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# AERO-UA

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# D3.2 Mid-term progress report on pilot projects in aeroengines

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| Dissemination Level | | |
|---|---|---|
| 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.

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# 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 provides 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 are structured around three key areas relevant to the challenges of ACARE SRIA / Flightpath 2050: Aerostructures, **Aeroengines** and Aerospace Manufacturing.

The task includes 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 could be combined with project meetings and events.

It is expected that based on the results of knowledge transfer pilot projects, the AERO-UA partners will prepare 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 is 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 will consider 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 will involve 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 are expected to contribute 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** planned M19 - M36:

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

## 2.1 Background to the pilot project

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.

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.

A Blade Health Monitoring (BHM) system is proposed to address potential problems with blade durability and reliability. Blade tip deflection will 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 aims to develop the concept of a BHM system for a selected Ivchenko engine. The diagnostic system will be offered to operators to enhance flight safety, performance and reduce operating costs. The system will monitor 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 have 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 will be 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 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 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.

Research activities of the Pisarenko Institute for Problems of Strength, National Academy of Sciences of Ukraine (PIPS), 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 possess 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, a 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.

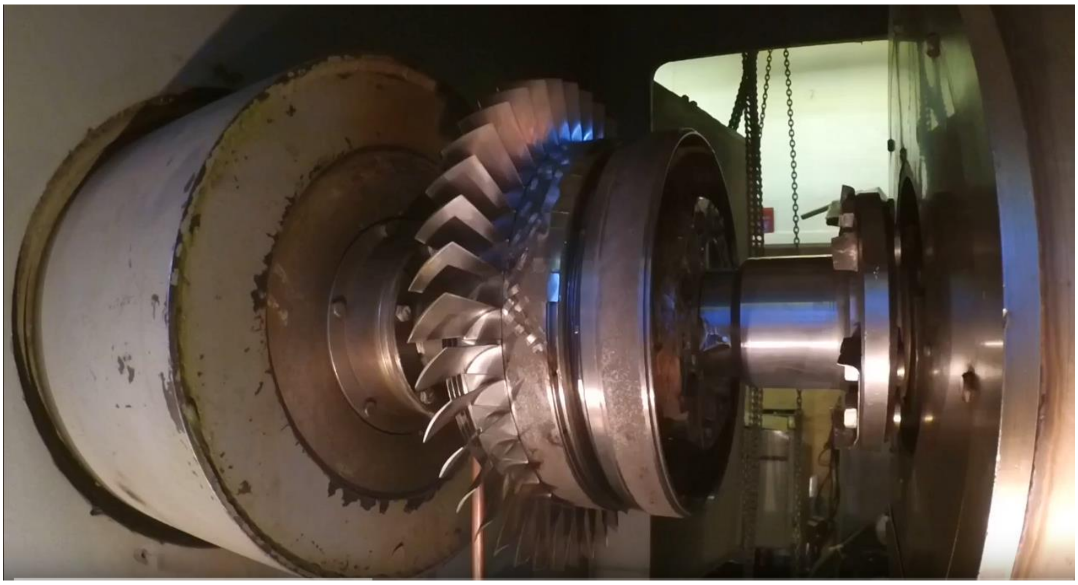

*Figure 2. Vacuum spin facility in IPS*

The KhAI 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 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.

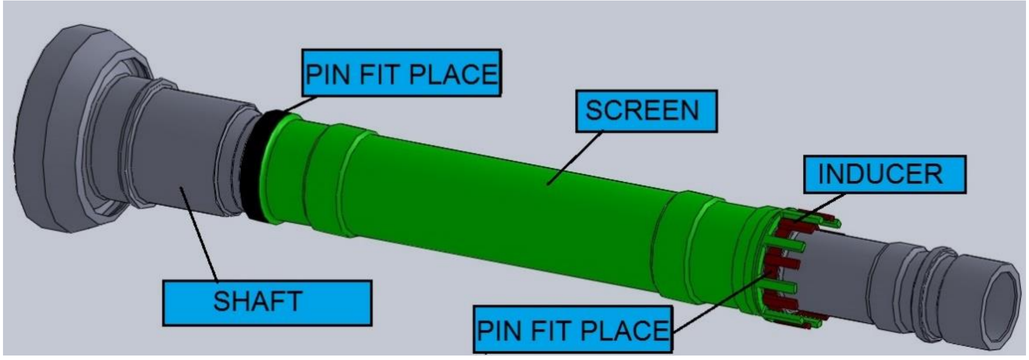


*Figure 3. Structure of the torque meter*

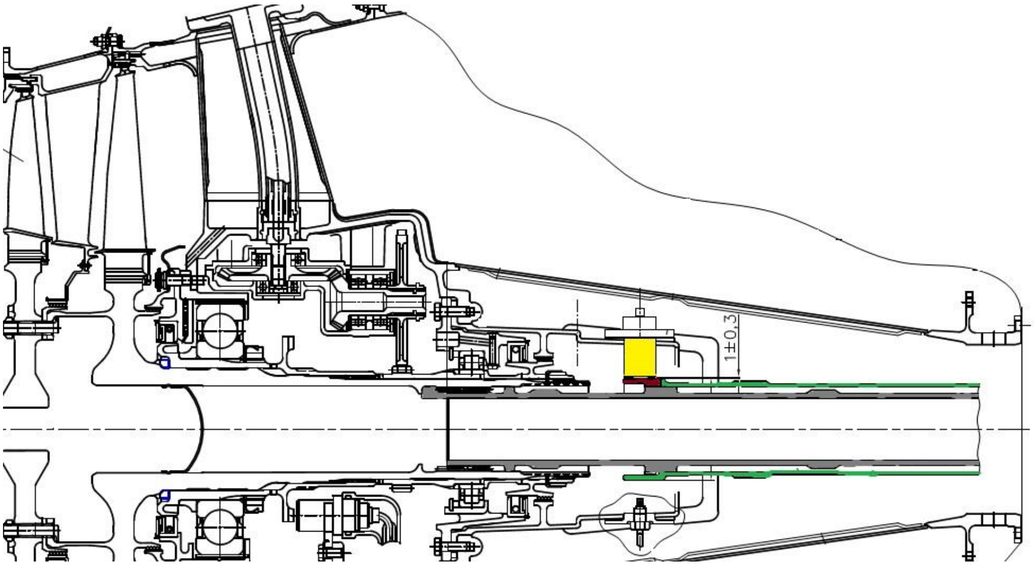


*Figure 4. Torque meter installed in the TV3-117 turboshaft*

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.

