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D3.5 Final report on pilot projects in aeroengines

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PU	Public	**X**
PP	Restricted to other program participants (including the EC Services)	
RE	Restricted to a group specified by the consortium (including the EC Services)	
CO	Confidential, only for members of the consortium (including the EC)	

The overall aim of the AERO-UA project is to stimulate aviation research collaboration between the EU and Ukraine through strategic and targeted support. AERO-UA is focused solely on Ukraine, because the country has a huge aerospace potential but a low level of aviation research collaboration with the EU. Ukraine's aerospace sector spans the full spectrum of systems and components development and production with OEMs, Tier 1 and 2 suppliers, aeroengine manufacturers, control systems manufacturers, R&D institutions, aeronautic universities, and SMEs. This is also reflected in the sector's important contributor to the country's economy (e.g. aircraft production of €1,9 billion in 2011).

Ukrainian aerospace organisations possess unique know-how that can help Europe address the challenges identified in the ACARE SRIA / Flightpath 2050 Report. Furthermore, following the signing of the Agreement for the Association of Ukraine to Horizon 2020 in March 2015, Ukrainian organisations are eligible to participate in Clean Sky 2 and H2020 Transport on the same funding terms as those from EU member states. Equally, genuine commercial opportunities exist for European aviation organisations to help modernise Ukraine's aerospace sector.

The AERO-UA project will achieve its overall aim via four high-level objectives:

1. Identifying the barriers to increased EU-UA aviation research collaboration;
2. Providing strategic support to EU-UA aviation research collaboration;
3. Supporting EU-UA aviation research knowledge transfer pilot projects; and
4. Organising awareness-raising and networking between EU-UA stakeholders.

The AERO-UA consortium is comprised of key EU and UA aviation organisations that will implement WPs closely mapped to the high-level objectives. The consortium will be supported by an Advisory Board involving Airbus, DLR, Min. Education and Science of Ukraine, Ukrainian State Air Traffic Services Enterprise and retired Director of EADS Jean-Pierre Barthélemy.

Table of Contents

1. Introduction

The task relating to the pilot projects between EU-UA partners in the field of aeroengines (Task 3.2) was part of WP3, EU-UA aviation research knowledge transfer pilot projects, as agreed under the AERO-UA Strategic and Targeted Support for Europe-Ukraine Collaboration in Aviation Research project.

This work package provided targeted support for EU-UA collaboration in aviation research in the form of knowledge transfer pilot projects to be implemented by the AERO-UA partners. The pilot projects were structured around three key areas relevant to the challenges of ACARE SRIA / Flightpath 2050: Aerostructures, **Aeroengines** and Aerospace Manufacturing.

The task included the organisation of short-term visits between the EU and UA partners, in order to exchange knowledge, receive training and/or conduct feasibility studies. Where possible, these visits were combined with project meetings and events.

Based on the results of knowledge transfer pilot projects, the AERO-UA partners prepared joint research publications for international peer-reviewed scientific journals, as well as for international conferences.

2. Pilot Project 3.2a: Engine health management system

According to the AERO-UA Grant Agreement (description of action), the main goal of this pilot project was to conduct a feasibility study for an engine health management system for an Ivchenko turboshaft or turbofan engine. As well as other new engine health management techniques, the project employed a non-contact blade vibration measurement technique applied by TECPAR / ITWL to increase blade durability by reducing the effects of natural resonances, aerodynamic instabilities and foreign objects ingestion. This involved numeric and experimental analysis of blade strength; development of miniature tip-timing sensors; characterisation of blade vibration in a test cell; fault modelling and diagnostic algorithms; and a flight ready diagnostic system.

The Ukrainian partners contributed especially in the following areas: understanding high cycle fatigue, experience in structural analysis and modelling of material durability; capability to test rotating components at the rig and in the engine test cell; capability to modify the casing to host sensors; and interest to implement the system and refine its business model.

Table 1. Participants of the pilot project 3.2a and their roles

	Partner name	Lead person	Role in the pilot project
1	Technology Partners Foundation (TECPAR) / Air Force Institute of Technology (ITWL)	Radoslaw Przysowa	coordination, instrumentation, blade vibration analysis
2	Ivchenko Progress SE	Aleksandr Koptev	structural analysis, provide test facilities, engine modification, system implementation
3	National Aerospace University – Kharkiv Aviation Institute (KhAI)	Sergiy Yepifanov	fault detection algorithms, instrumentation systems
4	University of Manchester (UoM)	Philip Bonello	tip-timing algorithms, Shaker Fatigue Testing
5	Pisarenko Institute for Problems of Strength, National Academy of Sciences of Ukraine (NASU)	Vadim Kruz	structural analysis, component rigs, high cycle fatigue

Milestones achieved until M18:

- Target platform identified: D-436-148FM turbofan
- Fan geometry and structural data available
- List of component rigs completed
- Preliminary design of sensors and measurement system
- Sections of feasibility study drafted

Milestones achieved during M19 - M36:

- Measurement system ready for testing
- Engine testing completed
- Vibration analysis performed
- Feasibility Study completed

2.1 Background to the pilot project

Engine Health Management (EHM), Prognostics and Health Management (PHM) and Blade Health Monitoring (BHM) systems can contribute significantly to monitor safety, improve asset availability and reduce costs of operating gas turbine engines. Several mechanisms such as dirt build-up, fouling, erosion, oxidation, corrosion, foreign object damage, worn bearings, worn seals, excessive blade tip clearances, burned or warped turbine vanes or blades, partially or wholly missing blades or vanes, plugged fuel nozzles, cracked and warped combustors, or a cracked rotor disc or blade cause the degradation and potential failures of gas turbines [3].

Gas turbines should be designed in such a way that blades are protected against exceeding the fatigue limits during operation. However, fatigue cracks in turbine blades still occur in practice, especially in the case of older structures operated in adverse conditions. Blade tip timing is widely used in the development and testing of gas turbines to ensure their structural integrity. The non-contact method is a reliable and efficient alternative to strain gauges.

A Blade Health Monitoring (BHM) system was proposed to address potential problems with blade durability and reliability. Blade tip deflection can be measured and analysed in real time to estimate remaining life and predict failure. At present, on-board applications of tip timing are few and less mature than ones in test cells. Improved and validated technologies such as magnetic sensors, numerical models, data processing algorithms and fault detection methods are required.

The pilot project aimed to develop the concept of a BHM system for a selected Ivchenko engine. The diagnostic system was offered to operators to enhance flight safety, performance and reduce operating costs. The system monitors vibration of compressor blades to reduce the risk of engine malfunction caused by icing, foreign object and inlet debris, warning about the onset of stall and surge of the compressor, accelerated wear of components and fatigue cracks of blades. Excessive vibration of the blades, if not monitored, can cause engine damage, longer downtime, even catastrophic failures due to the lack of information. The system is expected to provide maintainers with actionable condition indicators, indicating or bypassing the need for certain maintenance activities.

Implementation of a new BHM system is a complex process involving substantial knowledge and technology related to structural integrity, strength of materials, sensors, instrumentation and control systems as well as fault detection, isolation and identification. In the pilot project, the parties decided to prepare a joint engine test, aimed to measure fan blade vibration in a D-436-148FM turbofan. As a result, the method and tip-timing instrumentation was verified and also the real responses of the blades will be characterised.

Figure 1. D-436-148FM turbofan

2.2 Knowledge exchanged

During the reporting period, the EU and UA partners exchanged experiences and demonstrated their capabilities related to the design and testing of gas turbines and in particular the development of blades. Topics related to dynamics of rotating components and material strength, crucial for the development of the blade monitoring system, were discussed.

Ivchenko Progress[1] has the capability to carry out a full design cycle of a gas-turbine engine from the concept to small lot production (OEM). There are temporary problems with some products related to the discontinuation of cooperation with Russia because some components, materials and technologies from that country must be replaced by national or western counterparts.

The company operates several engine test benches and component test rigs. During the engine test, the parameters are monitored using digital and computer-based systems. Blade test rigs use shakers and strain gauges. Despite the lack of a non-contact measurement system and the limited degree of digitization of blade tests, experienced employees are able to measure the responses of higher forms of blade vibration. Vacuum spin facilities for testing discs for low-cycle fatigue and a compressor rig are available as well.

The tip-timing method has been successfully implemented at ITWL[2] in several platforms starting in the early 1990s. It was demonstrated that the fatigue crack growth in a blade is reflected by a decrease of the vibration frequency. The developed monitoring system made it possible to avoid the blades' operating with increased vibrations, which reduces their life and poses a safety risk. Positive results of this work led to the implementation of the SNDŁ-1b/SPŁ-2b system in the Polish Air Force, which enabled further operation of a turbojet with construction errors without the need to redesign it.

A recent BHM application in Poland is a system for a low-pressure steam turbine in a coal power plant, responding to problems with durability and reliability of last stage blades. The prototype system has been continuously monitoring blade vibration in the power plant since early 2017. Trends of amplitude and frequency are analysed to reduce the risk of failure.

[1] *Engine Test Bench* http://ivchenko-progress.com/?page_id=1549&lang=en
[2] https://www.itwl.pl/index.php/en/aero-engines-division

Research activities of the Pisarenko Institute for Problems of Strength, National Academy of Sciences of Ukraine (PIPS)[3], include:

- computational and experimental investigation of blade vibrations taking into account the effects of temperature, centrifugal force, external excitation and seeded faults
- detection of fatigue cracks and other flaws in rotating components
- reduction of resonant stress levels in blades through increase of damping
- increasing dynamic stability of bladed discs against flutter
- coating technology to enhance lifetime of blades

The institute contributes to the project with analyses of material strength and component dynamics to ensure reliability of the compressor system through increase of damping capacity and determination of threshold of blade dynamic stability against flutter. It has the extensive expertise necessary to estimate blade durability through material fatigue tests (HCF), fatigue life calculation, blade fatigue testing at shaker etc. PIPS possesses a vacuum spin rig which has recently been refurbished and can be used for blade testing. The dimensions of the vacuum chamber allow to carry out tests on real objects, such as turbomachines bladed disks with a diameter up to 1 meter, weight up to 75 kg and rotation speed up to 13000 rpm. In the test rig, an vibration excitation system is implemented, and includes a shaker and a mechanism for transferring the vibrator's movements to the rotating disk at a frequency of 5 to 5000 Hz, mounted coaxially with the disk.

Due to the presence of a shaker attached to the shaft of the rig, it is possible to set the required level of vibration amplitude and to carry out its monitoring by means of strain gauges. The rig is well suited to verify and calibrate the key components of the Blade Health Monitoring (BHM) system. Laboratory conditions make it possible to install a known damaged blade on the disk and to verify the possibility of its identification with the help of BHM, which can be the long-range direction of research.

Figure 2. Vacuum spin facility in PIPS

The KhAI[4] team designs control and measurement systems for gas turbines and has expertise in blade testing with strain gauges. In the pilot project, the university contributes to the overall concept of

[3] G.S. Pisarenko Institute for Problems of Strength of the National Academy of Sciences of Ukraine http://www.ipp.kiev.ua/
[4] Department of aircraft engine design https://k203.khai.edu/

the engine diagnostic system and develops diagnosis and fault detection methods. Failure modes with relatively high probability and severity of consequences have to be addressed to be identified with FMECA (Failure Mode, Effects and Criticality Analysis).

The KhAI Aircraft Engine Department developed a system for rotor torque measurement in the TV3-117 turboshaft engine using inductive sensors. It is a time-based measurement like blade tip-timing. In early 2017, KhAI and TECPAR / ITWL discussed this topic and considered writing a proposal for the Clean Sky 2 call: JTI-CS2-2017-CfP06-ENG-01-16 (Torque measurement in turbofan) but it was too late to complete it. Measurement uncertainty and calibration are challenging topics, interesting to both sides. The collaboration will be continued and other potential applications such as stationary turbines and aero-engines will be sought.

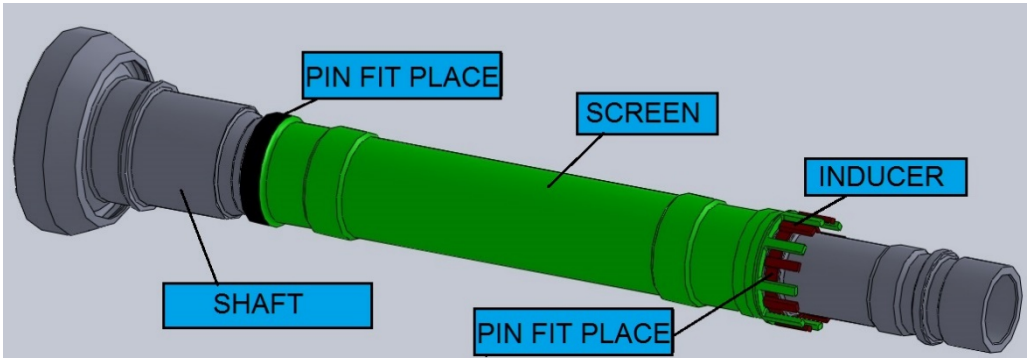


Figure 3. Structure of the torque meter

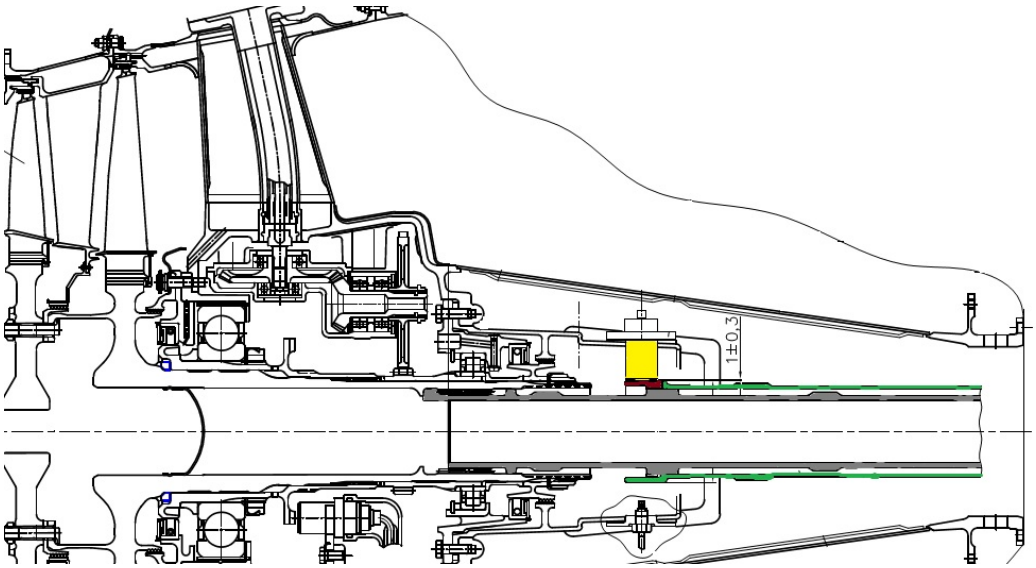


Figure 4. Torque meter installed in the TV3-117 turboshaft

KhAI and TECPAR / ITWL are both interested in high temperature electronics and measurement systems. Dr Edward Rokicki form ITWL builds metal-ceramic magnetic sensors for tip-timing able to operate in extreme environments. Dr Yuriy Gusev from KhAI designs high temperature strain gauges with a film sensitive element based on platinum and cermet and insulator-base from high-temperature cement of phosphate hardening. These technologies can create new research and business opportunities as robust sensors and actuators for the high temperature environment in engines that are needed for new generations of commercial engines and stationary turbines. Improvements of

measurement technology are expected to increase confidence in engine design tools and enhance performance in the field.

KhAI (S. Yepifanov, M. Ugryumov, S. Chernysh) and ITWL (R. Przysowa, B. Gawron) also cooperate in the field of modelling and monitoring engine performance, with participation of Ivchenko Progress (O. Khustochka), UoM (N. Bojdo) and MotorSich (Y. Dvirnyk). Several papers have been exchanged and joint research involving sharing engine data and models is planned. Two collaborative publications in this field were submitted for the EASN conference in Athens, 2-6 September 2019.

The Dynamics group in the School of Mechanical, Aerospace & Civil Engineering[5] (University of Manchester) is led by Dr Philip Bonello and Dr Jyoti Sinha. Their research is concerned with analysis (theoretical and experimental) of the dynamics of rotating machinery, which is essential for guaranteeing its structural integrity and development of non-contact methods for turbomachine blade vibration measurement with application in aero-engines and steam turbines. Several projects related to blade vibration analysis and online monitoring, modelling of cracks and life assessment have been performed, sponsored by industry and users. Comprehensive blade testing options are available in the Turbine Blade Vibration Test Facility where blades can be excited either by a shaker or a chopped air jet. The facility is enclosed in an acoustic chamber.

A current PhD project focuses on the calibration of blade tip timing (BTT) data against FEM predictions and is expected to create a standardised calibration approach which will facilitate and enhance the usage of BTT in existing applications and enable a continued BTT use in future-technology vehicles.

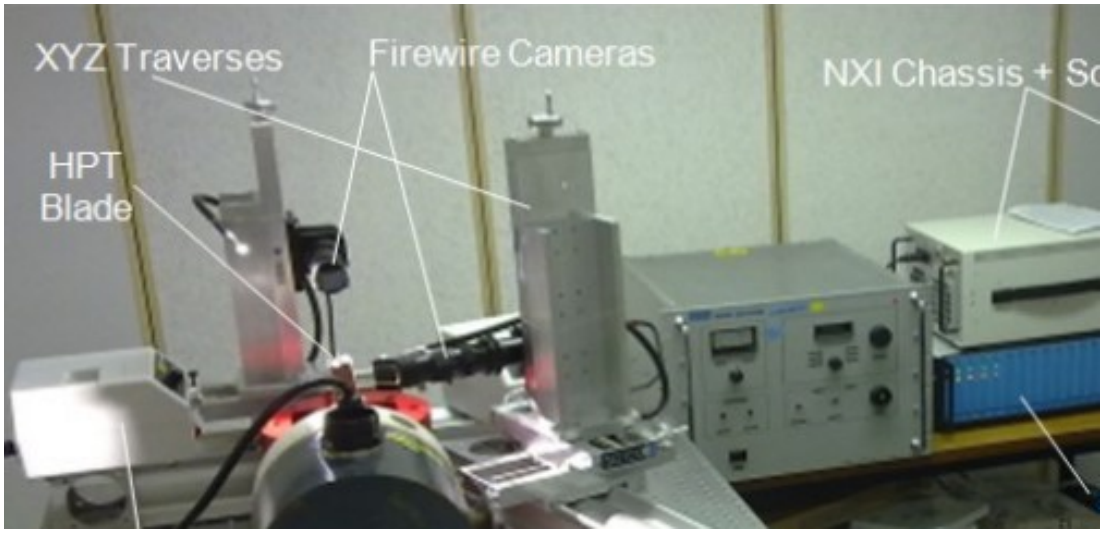


Figure 5. Turbine Blade Vibration Test Facility

[5] School of Mechanical, Aerospace and Civil Engineering. The University of Manchester, Manchester. Research areas - Rotordynamics https://www.mace.manchester.ac.uk/research/facilities/dynamics-and-vibration/

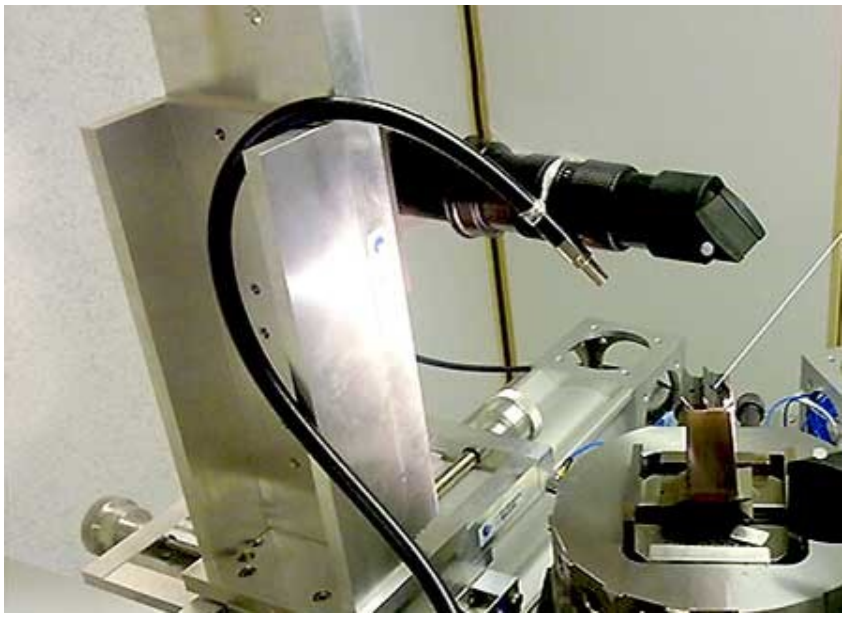


Figure 6. HPT Blade and Mass Block

2.3 Training provided

Despite the fact that training was not the major goal of the pilot project, the methodology of contactless blade testing and using the vibration data for blade health assessment was covered extensively during the meetings in Zaporizhia, Kyiv, Manchester and Warsaw. In particular, the University of Manchester organised a very successful workshop in November 2018 with several lectures and presentations related to the modelling and testing of rotating components. It also included labs and hands-on training on advanced instrumentation techniques.

