

The Problem of Ensuring Reliability of Gas Turbine Engines

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Abstract. Requirements to advanced engines for civil aviation are discussing. Some significant problems of ensuring reliability of advanced gas turbine engines are mentioned. Special attention is paid to successful utilization of new materials and critical technologies. Also the problem of excluding failure of engine part due to low cycle or high cycle fatigue is discussing.

1. Introduction

International (in EU) and national (in US and Russia) requirements to advanced gas turbine engines (GTE) for civil aviation are considering cardinal improvement of ecological characteristics and increasing fuel efficiency [1, 2]. It may have created impression that a problem of provision of flight safety and dependability is not actual now. Indeed, modern aviation engines work without hard life time. Particular engines work continuously on aircraft without change up to 50 thousand hours. Life of critical (main) parts of engines for small-medium distance aircrafts is up to 20-40 thousand cycles (for “hot” and “cold” parts of engines) respectively. Engines have running time for in flight shoot down more than 50 thousand hours from the entrance of engine type in service (which is enough to get permission for ETOPS-flights at the 180-min approach from the nearest suitable airdrome), and more than 300 thousand hours in further operation [2].

At the same time, development of engines which meets formulated requirements is impossible without utilization of new engine architectures (engine with opened fan rotor, engine with geared fan, intellectual engine, etc.), without utilization of new materials (first of all different composite materials, intermetallic alloys, gradient materials, materials received using additive technologies, smart materials), without significant toughening of working conditions of engine parts (in terms of mechanical loads, thermal conditions, running time, including work at extremely high gasdynamic parameters – gas temperature before turbine wheel $T_3^* \geq 1950$ K, air compression $\pi_{c^*} > 60$) [1]. Besides, requirements for engine certification for confirmation of possible provision of safe service, continuously become stricter. In particular, during last year’s new requirements (checking engine work under conditions of large ice crystals, mixed (ice-water) phase, under conditions of volcanic ash, confirmation of critical engine parts life taking into account possible defects, confirmation of engine work during single and flock birds ingestion, etc.) arose. At the same time requirements for increasing duration of ETOPS-flights and provision of possibility of engine utilization using reliability centered maintenance (RCM) have appeared.

Development of new advanced gas turbine engines with unique characteristics is impossible without successful utilization of new critical technologies. Critical engine technologies are technologies which provide quality improvement of engine competitiveness based on integration of new materials, new technological processes, design solutions, methods of designing and tests.



2. Critical gas turbine engine technologies.

Complexity of the task of ensuring strength reliability of gas turbine engine components was well illustrated by Rolls Royce in case of a high-pressure turbine (HPT) blade.

The blade operates at following conditions: pressure corresponding to the pressure at a depth of 500 m under water; temperature close to $\frac{1}{2}$ of the surface temperature of the Sun, which is more than 200°C above the melting point of the alloy (try not to melt a piece of ice in the oven at 200°C); high rotation frequency (above 12000 rpm), flow velocity at the blade tips significantly exceeding the speed of sound, and high load from centrifugal forces, which corresponds to the gravity of a large bus); influence of non-stationary forces, causing intense fluctuations; influence of an aggressive environment. Even so, each blade develops power equivalent to the engine of Formula 1 car. Before the replacement, the blade should pass 15 million miles. To create such a blade, it is necessary to integrate ~15 technologies, while ensuring economic efficiency [2].

A turbine blade has a complex external shape and an extremely complex cooling system, which are determined based on 3D-gasdynamic, heat transfer and strength methods, while taking into account non-stationary effects. A modern blade of a high-temperature turbine is made by casting of single-crystal nickel superalloys of the IV generation, containing up to ~10% of rhenium and ruthenium with optimal crystallographic orientation. To ensure an acceptable thermal state, the blade has an extensive perforation, usually obtained by laser or electroerosion methods. The blade has a protection against high temperature corrosion of inner cavities and a maintainable thermal barrier coating of the external surface, providing both protection against oxidation and reducing the temperature of material of the blade. High-pressure turbines of advanced engines will operate at an even higher gas temperature than modern turbines. It can be expected that to manufacture blades for these turbines, silicides of refractory metals will be used, which retain their operability at higher temperatures than modern nickel superalloys without using expensive and scarce alloying elements and also have lower density. To successfully create blades for advanced high-temperature turbines, new heat-resistant coatings will be required, which retain their efficiency at higher temperatures than modern coatings based on partially stabilized zirconium oxide.

