# PROJECT FINAL REPORT

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# 1 FINAL PUBLISHABLE SUMMARY REPORT

## 1.1 Executive summary

European aeronautics industry commitment (ACARE 2020 vision) is a result of the major concern in the 2000s to change the situation with the green house gas effects, mostly due to CO2 emissions, resulting in the objectives to:

- Reduce fuel consumption and $CO_2$ emissions by 50% (15-20% for the engine alone) per passenger kilometer
- Reduce perceived external noise by 50%
- Reduce NOx emissions by 80%

The work performed within the scope of the MICMEST project contributes to these efficiency and environmental improvements by developing the technology readiness level (TRL) of the Microwave Clearance Measurement System (MCMS). The validation of an accurate and reliable microwave-based measurement system of radial running clearances and axial rotor displacements in the low pressure turbine of an aeroengine could significantly contribute to improvement of efficiency of aviation gas turbine engines.

The objective of MICMEST project was further development, laboratory validation and demonstration of the MCMS on the Geared Turbofan Sustainable and Green Engine Demonstrator (SAGE4). The project led to the following major accomplishments:

- New blade shrouds including geometric features located on the tip of the shrouded blade were studied, designed and tested to provide an exploitable signal over a large range of axial position and radial clearance.
- A new spin rig was designed and built for the calibration and validation of the measurement system at system level in a realistic turbine casing environment in laboratory model before installation in the SAGE4 engine demonstrator.
- A sensor installation concept that meets SAGE4 demonstrator engine mounting requirements and containment constraints was designed and validated, enabling the installation of the sensors in SAGE4 demonstrator for the engine test
- The durability of the microwave sensors was demonstrated through a comprehensive laboratory temperature test campaign.
- The MCMS went through the entire SAGE4 engine test campaign. All along the testing phase the system proved able to record measurements data with no sensor failures. In addition, no degradation of the microwave sensors signal has been observed throughout the engine test campaign.

However there are still some remaining technology gaps to be addressed and solved before the ultimate objective of a suitable microwave system as part of an Active Clearance Control (AAC) system for series application and capability of flying. In light of the engine test results, the gaps that have been identified show that the system cannot be considered as fully validated in the engine environment is therefore not suitable for being used in production low pressure turbines in the configuration of SAGE4 engine.

The system calibration is the major gap of the methodology at present. Establishing an accurate physical model of the measurement appears the best way to get confidence on the accuracy of the method. Various improvements can also be foreseen to make more robust, general and reliable the clearance measurement process.

## 1.2 Project context and objectives

### 1.2.1 Context

European aeronautics industry commitment (ACARE 2020 vision) is a result of the major concern in the 2000s to change the situation with the green house gas effects, mostly due to CO2 emissions, resulting in the objectives to:

- Reduce fuel consumption and CO2 emissions by 50% (15-20% for the engine alone) per passenger kilometer
- Reduce perceived external noise by 50%
- Reduce NOx emissions by 80%

The work performed within the scope of MICMEST contributes to these efficiency and environmental improvements by developing the technology readiness level of a technology that would be a major component of the closed loop Active Clearance Control (ACC) system. A mature Microwave Clearance Measurement System should become significant contributor to the improvement of efficiency of the turbine of aviation gas turbine engine.

MICMEST was capitalizing on the work carried out by Meggitt SA in previous European research projects, namely NEWAC and DREAM. The development done under the DREAM project and others, was sufficient to prove the high-level feasibility of using the microwave system to measure clearance to shrouded blade tips during engine operation; it also demonstrated the robustness and survivability of the microwave probes to the harsh turbine environment. However, there were several aspects of the work done that require significant further research before the measurement system is acceptable for integration into an active clearance control system.

The main shortcoming of past work has been the inability to separate clearance and axial position measurements. This is important if axial position is expected to have an impact on accuracy of the clearance measurement as it could with microwave sensors. Second, the reliability of the algorithms to detect the measurement features used in the DREAM test was not of an acceptable level. The algorithms ran on a PC with at least 2 seconds delay and a fair amount of manual optimization. For active clearance control, the algorithms must be implemented in firmware in a robust and efficient way. Finally, in past work, the probe installation did not consider casing containment requirements that must be fulfilled if the system is to be potentially used in a production engine. The work of the MICMEST project contributes to the engine efficiency and environmental improvements by addressing all these concerns as well as others through the development of the technology readiness level (TRL) of the Microwave Clearance Measurement System (MCMS).

### 1.2.2 Objectives

The overall objective of MICMEST project was further development, laboratory validation and demonstration of the MCMS on SAGE4 demonstrator engine.

The following high level requirements were defined as performance targets for the MCMS developed within MICMEST:

- Requirement 1: Achieve high durability and operational reliability

  Essential for the application in production aero engines is a high durability and operational reliability of the sensors in the high temperature and pressure environment of the low pressure turbine casing over at least one engine maintenance interval (typically 5000 cycles). Moreover, their functionality must not be affected by the high temperature gradients occurring between the hot gas path boundary and cooler turbine casing parts.

- Requirement 2: Fulfil the turbine casing containment requirements
  The installation of the sensors in the turbine casing must fulfil the containment requirements for the casing. Additionally, the installation must enable field replaceability of the sensors.
- Requirement 3: Achieve adequate clearance measurement accuracy
  The uncertainty of the radial and axial position measurement must fulfil the requirements for the closed-loop ACC system of the SAGE4 demonstrator engine that is at least ±0.02 mm and ±0.05 mm uncertainty of radial and axial position measurements, respectively.
- Requirement 4: Implement adequate data format and transfer
  A small set of airfoil shrouds equally distributed around the circumference of one turbine stage is utilized as measurement targets for microwave signals. The clearance measurement system has to be capable of measuring radial and axial position data for each selected airfoil and revolution and delivering the maximum radial position and its corresponding axial position as well as the minimum and maximum axial position within intervals of 0.5 seconds to the controller of the closed-loop controlled ACC system. Moreover, for application in test engines the measurement system must additionally be capable of delivering measured radial and axial positions for each selected airfoil in real time to a test bed data acquisition system.

### 1.2.3 Work plan

The following basic sequence of activities undertaken to achieve the project objectives:

1. Perform a laboratory study to determine parameters for the SAGE4 Demonstrator application and improve on existing background work
2. Adapt existing industrial electronics and microwave probes for clearance measurement for use on the SAGE4 Demonstrator
3. Install the system on the SAGE4 Demonstrator and support the engine test to validate the measurement system

The work was broken down into five work packages:

WP1: Project management – It stood alone and lasted through the entire project.

WP2: Laboratory system development – It was dealing with all laboratory measurement system testing and the development directly related to the laboratory work. It also included a task dedicated to the final system verification before the engine test.

WP3: Preparation of Measurement system for implementation in SAGE4 Demonstrator - It included all engineering work and other tasks involved in integrating the microwave sensors in the SAGE4 Demonstrator.

WP4: Measurement electronics preparation - It included all engineering work and other tasks involved in integrating the measurement system for SAGE4 engine test..

WP5: Validation support of the measurement system on SAGE4 Demonstrator - It covered the measurement system validation through the SAGE4 Demonstrator with the clearance measurement system installed.

## 1.3 Achievements against objectives

### 1.3.1 Work Package 2

WP2 provided the theoretical and laboratory ground-work for application of the microwave system to radial clearance and axial position measurement of a low pressure turbine rotor. It included the development of innovative measurement features that were added to the blade shroud to enable the joint measurement of clearance and axial position. These measurement concepts have been tested and optimized in a laboratory setup until they fulfill the requirements for implementation on SAGE4 Demonstrator. Finally, the measurement system was validated in a laboratory setup with a realistic turbine casing environment model before installation on SAGE4 Demonstrator.

WP2 was divided in 3 subtasks:

1. Develop and test concepts for the measurement of axial shift using features attached to the blade shroud
2. Improve clearance measurement features and algorithms from previous work to ensure more robust and accurate clearance measurement
3. Design and implement a validation test for the complete measurement system prior to application in the SAGE4 Demonstrator test

The following subsections aim at providing the achievements against the objectives for each subtask of WP2.

#### 1.3.1.1 Design of measurement features for joint axial/clearance measurement

Measurement of clearance or axial position on shrouded blades requires adding measurement features on the blade shroud. While passing in front of the microwave probes, these measurement features generate excitation signals, which can be interpreted in terms of clearance and axial position (Figure 1).