In the session of AVT-306 held in Politecnico di Torino in April 2018, Prof. Yepifanov from the Kharkiv Aviation Institute presented the achievements and potential of the KhAI Laboratory of Aircraft Diagnostics. The team's achievements include the monitoring system of the AN-124 Ruslan aircraft and its D-18 engine, as well as the NK-93 engine for the Il-76LL aircraft. These are class IVHM / EHM systems with continuous analysis of approx. 100 parameters. As part of these projects, engine flow models, dynamics, thermal and durability models of assemblies and subassemblies as well as algorithms for error detection and identification were developed. The BUK-500 digital control system for the MS-500V engine and the BUK-117 digital control system for the TV3-117 turboshaft were built. Intelligent measuring systems such as observers and a torque meter for the TV3-117 engine were also shown. The team also deals with vibration analysis. It developed and tested a method for early detection of pumping on the basis of indications of vibration and pressure sensors.

During the working meeting in Zaporizhia in October 2018, Dr Przysowa presented a tutorial on the practical application of blade tip-timing and answered several questions on measurement capabilities and data processing methods.

2.4 Scientific and technical results

TECPAR / ITWL worked with Ivchenko on designing the instrumentation needed for blade vibration measurement. A mock-up sensor and the information required to design brackets was provided. Ivchenko Progress shared fan drawings, blade parameters and structural analysis results such as a

Campbell diagram which were studied by TECPAR / ITWL to prepare the planned engine testing and BTT data analysis.

Selected algorithms of phase estimation and their uncertainty models were tested at ITWL using simulated and archival tip deflection data. Numerical techniques, such as linear regression and polynomial least square fitting, were employed to process sample sensor signal in order to increase resolution in time and measure characteristics of the blade-related pulse, including zero-crossing, maximum amplitude, rise time and pulse width.

Ivchenko Progress invited ITWL specialists to support the bench tests of the D-436-148 turbofan in Zaporizhia (Figure 7). At the project meeting in Zaporizhia in April 2019, ITWL confirmed that new sensors (Figure 8) and the acquisition system were ready for engine testing. Ivchenko Progress designed and made sensor slots. Sensor placement was agreed in July. The partners have agreed to schedule the test for when slots in the fan casing are machined (which only take place after the project conclusion); the exact date depends on the availability of the test cell and engine. The ITWL team will be responsible for installing the data acquisition system and sensors, and for measuring the vibration of the blades.

Figure 7. Test cell of D-436-148FM turbofan

Figure 8. New BTT sensor developed at ITWL

Figure 9. New conditioning unit developed at ITWL

2.5 State of the art comparison

Blade Health Monitoring

Non-contact blade vibration measurement, known as blade tip-timing (BTT) or Non-contact Stress Measurement System (NSMS), is a successful technique for ensuring the structural integrity of bladed disks in jet engines and stationary turbines. The method uses several sensors mounted circumferentially to precisely determine temporary positions of each blade tip in every single rotation. It has found practical industrial applications for vibration analysis and blade health monitoring. Model-based data processing is necessary to determine the real amplitude and vibration.

The most important users of the technology are operators of turbomachinery, i.e. turbines, fans and compressors, especially those with design errors or operation spectrum deviating from the original design assumptions. The second group of users are engine manufacturers who apply the method primarily during product development. They usually have their own blade vibration analysis systems, but in some cases they order measurement services from independent contractors.

Industrial partners are interested in proven measurement solutions with increased efficiency which make it possible to design machines with greater durability and efficiency. Determining the real dynamic properties of the blades allows for designing the compressors and turbines in a way that reduces the risk of high cycle material fatigue which, under certain conditions, can lead to cracking and breaking of the blades. In comparison to strain gauges, non-contact vibration measurements contribute to substantial savings by the installation of sensors, but require advanced signal processing based on the model of the blade dynamics. The research methodology has been applied in industrial practice and the complexity of models is tailored to the expected vibration spectrum.

The market for blade tip-timing is not large compared to other non-destructive methods. On the European market, also in Poland, there are several teams applying and developing the method, mainly from Great Britain. The competition in the United States is even greater. Nevertheless, the developed solutions attract growing interest of customers in the USA, Europe and China, mainly due to focusing on

monitoring applications and designing measurement solutions with a limited number of sensors that can be applied in harsh conditions.

Systems for preventing excessive vibrations and fatigue of blades, reducing the risk of engine breakdown, represent a market niche which is still not filled by global companies. In Poland, there are 10-20 users from the operator group and a few component manufacturers. The first group is more promising, because it uses several hundred machines, mainly older types, which were designed several dozen years ago and the operators are usually Polish-owned. The group of manufacturers are usually production branches of western corporations that do not conduct much testing of new blade designs in Poland or do it to a limited extent.

Monitoring of blade vibrations using the non-contact method is an alternative to costly redesign and upgrades of the turbine or compressor. A world-unique blade vibration monitoring system for a steam turbine operating in the real time was proposed. It enables continuously monitoring the amplitude and frequency of blade vibration and generates alarms in case of an excessive vibration level. In response to a heads-up, the operator should change the operating parameters to reduce the risk of failure. The system makes it possible to avoid operating blades with elevated vibrations which reduce their service life and may lead to cracks and losing blades.

The effect of using the system is reducing the maintenance costs of the machine by increasing the mean time to failure (MTTF), reducing the average reaction time to developing damage, reducing the maintenance effort i.e. decreasing the frequency of inspections, reducing the scope of overhauls and the demand for spare parts. The use of the monitoring system reduces the risk of a serious machine breakdown, which results not only in the repair costs, but also contractual penalties related to downtime.

The Ukrainian institutions have a strong track record in ensuring structural integrity of rotating components and they mastered the traditional experimental approach based on strain gauges. They are familiar with tip-timing technology but used to depend on Russian partners for certain advanced measurement techniques. Ivchenko Progress and Ukrainian research centres are interested in introducing modern gas-turbine instrumentation technologies and EHM technologies and perform joint experimental research with European partners. In the Ukraine, ambitious research requiring large infrastructure can be carried out at significantly lower costs than in the European Union, contributing well to the greening the aircraft policy defined in Flight Path 2050.

Gas-Path Analysis

Engine performance models are a key component of engine design, development and field support processes. They are used to create and communicate performance specifications to prospective customers. They are used during the design/development process to predict operating conditions for engine components, to establish temperatures and pressures under which engine components must operate, and to support engine life calculations. They form the basis of data analysis tools used for development tests and for field monitoring of engines [1].

A variety of methods have been developed for Engine Health Management (EHM). Gas-Path Analysis (GPA) is one of the most widely used diagnostic techniques and was first introduced by Urban in 1967. It utilises changes in observable measured engine parameters such as rotational speed, fuel flow, pressures and temperatures, and compares those measurements to a ‘healthy’ baseline engine (or model simulation). Any deviation can then be used to detect, isolate and accommodate component faults manifested by changes in component efficiency and flow capacity.

Obtaining sufficiently accurate and practically useful solutions in GPA poses the following challenges [4]:

- Nonlinearity of the diagnostic problem

- Measurement uncertainty
- Availability of limited sensors
- Occurrence of multiple faults simultaneously
- Operating condition variations
- Lack of standards in defining and representing fault diagnostic problems
- Unavailability of data in the required type, quality and quantity
- Absence of Diagnostic Methods Validation Techniques

Effective fault diagnostic system is ideally expected to fulfil the following characteristics [4]: fault diagnostic accuracy, robustness, explanation facility, simplicity/user-friendliness, adaptability, memory and computational requirements, reliability, comprehensiveness, flexibility.

In the field of GT diagnostics, several methods have been developed. The available methods are categorized into two main groups: Model based (MB) and Artificial intelligence (AI) based.

MB diagnostic methods rely on the thermodynamic model of the engine. The relationship between the gas-path measurements and the performance parameters is determined by explicit mathematical and thermodynamic equations. The most common MB methods are: Gas-Path Analysis (GPA) and the Kalman Filter (KF). MB methods [4]:

- have more advantages in terms of early fault detection and online fault diagnostics;
- perform fault diagnosis with adequate accuracy;
- apply the real gas-path physics;
- have low model complexity and computational time.

On the other hand, MB methods are characterized by model uncertainties, measurement noise, and sensor bias and smearing effects (possibility of misinterpretation and false alarms).

AI methods give the most powerful and popular types of fault diagnostic algorithms. There are many different AI methods such as Artificial Neural Networks (ANN), Deep Learning (DL), Bayesian Belief Network (BBN), Expert Systems (ES), Fuzzy logic (FL), and Genetic Algorithm (GA). Algorithms based on AI methods require operational data with appropriate quality, quantity, and type or model simulation data, in the absence of operational data [4].

AI-based methods, in contrast to MB methods, can handle the effect of sensor noise and bias, the possible existence of multiple faults simultaneously, the fault identification problem using a limited instrumentation suite and the nonlinear relationship between the measurement parameters and the performance parameters. However, most AI-based techniques cannot give confidence limits on the output. In addition, they are not capable of diagnosing faults outside the domain of the data to which they have been exposed during training [4].

A practical tool to evaluate the performance and effectiveness of any algorithm is needed. Currently, no such tools are available. The following approaches can be found in the literature:

- Performance Metrics Approach;
- Benchmark Fault Cases Approach (e.g. ProDiMES);
- Comparison of Methods Approach.

Two main issues to solve which require further work: improving the effectiveness and reliability of the available fault diagnostic systems and developing practical tools to evaluate the effectiveness of the proposed techniques [4].

In the fault identification process, it is useful to find a relationship between the faults and their corresponding effects on the engine performance. The effects of main gas path component degradation on gas turbine performance are reported in several research studies. Zwebek et al. [5] provides a representation of component degradation used to simulate the effect of implanted faults on gas turbine

performance. Another valuable contribution, [6], investigated the effect of different kinds of faults on the engine compressor characteristics and included a more detailed discussion of fault modelling [7].

Extensive research in the field of gas turbine performance modelling and diagnostics has been carried out for many years by the researchers from the major engine OEMs and also from NASA Glenn Research Center, Netherlands Aerospace Centre, MTU Aero Engines, Cranfield University and the Laboratory of Thermal Turbomachines of the National Technical University of Athens (LTT/NTUA). New diagnostic methods and many different techniques are developed. These groups demonstrated the effectiveness of using benchmark fault cases to develop and evaluate the performance of diagnostic algorithms.

Ukrainian contribution

A modern gas turbine engine is a complex nonlinear dynamic system. Gas-dynamic processes and thermal processes occur in engine components and affect each other. The engine development requires the precise real-time simulation of all the main operating modes. One of the most difficult operating modes for modelling is cold stabilization [8]. Ukrainian institutions are developing a new method to model the engine dynamics considering its heating up. The method is based on the integration of three models: the gas-path dynamics model, the clearance dynamics model and the model of the clearance effect on the efficiency. The method was tested. For this purpose a specific turbofan engine was used.

The known studies in the area of gas turbine lifetime prediction do not provide the algorithms for on-line engine monitoring. Ukrainian institutions investigate a new method for developing “light” mathematical models to estimate static thermal boundary conditions for hot elements of gas turbine. Unlike those developed in the past, these models allow on-line lifetime monitoring of such elements [9].

The process of gas turbine development requires different mathematical models. In particular, physics-based nonlinear dynamic models are widely used in the development of control and diagnostic systems. Ukrainian institutions develop a novel method to enhance a detailed physics-based nonlinear gas turbine model. The methodology integrates two dynamic processes, a general engine transient and a clearance change [10].

The literature contains are many papers devoted to the enhancement of gas path diagnosis reliability. Different approaches in gas turbine diagnostics are considered. The literature review showed that in many cases such convenient ways to enhance the reliability as choosing the best approximation function and recognition technique as well as tailoring the function and technique, do not yield satisfactory results. Some new solutions are proposed in chapter [11] to reduce the gap between simulated diagnostic process and real engine maintenance conditions. Possible error sources are examined in the chapter and some methods are proposed to enhance the deviation accuracy.

Improving the safety of aviation systems is possible based on the methods of mathematical modelling of technical processes. Existing mathematical models, methods and the computer systems that implement them are widely used to solve problems of diagnosing the technical state but their use does not always guarantee a comprehensive assurance of the efficiency and resiliency of aviation systems [12]. Ukrainian institutions develop a methodology and propose an applied information technology for diagnosing turbofan engines. The developed classification problem solution method of technical condition is based on the use of modified probabilistic neural networks. The method uses quasi-solutions of nonlinear tasks for finding intervals of symptom values corresponding to the working state the object of diagnosis.

There are only a few software packages which provide the possibility of robust optimal design (for example, «Dakota, A Multilevel Parallel Object-Oriented Framework for Design Optimization, Parameter Estimation, Uncertainty Quantification, and Sensitivity Analysis», « IOSO Technology, Robust design

optimization », «ESTECO, modeFRONTIER», «Dassault Systems, Isight and Fiper», «DYNARDO, optiSLang», «NUMECA International, FineDesign3D», «Concepts NREC's, Agile Engineering Design System»).

The Ukrainian research team developed a new robust estimation methodology (M – estimation) based on the concept of invariance of the theory of optimal control and applied it to solving nonlinear multidisciplinary problems of ROD & IDS under uncertainty. The use of this methodology compared to existing methods will reduce the percentage of marriage in mass production of systems (to avoid the subsequent selective assembly). When monitoring systems, the new method – unlike existing ones – will ensure a reduction in the probability of incorrectly determining the state of the systems (errors of the third kind in classifying the state of the systems), as well as obtaining stable effective estimations of the unknown values (corresponding to the found state). There methodology and Software "ROD&IDS" allows searching for rational solutions of multi-objective MV-problem by hierarchical double-level solution synthesis scheme making. The scheme contains robust surrogate models of system and process and effective robust desired quantities estimation under parametric data uncertainties.

Many of the propulsion gas path diagnostic method solutions published in the open literature are applied to different platforms, with different levels of complexity, addressing different problems, and using different metrics for evaluating performance. This is why it is difficult to make a comparison. For this purpose, the Propulsion Diagnostic Method Evaluation Strategy (ProDiMES) software tool has been specifically designed to be made publicly available. ProDiMES is a publicly available tool which serves as the industry standard. It facilitates the development and evaluation of significant Engine Health Management (EHM) capabilities [13].

Work using this tool is also carried out with the participation of institutes from Ukraine [14]. The following work is planned with ProDiMES:

- True Negative Rate (TNR) should be increased up to 0.999 for better algorithms comparison;
- Fourth stage of lifetime prediction can also be included in the algorithm and verified using this software;
- Need to verify the algorithm during all the lifetime.

References

1. *Bryce A. Roth, David L. Doel, Jeffrey J. Cissell, "Probabilistic Matching of Turbofan Engine Performance Models to Test Data", GT2005-68201. Proceedings of ASME Turbo Expo 2005. June 6-9, 2005, Reno-Tahoe, Nevada, USA*
2. *Keith Calhoun Health Management at Rolls-Royce. PHM Society. 01 October 2009*
3. *Anastassios G. Stamatis (June 19th 2013). Engine Condition Monitoring and Diagnostics, Progress in Gas Turbine Performance, Ernesto Benini, IntechOpen, DOI: 10.5772/54409.*
4. *Fentaye, A.D.; Baheta, A.T.; Gilani, S.I.; Kyprianidis, K.G. A Review on Gas Turbine Gas-Path Diagnostics: State-of-the-Art Methods, Challenges and Opportunities. Aerospace 2019, 6, 83.*
5. *Zwebek A, Pilidis P. Degradation Effects on Combined Cycle Power Plant Performance—Part I: Gas Turbine Cycle Component Degradation Effects. Journal of engineering for gas turbines and power. 2003;125:651-7.*
6. *Aretakis N, Roumeliotis I, Mathioudakis K. Performance model "zooming" for in-depth component fault diagnosis. Journal of engineering for gas turbines and power. 2011;133:031602.*

7. *Mohammadreza Tahan, Elias Tsoutsanis, MasdiMuhammad, Z.A.Abdul Karim, Performance-based health monitoring, diagnostics and prognostics for condition-based maintenance of gas turbines: A review, Applied Energy, Volume 198, pp. 122-144, 2017.*
8. *Yepifanov, S. V., Zelenskyi, R. L., & Loboda, I. (2015). Modeling the gas turbine engine under its dynamic heating conditions. Journal of Engineering for Gas Turbines and Power. https://doi.org/10.1115/1.4028449*
9. *C. M. Herrera1, S. Yepifanov, I. Loboda, Improvement of turbine blade lifetime assessment by more accurate estimation of the thermal boundary conditions, Advances in Mechanical Engineering, Volume: 9 issue: 4, 2017.*
10. *R. L. Zelenskyi, S. V. Yepifanov, I. Loboda, Advanced Nonlinear Modeling of Gas Turbine Dynamics, DOI: http://dx.doi.org/10.5772/intechopen.82015*
11. *Igor Loboda (2012). Gas Turbine Diagnostics, Efficiency, Performance and Robustness of Gas Turbines, Dr.Volkov Konstantin (Ed.), ISBN: 978-953-51-0464-3, InTech, Available from: http://www.intechopen.com/books/efficiency-performance-and-robustness-of-gas-turbines/gas-turbinediagnostics.*
12. *М. Л. Угрюмов, В. Е. Стрелец, В. А. Горячая, Е. С. Меняйлов – Национальный аэрокосмический университет им. Н. Е. Жуковского «ХАИ», Украина, Методология и средства информационной технологии диагностирования технического состояния турбореактивных двигателей в условиях неопределенности входных данных, http: / / www.GTT. Ru, 2015.*
13. *https://www.grc.nasa.gov/WWW/cdtb/software/ehmbenchmark.html*
14. *I.Loboda, J.L.Perez-Ruiz, S. Yepifanov, A benchmarking analysis of a data-driven gas turbine diagnostic approach, Proceedings of ASME Turbo Expo 2018, June 11-15, 2018, Oslo, Norway.*

2.6 Dissemination

Below is a list of oublications that refer to the project results

1. F. Sirenko, S. Yepifanov, K. Podgorsky, And S. Nechunaev, “New approach to torque meter development and its calibration,” J. KONBiN, vol. 45, pp. 1–13, 2018.
2. S. Yepifanov Software for gas turbine engine modelling, identification automatic control and health management. Presentation for NATO STO AVT-306 committee. Torino 17.04.2018, Italy.
3. Sergiy Yepifanov Roman Zelenskyi, Aleksandr Khustochka Regularized identification in engine models matching with measured data. in AVT-306 Transitioning Gas Turbine Instrumentation from Test Cells to On-Vehicle Applications Athens 10-12.12.2018. NATO Science and Technology Organization. 10.14339/STO-MP-AVT-306-03-PDF
4. Sergiy Yepifanov Feliks Sirenko Roman Zelenskyi, Kostyantyn Podgorsky The precision analysis of a relative phase-difference torque measurement unit. in AVT-306 Transitioning Gas Turbine Instrumentation from Test Cells to On-Vehicle Applications Athens 10-12.12.2018: NATO Science and Technology Organization. 10.14339/STO-MP-AVT-306-12-PDF
5. Yaroslav Dvirnyk, Dmytro Pavlenko, Radoslaw Przysowa. Determination of serviceability limits of a turboshaft engine. EASN conference. Athens 2-6.09.2019.
6. Olexandr Khustochka, Sergey Chernysh, Sergiy Yepifanov, Mykhaylo Ugryumov, Radoslaw Przysowa. Estimation of performance parameters of turbine engine components using experimental data in parametric uncertainty conditions. EASN conference. Athens 2-6.09.2019.