The Dynamics group in the School of Mechanical, Aerospace & Civil Engineering (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.

### 2.3 Training provided

Despite the fact that no specific training was conducted, the methodology of contactless blade testing and using the vibration data for blade health assessment was covered extensively during meetings in Zaporozhe, Kyiv and Warsaw. It will be implemented shortly during the planned engine test.

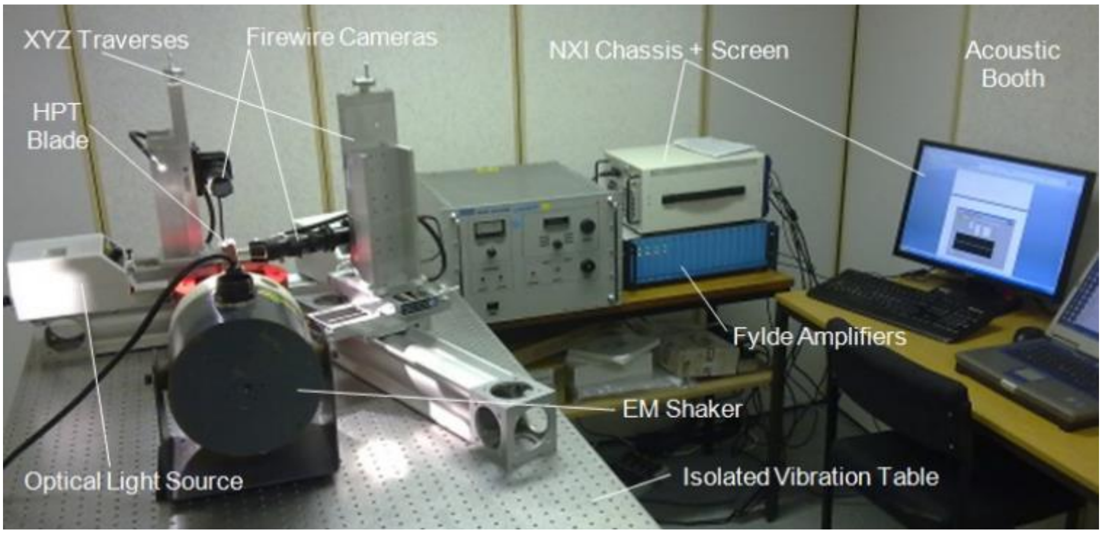


*Figure 5. Turbine Blade Vibration Test Facility*

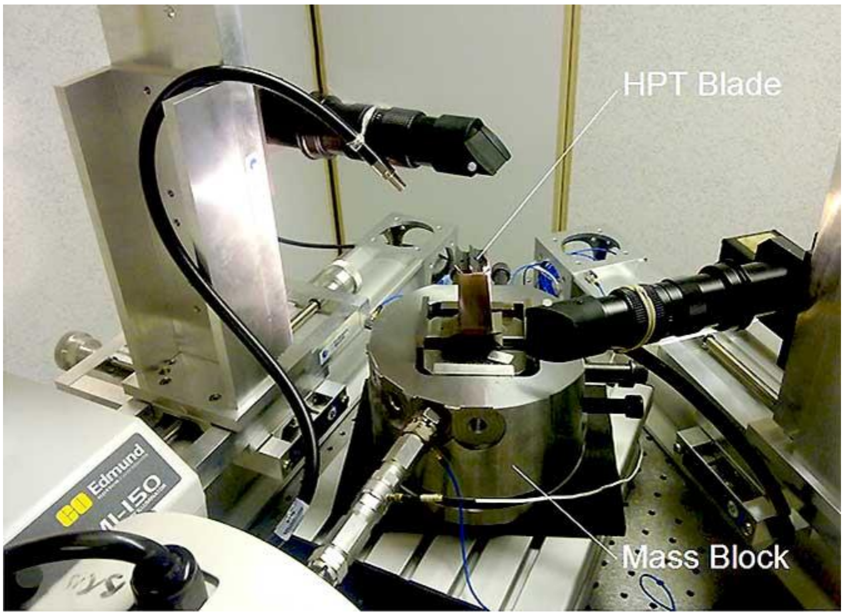


*Figure 6. HPT Blade and Mass Block*

## 2.4 Scientific and technical results

TECPAR / ITWL works 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, will be employed to process sampled 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.

*Figure 7. BTT sensors developed at ITWL*

*Figure 8. Test cell of D-436-148FM turbofan*

*Table 2. Schedule of the pilot project*

| Months | Task | Expected result |
|---|---|---|
| 1-12 | Review partner expertise and capabilities | Documented in mid-term progress report |
| 6-18 | Draft major sections of Feasibility Study | Feasibility Study Draft |
| 6-22 | Prepare engine test | Instrumentation and test plan |
| 22-24 | Perform engine test | Test report |
| 24-26 | Prepare testing report | Vibration analysis report |
| 30 | Complete Feasibility Study | Feasibility Study Report |

*References:*

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2. *School of Mechanical, Aerospace and Civil Engineering. The University of Manchester, Manchester. Research areas - Rotordynamics http://www.mace.manchester.ac.uk/our-research/research-themes/aerospace-engineering/specialisms/engineering-dynamics/areas/rotordynamics/*
3. *Engine Test Bench http://ivchenko-progress.com/?page_id=1549&lang=en*
4. *Department of aircraft engine design https://k203.khai.edu/*
5. *G.S. Pisarenko Institute for Problems of Strength of the National Academy of Sciences of Ukraine http://www.ipp.kiev.ua/*

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

According to the AERO-UA Grant Agreement (description of action), Ivchenko was to contact European aerospace companies and research organisations 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 a part of small-size aeroengine (Fig. 9) and consists of the following major parts: HPT, inter-turbine diffuser, LPT and turbine exhaust system.