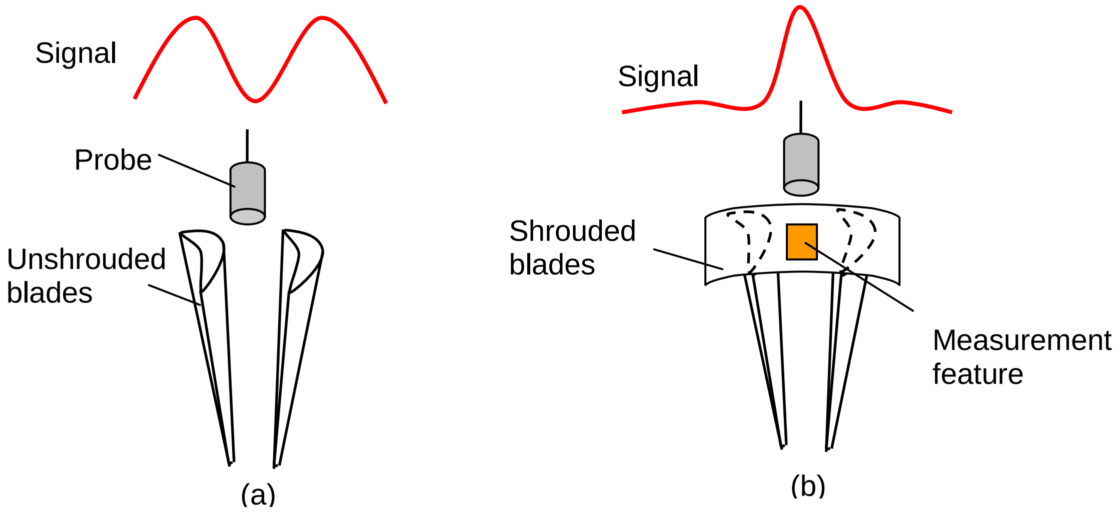


*Figure 1: Comparison of the measurement principle with shroud-less blades and shrouded blades*

From the previous work performed in the work package 4.4 “Active turbine” of former DREAM project, the best type of measurement features is based on a rib added to the shroud geometry. A rib corresponds to a step in distance between the microwave probe and the measured surface, which generates a signal modulation. By selecting different geometries of rib put together on the blades shroud, it is possible to get a set of signals useable for joint axial/clearance measurement. Several blades geometries were investigated such as features with sloped surfaces, triangular shapes or set in chevron.

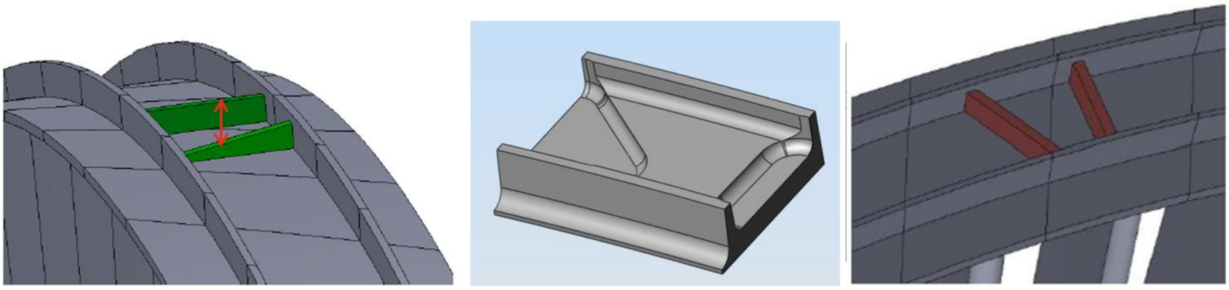

*Figure 2: Blade features studies for joint measurement of clearance and axial position*

Design trade studies and test loops lead to the selection of a concept based on three different ribs set on three adjacent blades. The first rib is dedicated to clearance measurement while the two other ones are used for axial measurement. This design presents a footprint and a mass suitable for turbine integration.

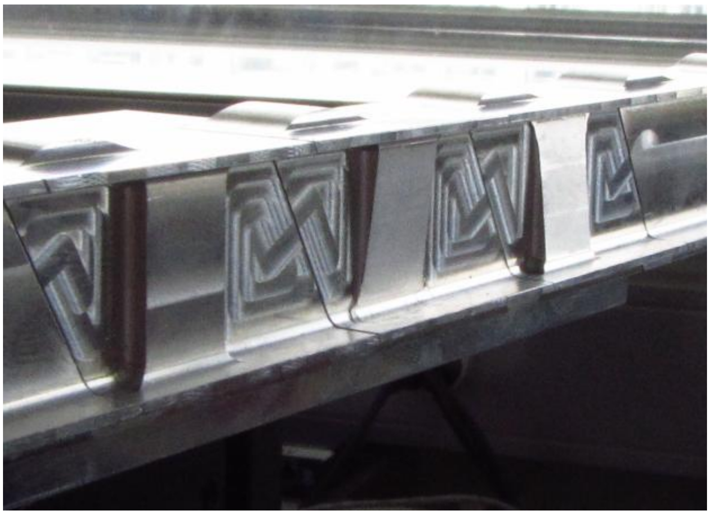

*Figure 3: The three ribs prototypes for joint measurement of clearance and axial position*

The measurement principle was firstly validated based on the use of four different types of blade shrouds: (a) one blade without any measurement feature (hereafter named “rib”) for blade detection purpose, (b) one blade with a flat rib for clearance measurement and two blades with a rib formed by an inclined plane in (c) upward and (d) downward directions for axial position measurement and finally Four sets of blades (a), (b), (c) and (d) were to be implemented along the rotor.

Because of supply chain issues related to the complexity introduced by the management of four different blade shrouds, MTU requested to limit the number of different blade shrouds at a maximum of two. According to this new limitation, the possibility of using only blade types (c) and (d) were investigating, simulated and tested on Meggitt’s validation test setup. This change also requested the development of novel blade detection algorithms and the development of modified joint axial and clearance measurement algorithms. The main impact of this change at laboratory level was a reduced measurement accuracy and range as well as a more complex blade detection method.

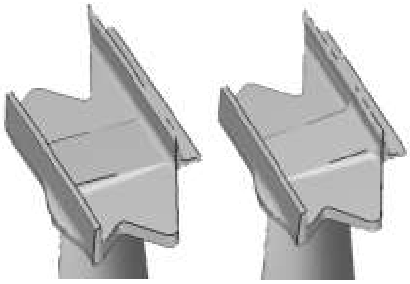

*Figure 4: Final blades to be implemented for joint axial/clearance measurement*

1.3.1.2 Laboratory testing of the measurement concept

To evaluate the feasibility of joint axial/clearance measurement, several laboratory tests have been performed. These test lead to the concept described in section 1.3.1.1. These laboratory tests have been firstly realized on a precision test setup usually used for concept studies and probes calibration. The obtained data have been analyzed and an innovative set of algorithms developed to extract axial and clearance information. At the end, the laboratory results showed the feasibility of the concept.

An extensive test campaign including several test conditions and measurements was then been performed with the test setup (validation spin rig) developed in the course of the project (see section 1.3.1.3). This validation of the whole measurement system was a prerequisite for the system integration and testing in SAGE4 Demonstrator.

The complete microwave measurement system, comprising the probe, the data acquisition hardware and data processing software was validated by measuring joint running clearance and axial rotor displacement for various positions. Two methods have been used to validate the system and define the system accuracy:

- Measurement of the axial and radial blades positions with the microwave system for a wide measurement range: The actual blades position was known by adapting the position relatively to the axial and radial displacement (known and adjusted through micrometer verniers).
- Measurement of the axial and clearance positions with the microwave system and with a reference laser sensor for each blade. This method has been applied to a limited number of positions.

The validation of the microwave measurement system has been performed with the final blades configuration for the engine test and thus with the final blade detection and measurements algorithms.

An example of measurement result is provided in Figure 5 for both radial clearance (left) and axial position (right). It shows a good agreement between the measurement performed with the microwave and reference sensors for each tested blade position.