7. Kyrylo Savchenko, Anatoliy Zinkovskii, Romuald Rządkowski, Vadym Kruts. An Influence Of Shroud Design Parameters On Static Stress State Of Blade Assemblies. EASN conference. Athens 2-6.09.2019.
8. R.Yu. Shakalo, M. Chalimoniuk Methods for inspection of inside cavity of cooled HPT blades with perspective cooling systems (in Russian). International Propulsion Engineering Congress 2-7.09.2019. Kobleve (3.2b)

3. Pilot Project 3.2b: Advanced low-cost small turbine

The AERO.UA pilot project 3.2b plan foresaw that Ivchenko would contact European aerospace companies and research organizations with the aim of conducting a joint feasibility study to further exploit the advanced, low-cost small turbine (400-470 kW), which Ivchenko began developing during the FP7 ESPOSA and FP6 CESAR projects.

The considered turbine is part of a small-size aeroengine (Figure 10) and consists of the following major parts: HPT, inter-turbine diffuser, LPT and turbine exhaust system.

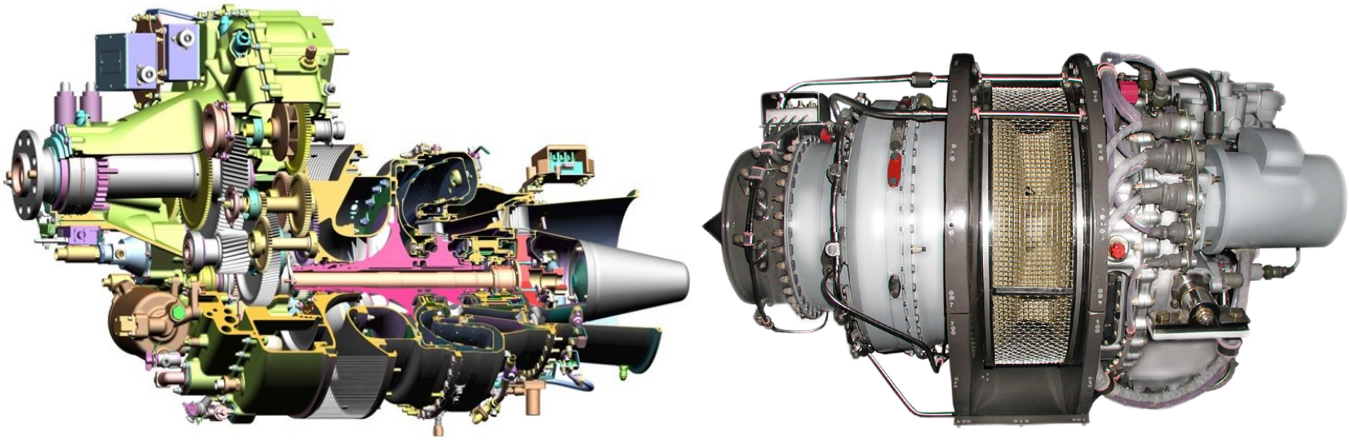


Figure 10. View of a small-size aeroengine with the considered turbine

An aeroengine with the considered turbine can be installed on small aircraft such as DA50JP7 (Diamond Aircraft, Figure 11, left), DART450 (Diamond Aircraft, Figure 11, right), etc.

Figure 11. View of the DA50JP7 (left) and DART450 (right) aircrafts

The considered HPT is a single-stage, axial-flow, transonic module with cooled nozzle guide vanes (19 vanes) and shroudless rotor cooled blades (34 blades).

The LPT is a single-stage, axial-flow and shrouded non-cooled module with guide vanes and rotor blades (44 blades).

The inter-turbine diffuser with fairings of four struts of the turbine bearing support is located between the turbines.

The LPT stator has a multi-splitter configuration. It contains small vanes (19 vanes) and large structural aerodynamic fairings of struts (4 fairings) which are used to support the engine shaft and house service devices.

The turbine outlet unit with three struts is located behind the LPT. A simplified diagram of the turbine is shown in Figure 12.

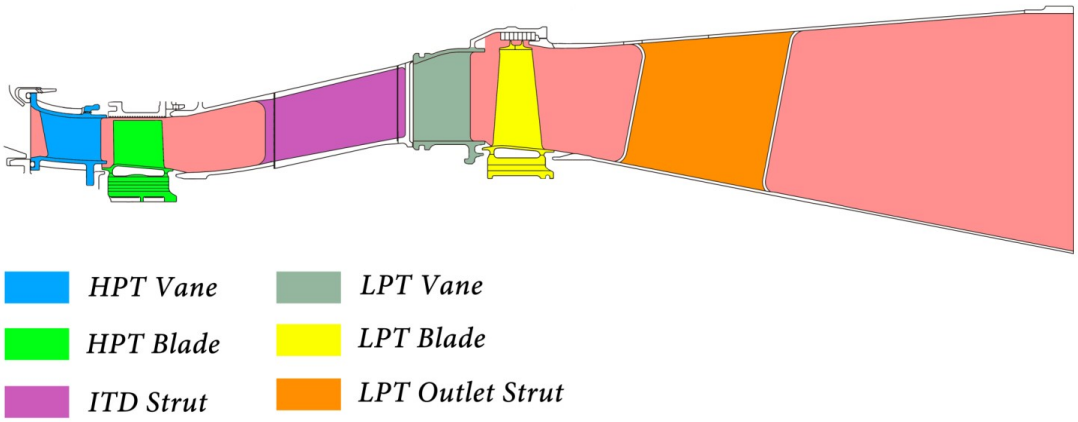


Figure 12. Schematic view of the considered turbine

Ivchenko defined the list of possible tasks to be performed within pilot project 3.2b with the aim of finding EU partners for joint research and cooperation on the topic “Advanced low cost small turbine”.

Ivchenko proposed this list of tasks to all AERO.UA consortium partners (and some companies that are not part of the consortium) and members of advisory board for consideration.

The list of proposed tasks covered the following areas:

- Turbine radial clearance investigations;
- Optimization of the turbine exhaust system;
- Advanced seals;
- Advanced materials and coatings;
- Erosion problems in small HPTs;
- Design and research of advanced cooling systems;
- HPT optimization;
- Investigation of the Combustor - Turbine interaction;
- Additive manufacturing of turbine stationary components;
- Computer tomography of turbine cooled blades.

The work on the proposed areas foresees the use of technologies that are currently under development at Ivchenko-Progress SE (for example, 3D metal printing, computer tomography, etc.). The AERO-UA project is seen as an opportunity to get acquainted with new technologies and approaches for solving the problems of turbomachinery with a purpose of their further introduction into the practice of designing and producing turbines at Ivchenko.

Feedback with proposals of cooperation within different tasks was obtained from companies from within and outside the AERO.UA consortium.

It was planned that after reviewing the proposals received joint EU-UA feasibility studies and some research activities (optional) within the AERO.UA project would be performed for the following tasks:

T.1 Turbine radial clearance investigations;

T.2 Optimization of the turbine exhaust system;

T.3 Optimization of the cooling system for small turbine rotor blades;

T.4 Additive manufacturing of turbine stationary components;

T.5 Computer tomography of turbine cooled blades;

T.6 Experimental definition of thermal conductivity of heat-resistant coatings of turbine cooled blades.

Table 2. Participants of the pilot project 3.2b and their roles

	Partner name	Lead person	Role in the pilot project
1	Ivchenko Progress SE	Aleksandr Koptev	T.1 – a) selection of the clearance measuring system and supplier; b) purchase or leasing of the measuring system – optional; c) system calibration, tests, calculations, redesign of the HPT casing to host the sensors and instrumentation, etc. – optional. T.2, T.3 – a) identification of partners; b) feasibility study; c) providing of the initial data to the partners, numerical investigations and optimization, experiments – optional. T.4 – a) identification of partners; b) feasibility study; c) search for appropriate metal powders for 3D printing of HPT vanes, providing of the CAD geometry of the HPT vane, tests of the 3D printed samples and verification of their properties, installation of printed vanes on the full scale AI-450 turboprop and tests on the Ivchenko test bench – optional. T.5 – providing two different HPT cooled blades for scanning with ITWL's CT scanner. T.6 – a) identification of partners, b) manufacturing of the samples, their coating and providing to ICiMB for thermal conductivity measurements.
2	Technology Partners Foundation (TECPAR) / Air Force Institute of Technology (ITWL)	Radoslaw Przysowa	T.1 – a) assessment of the possibility of using ITWL's optical measuring system within the task; b) system calibration, tests – optional. T.4 – scanning of the 3D printed vane. T.5 – scanning of two different HPT cooled blades provided by Ivchenko.
3	Warsaw University of Technology, Faculty of Power and Aeronautical Engineering, Institute of Aeronautics and Applied Mechanics	Zbigniew Rarata	T.2, T.3 – a) preparation of commercial and technical proposals aimed at collaboration with Ivchenko within the framework of the current tasks; b) optimization of the cooling system for small turbine rotor blades, optimization of the turbine exhaust system – optional.
4	IPPT institute of Polish Academy of Sciences	Krzysztof Kazmierczak	T.4 – a) preparation of a commercial proposal aimed at collaboration with Ivchenko within the framework of the current tasks – optional; b) printing of samples for verification of their properties – optional; c) tests of the printed samples – optional; d) printing of HPT vanes – optional.
5	Thermal Analysis Laboratory, Institute of Ceramics and Building Materials (ICiMB)	Joannę Pagacz	T.6 – a) preparation of commercial and technical proposals aimed at collaboration with Ivchenko within the framework of the current task, b) preparation and performing work related to ceramic coating thermal conductivity measurements

3.1 Background to the pilot project

3.1.1 Task 1 - Turbine radial clearance investigations

Increased efficiency in gas turbines is desirable. Measuring the clearance between moving rotor blades and stationary shrouds in the compressor and turbine sections of gas turbines is desired as the efficiency of a gas turbine engine is dependent upon, inter-alia, the clearance between the tips of its blades and the turbine casing. The smaller the clearances, the lower the gas leakage across the blade tips (Figure 13). However, under certain engine conditions, airfoils and their associated discs may experience thermal growth, thus increasing the risk of contact with the casing.

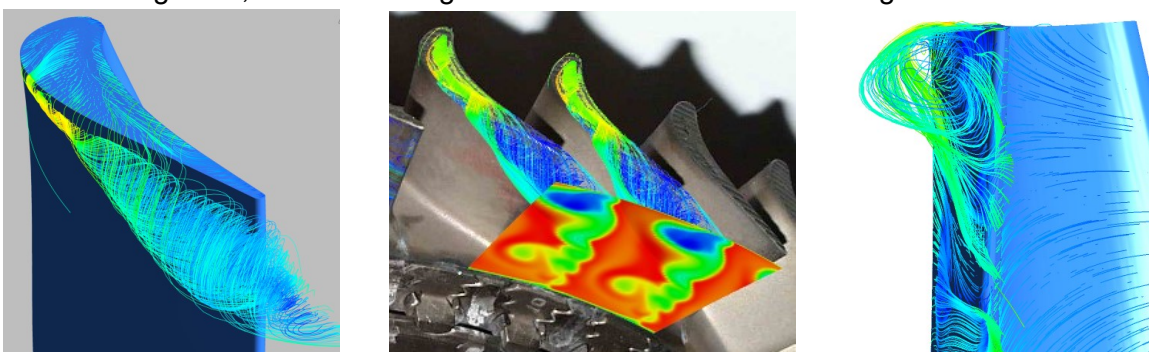


Figure 13. View of the blade over-tip leakage

Accurate measurement of the clearance between the tips of rotating blades and their associated casing is essential for gas turbine engine development.

Currently, all over the world, the measurement of radial clearances is becoming as routine a practice in engine development as thermometering, strain gauging, pressure measurement, etc.

With the increasing optimization of turbomachinery there is a growing demand for precise and easy-to-use measurement equipment.

Ivchenko specialists have considered various systems for measuring the radial clearance: optical, radar and capacitive.

After evaluating the possibility of using the considered systems for measuring radial clearance over the blade tips of high-temperature turbines, capacitive sensors were selected.

The capacitive method for monitoring radial clearance is based on the principle of converting non-electrical values into electrical capacitance values by using capacitive sensors and computer equipment with appropriate software.

A capacitive sensor is a parametric type transducer, in which the change in the measured value is converted into a change in the capacitive resistance.

In terms of design the capacitive sensor is a cylindrical electric capacitor. There are capacitive sensors, the action of which is based on changing the gap between the plates or the area of their mutual overlapping, deformation of the dielectric, changing its position, composition or dielectric constant.

The active surface of the capacitive non-contact sensor is formed by two metal electrodes which can be represented as the "expanded" capacitor plates. The electrodes are included in the feedback loop of a high-frequency self-oscillator adjusted in such a way that, in the absence of an object near the active surface, it does not oscillate. When approaching the active surface of a capacitive non-contact sensor, the object enters the electric field and changes the feedback capacity. The oscillator begins to produce oscillations, the amplitude of which increases as the object approaches. The amplitude is estimated by the following processing circuit, which generates the output signal.

The advantage of the capacitive method is the possibility of mounting the sensor in the hot area above the blades, with the other electronic equipment being at a distance and not exposed to high temperatures.

The main manufacturers of such systems for measuring and monitoring the radial clearance (clearance system) in compressors and turbines are the Pentair company (UK, CapaciSense system), Fogale (France, CAPABLADE system) and Thermocoax. These systems for measuring radial clearances are based on the theory of capacitive resistance and are a unique multi-channel tool for monitoring the condition of blades, carrying out calibrations in rotor installations of various applications.

A typical clearance system includes such basic elements as low-temperature (up to 200 ^{o}C) and high-temperature (up to 1400 ^{o}C without cooling) capacitive sensors, measuring lines, oscillators and demodulators, and data acquisition and processing unit.

The use of such a system makes it possible to resolve the following problems in determining the values of the radial clearance:

- the minimum clearance value for all blades; if it exceeds the allowable limit (set by the user), the program issues a warning;
- the maximum clearance value for all blades;
- the average clearance value for all blades;
- the value of the clearance for each of the blades;
- averaging the above parameters by the rotational speed;
- the ability to post-process the obtained data.

Different types of CapaciSense (Pentair) capacitive sensors are presented in Figure 14.

Figure 14. CapaciSense (Pentair) capacitive sensors – high (left), mid-range (middle) and lower (right) temperature sensors

High temperature sensors (Figure 14, left) are used predominantly for turbine applications. The inclusion of flutes and cooling apertures has advanced the operational capabilities of these designs to over 1400 °C / 2552 °F, allowing several years of operation.

Various shapes of THERMOCOAX capacitive sensors are shown in Figures 15-16 and an example of their installation on engine, in Figure 17.

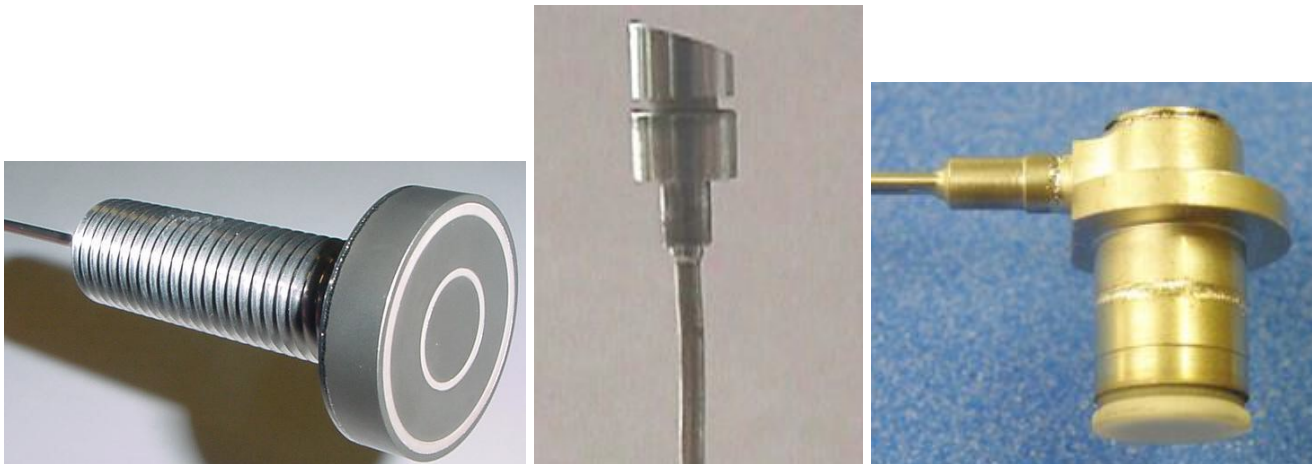


Figure 15. THERMOCOAX capacitive sensors – various shapes

Figure 16. THERMOCOAX capacitive sensor

Figure 17. THERMOCOAX capacitive sensors engine installation

Different types of Fogale capacitive sensors are shown in Figure 18.

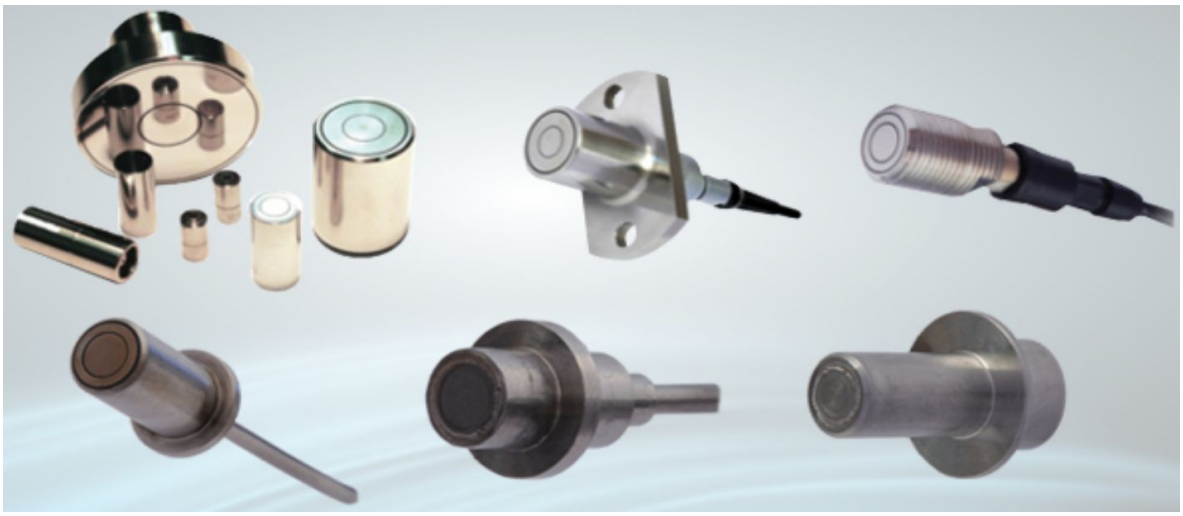


Figure 18. FOGALE capacitive sensors

The CapaciSense Solo (Pentair) system for measuring radial clearances is shown in Figure 19. This system was designed to be a perfect solution for industrial installations, the SOLO is a “one box” electronic solution. Each SOLO unit can be connected to up to 4 probes with up to 20 m of cable connected to them. The system outputs a blade passing signal for each channel which can be recorded by any measurement system, but is truly designed to work in conjunction with the CapaciSense CPM to give live average and blade by blade clearance data, as well as time of arrival tip timing data.