One of the most important tasks for successful creation of advanced engines is the task of ensuring high cooling efficiency of turbine blades. The use of double-walled blades with transpiration cooling is considered promising. Complexification of the blade design is impossible without improving the methods of its manufacture. Of great interest is the use of additive technology (AT) for the manufacture of blades with complex cooling layouts.

The next possible stage of development is the creation of turbine blisks using dissimilar materials [4]. It is possible to exclude in blisk joints between blades and disk. As a result, it is possible to reduce weight of a structure, increase efficiency, increase reliability (in particular, to eliminate the problems associated with fretting in joints). Blisks are widely using in compressor rotors. At the same time, requirements for materials of turbine disk and blades are significantly different. Casting single-crystal nickel superalloys are using for manufacturing of turbine blades, while powder alloys are mainly using for turbine disks. Blisks with component parts made of different materials may now be produced by powder metallurgy (by compacting separately fabricated blades and disks by hot isostatic pressing (Figure 1)), and in the future - using AT. Development of repair technologies is of great importance for widespread introduction of turbine blisks made from dissimilar materials.

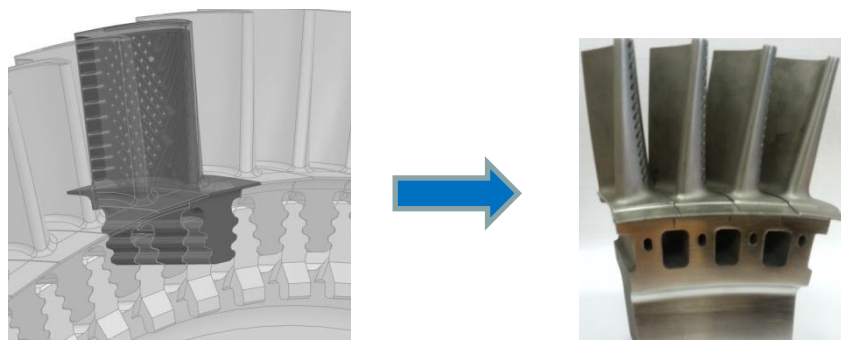


Figure 1. Section of bimetallic blisk of a turbine with cooled blades, developed in CIAM.

Without going into detail of all technologies needed to create a high-temperature turbine blade [2] with the required strength and reliability, we only note that all these technologies must be mutually linked and cost-effective. To develop these technologies, a multidisciplinary approach is required, and the extremely complicated process of creating a turbine blade depends on the structural and technological state of other engine parts, primarily other rotor and turbine stator parts.

The need for multidisciplinary approach is associated with a large number of often conflicting requirements for parts and components of a gas turbine engine. Some examples of recent activities in CIAM on multidisciplinary optimization of gas turbine engine components are given in [5, 6]. The role of robust design methods is also increasing. In addition, many of the requirements for the engine are in themselves of a complex nature. For example, in case of ingestion of bird flocks, hail, rain in the engine, there should be not only a hazardous failure (injection of fragments with large kinetic energy from engine case, non-localized fire, destruction of engine attachment points), but also unacceptable reduction of thrust. Therefore, in order to confirm compliance of an engine with this requirement, it is necessary both to develop methods for calculating blades damage when interacting with foreign objects entering a flow path, and methods for estimating engine thrust loss in the presence of blade damage. To increase an engine's resistance to the ingress of various foreign objects, it is necessary to develop and implement a large range of operational and design-technological measures. Of great importance, in particular, are development and implementation of methods for surface hardening of materials of fan and compressor blades.

New materials and design-technological solutions can be used in the engine only after reaching the VI level of technological readiness (on NASA scale) and the corresponding level of production readiness. Typically, the process of research of new structural material takes 10-15 years. All materials used in the engine must be carefully studied, which implies carrying out their special qualification - research of structural (realized in the design in the expected operating conditions) strength [7].

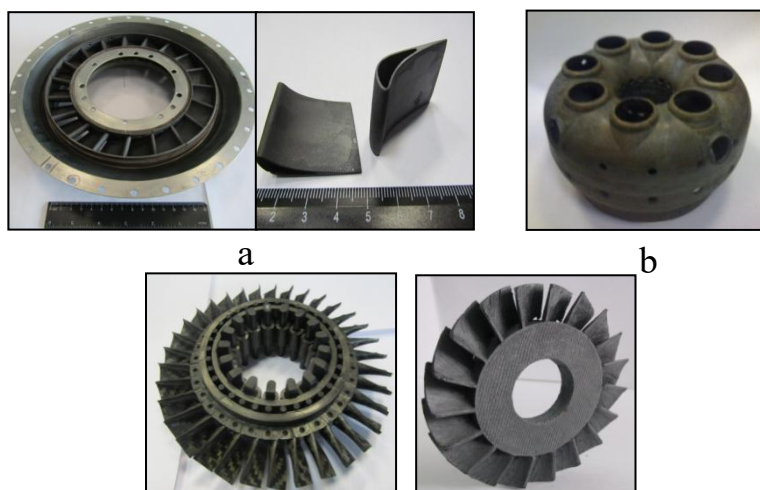
In advanced engines, we can expect usage of intermetallic alloys, alloys with a gradient of physical and mechanical properties; materials obtained using additive technology; smart materials. Various composite materials will find wide application.