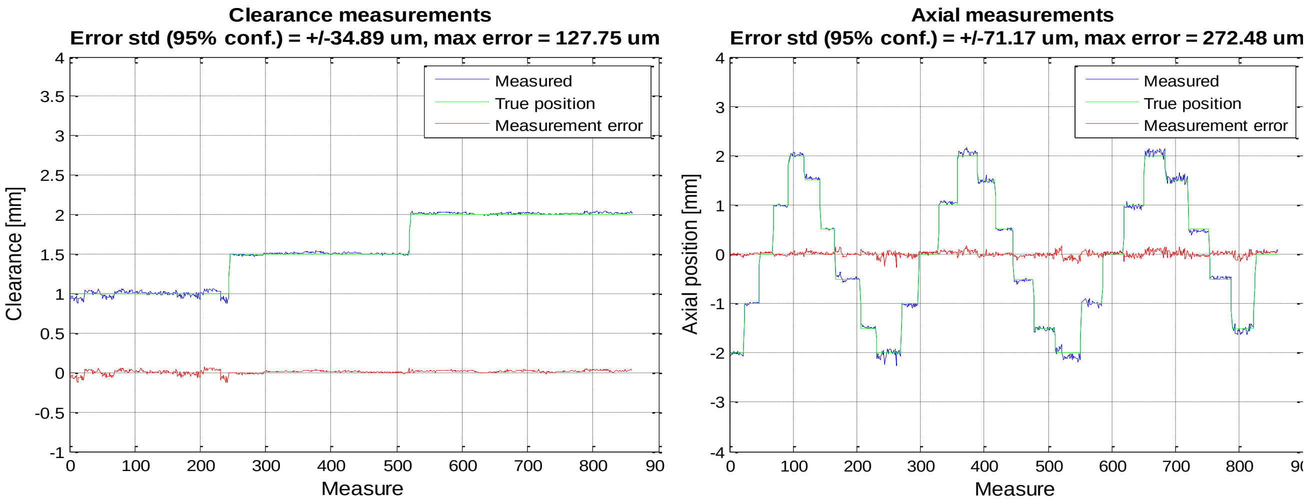


*Figure 5: Clearance and axial measurements for different blades positions*

From these measurements at various blade positions, the final measurement range of the microwave measurement system was determined in laboratory conditions for both radial clearance and axial position:

- Axial position measurement range: -4.0mm to +4.0mm
- Radial clearance measurement range: +0.7mm to +5.0mm

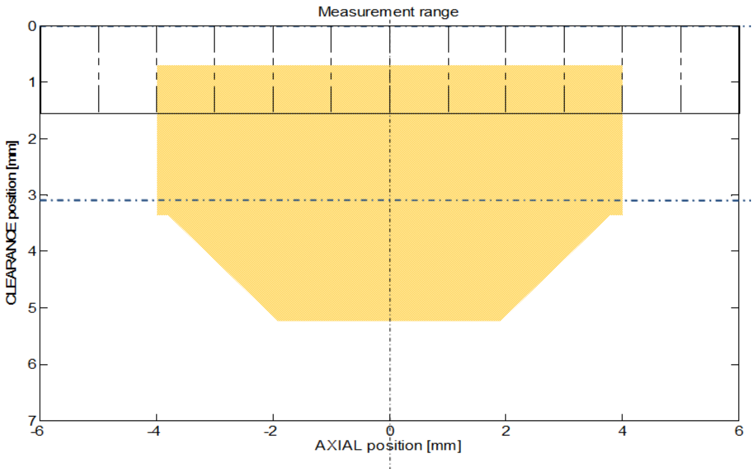


*Figure 6: Measurement range for microwave sensors in axial and radial direction*

The validation measurements also allowed the determination of the accuracy (measurement uncertainty) of the microwave measurement system in laboratory. The total measurement error measured and calculated on Meggitt's laboratory was +/- 25 μm in clearance and +/- 70 μm in axial position.

Finally, a sensitivity study of the measurement system with regard to probe mounting (orientation), engine liner motion (axial and radial) and blade-to-blade alignment was performed. The radial and axial sensitivity was determined in mm/deg or mm/mm for each perturbation source.

#### 1.3.1.3 Design of a new laboratory test stand for system validation

At the beginning of the project, only a precision test setup was available for the system evaluation. This calibration rig was not designed for representative operation of the microwave system as it is only capable to perform discontinued blade motions.

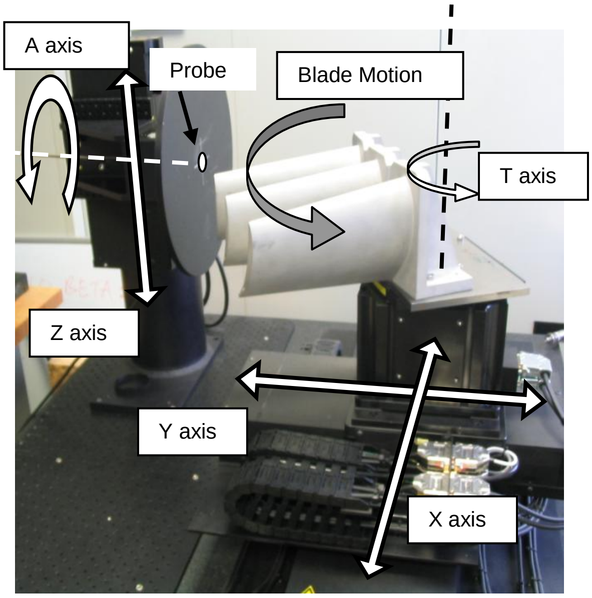


*Figure 7: Existing calibration rig*

Therefore, there was a need to design a second test setup with a more representative system operation enabling the blades to spin continuously. For the evaluation of the final measurement system in operation before the engine test, continuous motion was needed and multiple probes were installed all along the circumference of the spin rig.

| Calibration rig | Spin rig |
|---|---|
| Probe calibrations and concept studies | Analyses of system performance in terms of accuracy and precision |
| Only a few blades mounted at the same time | Complete rotor |
| Discontinuous motions | Continuous motions |
| Very slow motions | Slow motions |
| Real blades mounting with different rotor diameter is possible | Only blades that are specifically designed for the rig can be mounted |
| Only one microwave probe | Four microwave probes |

*Table 1: Functional comparison between the existing calibration rig and the new spin rig*

The new spin rig includes a rotor and a casing. The rotor can be moved relatively to the casing to vary clearance or axial position.

Microwave sensors can be mounted at different locations on the casing. In order to get a reference on clearance values, laser probes are mounted in parallel with the microwave system. A data acquisition system collects the data during test campaigns.

The rotor is driven by an electrical motor and an associated controller. An emergency stop is wired to the power unit, to the motor controller and to a safety break. When activated, it shuts down electrical power, stops the motor and breaks the rotor. The power unit is equipped with circuit-breaker.

The rotor is composed with a shaft and a hub mounted on it. The wheel can be arranged with different type of blades. The wheel can be set everywhere on the shaft thanks to a clamping fixture. The rotor is driven by a belt system connected to an electrical motor. The safety break is mounted at the other end of the shaft. The shaft is maintained by two balls bearings mounted on supports. Finally, all the test setup is protected during operation by a plexiglas cage for safety purpose.