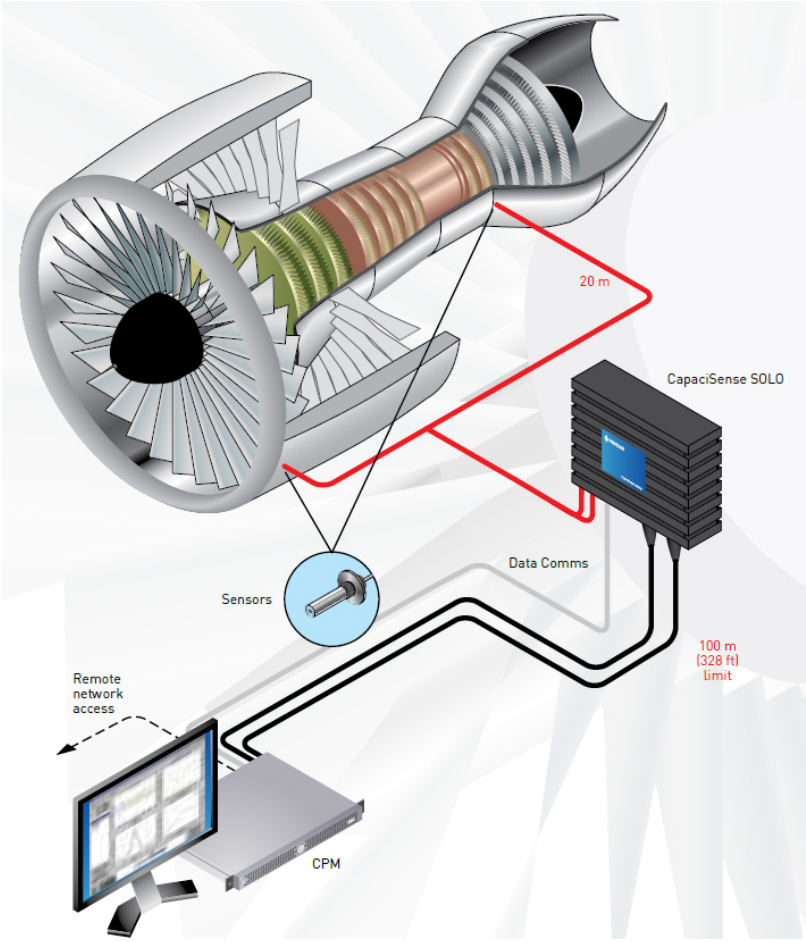


Figure 19. CapaciSense SOLO system components

Task objective:

- to obtain exact turbine rotor-stator clearance values in test conditions
- to verify computational predictions

Task activities:

- feasibility study (selection of the appropriate type of measuring system and supplier);
- purchase or leasing of the measuring system – optional;
- research activities (system calibration, tests, calculations, redesign of the HPT casing to host the sensors and instrumentation, etc.) - optional.

3.1.2 Task 2 - Optimization of the turbine exhaust system

The turbine exhaust duct (TED) is an important and integral part of any gas turbine engine. Its gas dynamic efficiency directly affects the turbine power and fuel efficiency of the engine.

The complexity of the turbine exhaust duct gas-dynamic design is attributed to the following main factors:

- diffusive nature of the flow (the tendency of the flow to separation);
- layout conditions on the aircraft (the need to deflect the flow at significant angles in conditions of limited dimensions).

The joint solution of these problems presents a serious challenge in the design of engines.

The exhaust system of the considered advanced small turbine is presented in Figures 20-21.

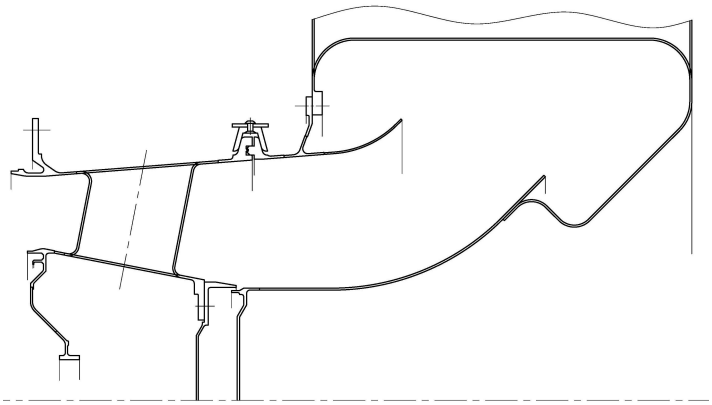


Figure 20. Meridional section of the considered TED

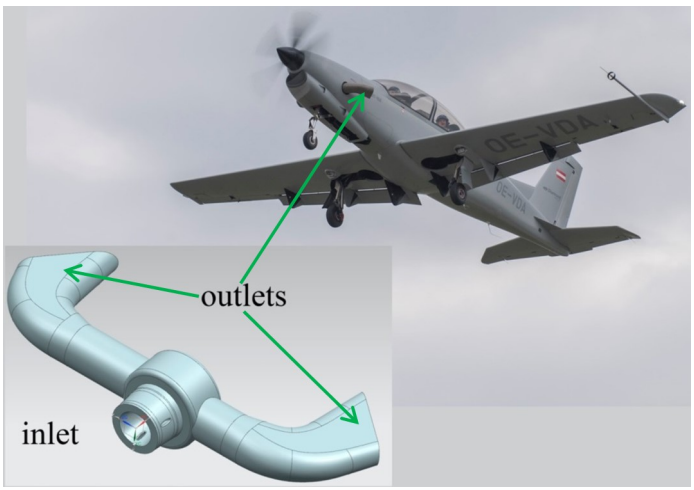


Figure 21. Exhaust system of the considered advanced small turbine

Before the appearance of the computational fluid dynamics methods (CFD), the design of the TED was performed using generalized experimental dependences that allowed for selecting the main geometric parameters and estimating the gas dynamic efficiency. The development (improvement) of exhaust systems was carried out exclusively by experimental methods, and mostly on full-scale exhaust devices.

The development of computational fluid dynamics methods affected the process of TED designing (as well as the rest of the engine components). The use of CFD methods makes it possible to evaluate the effect of individual structural elements, to choose a more optimal profile of the flow section in the specified dimensions.

However, at this stage, when designing with CFD, the following problems exist:

- when searching for the optimal profile of the TED flow section, a significant number of interrelated geometric parameters must be taken into account, which complicates the optimization problem;
- the use of RANS calculations for diffuser ducts does not always give a satisfactory result when comparing the calculation results with the experimental data, which is due to unsteady flow;
- the application of unsteady calculations requires considerable computing resources.

Task objective:

- to improve the efficiency (reduce total pressure losses) of the turbine exhaust system

Task activities:

- identification of partners;
- feasibility study - optional;
- research activities (numerical investigations and optimization, experiments) - optional.

3.1.3 Task 3 - Optimization of the cooling system for small turbine rotor blades

In order to increase the efficiency and the power of modern gas turbines, designers are continually trying to raise the maximum turbine inlet temperature. Over the last decades the temperature has risen from 1500 K to 1850 K for big engines and from 1300 K to 1450 K for small engines. Only about 25% of this temperature increase can be attributed to improved alloys. New materials, such as ceramics, could help to increase this maximum temperature even more in the future. However, most of the recent improvements in inlet temperature come from better cooling of the blades and a greater understanding of the heat transfer and the three-dimensional temperature distribution in the turbine passage. Higher gas temperature generally causes increased blade temperature and greater temperature gradients, both of which can have a detrimental effect on service life. As of today, improvements in computational techniques in turbomachines tend to be more widely applied by industrial researchers because the numerical approaches are quite advantageous in comparison with experimentation, due to ease of modelling, complicated geometry and an unsteady flow nature.

The baseline geometry of the cooling system of the considered HPT blade is shown in Figure 22. This blade has a convective serpentine cooling system with finning of internal surfaces. The cooling air flows into the flow section through four slots near the blade's trailing edge.

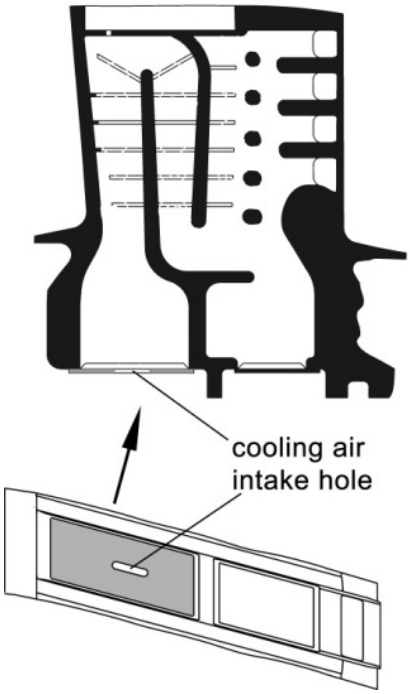


Figure 22. HPT baseline blade cooling system

Task objective:

- to increase the lifetime of the HPT blade.

In order to increase blade lifetime and to consider the possibility of reducing the temperature of turbine blades by changing the design of internal cooling channels, it is necessary to carry out calculations to determine the optimal geometry of the cooling channels and the optimal options for heat transfer enhancement in the internal channels of the blade. In order to increase the high-temperature erosion resistance of the blade, it is also necessary to reduce the temperature of the leading edge on the suction side at the blade periphery.

Task activities:

- identification of partners;
- feasibility study - optional;
- research activities (numerical investigations and optimization, experiments) - optional.

3.1.4 Task 4 - Additive manufacturing of turbine stationary components

Additive manufacturing, also known as 3D printing, offers a completely new, wide range of possibilities for product design. Leaving behind the restrictions of conventional manufacturing methods, new integral solutions featuring complex structures become possible. Nevertheless, this new technology has limitations and restrictions as well. Product developers need a profound knowledge on the design for additive technologies and the manufacturing process itself, in order to ensure that the desired product is buildable and will meet its respective specifications.

3D printing is finding its way into almost every industrial and manufacturing sector, but its introduction in turbomachinery has been relatively slow. Due to the extremely high temperatures, enormous pressures, high rotational speeds and large parts involved, turbomachinery has turned out to be one of the most difficult application fields for 3D printing.

However, the technology has evolved to the point where it can now produce viable turbine and compressor parts. In fact, it can create structures that are more efficient, more intricate and longer lasting than those made by conventional manufacturing methods. Many different components can be produced on demand, eliminating long lead times for foundry-produced parts. As a result, 3D printed components can be produced ten times faster than conventional means.

On the maintenance side, additive manufacturing opens the door to easier and faster repairs.

3D printing in plastic has been used in commercial applications since the 1980s. But in metal, it became commercially available only in 2005. This technology takes three-dimensional engineering design files and transforms them into fully functional and durable objects. Metals and plastics - and now even ceramics - can be employed.

Initially, AM was used primarily in prototyping. But today, it has become a proven approach to manufacturing. Certainly, casting can and should be used to create larger or less complex high-volume parts. But casting itself limits component geometry. 3D printing enables far more complex geometries as well as means of reducing the number of welds needed in components.

Task objectives:

- to investigate the possibility of the installation of 3D printed HPT vanes (Figure 23) and sectors of stationary shroud (Figure 24) on a small aeroengine designed by Ivchenko.

Figure 23. View of the considered HPT vanes

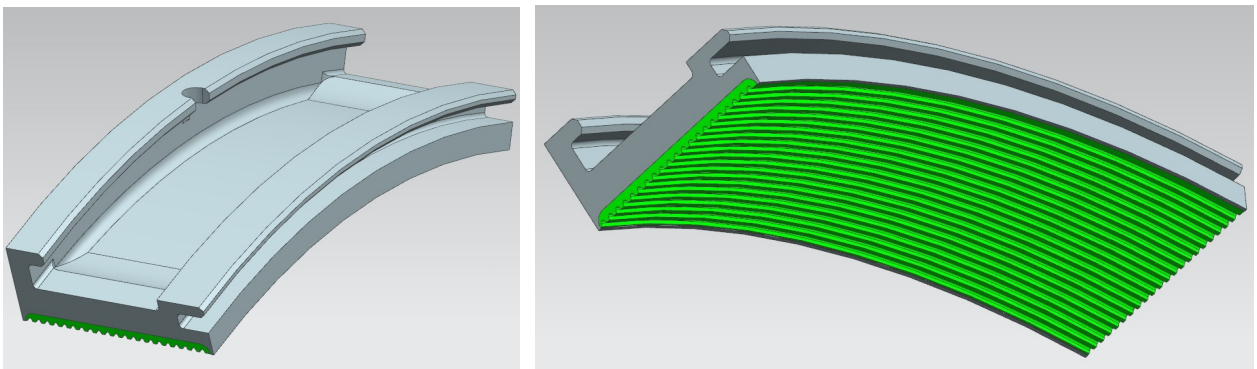


Figure 24. View of the considered stationary shroud

Task activities:

- identification of partners;
- feasibility study - optional;
- research activities – optional

The research activities of this task were as follows:

- finding metal powders for 3D printing with properties similar to the material ZhS6U-VI (for vanes) and EP-648 and M-427.25 (for stationary shroud);

- printing samples of this material;
- testing the 3D printed samples and verifying their properties;
- printing vanes and stationary shroud;
- installing the 3D printed parts on a full scale AI-450 turboprop and testing on the Ivchenko test bench.

3.1.5 Task 5 - Computer tomography of turbine cooled blades

The process of aircraft operation involves defects and failures of various types that affect aircraft driving systems, in particular rotating parts, where turbine and compressor blades are the most endangered components. Such defects entail the need to dismount the entire engine and, consequently, to set the aircraft for a long downtime and to bear substantial financial expenses.

Defects of blade may be classified to several groups according to underlying reasons that are mutually interdependent. The most frequent reasons for defects and failures include:

- manufacturing faults,
- unskilled repairs and upgrades,
- improper operation and maintenance.

Shortcomings in quality of manufacturing and repairs comprise a large group of operational defects that are detected in inner areas of avionic engines, e.g. during endoscopic inspections.

These defects are not in the scope of the user's control and users in no way may counteract them.

Such defects may appear within the entire lifetime period of the equipment and demonstrate a random and stochastic nature.

Repairs and overhauls of driving systems provide the opportunity to evaluate technical condition of rotating parts in a more detailed manner with the use of various NDT techniques that include:

- visual inspection,
- dye penetrant inspection (DPI) or liquid penetrant inspection (LPI),
- ultrasonic inspection,
- conventional (2D) X-ray inspection,
- other techniques.

However, diagnostic capacities of all the above techniques are strictly limited and are thus still insufficiently reliable for assessment of internal invisible defects or failures like subsurface cracks. Currently, the technical condition of blades (e.g. overheating) is assessed by diagnostic personnel mainly by visual inspection with the possibility to verify the diagnostic conclusions by means of destructive methods when metallographic examinations are carried out.

Under such circumstances, the method of computer tomography (CT) provides much better results compared to other test techniques. Although it is a non-destructive technique, it allows detection and verification of defects and flaws also inside the material solid.

In order to diagnose aircraft structures it is indispensable to reproduce the inner structure of the object with high accuracy to e.g.: take geometry measurements, study the material structure, defects as well as to evaluate their condition e.g. during repair (thermal damages, subsurface microcracks, microcracks inside the base material, structural changes, impurities of inner canals etc.). Due to the above, the best results are obtained by using the method with linear detector (Figure 25). In this method the radiation beam is limited by aperture to flat beam and digital linear detector is applied (one series of sensors). Having completed the object rotation of 360°, a flat roentgen slice image is acquired. To obtain a spatial image of the object, it is also necessary to move it along the vertical plane and perform a full rotation at every step. A full 3D image is visible after processing all collected data.

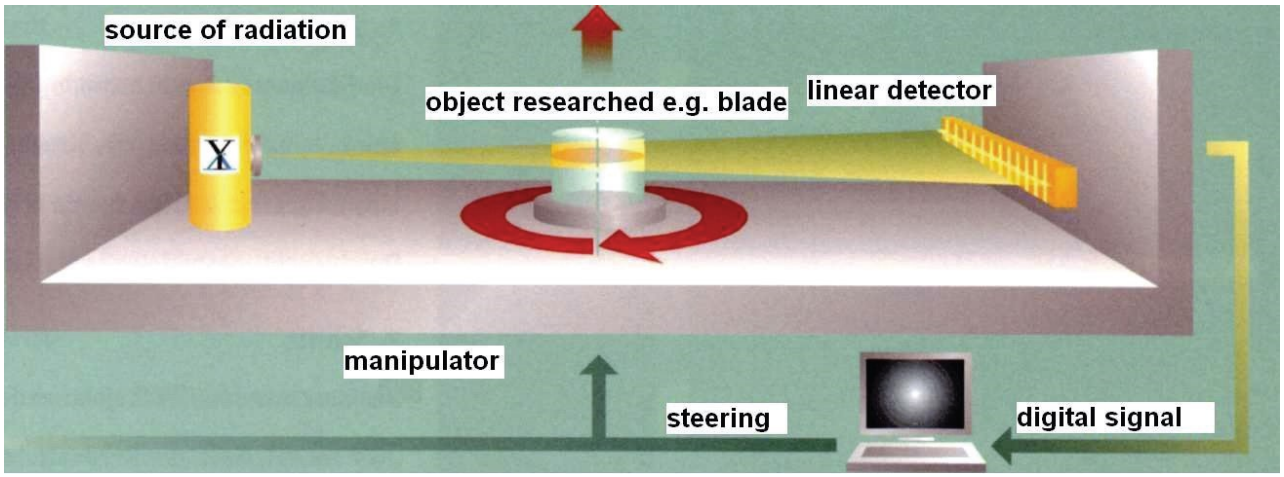


Figure 25. The example of a tomography investigation with use of a linear detector

Task objective:

- to develop a method for monitoring the internal cavities of cooled turbine blades using CT.

Task activities:

- scanning of two different HPT blades designed by Ivchenko-Progress SE with CT scanner.

3.1.6 Task 6 - Experimental definition of thermal conductivity of heat-resistant coatings of turbine cooled blades

Ceramic thermal barrier coatings (TBCs) have received increasing attention for advanced gas turbine engine applications. The advantages of using low thermal conductivity TBCs include potentially higher engine efficiency by increasing gas temperatures, and improved engine reliability by reducing engine hot-section component temperatures.

One may ask why a monolithic ceramic is not used in these applications and in most wear applications. Monolithic ceramics have poor thermal shock resistance and low fracture toughness. The metallic substrate to which a coating is applied provides the necessary toughness to enable many applications where coatings are used. Ceramics are applied as graded, layered, or monolithic coatings. The thermal conductivities of these coatings must be known for engineering design and for design of new coating systems for future applications. As new coating systems are developed with lower thermal conductivities and higher mechanical reliabilities, thinner coatings can be used.

A 30% reduction in thermal conductivity translates into an approximately 100 °C increase in temperature difference across a 200 μm thick coating. Alternatively, a 30% reduction in thermal conductivity would need 30% less coating thickness in order to produce the same surface temperature.

The development of advanced ceramic barrier coatings aims at significantly increasing engine operating temperature while simultaneously reducing air cooling, in order to meet future engine low emission, high efficiency and improved reliability goals. The future ceramic coating systems must be designed with increased high temperature stability, lower thermal conductivity, and improved thermal stress and erosion resistance.

Advanced low conductivity and high temperature capable TBC development requires testing techniques that can accurately and effectively evaluate coating thermal conductivity and stability under expected engine high-heat-flux and thermal cycling conditions.

A variety of absolute and comparative methods are currently used to measure thermal conductivity or diffusivity, including both transient and steady-state techniques. Laser-flash, hot-wire, and three-

omega methods are the most widely used transient techniques. The laser flash analysis (LFA) is used commonly and is typical of the non-contact transient method.

An instantaneous heat pulse is generated by the absorption of the laser energy on the front surface of the sample and it transmits to the rear surface on which the temperature rise is detected by an IR sensor. The principle flash technique scheme and LFA system scheme are shown in Figures 26-27. Using the measured signal and sample thickness (d), the thermal diffusivity (a) and finally the thermal conductivity (λ) can be calculated by means of the following formula:

$$\lambda(T) = a(T) \cdot c_p(T) \cdot \rho(T)$$, where

λ - Thermal conductivity,

T - Temperature,

a - Thermal diffusivity,

C_p - Specific heat capacity,

ρ – Density.