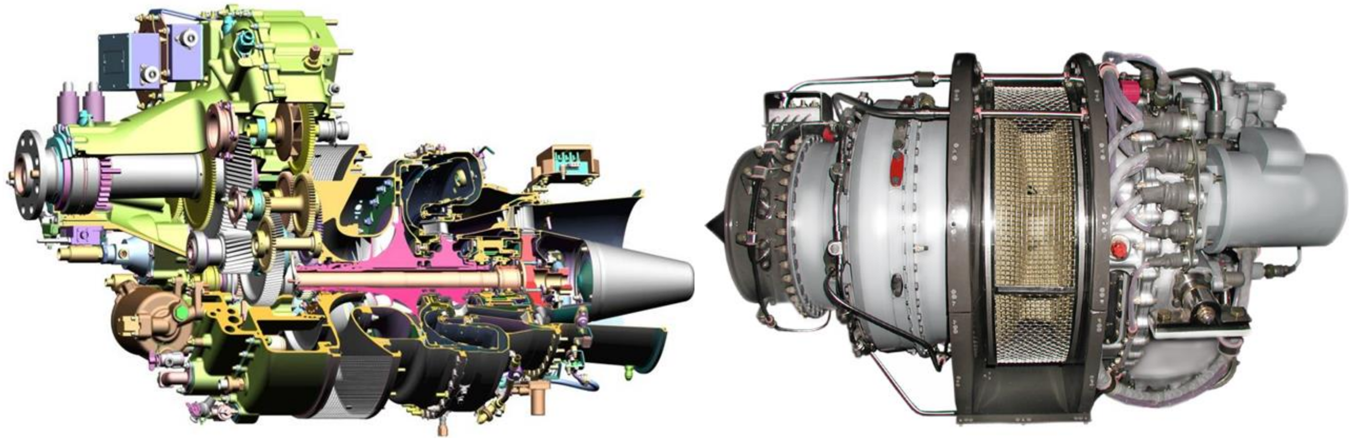

*Figure 9. View of a small-size aeroengine with the considered turbine*

An aeroengine with the considered turbine can be installed on small aircrafts such as DA50JP7 (Diamond Aircraft, Fig. 10, left), DART450 (Diamond Aircraft, Fig. 10, right), etc.

*Figure 10. 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. 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 diagram of the turbine is shown in Figure 11.

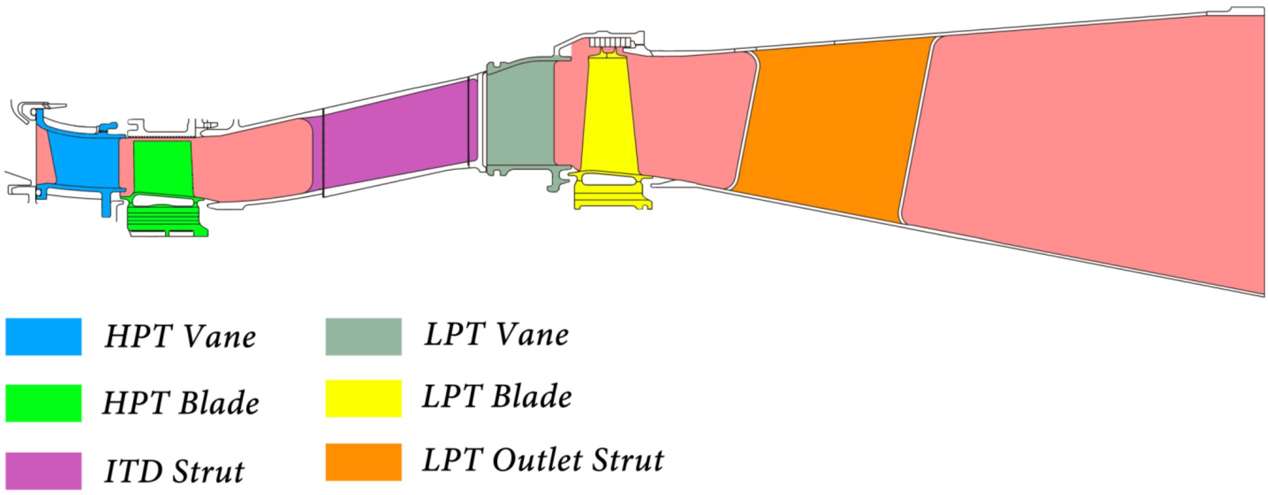


*Figure 11. Schematic view of the considered turbine*

Ivchenko defined the list of possible tasks to be performed within pilot project 3.2b with the aim to find 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 in the proposed directions assumes the use of technologies that are currently under development (mastering) at Ivchenko-Progress SE (for example, 3D metal printing, computer tomography, etc.). In addition, the AERO-UA project is considered an opportunity to get acquainted with new technologies and approaches for solving the problems of turbomachinery with the aim of their further introduction into the practice of designing and producing turbines at Ivchenko.

Feedback with proposals of cooperation within different tasks was obtained both from AERO-UA consortium member and non-member companies.

After reviewing the proposals received it was planned to perform joint EU-UA feasibility studies and some research activities (optional) within the AERO-UA project 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.

*Table 3. 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.<br>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.<br>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 turboprop AI-450 and tests on the Ivchenko test bench – optional.<br>T.5 – providing of two different HPT cooled blades for scanning with ITWL's CT scanner |
| 2 | Technology Partners Foundation (TECPAR) / Air Force Institute of Technology (ITWL) | Radoslaw Przysowa | T.1 – a) assessment of the possibility of using of the ITWL's optical measuring system within current task; b) system calibration, tests – optional.<br>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 frame of the current tasks; b) optimization of the cooling system for small turbine rotor blades, optimization of the turbine exhaust system – optional. |
| 4 | Institute of Fundamental Technological Research, Polish Academy of Sciences (IPPT) | Krzysztof Kazmierczak | T.4 – a) preparation of commercial proposal aimed at collaboration with Ivchenko within the frame 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. |

**Milestones** achieved until M18:

- T1 Turbine radial clearance investigations – different types of radial clearance measuring systems considered, several commercial proposals from EU suppliers received.