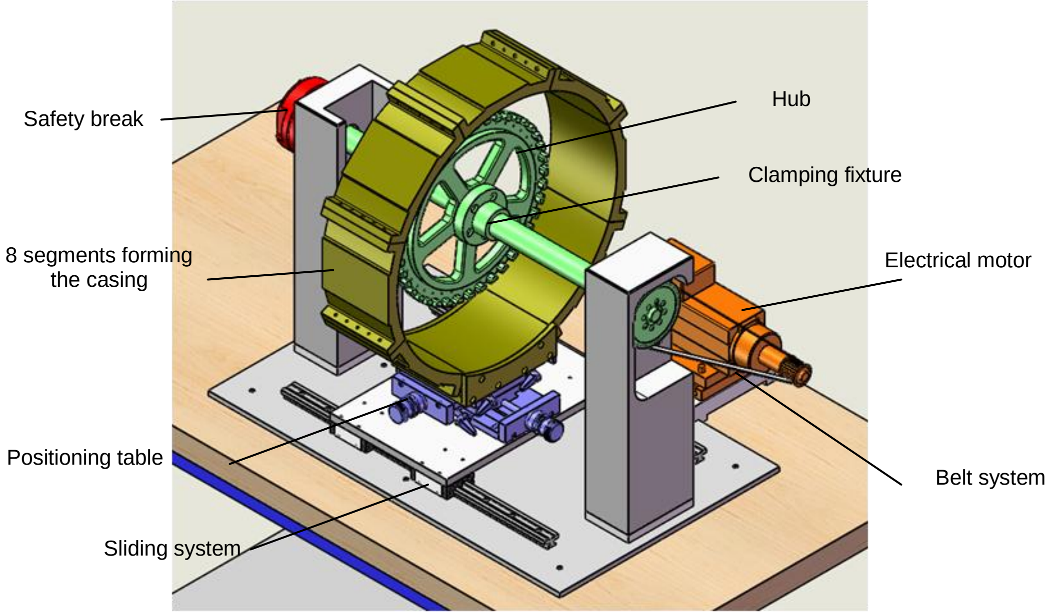


*Figure 8: CAD View of the validation rig*

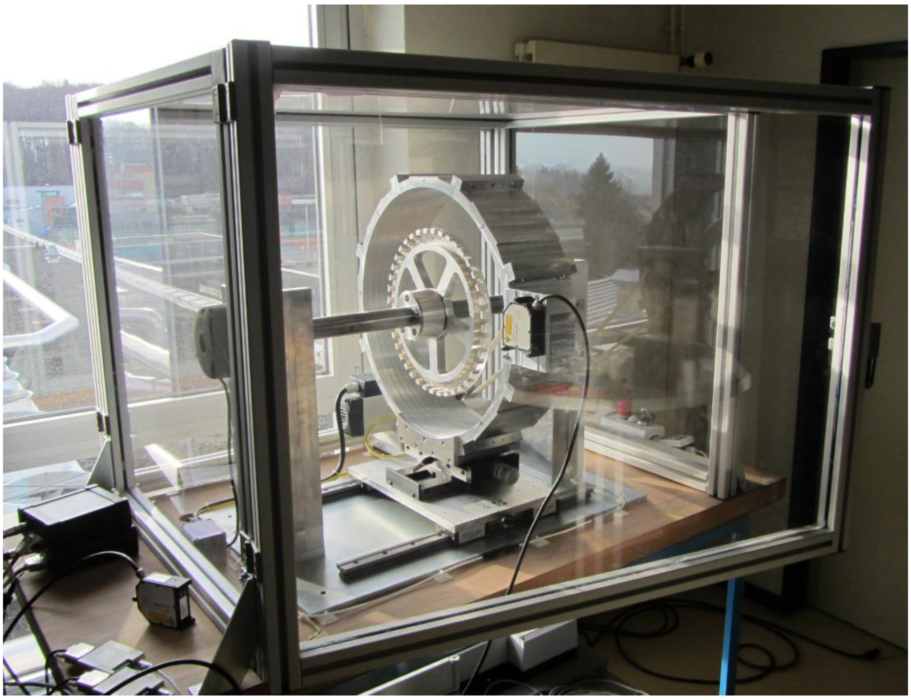

*Figure 9: The new spin rig for system testing and validation*

The spin rig was successfully designed, assembled and validated through a specific validation test procedure. Its main characteristics are provided in the table below.

| | |
|---|---|
| Clearance range | 0-12 mm, can be set by moving all the casing in the horizontal frame or by setting individual blade mountings |
| Axial range | ±50 mm, range of the positioning table |
| Casing inner diameter | 500 mm |
| Rotor diameter | 496 mm (nominal) or 476mm by changing any individual blade mounting |
| Nominal clearance | 2 mm |
| Individual blade clearance tuning | 0-10mm |
| Number of blades | To be defined, depends on application |
| Speed | 600 RPM (maximum), controllable through voltage input or with a remote control |
| Maximum torque | 5.6 N.m |
| Breaking torque | 16 N.m |
| Belt system ratio | 3:1 |
| Temperature | Room temperature |

*Table 2: Spin rig characteristics*

### 1.3.2 Work package 3

WP 3 includes all the engineering tasks required to install the microwave clearance measurement system on SAGE4 Demonstrator engine. This comprises the design of the probe installation and final drawing of the measurement features added to the blade shrouds.

WP3 was divided in 3 subtasks:

1. Design probe installation for SAGE4 Demonstrator engine based on Meggitt's standard industrial 24 GHz microwave probe core
2. Design measurement features on blade shrouds for SAGE4 Demonstrator engine test
3. Demonstrate probe durability through laboratory environmental test

The following subsections aim at providing the achievements against the objectives for subtask 1 and 3. Subtask 2 has already been covered as part of the work carried out in WP2 as can be seen in section 1.3.1.

#### 1.3.2.1 Design of the probe installation on the engine

The microwave sensor consists of a probe body, an adaptor, an integrated length of high temperature RF cable and a 3.5mm RF connector as can be seen Figure 10.

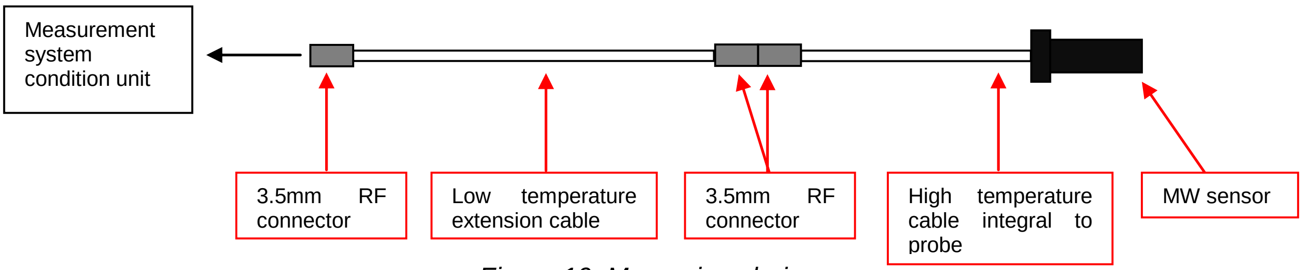


*Figure 10: Measuring chain*

The microwave sensor has two mechanical interfaces; one at each of its two ends. At the rear end of the sensor, the integrated high temperature RF cable terminates in a 3.5mm RF connector. This connector mechanically interfaces with the 3.5mm RF receptacle of the low temperature extension cable.

In order to mechanically engage with the engine, a bespoke adaptor has been designed. The adaptor welds to the core of the probe and ensures that when installed, the probe penetrates to the correct depth with respect to the turbine blades while maintaining the correct orientation with respect to the gas flow. The geometry of the adaptor is critical for ensuring that the sensor is located correctly and gives the correct output signal.

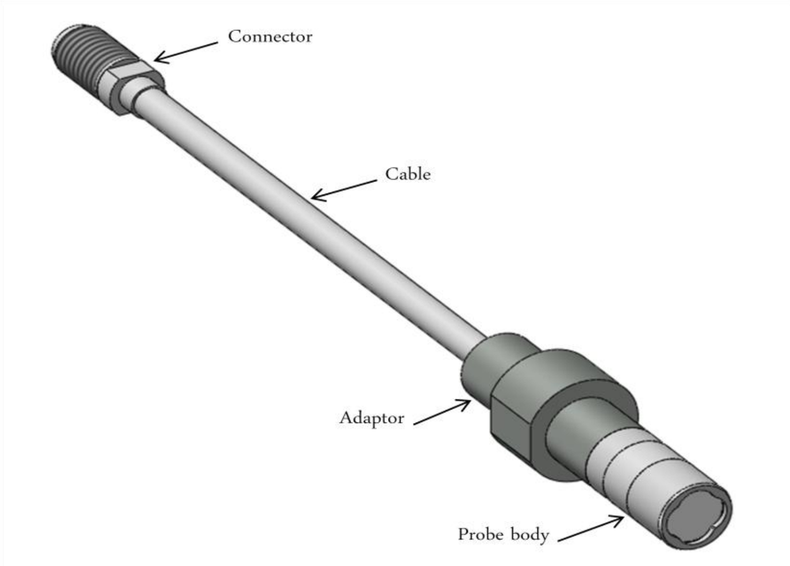


*Figure 11: Assembled Microwave Sensor*

Upon installation, the finished assembly is inserted into a port located in the wall of the turbine casing. The probe is pushed in until the shoulders of the adaptor engage with the mating face on the port. The distance between the front face of the probe and the shoulders of the adaptor has a very fine tolerance to ensure that the correct distance between the probe and the turbine blades is maintained. A gland nut is then used to secure the adaptor from behind, thus ensuring a sound fit and a good seal. This arrangement ensures that over tightening of the gland nut does not exert an excessive load on the sensor. Figure 12 gives a representation of the sensor fitted into the port.

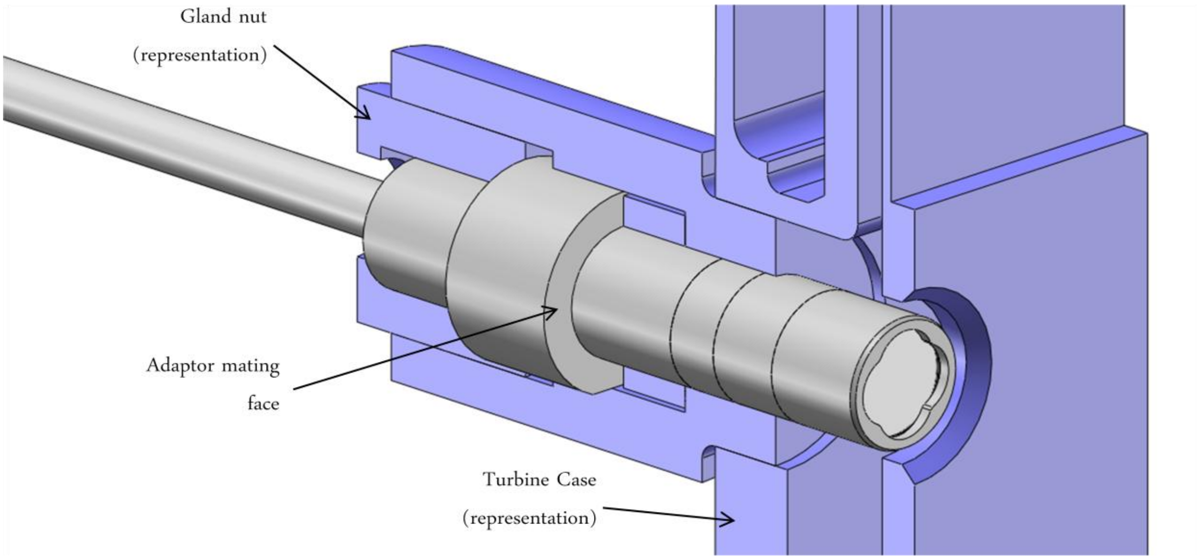


*Figure 12: Representation of installation*


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The materials of the sensor probe core have been selected with the RF performance and the thermal environment taken into consideration. The front face of the probe is in direct contact with the gas path and sees very high temperature during operation. Behind the probe the air is much cooler.