Polymeric composite materials (PCM) are widely used for light fan blades (particularly on GE90, GENX, LEAP engines) and "cold" stator parts (including fan casings on GENX, LEAP). The use of these materials can significantly reduce engine weight, improve environmental performance (reduce noise level), improve reliability. Engine layout with an open fan rotor is one of the promising solutions that allow to significantly increase economic efficiency of an engine. However, there is no fan casing in this layout, the presence of which allows to reduce the criticality of a fan blade failure. Apparently, the only way to ensure operational safety is to confirm practical impossibility of destruction of a fan blade, and the most realistic way to implement this approach is to use a carbonplastic fan blade. Figure 2 shows a carbonplastic model of a fan blade prepared for testing on a spin rig.



Figure 2. The carbonplastic fan blade installed on a spin rig.

The use of metallic or intermetallic composite materials (primarily the use of materials with a titanium or titanium aluminide mould) for the manufacture of shafts, compressor blings, parts of engine attachments to an aircraft will also significantly reduce weight and improve reliability of engines. Over the years, activities were carried out on the use of monolithic ceramic materials for GTE parts [8]. These materials have a relatively low density and retain a sufficiently high strength to higher temperatures than nickel superalloys. However, the area of successful application of monolithic ceramic materials in gas turbine aircraft engines is limited mainly by elements of hybrid and ceramic bearings [9]. The use of hybrid rolling bearings (with ceramic rolling elements and metal rings) ensures an increase in life of bearings operating at high values of the parameter Dn (D – diameter between axes of rolling elements, n – angular velocity). The use of ceramic rolling bearings (with ceramic rolling elements, rings and a cage of, for example, carbon-carbon) can significantly reduce the requirements for lubrication and cooling of bearings, reduce weight. In this case, installation of ceramic rings on a metal shaft or in a metal housing should be carried out taking into account difference in coefficients of linear temperature expansion of the materials. To use materials based on ceramics for other engine parts, it was necessary to switch to ceramic composite materials (primarily silicon carbide reinforced with SiC fibers) with higher mechanical properties. For a long time, activities were also conducted on the use of carbon-carbon materials in GTE, which have high absolute and specific values of strength and rigidity at extremely high temperatures, and also a low coefficient of linear thermal expansion. However, to ensure reliable protection of parts, which were manufactured using these materials, from high-temperature oxidation, it turned out to be worthwhile to move from the carbon matrix to the ceramic matrix [8]. Currently, in the engines of the LEAP and GE9X families, ceramic composite materials, the use of which allows to reduce weight, increase fuel efficiency, and reduce the emission of harmful substances, have already found application. Figure 3 shows parts of a small-sized engine made of ceramic composite materials, which are under investigation in the CIAM.



c

Figure 3. Parts made of ceramic composite materials.

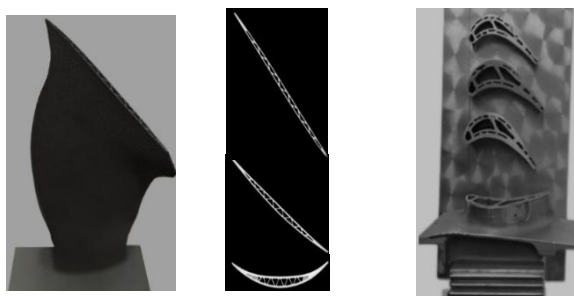
a – turbine stator, b – flame tube, c – turbine wheel

Thorough activities on the creation of materials operable at extremely-high (over 1600 °C) temperatures continue.