- T2 Optimization of the turbine exhaust system – EU partner (Warsaw University of Technology, Faculty of Power and Aeronautical Engineering, Institute of Aeronautics and Applied Mechanics) was identified. Commercial and technical proposals received from the partner.
- T3 Optimization of the cooling system for small turbine rotor blades – EU partner (Warsaw University of Technology, Faculty of Power and Aeronautical Engineering, Institute of Aeronautics and Applied Mechanics) was identified. Commercial and technical proposals received from the partner.
- T4 Additive manufacturing of turbine stationary components – EU partner (Institute of Fundamental Technological Research, Polish Academy of Sciences IPPT) was identified. Ivchenko specialists together with IPPT specialists started discussing the technical and organizational issues of joint works within the current task.
- T5 Computer tomography of turbine cooled blades – EU partner (Air Force Institute of Technology ITWL) was identified. It is planned to scan two different HPT cooled blades designed by Ivchenko with ITWL's CT scanner in May 2018.

**Milestones** planned M19 - M36:

- T1 Turbine radial clearance investigations – select the appropriate type of the measuring system and supplier; make a purchase or take a lease of the measuring system – optional; perform research activities (system calibration, tests, calculations, redesign of the HPT casing to host the sensors and instrumentation, etc.) - optional.
- T2 Optimization of the turbine exhaust system – perform research activities (numerical investigations and optimization, experiments) - optional.
- T3 Optimization of the cooling system for small turbine rotor blades – perform research activities (numerical investigations and optimization, experiments) - optional.
- T4 Additive manufacturing of turbine stationary components – perform research activities (find the metal powder for 3D printing with properties similar to the material ZhS6U-VI, print samples of this material; test the 3D printed samples and verify their properties; print turbine vanes; install the 3D printed vanes on the full-scale turboprop AI-450 and test on the Ivchenko test bench; etc.) – optional
- T5 Computer tomography of turbine cooled blades – scan two different HPT cooled blades designed by Ivchenko with ITWL's CT scanner in May 2018.
- T1-T5 – release reports for feasibility studies and research activities performed.

## 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 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. Thus, the smaller the clearances, the lower the gas leakage across the blade tips (Figure 12). However, under certain engine conditions, aerofoils and their associated discs may experience thermal growth, thus increasing the risk of contact with the casing.

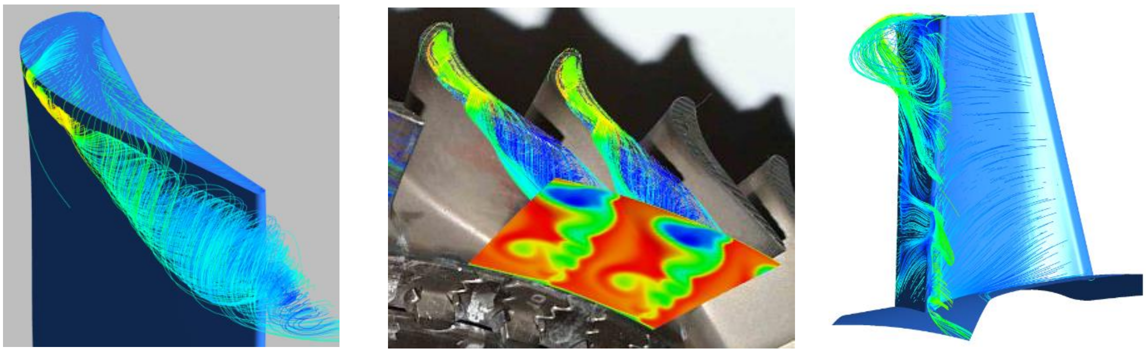

*Figure12. View of the blade over tip leakage*

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

Currently, the measurement of radial clearances, all over the world, becomes the same routine practice for 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 blades 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 rest of the electronic equipment at a distance and not exposed to high temperatures.

To date, Pentair company (UK, CapaciSense system), Fogale (France, CAPABLADE system) and Thermocoax are the main manufacturers of such systems for measuring and monitoring the radial clearance (clearance system) in compressors and turbines. 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 °C) and high-temperature (up to 1400 °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 solve 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 13.

***Figure 13. CapaciSense (Pentair) capacitive sensors – high (left), mid-range (middle) and lower (right) temperature sensors***

High temperature sensors (Fig. 13, left) are used predominantly for turbine applications. The inclusion of flutes and cooling apertures has advanced the operational capabilities of these designs over to 1400 °C / 2552 °F, allowing several years of operation.

Various shapes of THERMOCOAX capacitive sensors are shown in Figures 14-15 and an example of their installation on engine, in Figure 16.

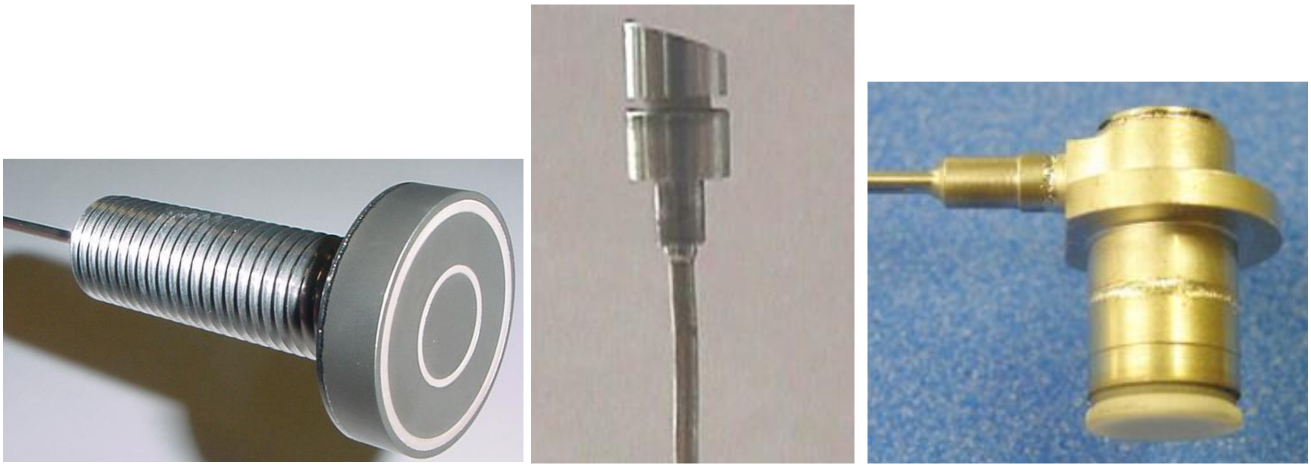

***Figure 14. THERMOCOAX capacitive sensors – various shapes***


*Figure15. THERMOCOAX capacitive sensor*

*Figure16. THERMOCOAX capacitive sensors engine installation*

Different types of Fogale capacitive sensors are shown in Figure 17.