#### 1.3.2.2 Probe durability tests

A comprehensive laboratory temperature testing has been done with the microwave tip clearance probe in addition to the experience accumulated on real engines with the same sensor design. The temperature tests performed in laboratory – although not entirely representative of the real engine environment – are good indicators of the probe survivability. Two different tests were done:

- Isothermal bake at 900°C: In this test, 4500 hours were accumulated successfully with the probe. During the whole test, the microwave performance of the probe was still good and was characterized using a high-precision network analyzer.
- Temperature cycling test: The sensor was heated until it reached 820°C and then pulled out of the oven at ambient temperature. These cycles from 820°C to ambient temperature are quite harsh even compared to what the probe undergoes into the engine and they have been repeated for about 1000 cycles. The microwave performance of the probe and the probe mechanical integrity have been validated up to 1000 cycles. This very severe test is considered as a good indicator of the probe durability over 5000 engine cycles which is the ultimate goal for potential series applications of the microwave measurement system.

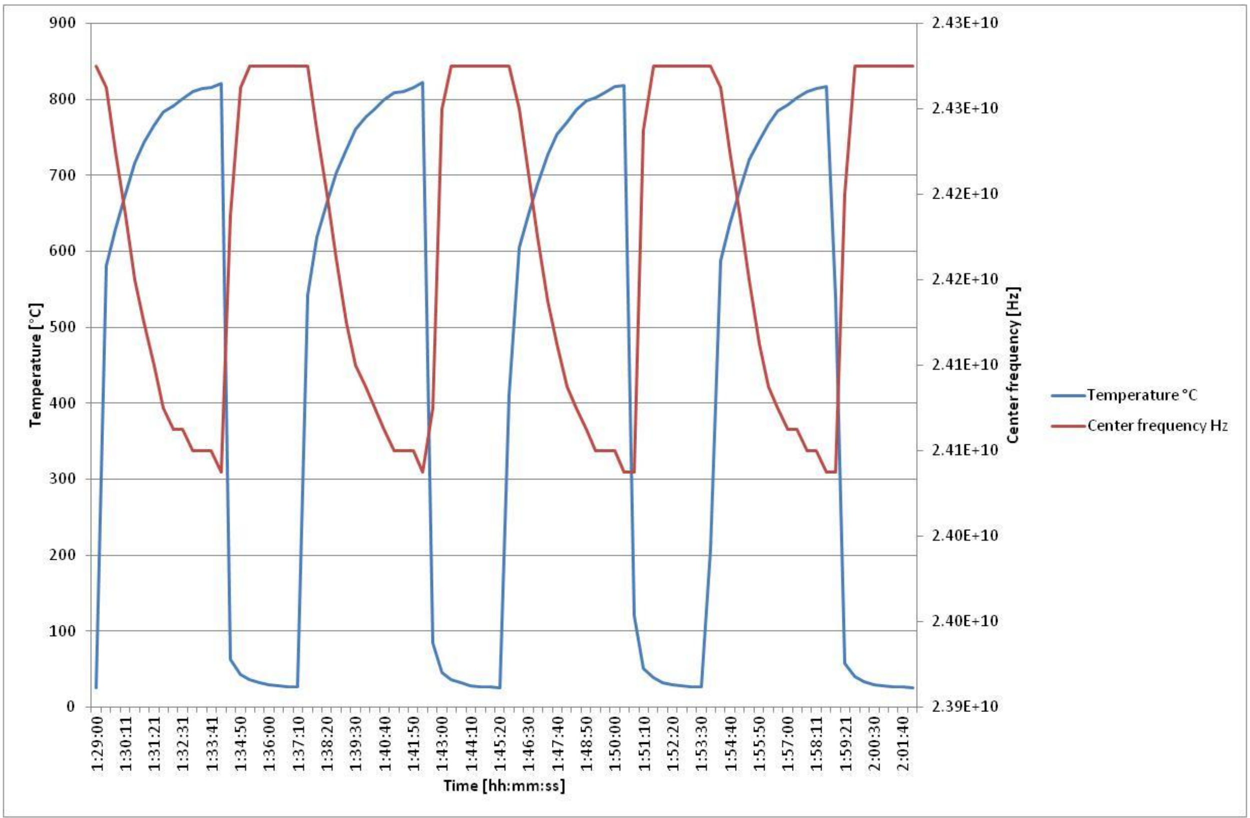


*Figure 13: Laboratory temperature cycling tests – thermal profile and probe resonant frequency*

### 1.3.3 Work package 4

WP4 included all the engineering tasks required to prepare the existing industrial electronics for SAGE4 Demonstrator test. It was divided in 3 subtasks:

1. Define measurement electronics for SAGE4 Demonstrator engine test
2. Implement the final signal processing software in electronics firmware
3. Implement the data transfer protocol in electronics firmware

The choice of the Meggitt's standard industrial 24GHz tip clearance electronics which are part of the VM600 condition monitoring platform was made for MICMEST laboratory and engine tests.

The measurement system is composed of 3 microwave probes with integral high temperature cable, extension cable, VM600 rack with processing cards and an Ethernet connection between the processing unit and a PC, as seen in Figure 14.

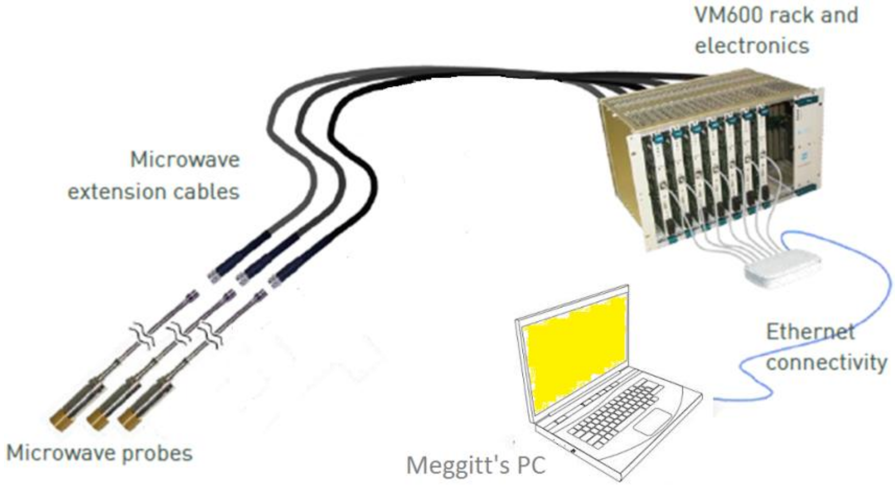


*Figure 14: Meggitt's microwave measurement system*

The blades positions were computed and provided to MTU's test experts directly through a graphical user interface on a PC.

For the joint axial and clearance measurement, the signal of each microwave sensor was processed and converted into an axial and radial position of the blades. Processing and converting steps were performed directly on the processing cards of the system electronic box (VM600) and on a PC provided by Meggitt.

During the engine test, the acquisition and processing software allowed the user to continuously configure, control and record the microwave measurement system. Various data about the measurements such as blades axial and radial position, blades patterns, sensors characteristics or rotational speed were made available. Information was provided through the same graphical user interface as shown in Figure 15.