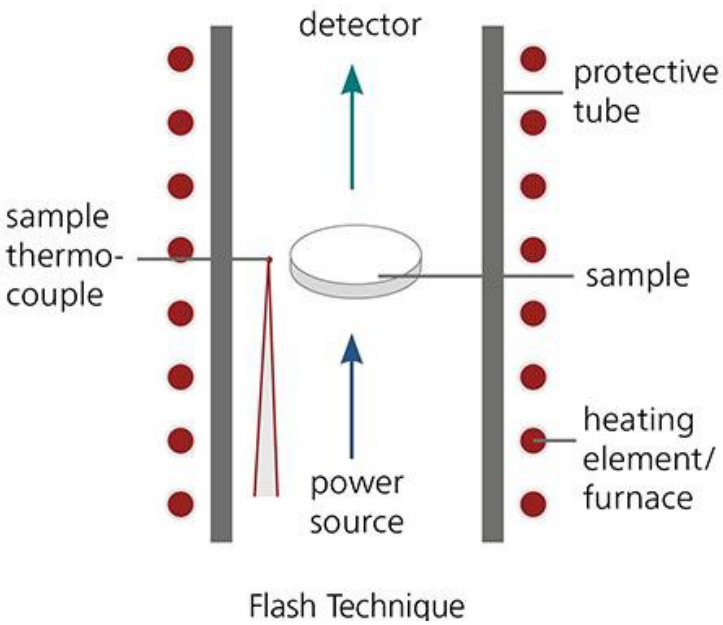


Figure 26. Principal laser flash technique scheme

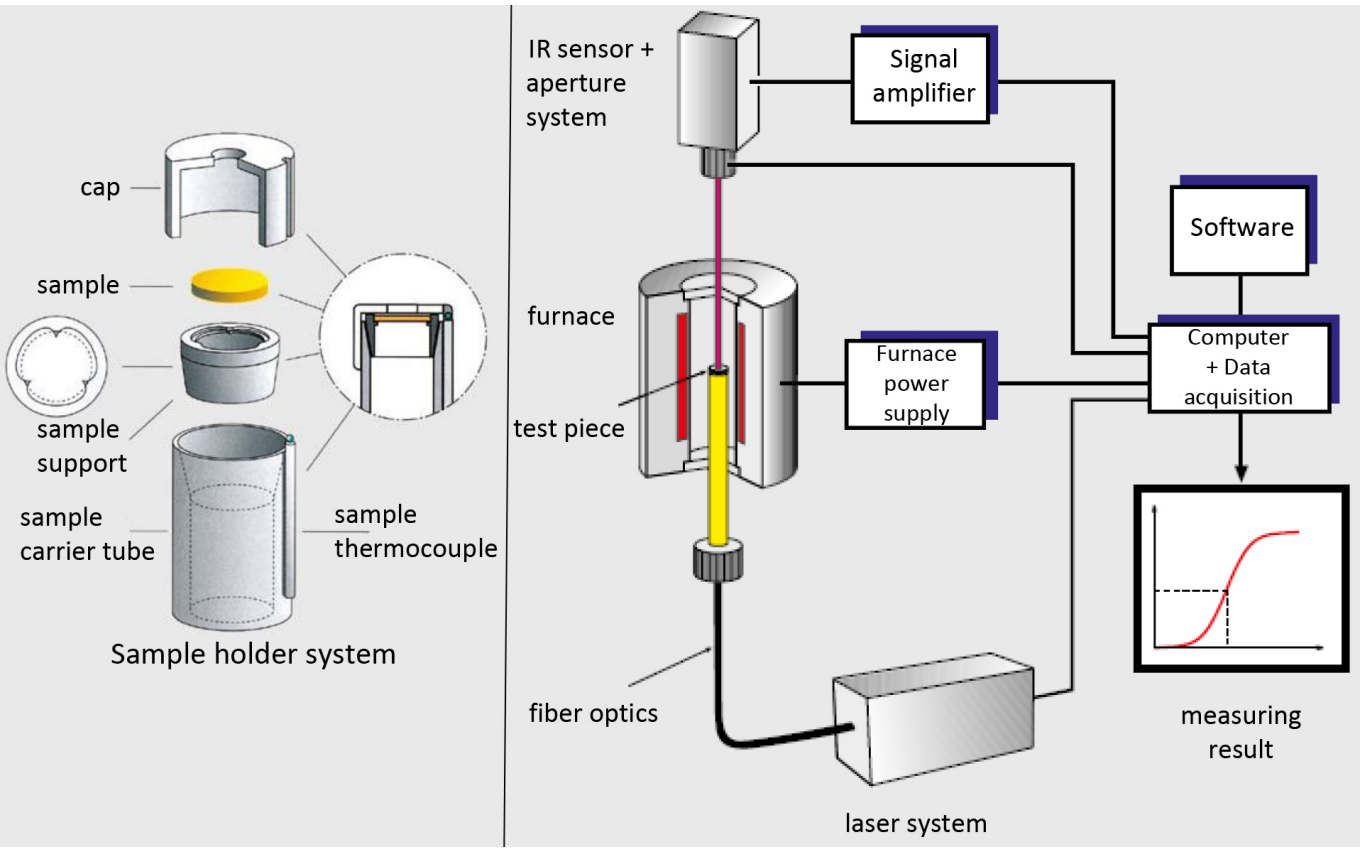


Figure 27. LFA system scheme

This method is widely used because of the small sample size required and the ease and rapidity with which a measurement can be made. The disadvantage of this method is that density and heat capacity also need to be known or measured to calculate thermal conductivity.

Specific heat capacity can be measured using DSC analysis.

Based on ISO11357-1, heat flow DSC is a technique in which the difference between the heat flow rate into a sample pan and a reference pan is determined as a function of temperature and/or time. During such measurement, the sample and reference are subjected to the same controlled temperature program and a specified atmosphere.

In practice, a sample is placed inside a pan and then positioned inside the measurement cell of the DSC instrument (Figure 28) along with an empty reference pan.

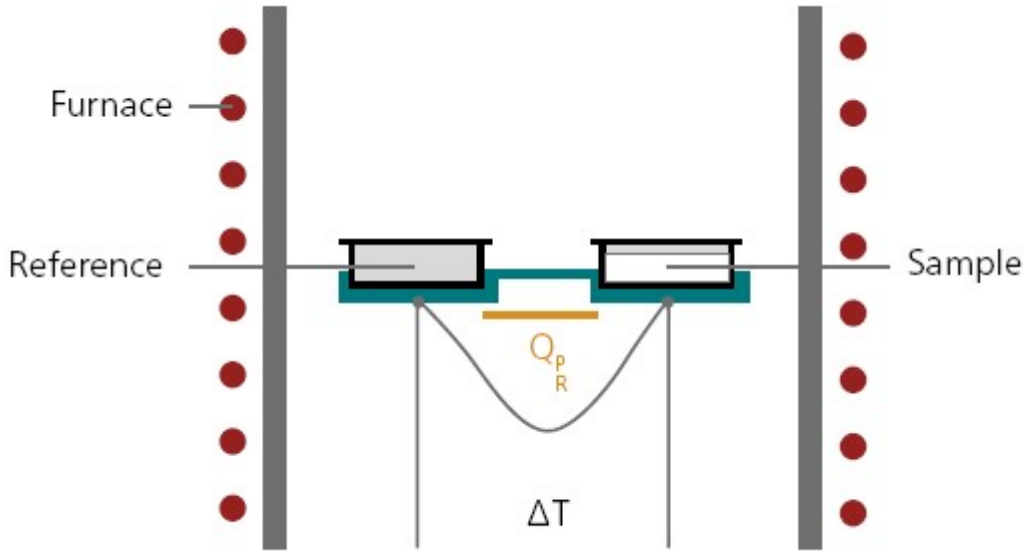


Figure 28. Scheme of heat flow DSC cell

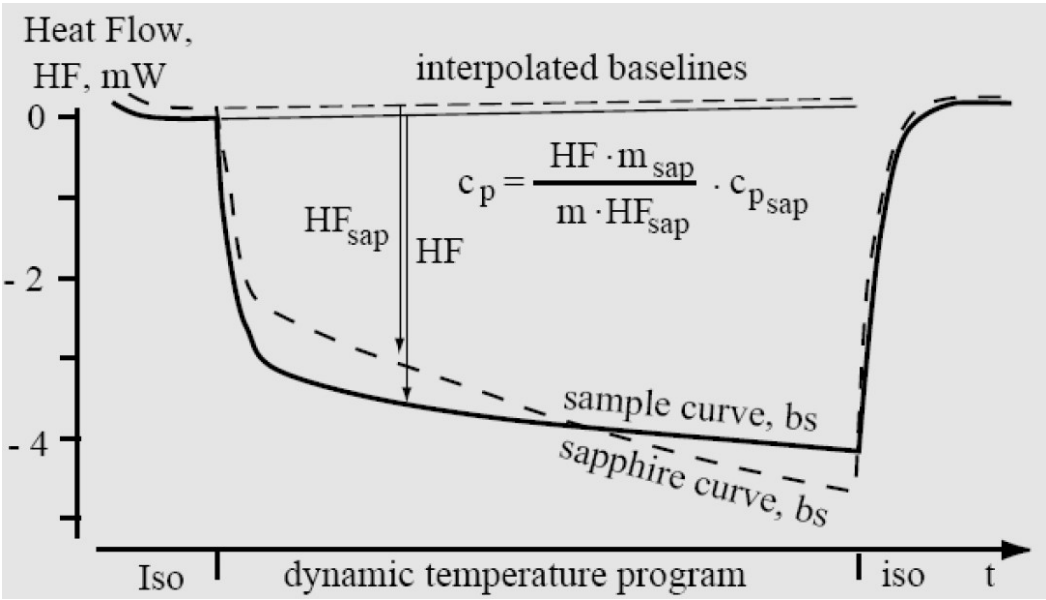


Figure 29. Measurements during "sapphire" method of specific heat determination

Information about thermal expansion and density change can be given by dilatometry (DIL) analysis which is a thermoanalytical technique used to measure the expansion or shrinkage of solids, powders, pastes and liquids under negligible load when subjected to a controlled temperature/time program.

In order to determine the coefficient of expansion the following formula is used:

$$\alpha = \frac{1}{L_0}\left(\frac{\Delta L}{\Delta T}\right),$$

where α - coefficient of expansion, L_0 - initial sample length, ΔT - change in temperature and ΔL - change in length.

DIL high temperature furnace scheme is shown in figure 30.

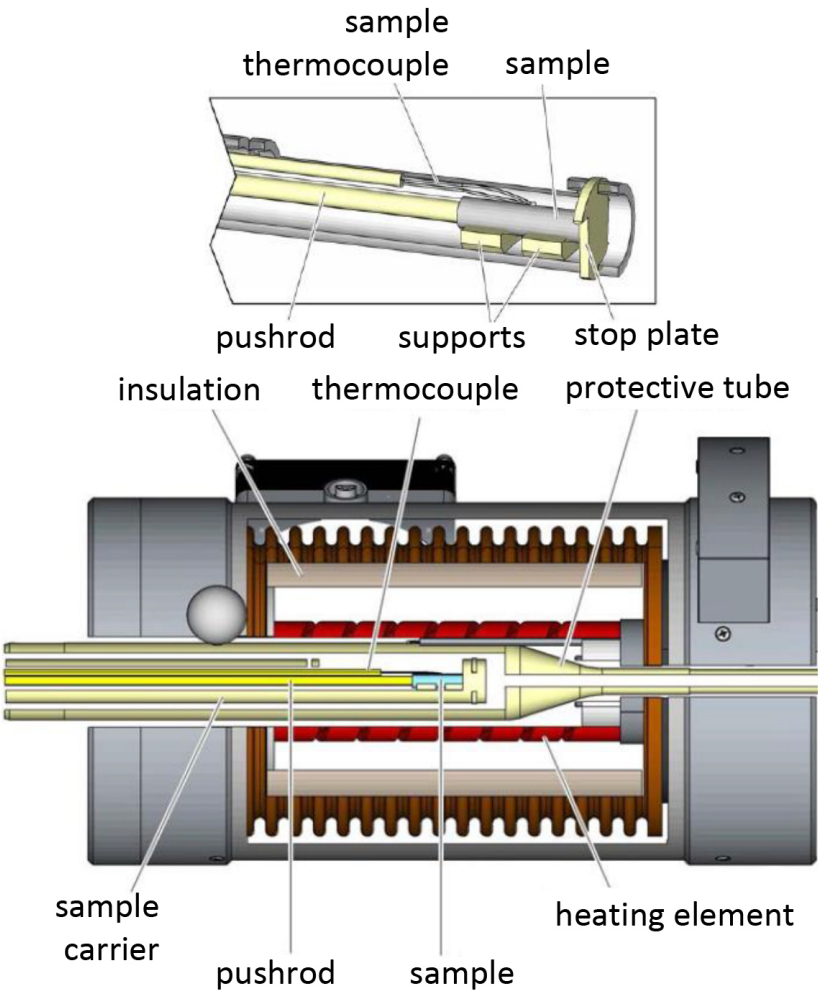


Figure 30. DIL high temperature furnace scheme

Task objective:

- development of the methodology of definition of thermal conductivity of ceramic coatings;
- definition of thermal conductivity of ceramic coating with a thickness of 0.1 mm (deposited on metal samples with two different techniques) within the temperature range of 1000 – 1100 °C.

Task activities:

- experimental definition of thermal conductivity of heat-resistant coatings deposited on samples provided by Ivchenko (ICiMB)

3.2 Knowledge exchanged

3.2.1 Task 1 - Turbine radial clearance investigations

In order to gain experience in the field of radial clearance measurements Ivchenko's specialists contacted their colleagues from «Zorya-Mashproekt», Mykolayiv, Ukraine (who have experience of using micro-wave radial clearance measurement system) and colleagues from ITWL, Warsaw, Poland, who work with optical systems.

Technical requirements for measuring systems were defined and provided to ITWL, Pentair (CapaciSense) and Fogale in order to evaluate the possibility of using their systems for clearance measurements in an advanced turbine for small turboprop.

3.2.2 Task 2 - Optimization of the turbine exhaust system

Ivchenko specialists discussed the technical issues of joint work within the task with Polish partners (Warsaw University of Technology Faculty of Power and Aeronautical Engineering, Institute of Aeronautics and Applied Mechanics) during two on-site visits to Warsaw in September 2017 and May 2018 and by means of e-mail exchanges and web-meetings.

3.2.3 Task 3 - Optimization of the cooling system for small turbine rotor blades

Ivchenko specialists discussed the technical issues of joint work within the task with Polish partners (Warsaw University of Technology Faculty of Power and Aeronautical Engineering, Institute of Aeronautics and Applied Mechanics) during two on-site visits to Warsaw in September 2017 and May 2018 and by means of e-mail exchanges and web-meetings.

3.2.4 Task 4 - Additive manufacturing of turbine stationary components

Ivchenko specialists discussed the technical and organizational issues of joint work within the task with Polish partners (IPPT institute of the Polish Academy of Sciences) during the on-site visit to Warsaw in May 2018 and by means of e-mail exchanges and web-meetings.

3.2.5 Task 5 - Computer tomography of turbine cooled blades

Ivchenko specialists discussed the technical and organizational issues of joint work within the task with Polish partners (TECPAR / ITWL) during two on-site visits to Warsaw in May 2018 and August 2018 and by means of e-mail exchanges and web-meetings.

3.2.6 Task 6 - Experimental definition of thermal conductivity of heat-resistant coatings of turbine cooled blades

Ivchenko specialists discussed the technical and organizational issues of joint work within the task with Polish partners (ICiMB) during two on-site visits to Warsaw in May 2018 and August 2018 and by means of e-mail exchanges.

3.3 Training provided

3.3.1 Task 1 - Turbine radial clearance investigations

Ivchenko specialists visited the presentation of the system for measuring radial clearances and vibrations of rotor blades by CapaciSense (Pentair), held on May 15, 2017 in Zaporizhia, Ukraine. Within the framework of this event, representatives of CapaciSense (Pentair) have presented the measuring systems developed by their company, answered the questions related to the installation, calibration, operation and maintenance of these systems.

3.3.2 Task 2 - Optimization of the turbine exhaust system

Ivchenko specialists attended a five-day classroom training course dedicated to single and multiple objective optimization by means of NUMECA software.

The training course was held on December 05-09, 2016 in Brussels, Belgium.

3.3.3 Task 3 - Optimization of the cooling system for small turbine rotor blades

Ivchenko specialists attended a four-day classroom training course dedicated to modelling of the turbine cooling by means of NUMECA software.

The training course was held on March 12-15, 2018 in Brussels, Belgium.

3.3.4 Task 4 - Additive manufacturing of turbine stationary components

Ivchenko specialists attended a training course dedicated to additive manufacturing, 14-16.05.2018, IPPT, Warsaw, Poland.

3.3.5 Task 5 - Computer tomography of turbine cooled blades

Ivchenko specialists attended training courses dedicated to X-ray computer tomography, 14-16.05.2018, ITWL, Warsaw, Poland and 20-22.08.2018, ITWL, Warsaw, Poland.

3.3.6 Task 6 – Experimental definition of thermal conductivity of heat-resistant coatings of turbine cooled blades

Ivchenko specialists attended a training course dedicated to thermal conductivity measurements, 20-22.08.2018, ICiMB, Warsaw, Poland.

In addition, Ivchenko specialists visited the University of Manchester in November and participated in the “Composites in Action” workshop and in a workshop on the dynamics of machines, in particular aircraft engines, aimed at getting acquainted with the achievements of the dynamic analysis group of the University of Manchester and to initiate research cooperation.

3.4 Scientific and technical results

3.4.1 Task 1 - Turbine radial clearance investigations

Different clearance measuring systems were considered by Ivchenko.

Because of very hostile environment in considered turbine it is not possible to use ITWL’s optical system in this task in contrast to capacitive systems.

Commercial proposals from several EU suppliers were received and considered by Ivchenko.

The contract for making a purchase of the radial clearance measuring system was made with ***Pentair**** in April 2019. According to the contract the measuring system will be delivered to Ivchenko not later than in October 2019.

** 2018 - Pentair Thermal Management (CapaciSense) becomes nVent CapaciSense; 2019 - nVent Capacisense becomes part of Gadcap Technical Solutions UK Ltd.*

3.4.2 Task 2 - Optimization of the turbine exhaust system

In order to perform works within the Task 2, Pilot project 3.2b the following partner was found:

Warsaw University of Technology Faculty of Power and Aeronautical Engineering, Institute of Aeronautics and Applied Mechanics, Warsaw, Poland.

Commercial and technical proposals aimed at collaboration with Ivchenko within the Pilot Project 3.2b Task 2 were received from the present partner:

Offers № ZA/1/2018 and № ZA/2/2018

Ivchenko became a NUMECA company (Brussels, Belgium) software user in 2016 and every year since (2017-2019) bought new modules of the NUMECA software and new licenses/seats.

Ivchenko specialists attended a classroom training course dedicated to single and multiple objective optimization by means of NUMECA software (05-09.12.2016, Brussels, Belgium).

After consideration of obtained proposals and taking into account current state of preparedness of Ivchenko specialists for solving Task 2 Ivchenko decided to perform task 2 on its own.

For the moment, an internal plan for further activities on current topic was developed. This plan includes numerical and experimental works aimed at optimization of the advanced small turbine exhaust system (Ref. Figure 31). Ivchenko specialists have started implementation of this plan with numerical investigations. In order to ensure a systematic and efficient search among many shape variations, a fully 3D CAD (computer aided design) parametric model of the turbine exhaust system was developed. Design search and optimization has been performing by means of advanced CFD (computational fluid dynamics) optimization tool based on design of experiments methodologies and response surface methods.

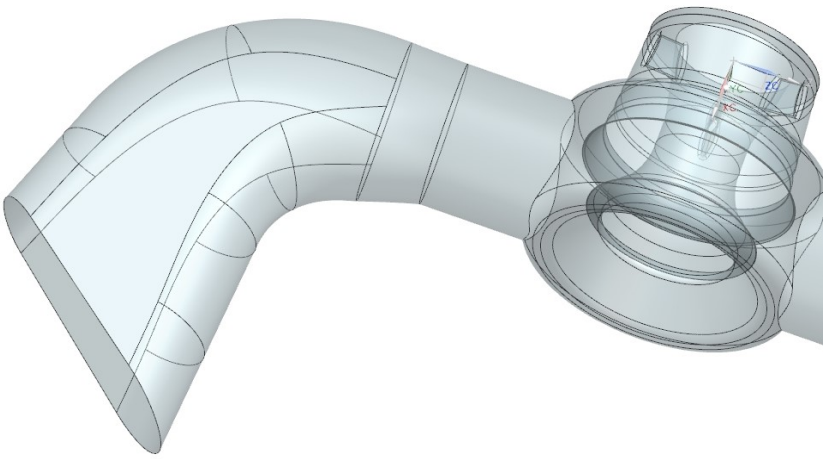


Figure 31. Baseline geometry of the advanced small turbine exhaust system

In addition to flow path shape modifications, variants of exhaust system geometry with different guide walls inside the exhaust tubes (Ref. Figure 32) is being considered during the optimization.