At the same time, special qualification of composite materials is much more complicated than in case of metallic alloys [2]. The anisotropy of physical and mechanical properties and structural irregularity of these materials necessitate a significant increase in the nomenclature of characteristics required for the design of components made from these materials and the number of test articles. Since the composite material is usually created for a particular component, it is not enough to determine characteristic values of a material realized in a component using simple shape samples, which is due to differences in structures of the material of the component and the sample, technologies for their production, and influence of scale effect. In addition, the characterization of composite materials is difficult due to specific properties of particular materials. For example, in the study of polymeric composite materials (PCM), great attention must be paid to obtaining data on the influence of process-dependent parameters and possible operational influences on the strength properties of materials. According to Boeing, when the PCM was introduced, the volume of tests had to be increased by a factor of 20 compared to using traditional alloys [10]. Advanced high-temperature materials must be tested at extremely high temperatures. This means that the test sample must be heated to the required temperature; clamped and loaded, providing centering; necessary measurements must be carried out. In this case, all the test equipment (heaters, screens, grippers, extensometers) can be made, for example, from refractory alloys (for testing in vacuum), carbon-carbon (for testing in a protective environment), ceramics or refractory alloys with coatings (for testing in air) [11]. It is also possible to carry out tests in air with samples located outside the heating zone, however, the thermal stresses arising in the test sample must be taken into account. It should also be noted that there is an insufficient number of standards that can be used for testing of samples made from composite materials.

Activities on the use of AT for manufacture and repair of aircraft engine parts are rapidly developing. AT allows you to obtain various parts that cannot be obtained by other methods, including parts with complex shapes, parts made from dissimilar materials, parts from materials with a gradient of properties. The use of AT in the manufacture and/or repair of aircraft engine parts can reduce the time and money spent on manufacturing/repair, reduce weight, reduce the number of parts and simplify the assembly, increase efficiency, durability and reliability.

CIAM (Magerramova L.A., et.al.) together with other enterprises (NIAT, Saturn, IL & ST, NPO System, Diaprom, SOVTEST ATE, etc.) generates scientific and technological know-how on the application of AT in design (including using topological optimization), manufacturing or repair of turbine blades with advanced cooling layouts (including double-wall blades), hollow turbine discs, hollow fan blades, compressors blisks, equipment for casting of cooled turbine blades (including ceramic rods), flame tubes sections of combustion chambers, front modules of combustion chambers, different stator parts (including cellular structures), ceramic parts of turbines. Some models of parts designed, manufactured with AT from metal alloys and undergoing studies in the CIAM are shown in Figure 4 [12,13].



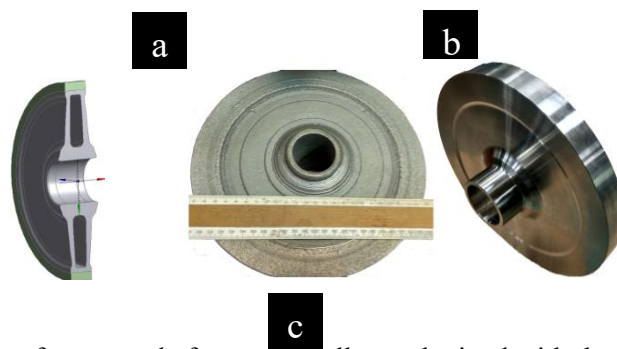


Figure 4. Some models of parts made from metal alloys, obtained with the help of AT

a – hollow fan blade, b – turbine blade, c – hollow turbine disk.

Reliable prediction of strength and longevity of aviation GTE parts does not lose its relevance. It is necessary to take into account complex mode of deformation, joint influence of various damaging factors, effect of a stress history on the strength. Widely applied principles of independent influence of damaging factors and a linear damage accumulation rule can give a significant error, and for the use of more accurate models a large amount of experimental data and application of probabilistic approaches are needed.

The task of prediction of longevity is simplified in the presence of one prevailing mechanism of damageability.

3. Prevention of fatigue failure.

For critical (main) engine parts of multi-engine aircraft, generally, the main damaging factor is low-cycle fatigue. In accordance with modern certification requirements, the life of these parts should be determined taking into account possible defects [11]. In this regard, currently, life of these parts is confirmed with the parallel use of two approaches - without taking into account initial defects (before formation of so-called engineering fatigue crack having a depth of ~ 0.4 and a length of ~ 0.8 mm), with an assessment of all hazardous areas of stress concentration and taking into account defects (based on a deterministic or probabilistic approach). Currently, certain metallurgical defects are necessarily taken into account (the presence of a solid α -phase in titanium alloys and ceramic inclusions in disks of powdered nickel alloys, porosity during casting or welding); technological defects (arising from production of holes in parts) and operational defects (from operational experience of similar builds). For the operation, the lesser of the obtained life values (with the reserves necessary to ensure operational safety) is allowed. The presence of large defects, dimensions of which are difficult to determine (unfavorable texture in heat-resistant titanium alloys, oxides and carbides along the boundaries of primary grains in powdered nickel alloys) should be eliminated by technological methods. The main methods of increasing longevity of parts, including taking into account possible presence of initial defects, are well known. However, in all these areas, research can and must continue. Much attention should also be paid to registration of the accumulated damageability for each part with subsequent evaluation of the residual life [16].