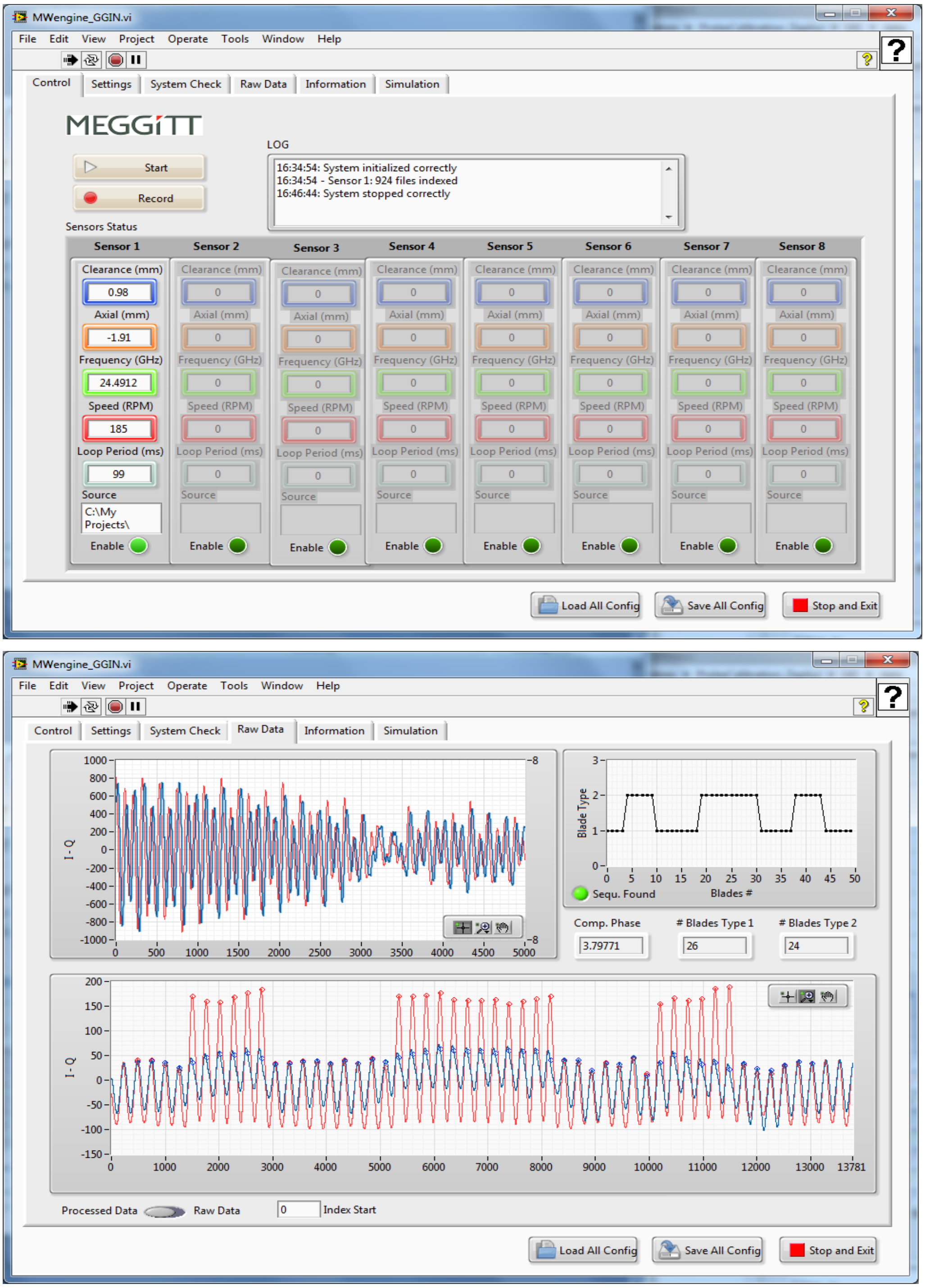


*Figure 15: Example of measurement with the acquisition and processing software*

### 1.3.4 Work package 5

In WP5, the measurement system was built, delivered, installed, tested and validated on SAGE4 engine demonstrator. WP5 was divided in 3 subtasks:

1. Manufacturer and deliver the measurement system for SAGE4 demonstrator test
2. Apply the measurement system to measure clearance and rotor axial position throughout SAGE4 demonstrator test
3. Evaluate performance of the measurement system through the SAGE4 demonstrator test

The following subsections aim at providing the achievements against the objectives for each subtask of WP5.

#### 1.3.4.1 Measurement system delivered for SAGE4 demonstrator engine test

Four microwave sensors have been manufactured and delivered to MTU. Three probes were mounted in the SAGE4 Demonstrator Engine and one was kept as a spare. The measurement performance of the four sensors has been validated prior to the delivery. The sensors were individually calibrated in an environment representative of the engine in terms of installation, blade geometry and sensor's surroundings using the MICMEST dedicated validation test setup (see section 1.3.1).

The measurement system including electronics, racks and connection cables was also shipped to MTU. The electronic hardware was composed of one industrial VM600 system which included 4 complete measurement channels (3 channels connected to the sensors installed in the engine and one spare channel). Each channel was composed of 3 electronic cards: A processing card connected via a back plane to a microwave card including a continuous wave (CW) type radar module. This module generates the microwave signals, sends it to the connected 24 GHz probes, receives it back and performs down-conversion. The output is two baseband frequency inphase and quadrature channels (called I and Q) supplied to the processing card.

*Figure 16: Extension cable (7m)*


*Figure 17: VM600 rack with processing cards*

The modules are capable to work at a frequency within a range between 23.4 and 24.4GHz (minimal bandwidth of 1 GHz). The definition of this minimal frequency range corresponds to the antenna transmission frequency of the microwave probes at ambient temperature and to cover its shift due to temperature variations and to the coupling between the shrouded blades and the antenna.

Acceptance Test Results were performed and provided for all the cards delivered for the engine test.

Four 7-meter extension cables for interconnecting the electronics and the sensor high temperature integral cable were also delivered (3 cables mounted in the engine test cell and 1 spare). The characterization of the cable was performed for all the extension cables before delivery. In particular, the cable attenuation in dB/m and total cable attenuation at 24 GHz was measured and provided as part of the acceptance test results for the extension cables.

A final functional test was performed at system-level on Meggitt's spin rig to validate the whole system before shipment to MTU for the engine test. A combined measurement of blade tip clearance and axial position was done. The blades position was set from +0.1 to +1mm in clearance and -1 to +1 in axial direction. The aim of this test was to validate the correct functionality of the whole chain, including the microwave extension cables, the electronic cards, the firmware and the processing software.

This functional test was performed for each channel. A typical test result for one channel is provided in Figure 18 and demonstrates the operability of the system for both axial and clearance positions measurements.

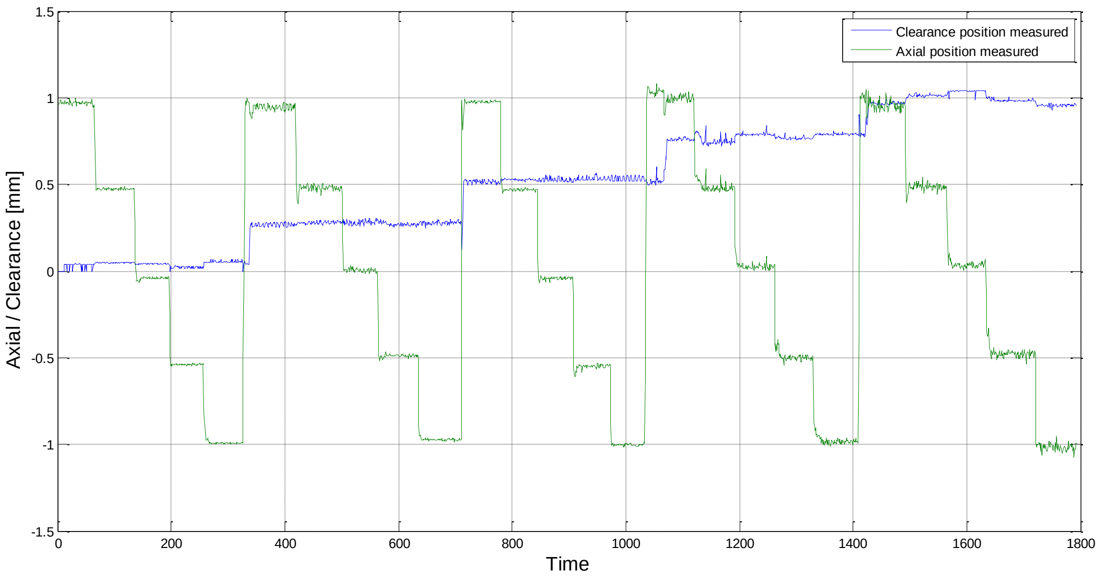


*Figure 18: Validation test results of the combined axial/clearance measurements of the blades position on Meggitt's spin rig*

### 1.3.4.2 SAGE 4 demonstrator engine test

The microwave measurement system was installed on the engine for the whole test campaign from October to December 2015.