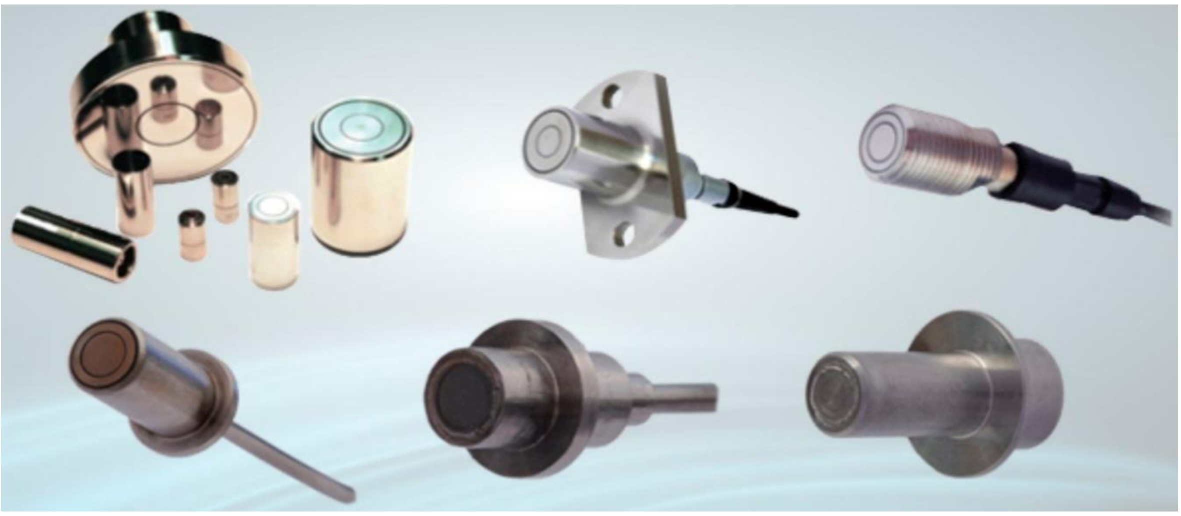

*Figure 17. FOGALE capacitive sensors*

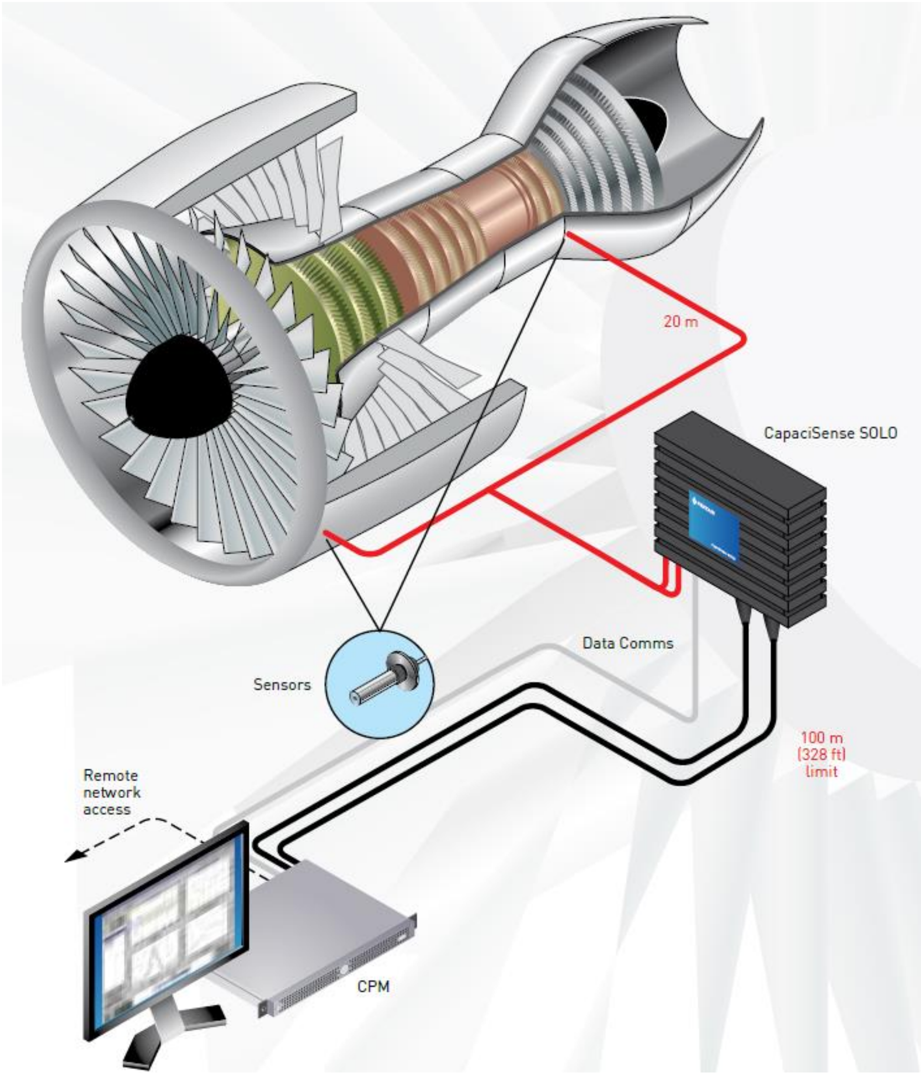


*Figure 18. CapaciSense SOLO system components*

The system for measuring radial clearances CapaciSense Solo (Pentair) is shown in Figure 18. This system was designed to be a 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 your own 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.

*Task objective:*

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

*Work to be performed:*

- 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 due 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 19-20.