The main cause of the defect high appearing during operation of aircraft engines remains the high-cycle fatigue. This is due to the significant difficulty of predicting both the vibrational state of parts and the resistance of materials to high-cycle fatigue. When creating advanced engines, the problem of preventing destruction of parts from the high-cycle fatigue due to increased loading of turbomachines; the use of wide-chord blades with a dense frequency spectrum of natural frequencies; the use of builds with low damping; strengthening of coupling of vibrations; the growth of static stresses in parts and increase of temperature in these parts; increase in engine running time before removal for repair; the use of materials with reduced plasticity.

In recent years, a large amount of activities have been performed and continues to be carried out in the USA (as part of the special Air Force program, [17]), European countries and Russia, to prevent

destruction from high-cycle fatigue, including prediction of vibratory stresses under forced oscillations, flutter analysis, non-contact methods of analysis of vibrations, investigation of permissible damages in the material, damping of vibrations, improvement of methods for determining resistance to high-cycle fatigue (study of the influence of stress cycle asymmetry on fatigue, the influence of other damaging factors, study of fatigue resistance of titanium alloys in the gigacyclic region, fatigue mechanisms of single-crystals, etc.), development of strengthening methods, development of robust design methods, etc. As an example of activities aimed at preventing destruction from high-cycle fatigue, Figure 5 shows a diagram of a system for diagnosing vibrations of turbomachine blades developed at CIAM and protected by 7 patents of Russian Federation. Sensors include gas pressure pulsation sensors, vibration sensors for stator parts, sensors for alteration of radial clearance in turbomachines. Signal processing is carried out using fast Fourier transformation, wavelet transformation, Prony's method. Currently, most studies of the vibrational state of turbomachine blades and resonant tests are carried out in Russia using these methods (see, for example, [18]). Systems for the non-contact vibration diagnostics of the blades (tip timing type) also find wide application in laboratory testing of engines, including dynamic spin rigs [19].

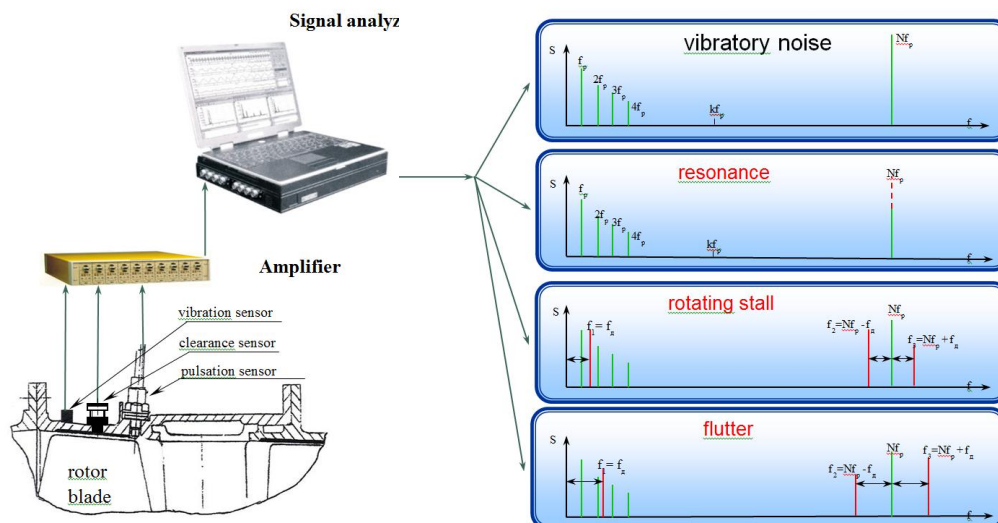


Figure 5. The non-contact system of vibration diagnostics of turbomachine blades in real time.

$F_d = f_b \pm mf_r$, where N – the number of blades; m – number of deformation waves; f_r – rotor frequency; f_b – blade frequency

To ensure the reliability of aircraft engines, it is of great importance to develop methods for complex multi-parameter diagnostics of technical condition utilizing remote diagnostic centers. In recent years, there have been significant achievements in this direction. As an example, methods and means of diagnosing the technical condition of aircraft drives developed by CIAM [20] can be cited. Especially great opportunities are revealed by using methods and means of determining the kinematic error of gearing.

The task of ensuring strength reliability remains actual at the development of advanced aircraft engines, and the complexity of its solution increases for each new generation of engines.

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