The output of the measurement system was checked on a daily basis by MTU thanks to MICMEST SW user interface. Meggitt actively supported the installation of the sensors and electronics in the engine test bed and the operation of the measurement system throughout the engine test. Data were analyzed during the whole test campaign and last minute modifications were performed on the system to try to improve its performance throughout the engine test campaign. To this end, the Meggitt team had to travel to MTU premises in Munich a couple of times over the total duration of the engine test preparation and conduction. Actions were taken between each validation step to try to fix the issues encountered throughout the engine test campaign and to improve the performance of the measurement system. Meggitt's support to the system validation through the engine test campaign included the following steps:

- *First engine trial (rotor turned by hand):* The system was set-up for the special configuration of this test and data from actual engine blades were acquired for the first time at very low speed and without the tachometry signal (external rotor speed information). The collected raw data were processed and analyzed and preliminary clearance measurements were calculated.
- *Dry crank 1:* This step was originally to assist to the engine dry crank (using the starter motor) but it was finally not performed due to issues with the engine. This slot was finally used to install and test the MICMEST measurement equipment to have it ready for the engine test programme.
- *Dry crank 2:* This step was aiming at validating the functionality of the measurement system once fitted in the test cell and to record data in this final configuration (system integrated to the engine test cell and instruments). Some modifications were applied to the microwave software interface prior to the tests and two engine test runs were acquired at low speed. This test raised some issues with the use of the tachometry signal in the measurement software that were then resolved.
- *Thermal survey:* The objectives of this step were to fix reported problems with the microwave acquisition software encountered in the previous test sequences to ensure proper measurement and data recording and to assist to the engine thermal survey which was the most interesting and important validation test for the MCMS. Observations showed that the detection of the blade sequence was not always correct. Indeed, the system was performing blade detection and blade type identification but not always identified correctly the blade type. However, it provided clearance and axial positions of the blades. The root cause has been identified in the blade classification algorithm that has been then redesigned to solve this issue (see next validation step). During this step, the system provided better and more consistent blade detection but blade classification still needed to be improved.
- *Engine cycling:* This test aimed at validating the modifications applied to the measurement software after having analyzed the data from the thermal survey. Improved algorithms were implemented to fix the problem related to blade classification and they proved to increase the reliability and repeatability of the system. The correctness of the blade classification process has been verified through the SW interface and the number of unrealistic measures has been reduced. During this step, another source of measurement error linked to the blade detection algorithm which could generate noisy measurement results was identified.

The post-processing activities performed in parallel and after SAGE4 engine test aimed – among other things – at fixing the issue related to the accuracy of the blade detection encountered in the last validation step on the engine and are further described in section 1.3.4.3.

The MCMS operated through the entire SAGE4 engine test campaign. All along the testing phase the system proved able to record measurements data with no sensor failures. In addition, no degradation of the microwave sensors signal has been observed throughout the engine test campaign.

#### 1.3.4.3 Validation of the measurement system through SAGE4 Demonstrator

*Test purpose*

The purpose of the test was to validate the microwave measurement system through SAGE4 engine test campaign. To this end, the objective of this test was manifold:

- Demonstration of the capability of the microwave system to measure clearance and axial rotor displacement during the engine test in realistic operating conditions
- Characterisation of the properties of the measurements in terms of stability, repeatability, coherence between the sensors without requiring manual optimisation
- Identification of possible weaknesses of the system and needs for adjusting the processing from laboratory model test rig to engine test rig

*Test set-up*

For the engine test, the VM600 electronic rack has been installed in a "security room" just above the engine test room as described in Figure 19 hereafter (engine front view). An Ethernet cable was connecting the VM600 and Meggitt's laptop that was located in a control room. In addition to microwave cables, the VM600 was receiving power supply and a tachometer signal from MTU test bench. Meggitt's laptop was also receiving a time reference signal from MTU test bench.

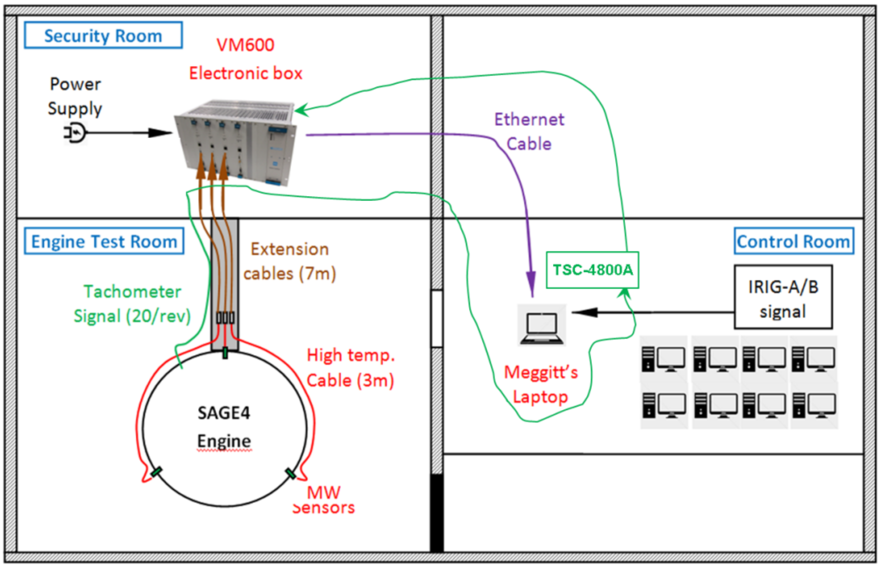


*Figure 19: Microwave measurement system installation*

The 3 microwave sensors were looking at the blades of the 3rd stage of the low pressure turbine of SAGE4 engine. They were equally spaced along the circumference of the engine at about 120° from each others.

*Test results*

The MCMS was installed on the demonstrator engine for the whole test campaign and data were collected for various engine test sequences (e.g. dry crank, engine start, thermal survey, cycling, IMI (Idle, Max power, Idle) cycles repetitions. The test sequence used for the MCMS technology assessment and for which test results are provided in the present document is the thermal survey.

The thermal survey tests were performed during two separate days on November 4th and November 6th 2015. They consisted of the engine operating from idle to maximum thrust with or without intermediate thrust steps. The engine operating setting for each step was then kept stable for a period of time such that the engine comes to a thermal equilibrium so the interesting engine parameters can be measured without thermal transient influence.

The measurements performed on the 6th of November during the engine thermal survey allow assessing the behaviour of the microwave tip clearance measurement system during thermal test as various operating conditions were covered.

Clearance and axial measurements have been performed during this test sequence. The MICMEST software interface was providing pseudo real time display of the microwave sensor signals as well as the clearance and axial position measurements. Figure 20 shows the raw measurement of one sensor as an example with the indication of the blade sequence found on the top right graph as well as the blade signal with detected blades marked on the bottom graph. The top left graph shows the frequency sweep measurement used for the cable compensation.


*Figure 20: Snapshot of signal acquisitions taken from the SW user interface*

As described in section 1.3.4.2, some modifications were performed on the MCMS measurement software during the test campaign to improve the quality of the measurements. Other modifications were also implemented in post-processing after the test. This periodic report only provides the final post-processed results in Figure 21. The first graph represents the engine speed profile applied for this test sequence and the second graph the measurement results (clearance as a function of time). The test sequence lasted for about 3h35 minutes. During this period the speed ranged from 22%

to 100% N1 speed and back in 12 ascending and then descending intermediate steps as shown in Figure 21 below. Engine idle condition corresponding to 22% N1 speed and 100% for the maximum takeoff thrust. Between each step, the engine speed was stabilized until thermal equilibrium was reached.