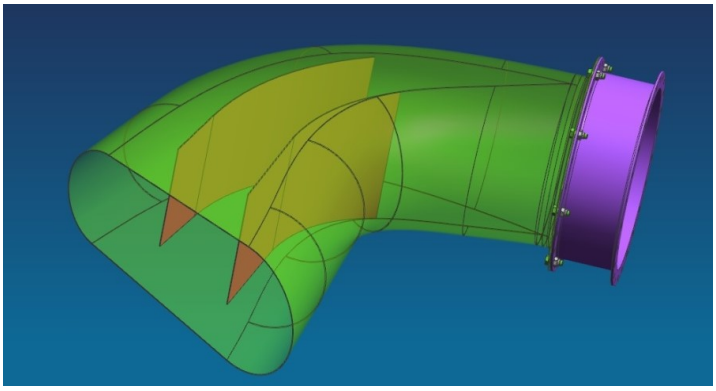


Figure 32. Variant of exhaust geometry with guide walls inside the exhaust tubes

3.4.3 Task 3 - Optimization of the cooling system for small turbine rotor blades

In order to perform works within the Task 3, Pilot project 3.2b the following partner was found:

Warsaw University of Technology Faculty of Power and Aeronautical Engineering, Institute of Aeronautics and Applied Mechanics, Warsaw, Poland.

Commercial and technical proposals aimed at collaboration with Ivchenko within the Pilot Project 3.2b Task 2 were received from the present partner:

Offers № ZA/3/2018 and № ZA/4/2018

Ivchenko became a NUMECA software user in 2016 and every following year (2017-2019) bought new modules of the NUMECA software and new licensees/seats.

Ivchenko specialists attended a classroom training course dedicated to the modelling of turbine cooling by means of NUMECA software (12-15.03.2018, Brussels, Belgium).

After consideration of obtained proposals and taking into account current state of preparedness of Ivchenko specialists for undertaking Task 3 Ivchenko decided to perform Task 3 on its own.

For the moment, an internal plan for further activities on current topic was developed. This plan includes numerical and experimental works aimed at optimization of the cooling system for small turbine rotor blades. Ivchenko specialists have started implementation of this plan with investigations aimed at reducing of the temperature of the leading edge on the suction side near the blade tip. Different blade cooling system geometries are under consideration (some of them are shown in Figure 33).

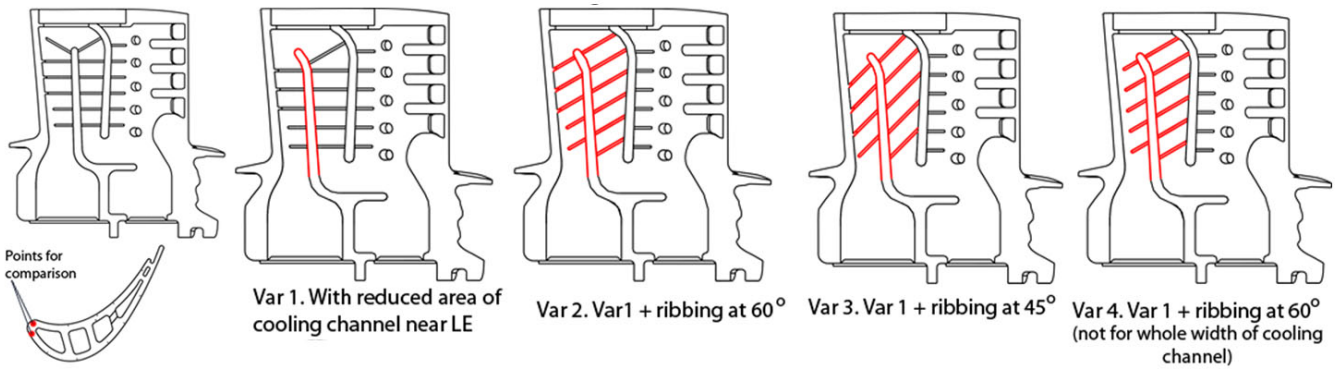


Figure 33. Base variant of blade cooling system geometry with indication of points for temperature comparison and 4 new studied variants of blade cooling system geometry

3.4.4 Task 4 - Additive manufacturing of turbine stationary components

In order to perform work within the Task 4, Pilot project 3.2b the following partners were found:

- IPPT institute of Polish Academy of Sciences, with 3D printing laboratory which is a part of the KEZO research centre managed from IMP Gdansk.

- Air Force Institute of Technology (ITWL), Warsaw, Poland.

IPPT's 3D printing laboratory is equipped with EOS INT M280 System (3D metal printer, Figure 34) which can be used for single or low serial production of metal parts by direct metal laser sintering method.

The machine can build parts from materials such as stainless steels, maraging steels, aluminium, nickel superalloys, cobalt chromium superalloys, titanium alloys. Build volume: 250 mm x 250 mm x 325 mm. The machine has the ability to change the setting parameters of the sintering process, which makes it possible to carry out R & D work.

Figure 34. View of laser sintering system EOSINT M 280

The machine can build parts from materials such as stainless steels, maraging steels, aluminium, nickel superalloys, cobalt chromium superalloys, titanium alloys. Build volume: 250 mm x 250 mm x 325 mm. The machine has the ability to change the setting parameters of the sintering process, which makes it possible to carry out R & D work.

Initially it was planned to consider 3D printing of HPT vane and HPT shroud. But during the discussions between Ivchenko's and IPPT's specialists it became clear that since the cover body has to be sintered on top of the shroud body (which is not flat) it would not be possible to do it with powder-bed fusion technology (used at IPPT), which requires flat surfaces.

As a result, only HPT vane 3D printing will be produced within 3.2b pilot project Task 4.

During two visits to Warsaw, Poland in May 2018 and August 2018 Ivchenko specialists familiarized themselves with the metal printing (IPPT) and CT scanning (ITWL) equipment technology.

Work performed during the period May 2018 – August 2019:

- the mathematical model of the HPT vane (Figure 35) was developed by Ivchenko and provided to IPPT;
- IPPT performed printing of the aluminium vane (Figure 36);
- ITWL carried out CT scanning of this vane (Figure 37);
- 3D printed geometry was analysed by Ivchenko;
- Ivchenko developed the "Joint work plan for HPT guide vane 4500401001 manufacturing with additive technology" and provided it to IPPT and ITWL for approval.
- Ivchenko found the supplier of metal powder of the material ZhS6U-VI for HPT vane printing;

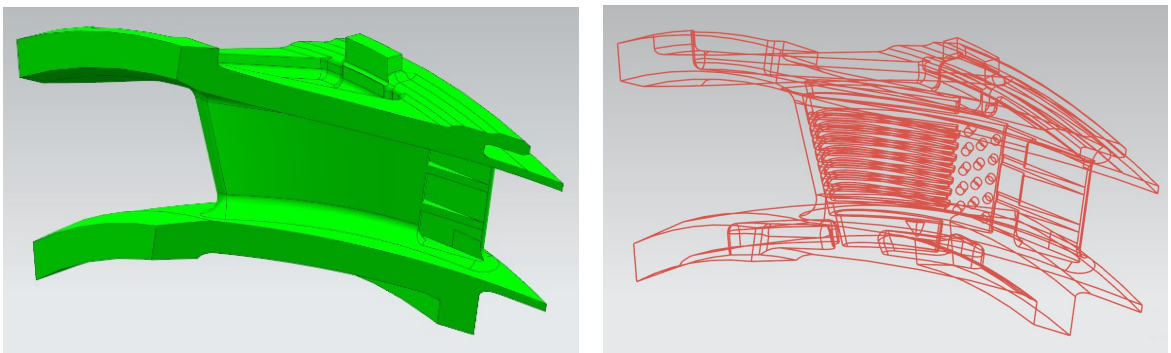


Figure 35. View of the 3D model of the considered HPT vane

Figure 36. View of the printed aluminium vane

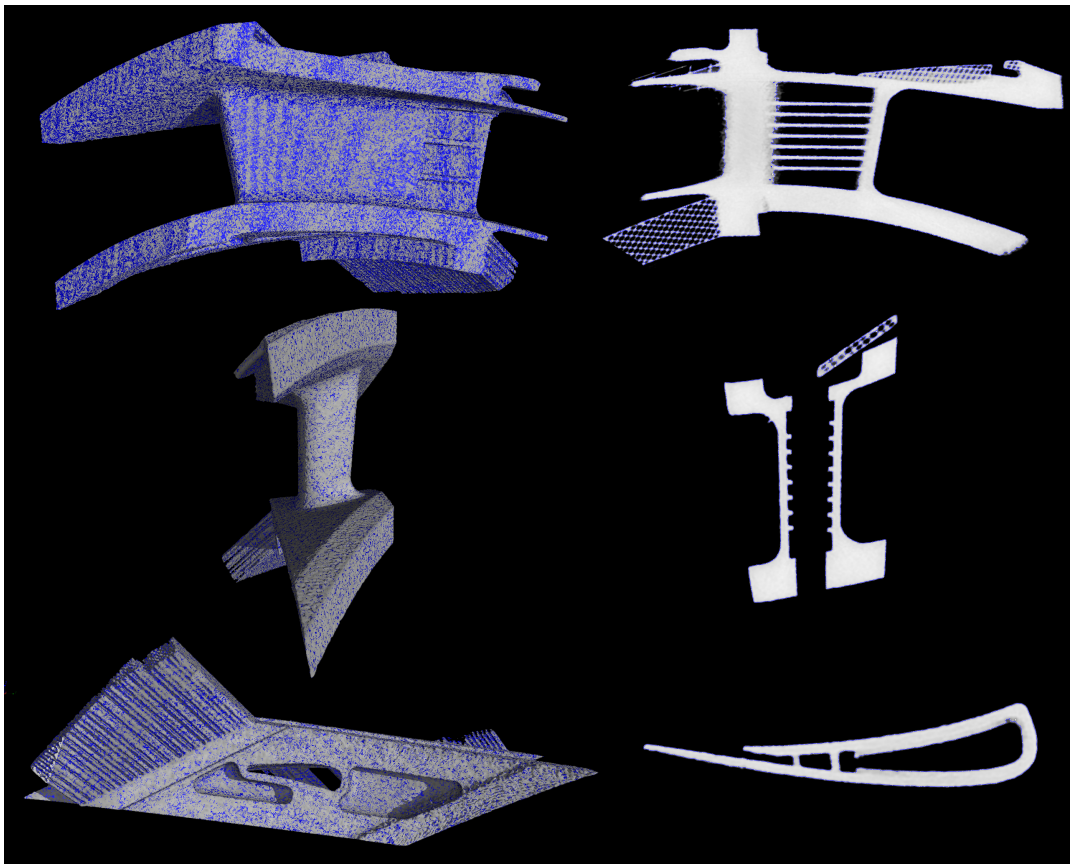


Figure 37. Scanned images of the printed aluminium vane

In March 2019 joint work within this task was frozen because of the inability of the IPPT institute of the Polish Academy of Sciences to continue supporting Ivchenko with the additive manufacturing (AM) of turbine stationary components due to temporary loss of staff with the required AM expertise. However, both sides are still interested in further collaboration. The joint work is scheduled to resume in September 2019.

3.4.5 Task 5 - Computer tomography of turbine cooled blades

In order to perform works within the Task 4, Pilot project 3.2b the following partner was found:
Air Force Institute of Technology (ITWL), Warsaw, Poland.

ITWL's CT system v/tome/x m 300 (Figure 38) with maximum voltage/power of the X-ray tube being 300 kV/500 W was used for performing the current task. This device is also equipped with an X-ray tube for nanotomography with voltage/power of 180 kV/15 W. It allows for conducting research work encompassing a wide range of aircraft materials, e.g.: titanium alloys, steels, composite materials, etc. Non-destructive tests might be carried out with a very high resolution. Defects below 0,5 µm are detected by using the X-ray tube with 180 kV and materials with high density, e.g.: titanium aircraft blades, by applying the X-ray tube with 300 kV. The weight of the elements under study: up to 50 kg, with dimensions of 500 x 500 x 600 mm.

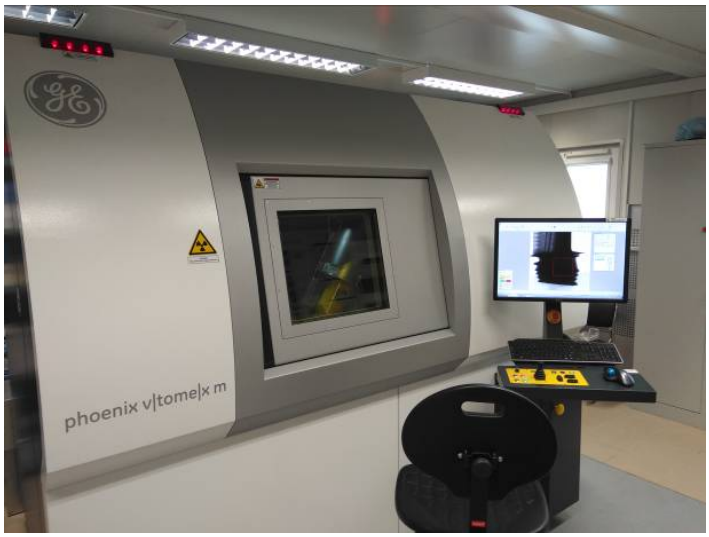


Figure 38. The V/Tome/x m 300 tomograph owned by ITWL

To date, ITWL has successful experience in the tests of high-pressure turbine blades from RD-33 engine. The system owned by ITWL CT is one of the few in Europe to provide the power making it possible to fully X-ray the turbine blades. Having X-rayed and screen refreshed the 3D image during the verification process in a specialized VGStudio MAX 3.0 software, the shape and possibility of inner channels, manufacturing defects (cracks, lack of additional material, air voids), geometry and thickness of walls (also inner walls) on the whole height of blades, can be checked. Blades can be verified in all directions.

On August 20-21, 2018, scanning of SE Ivchenko-Progress turbine blades was carried out in ITWL, Warsaw using the X-Ray tomograph in order to develop a method for monitoring the internal cavities of cooled turbine blades using computer tomography.

HPT blades (previously discarded during manufacture) with different cooling systems were selected for scanning: blade 1 and blade 2 (Figures 39-40).

Blade 1 (Fig. 39a) has a convective-film cooling system with a developed serpentine system of internal channels having transverse fins.

The cooling system of blade 2 (Fig. 39b) is formed by five internal cavities 1-5 (Fig. 39b), which are not interconnected and are separated by transverse fins 6-9 (Fig. 39b). Each of the internal cavities consists of channels interconnected by bridges.

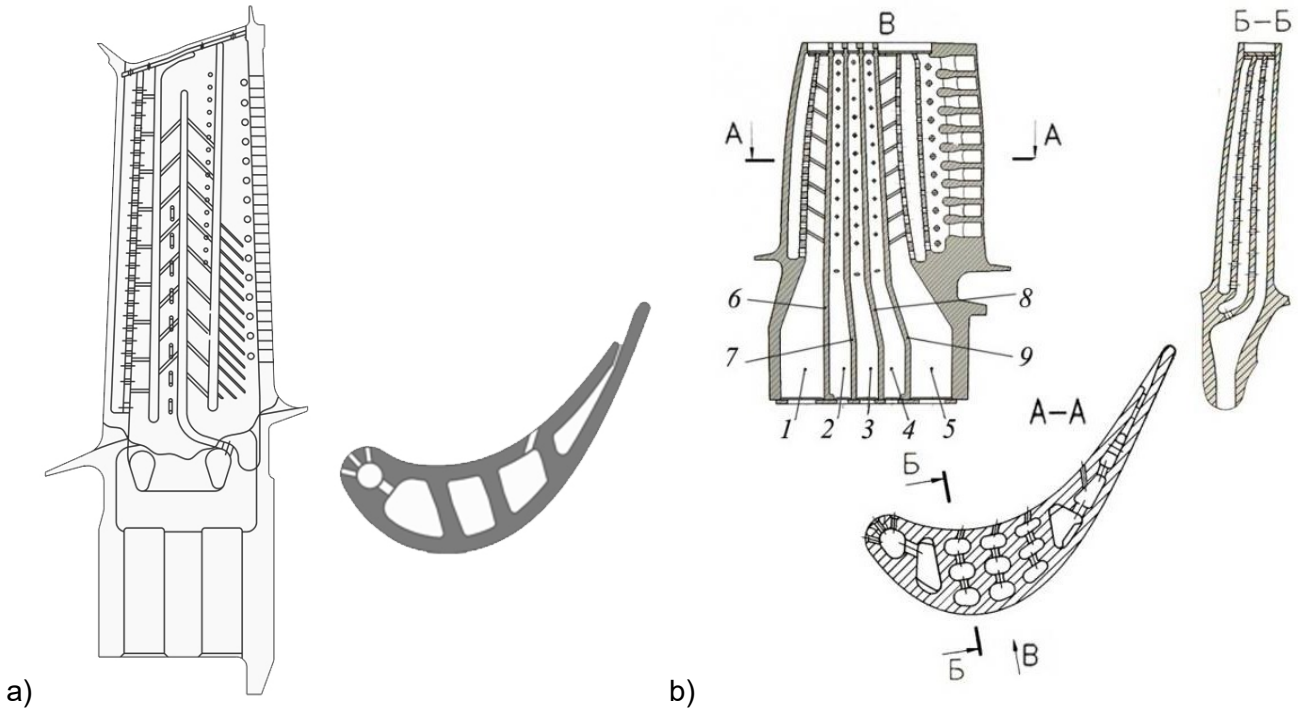


Figure 39. Demonstration of cooling internal passages of the considered blades.
a - blade 1, b – blade 2

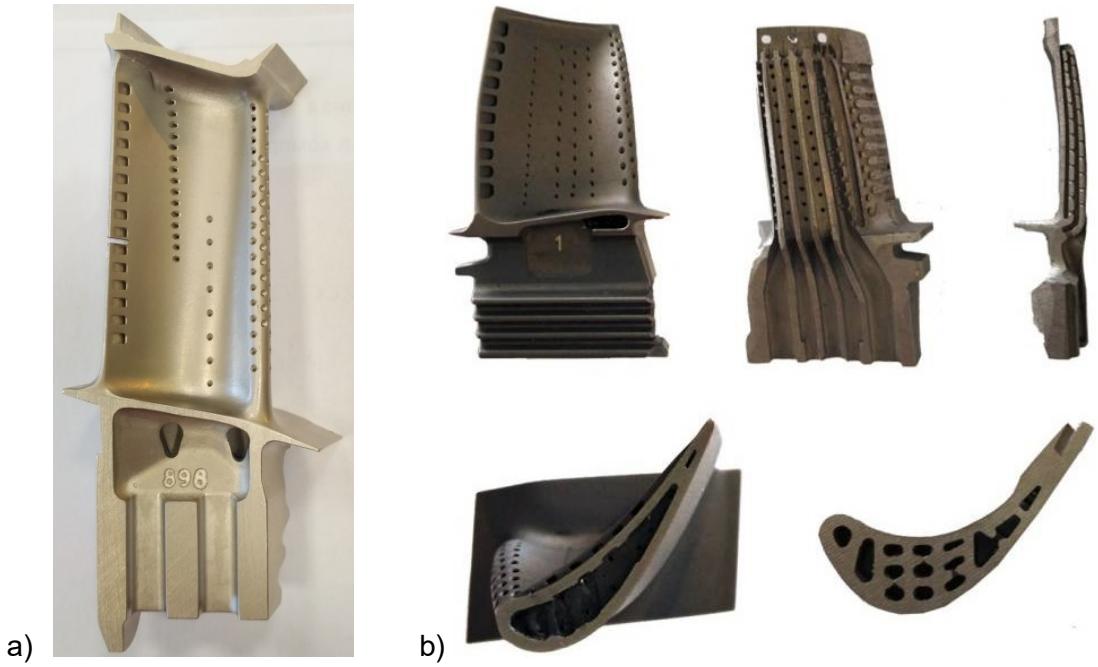


Figure 40. View of manufactured blades 1 (a) and 2 (b)

The selected HPT blades were discarded during the manufacturing process due to defects in the internal cavities, such as discontinuity, run-out (displacement) of the rod, cutting of perforations into the walls during electrical discharge machining, unacceptable debris cavities.

The identification of such defects under the conditions of established production is associated with very labour-intensive inspection operations, and in some cases the inspection is completely impossible without the destruction of the part or without the implementation of costly repairs. Given this, there is a risk of installing parts with defects on the product.

During scanning turbine blades 1 and 2 on the tomograph, the defects in the internal cavities were clearly visible and classified (Ref. Figure 41-43).

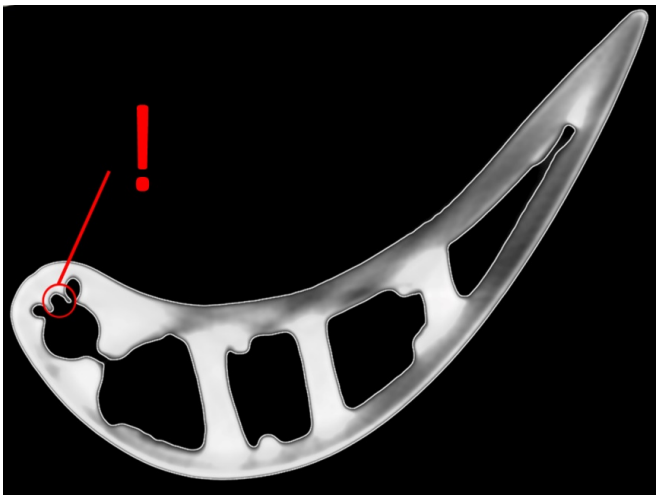


Figure 41. Gathering of film-cooling holes, displacement of the rod

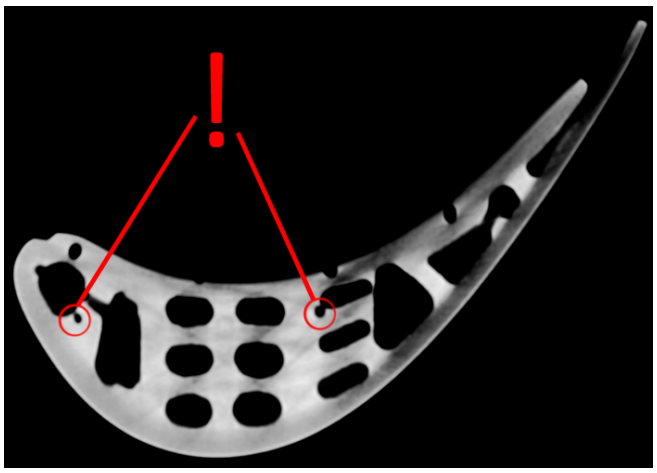


Figure 42. Cutting of perforations into the walls

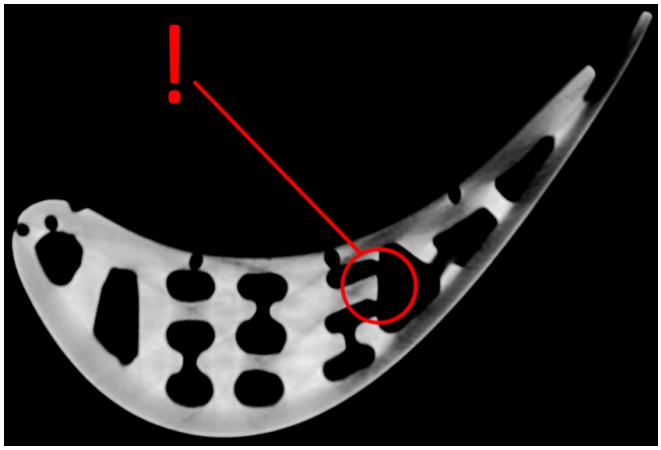
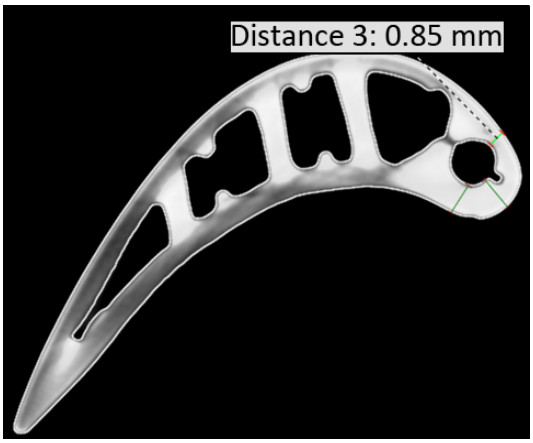


Figure 43. Displacement of the rod

At the same time, the debris cavities were not visible; it may be necessary to increase the quality of scanning, which would increase the inspection time.

The VGStudio software allows for inspecting geometric dimensions specified in the drawing (Ref. Figure 44-45). However, for the inspection of geometric dimensions specified in the drawing, additional special equipment is needed to install the blades during scanning. Without such equipment, combining the coordinate system of an inspected blade with the coordinate system in a mathematical model is a labour-intensive process that is not always possible. Without combining the coordinate system (or without proper positioning in the VGStudio software) that inspection of geometric dimensions, airfoil profile, etc. is impossible or not indicated.

a) 

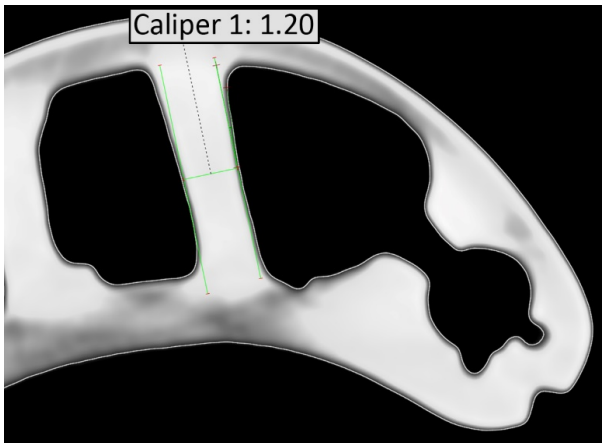
b) 

Figure 44. Wall thickness control (a) and internal fins thickness control (b)

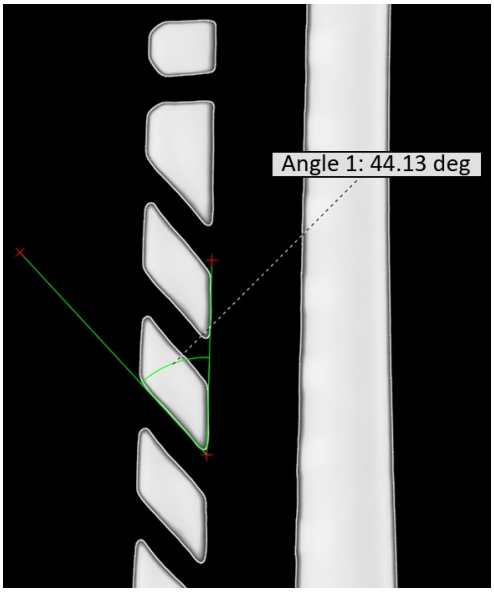


Figure 45. Control of the angle of perforations

With a clear visualization of the part borders, the dimension inspection in the VGStudio software is possible with an accuracy of up to 0.01 mm. The sharpness of the borders depends on the scanning quality. The scanning quality depends on the dimensions of the part, lamp power and scanning time.

Additionally, the welded joint of HPT nozzle guide vanes (Ref. Figure 46) was inspected. Given that the welded joint is very small (approximately 0.03 mm) and that it connects two homogeneous materials, the inspection of such joint is very labour-intensive. Nevertheless, during the inspection, it was possible to classify the discontinuity of the welded joint (Ref. Figures 47-48).

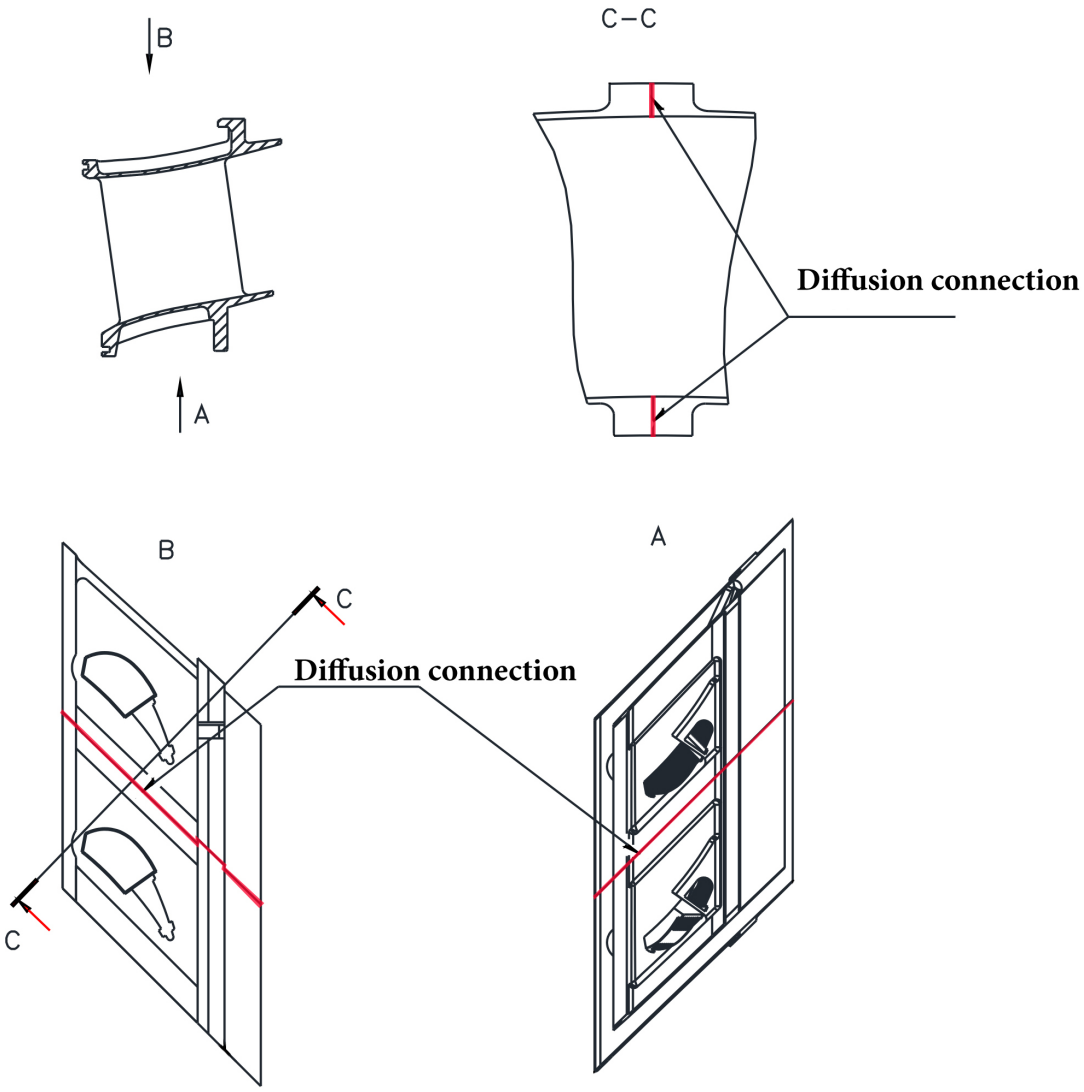


Figure 46. View of the studied HPT vanes and joint

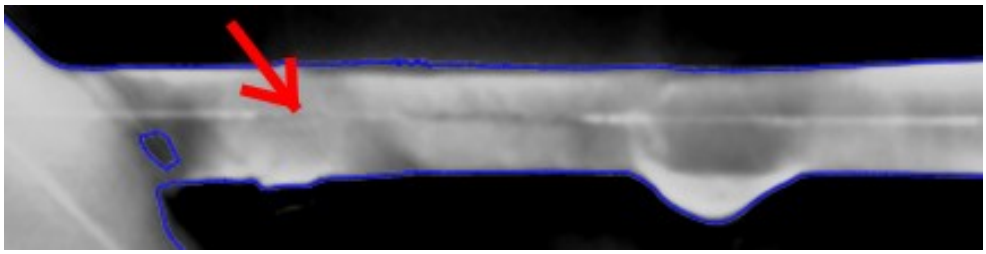


Figure 47. Discontinuity of the welded joint

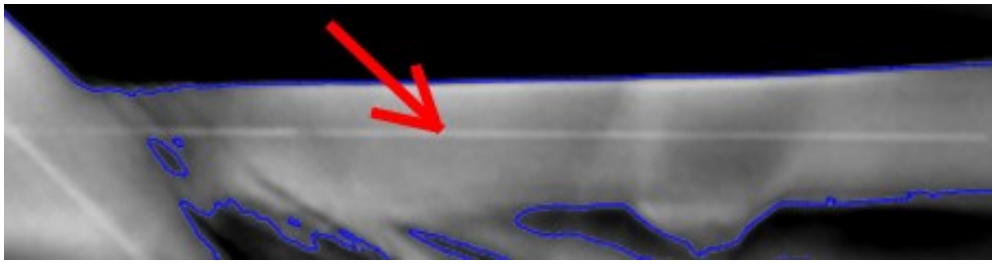


Figure 48. Quality welded joint

Conclusions:

1. The use of tomography allows for identifying defects and deviations in the internal cavity of the blades, as well as defects in the joints.
2. The use of tomography to inspect the geometric dimensions of the part is most likely not advisable due to its high complexity.
3. The use of tomography is advisable, for example, when performing certification of moulds for blade manufacture, i.e. for single measurements or measurements with a small periodicity.
4. The feasibility of using tomography in mass production must be evaluated taking into account the economic effect of its introduction.
5. It is possible that mass production requires more efficient tomographs or their complexes.

3.4.6 Task 6 - Experimental definition of thermal conductivity of heat-resistant coatings of turbine cooled blades

During two visits to Warsaw, Poland in May 2018 and August 2018 Ivchenko specialists held negotiations with the ICiMB representatives about cooperation aimed at performing measurements of thermal conductivity of ceramic coatings used for coating Ivchenko turbine blades. As a result of these negotiations, it was agreed that Ivchenko would manufacture the samples required for performing the work within the current task. One part of the samples was coated by ceramic coating using Ivchenko's technique. Other samples were coated using the technique of the Paton Turbine Technologies Co Ltd, Kyiv, Ukraine. Then all the samples were delivered to ICiMB for the thermal conductivity measurements.

Scheme of the samples for the measurements with dimensions is presented in Figure 49.

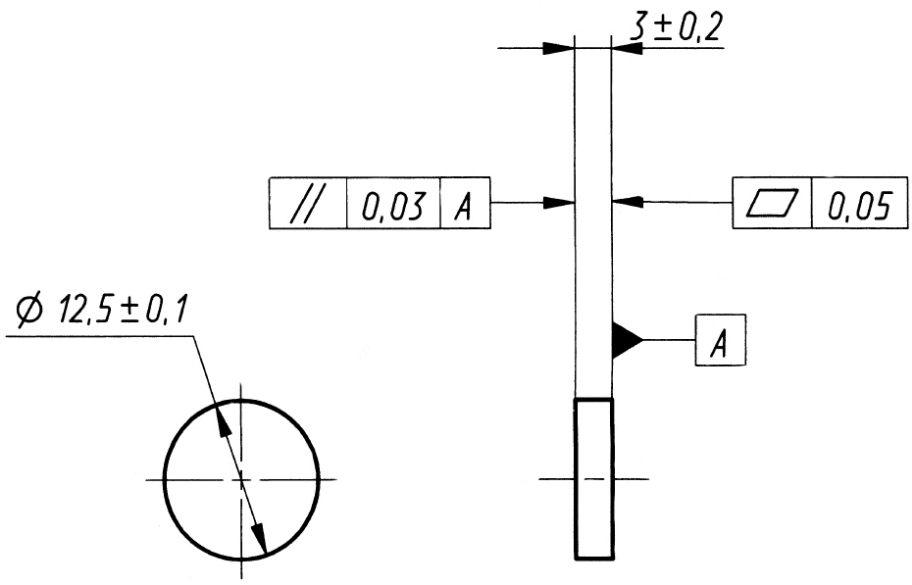


Figure 49. Geometry of the samples for thermal conductivity measurements (dimensions provided for a sample without a coating)

Coating of surface A (ref. Figure 49) is a gas-circulating chrome-calorizing with the following covering with a metallic sublayer and a heat-resistant coating.

Thickness of the chrome-calorizing is 0.015 – 0.035 mm;

Thickness of the metallic sublayer on surface A is 0.06 – 0.08 mm;

Thickness of the heat-resistant coating on surface A is 0.08 – 0.10 mm;

Roughness of the coated surface A: Ra =0.4.

For the moment, ICiMB provided technical (including requirements to samples) and commercial proposals to Ivchenko. Ivchenko considered these proposals and started the process of drawing up a contract for performing joint work with ICiMB. Also, Ivchenko started manufacturing samples according to the obtained requirements.

3.5 State of the art comparison

Today, the sphere of Ivchenko-Progress activities covers design, manufacture, test, development, certification, putting into series production and overhaul of gas turbine engines for aviation and industrial applications. The company has more than 60 design, quality and reliability certificates from international bodies including Bureau Veritas, EASA, Central Civil Aviation Administration of China, IAC AR and GosAviaSluzhba of Ukraine.

The research and test facilities of the company are continuously improved and are amongst the most advanced in the world. They include 17 test benches and 78 rigs used for solving various problems related to engine testing, component development, certification, reliability and fuel-consumption.

In view of aforesaid, for the moment, Ivchenko sees its main role in possible EU-UA collaboration as a performer of different experiments concerning engine parts, modules or full-scale engines on its own test benches. Also having great experience in designing of a wide range of gas turbine engines Ivchenko is interested in cooperation with EU companies aimed at design and development or modernization of aero-engines or their parts.

3.5.1 Task 1 - Turbine radial clearance investigations

Within the AERO-UA project Ivchenko made a purchase of the CapasiSense system equipment for advanced small turbine radial clearance measurements. This system is developed in line with latest progress in all the associated technologies and this solution is the world's state of the art for radial clearance measurements in high temperature gas turbines.

3.5.2 Task 2 - Optimization of the turbine exhaust system

Aerodynamic optimization has become an indispensable component for any aerodynamic design, including gas turbine exhaust systems. With advancements in computational power, automated design optimization procedures have become more competent and it helped to reduce the number of experiments during design and optimization of the systems. Though experiments are still very important.

Ivchenko uses the joint numerical-experimental approach for optimization of the turbine exhausts.

For numerical optimizations Ivchenko uses different software (for instance, Numeca Design3D) dedicated to performing aerodynamic parametrization and optimization of the geometry (including taking into account numerous operational and geometrical uncertainties, under which the industrial products operate). Further, Ivchenko's manufacturing and testing capabilities allow to manufacture most promising variants of the investigated geometry (obtained numerically) and test them on Ivchenko's test benches and rigs. Such philosophy used by Ivchenko (calculation + experiment) for optimization is the most reliable approach to date.

3.5.3 Task 3 - Optimization of the cooling system for small turbine rotor blades

Due to complexity of the design and manufacturing of small turbine rotor blades with internal cooling systems, normally, rotor blades of small turbines are not cooled. In this context the small turbine

blade designed by Ivchenko and considered within the pilot project 3.2b, is unique, because it is cooled. The blade has serpentine cooling system with regularly spaced turbulators on the interior walls and trailing edge channels with pressure side slots. Due to the lack of information about other small turbine cooled blades, the world's state of the art in turbine cooling will be considered concerning bigger turbine blades.

The current state of the art in turbine cooling is the culmination of several decades of both development and experience. The actual mechanisms of internal cooling and film cooling, the two main methods in use, have in fact been demonstrated for roughly 50 years now. What has changed over that period of time is an increase in our fundamental knowledge of the cooling methods, an introduction of several variants upon such methods as turbulators, pin fins, and diffuser shaped film holes, incremental improvements in super alloy temperature capabilities, the introduction and widespread use of thermal barrier coatings, the introduction of new manufacturing methods (e.g. laser drilling) and the advancement of investment casting technology, and experience. The change driving all of these advancements has been the constant increase in turbine inlet temperatures plus the demand for lower specific fuel consumption. Cooling techniques have not made any revolutionary changes, but rather the methods and their many variations have been forced to keep up with turbine components requiring greater amounts of cooling air in order to survive. Testing and experience, applied to the same fundamental methods, have contributed the most over time.

The state of the art now contains dozens of internal component cooling methods, most centered on a few bulk forms of cooling such as serpentine channels and impingement, with their many variations. Film cooling in contrast, while seeking innovative geometries and deployments, still relies mainly on only a handful of basic forms that have been known for 40 years.

A typical state of the art cooled HPT blade is depicted in Figure 50. The blade is cooled mainly with a serpentine channel having regularly spaced turbulators on the interior pressure and suction side walls, impingement in the high heat load leading edge region, trailing edge channels with pressure side bleed slots, and strategically placed rows of film holes. A state of the art turbine blade uses between 5 and 8% of compressor discharge air for cooling of the airfoils, platforms, and tips. The blade's opposing shroud, or blade outer air seal, may use 1 to 3% air.

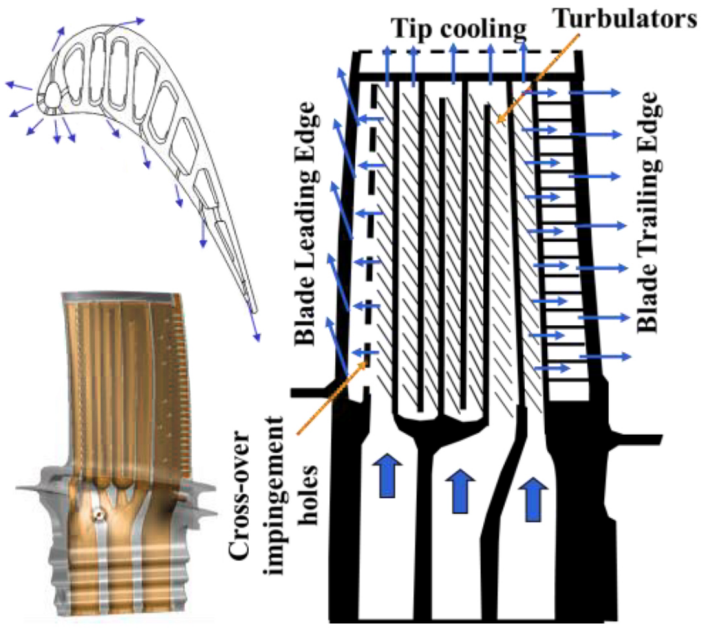


Figure 50. Typical state of the art cooled HPT blade

At the present time, state of the art has reached to a nearly flat portion of the technology curve plateau in overall cooling effectiveness (Figure 51). State of the art includes and continues to use in practice all of the technologies and designs below this plateau. Fundamentally, a turbine blade must next undergo a more revolutionary change to progress further.

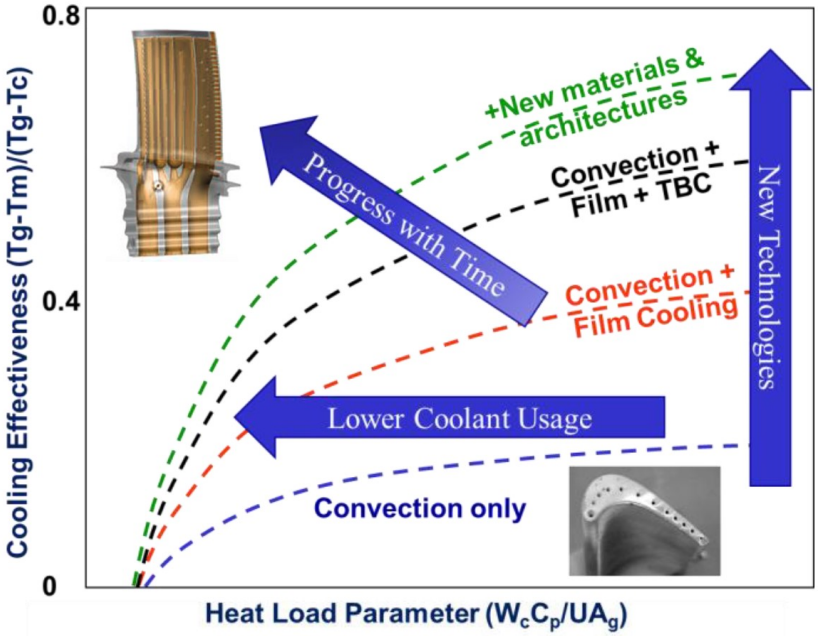


Figure 51. Notional component cooling technology curves

For the moment one of the most promising Ivchenko's designs for the HPT blade cooling system with turbine inlet temperature of 1900K and above is the wall-cooled design or a system with inter-wall cooling (Ref. Figures 52-53). The HPT blade with such inter-wall cooling system was designed and manufactured from high-temperature nickel alloy by Ivchenko. Blade design was patented in 2011 (1 - Ukrainian patent "Turbine Cooling Blade" № UA 62233 U, registered 25.08.2011; 2 - Russian patent "Turbine Cooling Blade" № RU 117505 U1, registered 25.08.2011).

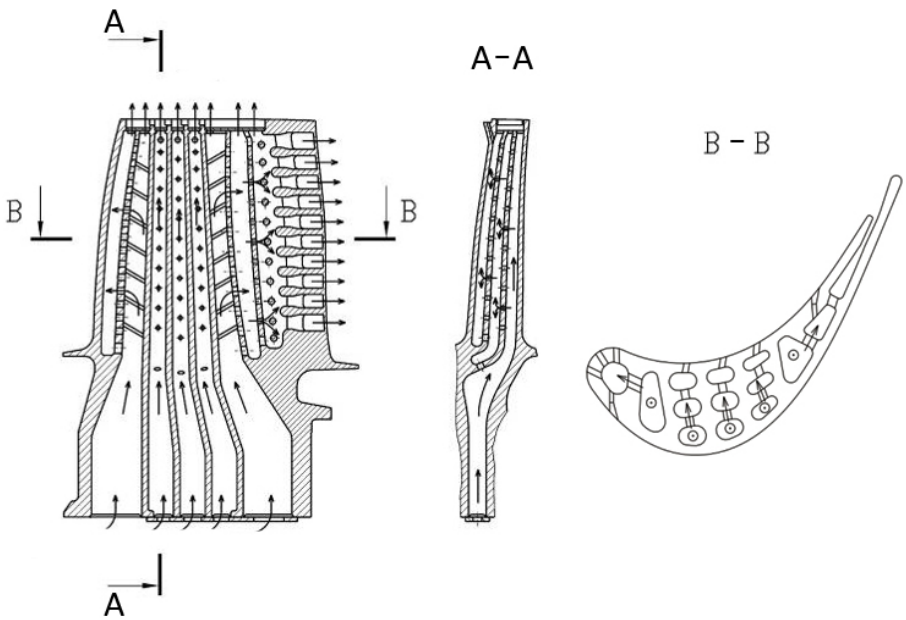


Figure 52. HPT blade with inter-wall cooling system designed by Ivchenko

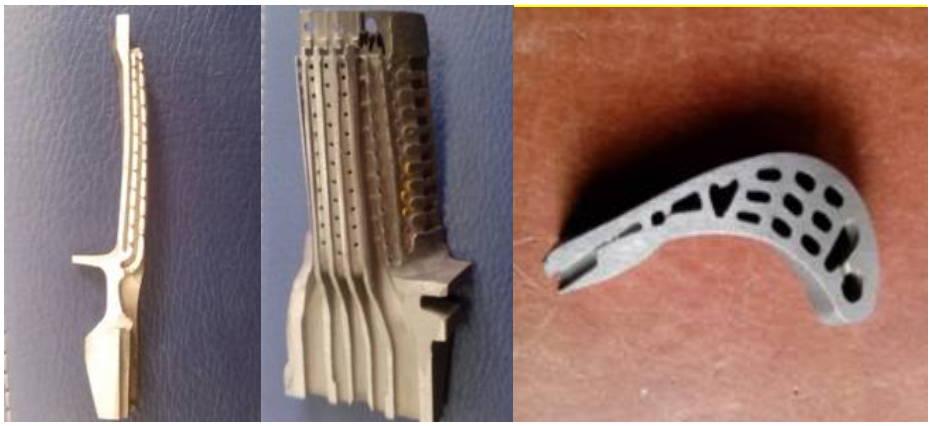


Figure 53. View of the manufactured HPT blade with inter-wall cooling system

In order to evaluate the efficiency of this perspective cooling system Ivchenko performed a row of tests when the HPT rotor was assembled with both types of blades: blades with the baseline cooling system (typical internal convection (serpentine) cooling configuration with film cooling) and blades with the inter-wall cooling system.

Obtained results showed that the life cycle of HPT rotor blade with the inter-wall cooling system is 4 times longer than the life cycle of the blade with the baseline cooling system. Also, the inter-wall cooling system provides 50-70 K turbine inlet temperature increase for the same blade lifetime.

3.5.4 Task 4 - Additive manufacturing of turbine stationary components

Today, the aerospace industry has come to the point of full scale serial production with AM for certain components, and the trend is that the number of parts and applications is steady increasing. Companies such as Airbus, GE and Siemens are heavily investing in equipment to ramp up the production speed with ambitions of several thousands of machines in the 2020's.

Current AM applications are mainly for low stressed "static parts" that are non-critical, and made out of traditional construction materials. However, official press releases from numerous aerospace companies have stated that more advanced AM parts will be used in the future.

Another method of AM production in aerospace is by adding material to an existing part in order to improve thickness, and thus increase strength. This enables prolonged use of parts as they can be repaired instead of scrapping them, and building completely new parts, thus streamlining production of aerospace components.

Below are selected examples of AM used in the gas turbine engine industry:

– **Siemens** is a pioneer in AM and already uses the technology for rapid prototyping. Furthermore, the company is now developing solutions ready for series-production for manufacturing gas turbine burner nozzles and repairing burner heads. Just recently Siemens achieved yet another breakthrough: the first gas turbine blades ever to be produced using AM have successfully finished performance testing under full-load conditions.

– **GE Aviation** aero engine manufacturer has decided to produce 35% of the upcoming advanced turboprop (ATP) engine for the Cessna Denali business jet by AM.

Engine fuel nozzles for the Leap 1A engine are a product that is in serial production in the GE AM plant. Both the engine and the AM produced fuel nozzle are in full service operation on the Airbus A320 NEO family of aircraft operated by e.g. SAS and Lufthansa. Managed to lower cost, weight and number of parts with increased performance, the AM produced part has helped reduce fuel consumption in the engine. There are orders of more than 4500 engines.

– **Honeywell Aerospace** today uses AM to produce Inconel parts for series production for aero engine components. Research is ongoing around other materials.

The Sintavia metal additive manufacturing company has also announced that it has been approved to manufacture components for Honeywell Aerospace using powder bed fusion. Honeywell parts which include gas turbine auxiliary power units (APUs), turboshaft engines, turbofan engines, and engine control valves, all of which contain extensive metal components and may now be 3D printed using Sintavia's powder bed fusion process.

– **Rolls-Royce** has announced that 3D printing is leading the way for the next generation of aircraft engines. Competing with GE, and reinforcing the global industrial 3D printing market, Rolls-Royce has performed flight-tests of the largest 3D printed aerospace component to ever power an aircraft. Incorporated into its Trent XWB-97 engine, the UK aerospace manufacturer and defence contractor has 3D printed a titanium structure that measures 1.5 m in diameter and is 0.5 m thick. The front bearing housing contains 48 aerofoils and was manufactured using Arcam's electron beam melting technology, as a result of research performed with University of Sheffield and the UK's Manufacturing Technology Centre.

Presented below are the main global drivers, challenges and trends relating to AM technology.

Drivers:

- Less material usage - more near net-shape components mean a reduced need for material (especially important for expensive materials such as Ni-based alloys and Ti-alloys)
- Less post processing - better net-shapes also mean less machining and post-processing needed, and since machining is a significant cost for many aerospace components this enables cost savings
- Shorter lead times - enables manufacturing on demand rather than needing to keep warehouses filled with stocked forgings etc.

Challenges:

The main challenge is to fulfil the aerospace industry's qualification requirements for materials, process and production chain. Other challenges are:

- Robustness and qualification of produced parts – to achieve serial production of parts, there must be ways to guarantee that all AM produced components maintain the same quality.
- Post processing - for engineered surfaces on complex structures to maintain excellent fatigue properties efficient post processing methods must be developed to be able to refine the AM surfaces to maintain good fatigue properties.
- NDT methods – Efficient testing methods need to be developed that are suited for AM components in serial production.
- Material properties – are dependent on the processing routes and must be optimized for aerospace demands.
- Increased production rates and robust process – to be able to ramp up production rates, the machines must be faster to increase throughput of parts. The machines must also be able to guarantee uniform production regarding build speed, material properties and successful throughput.

Trends:

- Market trends are that a larger number of parts are to be AM-produced. Moving into more critical parts.

- New standards for AM processes as well as special AM materials are being developed. AM material is neither a forged nor a cast material but rather a new kind of material.
- "Design for AM" enables a new way of designing components, and this way of thinking is imperative in order for AM to become fully utilised.
- With increased experience, improved control systems, more robust AM processes, it will become possible to manufacture AM components for more stressed and loaded applications.

For the moment Ivchenko has not used 3D printed metal components in the design of its engines. The current task is a first step for Ivchenko specialists towards the metal AM technology.

Due to AM early stage of implementation in Ukraine, the number of professionals with competence in additive manufacturing technologies is small and training programs or specific courses (industry-oriented) are few in number. Also, lack of knowledge at the level of potential users and a lot of concerns (such as costs and investments for initial implementation, absence of standards for materials, cost of materials and their availability, lack of an in-process monitoring, need of post processing treatment, lack of specialized staff, etc.) act as a limit to AM growth in Ukraine.

Therefore, EU-UA collaboration within the topic of AM is very important for Ukrainian aerospace organizations such as Ivchenko.

3.5.5 Task 5 - Computer tomography of turbine cooled blades

At present Ivchenko uses the following types of nondestructive inspection of turbine blades cooling systems during manufacturing, repairs and overhauls:

- Visual examination;
- Luminescent examination;
- Mechanical examination;
- Liquid and air penetrant testing;
- Eddy current testing;
- Ultrasonic testing;
- Conventional X-Ray 2D scanning.

Cooperation with ITWL within task 5 of the pilot project 3.2b allowed Ivchenko specialists to get acquainted with 3D X-Ray CT approach and perform inspection of Ivchenko's blades with the CT scanner. Obtained results (which, for some types of defects, were better compared to other tried techniques) showed good potential of using computer tomography for cooled blades inspection.

3.5.6 Task 6 - Experimental definition of thermal conductivity of heat-resistant coatings of turbine cooled blades

N/A

3.6 Dissemination

3.6.1 Task 1 - Turbine radial clearance investigations

After the completion of joint work with PENTAIR, UK on calibration of the measuring system and experimental investigation of changes of advanced small turbine radial clearance during engine operation a technical paper considering the comparison between numerically and experimentally obtained turbine radial gaps at different operational conditions will be written and submitted to be

presented at the XXV International Propulsion Engineering Congress, Kobleve, Ukraine, in September 2020.

3.6.2 Task 2 - Optimization of the turbine exhaust system

Dissemination activities for this task are not planned.

3.6.3 Task 3 - Optimization of the cooling system for small turbine rotor blades

Dissemination activities for this task are not planned.

3.6.4 Task 4 - Additive manufacturing of turbine stationary components

After the completion of joint works with IPPT, Poland on 3D printing and testing of HPT vane of small advanced turbine designed by Ivchenko a joint (IPPT, Ivchenko) technical paper considering the possibility of installation of 3D printed vanes on the small turboprop engine will be written and submitted to be presented at ASME Turbo Expo Conference, Pittsburgh, Pennsylvania, USA, June 7–11, 2021.

3.6.5 Task 5 - Computer tomography of turbine cooled blades

In order to disseminate obtained results within the current task, the technical paper “Methods of control of internal passages of HPT cooled blades with perspective cooling systems” was written, submitted and accepted to be presented at XXIV International Propulsion Engineering Congress, Kobleve, Ukraine, 2-7 September, 2019.

3.6.6 Task 6 - Experimental definition of thermal conductivity of heat-resistant coatings of turbine cooled blades

After the completion of joint work with ICiMB, Poland and Paton Turbine Technologies Co Ltd, Ukraine within the current task, a technical paper considering the development of the methodology of ceramic coatings thermal conductivity definition and comparison between measured thermal conductivities of two ceramic coatings deposited on samples with two different techniques, will be written and submitted to be presented at the XXV International Propulsion Engineering Congress, Kobleve, Ukraine, September, 2020.

4. Progress with respect to WP3 performance indicators

Work Package (High-Level Objective)	Performance indicators	Amount achieved by end of project (M36)	Target by end of project (M36)
WP3. EU-UA aviation research knowledge transfer pilot projects (High-Level Objective 3)	• No. of short term staff exchanges about engine health management system	39	> 6
	• Feasibility study on engine health management system	1	1
	• No. of short term staff exchanges about advanced low-cost small turbine	29	> 4
	• Feasibility study on advanced low-cost small turbine	1	1

Completed visits:

- **11-12.10.2016, Hamburg** - ***AERO-UA Project Kick-off Meeting***
- 3-7.04.2017, Stockholm - Ivchenko's specialists participated in ETC Conference in Sweden
- **5-6.04.2017, Zaporizhia** - R. Przysowa, TECPAR / ITWL, and S. Epifanov, KhAI, visited Ivchenko Progress SE, factory tour to design office, assembly shop, experimental complex
- **19-20.04.2017, Kyiv** - AERO-UA Project Meeting, visit to Antonov factory airport , 401 plant and PIPS NASU
- 3-8.09.2017, Manchester - Ivchenko's specialists participated in ISABE Conference in UK
- **20-22.09.2017, Warsaw** - AERO-UA Project Meeting, visit to ITWL, WZL-4, Warsaw University of Technology
- 27-29.09.2017, Warsaw - KhAI professors visiting ITWL
- 16-20.10.2017, Bucharest - Ivchenko's specialists participated in CEAS Conference in Romania
- **14-16.05.2018, Warsaw** - Ivchenko team visited ITWL and IPPT for discussions and cooled blade scanning (T.4 and T.5)
- **29.05-1.06.2018, Kharkiv** - AERO-UA Project Meeting
- 11-15.06.2018, Oslo - Ivchenko specialists participated in ASME Turbo Expo
- **22.08.2018, Warsaw** - Ivchenko specialists visited ICiMB for preliminary negotiations in the field of measurements of thermal conductivity of ceramic coatings
- **20-22.08.2018, Warsaw** - Ivchenko specialists visited ITWL, Warsaw, for cooled blade scanning
- **19-23.11.2018 Manchester** - Ivchenko specialists visited the University of Manchester and participated in the "Composites in Action" workshop and in a workshop on the dynamics of machines, in particular aircraft engines, aimed at getting acquainted with the achievements of the dynamic analysis group of the University of Manchester and to initiate research cooperation
- **4-7.12.2018, Toulouse** - AERO-UA Project Meeting;
- 8-12.04.2019, Lausanne - Ivchenko specialists participated in ETC Conference
- **24-26.04.2019, Zaporizhia** - AERO-UA Project Meeting;
- 20-24.05.2019, Delft - Ivchenko specialists participated in AIAA/CEAS Aeroacoustics Conference
- **1-2.09.2019, Athens** - ***AERO-UA Final Project Meeting***.