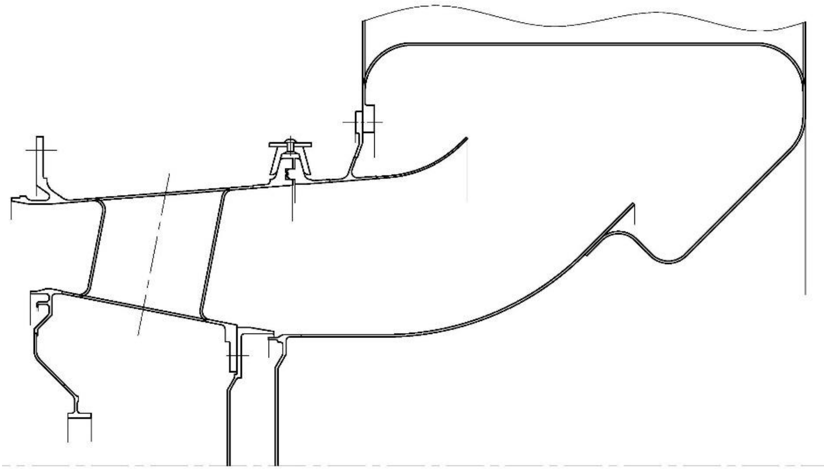

*Figure 19. Meridional section of the considered TED*

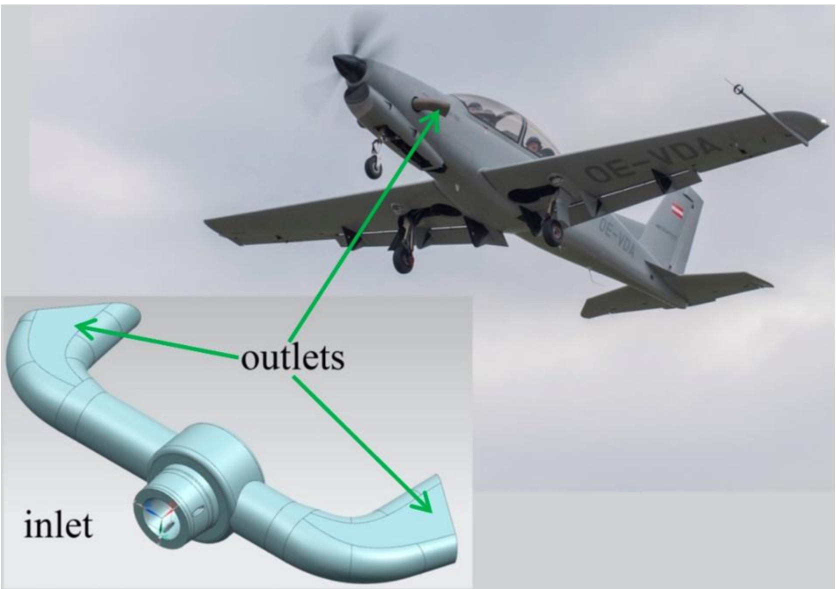


*Figure 20. Exhaust system of the considered advanced small turbine*

Before the appearance of computational fluid dynamics methods (CFD), the design of the TED was performed using generalized experimental dependences that allowed to select the main geometric parameters and to estimate 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 appearance of computational fluid dynamics methods affected the process of designing the TED (as well as the rest of the engine components). Using CFD methods, it is possible to evaluate the effect of individual structural elements, to choose a more perfect (optimal) profile of the flow section in the specified dimensions.

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

- 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 calculations in the RANS statement 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

*Work to be performed:*

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

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

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 its 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 21. 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 trailing edge.

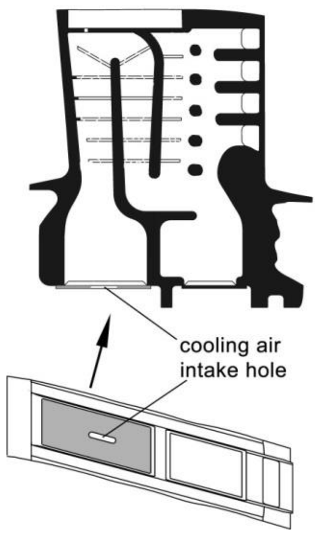


*Figure 21. HPT baseline blade cooling system*

*Task objective:*

- to increase the life time 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.

*Work to be performed:*

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

### 3.1.4 Task 4 - Additive manufacturing of turbine stationary components

Additive manufacturing 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 are now available. 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 meets its respective specifications.

3D printing, also known as additive manufacturing, 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 by conventional means. On the maintenance side, additive manufacturing opens the door to easier and faster repairs.

3D printing in plastic has been around in commercial usage 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.

*Figure 22. View of the considered HPT vanes*

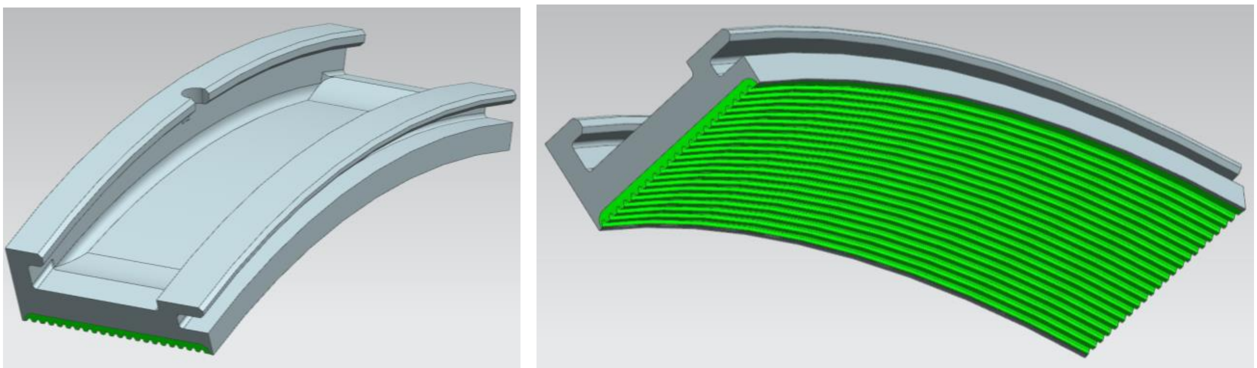

*Figure 23. View of the considered stationary shroud*

*Task objectives:*

- to investigate the possibility of the installation of 3D printed HPT vanes (Figure 22) and sectors of stationary shroud (Figure 23) on a small aeroengine designed by Ivchenko.

*Work to be performed:*

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

*Within this task the following research activities are being considered:*

- Find the 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);
- Print samples of this material;
- Test the 3D printed samples and verify their properties;
- Print vanes and stationary shroud;
- Install the 3D printed parts on the full-scale turboprop AI-450 and test 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 components at greatest risk. 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 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, so they are still insufficiently reliable for assessment of internal invisible defects or failures like subsurface cracks etc. 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) enables to achieve much better results as compared to other test techniques. Although it is a non-destructive technique, it allows detection and verification of defects and flaws also inside solid material.

To diagnose aircraft structures it is necessary to reproduce the inner structure of the object with high accuracy, e.g.: to take geometry measurements, study the material structure, defects as well as to evaluate their condition e.g. during repair (thermal damage, 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 24). 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 required to move it along the vertical plane and perform a full rotation at every step. The full 3D image is visible after having processed all collected data.

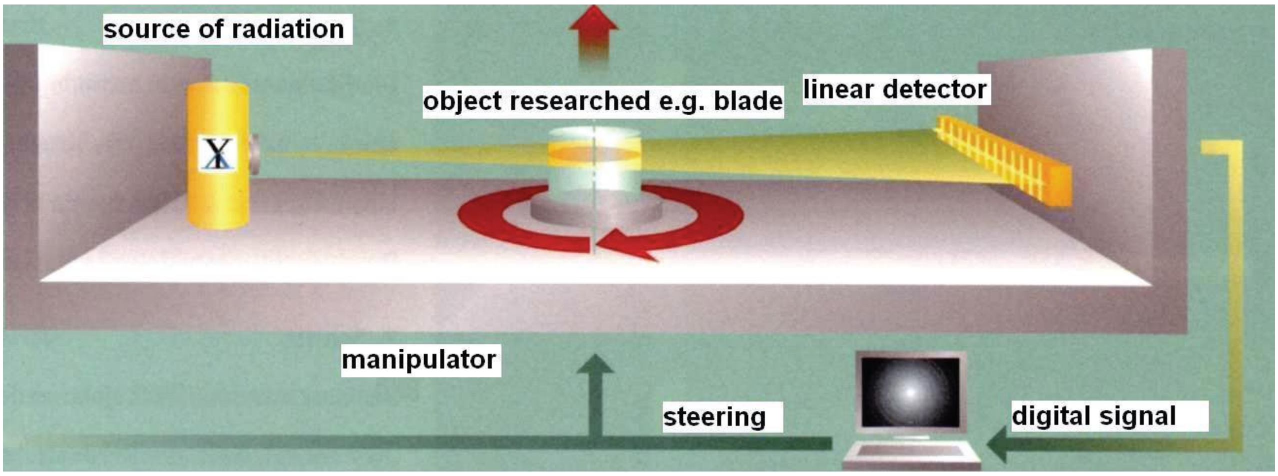


*Figure 24. The example of a tomography investigation with use of a linear detector*

*Task objective:*

- to perform CT analysis of HPT blades

*Work to be performed:*

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

## 3.2 Knowledge exchanged

During the reporting period, the EU and UA partners discussed issues relating to the planned joint feasibility study to be conducted with the aim to further exploit the advanced, low-cost, small turbine (400-470 kW), which Ivchenko began developing during the FP7 ESPOSA and FP6 CESAR projects.

### *3.2.1 Task 1 - Turbine radial clearance investigations*

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

Technical requirements for measuring systems were defined and provided to TECPAR / ITWL, CapaciSense (Pentair) 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 works within current task with Polish partners (Warsaw University of Technology, Faculty of Power and Aeronautical Engineering, Institute of Aeronautics and Applied Mechanics) 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 works within current task with Polish partners (Warsaw University of Technology, Faculty of Power and Aeronautical Engineering, Institute of Aeronautics and Applied Mechanics) 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 current task with Polish partners (Institute of Fundamental Technological Research, Polish Academy of Sciences IPPT) 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 current task with Polish partners (TECPAR / ITWL) by means of e-mail exchanges and web-meetings.

### 3.3 Training provided

#### *3.3.1 Task 1 - Turbine radial clearance investigations*

The specialists of Ivchenko observed a presentation of the system for measuring radial clearances and vibrations of rotor blades by CapaciSense (Pentair), held on May 15, 2017 in Zaporozhye, Ukraine. Within the framework of this event, representatives of CapaciSense (Pentair) 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*

The specialists of Ivchenko attended a five-day classroom training dedicated to single and multiple objective optimization by means of NUMECA software. Training was held on 5-9 December 2016 in Brussels, Belgium.

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

The specialists of Ivchenko attended a four-day classroom training dedicated to modelling of the turbine cooling by means of NUMECA software. Training was held on March 12-15, 2018 in Brussels, Belgium.

#### *3.3.4 Task 4 - Additive manufacturing of turbine stationary components*

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#### *3.3.5 Task 5 - Computer tomography of turbine cooled blades*

–

### 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 the very hostile environment in the considered turbine, in this task it is impossible to use ITWL’s optical system, in contrast to capacitive systems.

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

### *3.4.2 Task 2 - Optimization of the turbine exhaust system*

To perform works within the Task 2, Pilot project 3.2b a 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 frame of the Pilot Project 3.2b Task 2 were received from the present partner:

- *Offers № ZA/1/2018 and № ZA/2/2018*

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

To perform works within the Task 3, Pilot project 3.2b a 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 frame of the Pilot Project 3.2b Task 2 were received from the present partner:

- *Offers № ZA/3/2018 and № ZA/4/2018*

### *3.4.4 Task 4 - Additive manufacturing of turbine stationary components*

To perform works within the Task 4, Pilot project 3.2b a partner was found:

- *Institute of Fundamental Technological Research, Polish Academy of Sciences IPPT, with 3D printing laboratory which is a part of the KEZO research center managed from IMP Gdansk (http://kezo.pl, https://www.imp.gda.pl/fileadmin/files/jablonna/folder_Jablonna_en.pdf)*

IPPT's 3D printing laboratory is equipped with EOS INT M280 System (3D metal printer, Figure 25) which can be used for single or low serial production of metal parts by direct metal laser sintering method.


*Figure 25. 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.

During the discussions between Ivchenko and IPPT specialists it became clear that since the cover body has to be sintered on top of the shroud body (which is not flat) it is not 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 considered within 3.2b pilot project Task 4.

### 3.4.5 Task 5 - Computer tomography of turbine cooled blades

To perform works within the Task 4, Pilot project 3.2b a partner was found:

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

In 2012 the ITWL installed a CT system from ITA-Polska, a representative of GE Phoenix: v/tome/x m 300 (Figure 26) with maximum voltage/power of X-ray tube being 300 kV/500W. This device is also equipped with X-ray tube for nanotomography with voltage/power of 180kV/15W. It allows to conduct research works 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 180kV and materials with high density, e.g.: titanium aircraft blades, by applying the X-ray tube with 300 kV. The weight of elements under study: up to 50 kg, with dimensions of 500 x 500 x 600 mm.

*Figure 26. The V/Tome/x m 300 tomograph owned by ITWL*

ITWL has positive experience in the tests of high-pressure turbine blades from the RD-33 engine. The CT system owned by ITWL is one of the few in Europe to feature the power enabling 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 might be verified in all directions.

Below there are some examples of images from scanned blades provided by ITWL (Figure 27).

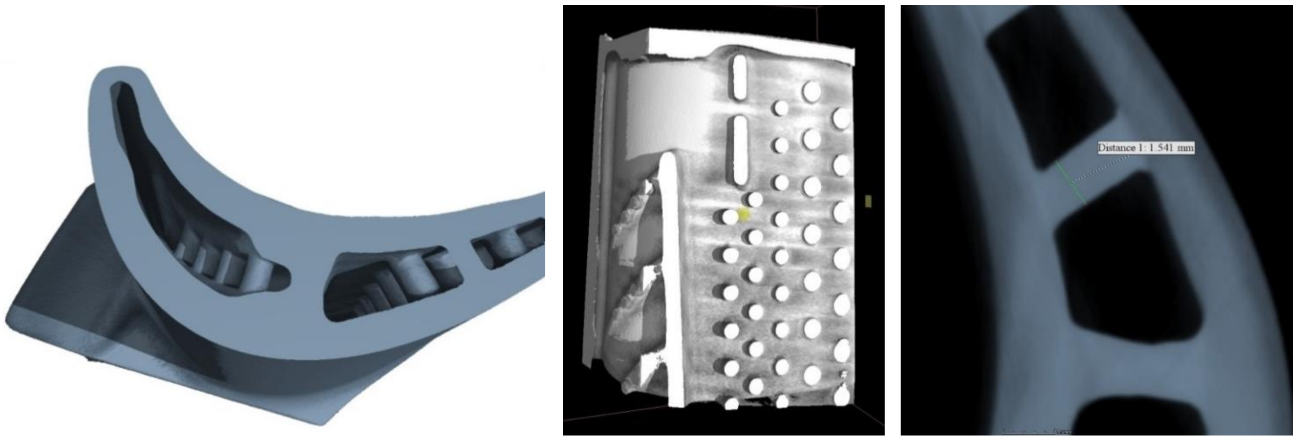


*Figure 27. Images of scanned blades (provided by ITWL)*

It is planned to perform CT scanning of two different HPT cooled blades designed by Ivchenko with ITWL's tomograph in May 2018.

*Table 4. Schedule of the pilot project*

| Months | Task | Expected result |
|---|---|---|
| 1-18 | Definition of the possible tasks to be performed within the pilot project 3.2b. Identification of partners. | Documented in mid-term progress report |
| 18-32 | Perform and complete feasibility studies and research activities (optional) for pilot project 3.2b tasks | Feasibility Study Draft |
| 33-36 | Prepare Feasibility Study reports | Feasibility Study reports |
| 33-36 | Prepare Research activities reports (optional) | Research activities report |

## 4. Progress with respect to WP3 performance indicators

| Work Package (High-Level Objective) | Performance indicators | Amount achieved by project midpoint (M18) | Target by end of project (M36) |
|---|---|---|---|
| **WP3. EU-UA aviation research knowledge transfer pilot projects**<br><br>***(High-Level Objective 3)*** | • No. of short term staff exchanges about engine health management system<br>• Feasibility study on engine health management system<br>• No. of short term staff exchanges about advanced low-cost small turbine<br>• Feasibility study on advanced low-cost small turbine | 3<br>*in progress*<br>3<br>*in progress* | > 6<br>1<br>> 4<br>1 |

### 4.1 Task 3.2: Pilot projects between EU-UA partners in the field of aeroengines - meetings

Completed visits:

- 11-12.10.2016, Hamburg - AERO-UA Project Kick-off Meeting
- 03-07.04.2017, Stockholm - Ivchenko's specialists participated in ETC Conference in Sweden
- 5-6.04.2017, Zaporozhe - 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
- 03-08.09.2017, 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

Planned visits:

- 16-19.04.2018, Torino - R. Przysowa, TECPAR / ITWL, and S. Epifanov, KhAI, will participate in 41st AVT Panel in Italy
- 14-16.05.2018, Warsaw - Ivchenko Progress team will come to ITWL for discussion and cooled blade scanning
- 29.05-1.06.2018, Kharkiv - AERO-UA Project Meeting
- 11-15.06.2018, Oslo - R. Przysowa, TECPAR / ITWL, and S. Epifanov, KhAI, and Ivchenko's specialists will participate in ASME Turbo Expo
- 2018, Zaporozhe – TECPAR / ITWL will support engine test in Ivchenko Progress SE
- M24, Toulouse - AERO-UA Project Meeting
- 10-14.12.2018, Athens - R. Przysowa, TECPAR / ITWL, and S. Epifanov, KhAI, will participate in AVT-306 Specialists' Meeting in Greece
- M30, Zaporozhe - AERO-UA Project Meeting
- M36, Kiev - AERO-UA Project Meeting