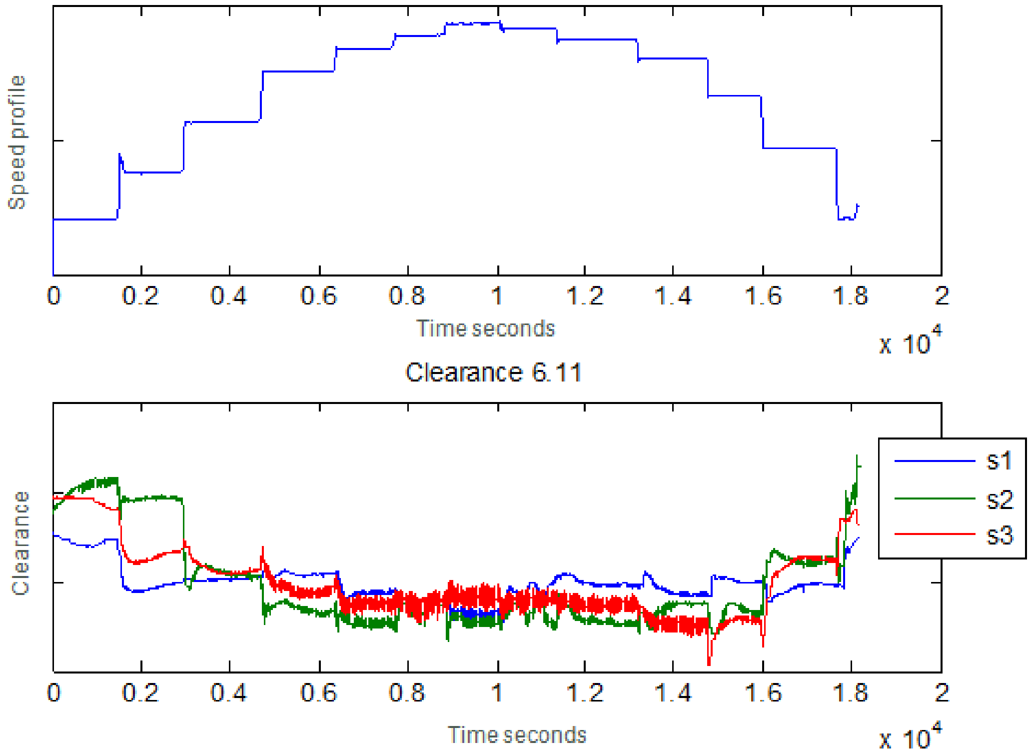


*Figure 21: Final test results for the 3 microwave sensors for engine thermal survey cycle*

With this test, the results analysis is focused on the assessment of the stability of the measurements for constant speed areas, the relationship between the measurements performed with and without using the axial information and the trending of the clearance measurements on speed changes.

As we did not possess ground truth data or data coming from an independent measuring system, we could not truly assess the accuracy of the measurements. As a consequence and to characterize our results, we computed for each sensor for clearance and axial measurements when applicable:

- The correlation between same sensor measurements on similar cycles $C_{Scyc}$
- The variance of measurements at constant speed $V_{Scs}$
- The correlation between measurement and speed $C_{SClSp}$
- The correlation $C_M$ and average difference *D<sub>M</sub>* for clearance computed with and without axial measurements
- The correlation between different sensor measurements $C_{SASB}$

Results collected during the test are summarized in the tables below for radial running clearance and axial position measurements and for each measuring channel.

| Sensor \Clearance | $C_{Scyc}$ | $V_{Scs}$ (mm) | $C_{SClSp}$ | $C_M$ | $C_{SASB}$ |
|---|---|---|---|---|---|
| 1 | 99.6% | 0.04 | -68% | 99.8% | S1S2 61% |
| 2 | 95.1% | 0.05 | -92% | 95.6% | S2S3 73% |
| 3 | 99.3% | 0.01 | -84% | 99.9% | S1S3 87% |

*Table 3: Summary of the clearance measurement analysis*

| Sensor \Axial | $C_{Scyc}$ | $V_{Scs}$ (mm) | $C_{SAxSp}$ |
|---|---|---|---|
| 1 | 98.7% | 0.041 | -3% |
| 2 | 94% | 0.037 | 16% |
| 3 | 98.5% | 0.203 | -64% |

*Table 4: Summary of the axial measurement analysis*

## 1.4 Technology evaluation

### 1.4.1 Major accomplishments

The resulting achievements from the work performed and in light of the engine test results are the following compared to the previous DREAM project:

- The cross sensitivity between the radial clearance and axial displacement of the microwave sensor was reduced drastically. The ribs added to the shrouded blades were designed with this objective of improving the radial clearance measurement by minimizing the effect of the change of relative position between the blade tip and the probe.
- The radial clearance and axial position were both provided by the microwave sensor as a result.
- Blade detection has been highly improved and with the engine test it was demonstrated that at the different engine conditions, it works reliably.
- Blade sequence detection could differentiate between two different types of ribs added on the shrouded blades.
- Having radial clearance measurement points around the circumference, with one rib on each shrouded blade, it was possible to measure individual blade clearance (in configuration as SAGE4 low pressure rotor were each blade has a platform or shroud at its tip and they are not attached together).
- The absence of an independent way of measuring the clearance makes hardly possible to quantitatively establish the accuracy of the measurements. It can be observed a general anti-correlated behaviour of the phase with respect to the speed and an overall acceptable correlation between sensors measurements.

### 1.4.2 Technology gaps

There are still some remaining technology gaps to be addressed and solved before the ultimate objective of a suitable microwave system as part of an Active Clearance Control (AAC) system for series application and capability of flying.

The calibration maps trained in laboratory could not be representative enough of the real engine particularly due to different environment (honeycomb, very small and confined volume) and larger temperature variation range. Their use to extrapolate the measurements from lab rig to engine rig to get an absolute measure is questionable.

It is our opinion that the use of a calibration mapping represents the major gap of such a technology at present. The only reasonable way to use a measurement process based on calibration would consist of estimating the calibration map directly on the turbine rig by using an independent measuring system to establish the ‘ground truth’.

Therefore a data driven approach does not allow assessing the accuracy of the measurements. The need of an accurate physical model and understanding of the microwave measurement in short range in the actual engine appears the only way to increase the system TRL.

Finally, cable compensation technique and IQ mixer imbalance errors represent also a limitation to achieve accuracies below 0.1 mm for absolute radial clearance measurements. But those are expected to be of second order and should only be of concern once the overall accuracy of the measurement will be improved by better understanding of the physics and system’s modelling.

### 1.4.3 Status against specifications

In the table below are provided the status of the MCMS performance against the original system requirements listed in section 1.2.2.

| Requirement | Met | Comments |
|---|---|---|
| High durability and operational reliability | Y | Measurements have been collected continuously during the whole test campaign. Only minor issues with the acquisition software which prevented fully automated operation, it had to be restarted daily due to a memory leak.<br>No signal degradation have been observed or prevented to complete the measurement process. Sensors have proven to be reliable in the high temperature and pressure environment. However, the duration of the engine test (100 hours and about 400 cycles) did not allow proving the sensor survivability in operation but this was validated by previous DREAM engine test and further laboratory testing (temperature cycling and isothermal bake tests). |
| Fulfillment of turbine casing containment requirements | Y | The installation of the sensors in the turbine casing fulfills the requirements for SAGE4 demonstrator engine* and are field replaceable.<br><br>* Note: Designs were proposed for an integration that fulfills production containment requirements but it was not implemented on SAGE4 for practical reasons since the change of scope (no integration into the closed loop ACC) |
| Measurement range | Y | System setup allows measurement in the full range specified. |
| Adequate clearance measurement accuracy | N | Test analysis seems to indicate that ±0.02 mm and ±0.05 mm uncertainty of radial and axial position measurements are not achieved. The absence of reference measurement during the engine test besides the concurrent capacitive probes does not allow an accurate assessment of the reached measurement accuracy during engine operation. |
| Data format and transfer | N | The data format defined was respected and all the engine test measurements were recorded as unprocessed data as well as in text file including time stamp, rotor speed, clearance and axial position.<br>Measurement rate of 0.5 sec. not achieved during the engine test although technically this is not a problem. Due to a bug in the microwave sensor firmware, the measurement of the blades had to be performed twice, the first one being thrown away. In average, the measurement rate achieved was 0.7-0.8 sec.<br><br>Note: No special communication protocol to provide measurement to a control or other system was designed since the change of scope (no integration into the closed loop ACC). |

*Table 5: General clearance measurement system requirements*

## 1.5 Deliverables and milestones

There were no major deviations from the work programme for milestones and deliverables. They are all achieved / completed.

### 1.5.1 List of deliverables

| Del. no. | Deliverable name | WP no. | Lead beneficiary | Dissemination level | Delivery date from Annex I | Actual / Forecast delivery date | Status |
|---|---|---|---|---|---|---|---|
| D1.1 | Detailed project plan | 1 | 1 | CO | 2 | 2 | Completed |
| D2.1 | Laboratory test stand available | 2 | 1 | CO | 12 | 12 | Completed |
| D2.2 | Laboratory testing complete | 2 | 1 | CO | 14 | 14 | Completed |
| D3.1 | Implementation concept of measurement system for SAGE4 Demonstrator | 3 | 1 | CO | 23 | 25 | Completed |
| D5.1 | Delivery of sensors | 5 | 1 | CO | 29 | 28 | Completed |
| D5.2 | Delivery of measurement system | 5 | 1 | CO | 37 | 37 | Completed |
| D5.3 | Validation of measurement system through SAGE 4 Demonstrator completed | 5 | 1 | CO | 47 | 47 | Completed |

*Table 6: List of deliverables*

### 1.5.2 List of milestones

| Milestone. no. | