was estimated from the obtained results.

Proposed procedure will allow to avoid expensive and unsuccessful test of the whole separator.

5. Conclusion
A method for determining the endurance limit of a large part of an aircraft engine such as the flow separator made of polymer composite material is developed and consists in replacing the tests of the entire separator with tests of individual structural elements cut from the part.

The procedure of the flow separator endurance limit determination is based on:

- calculation of natural frequencies and mode shapes for the whole separator,
- choice of shape, dimensions and fixation of the elements that could be cut from the separator in such a way that their own test frequency was close to the natural frequency of the flow separator on the engine,
fatigue tests of elements to determine the endurance limit of separator
The developed technique allowing estimation with minimal cost the fatigue strength margin of aircraft engine parts, for which the local fatigue resistance significantly depends on the design features and manufacturing technology.

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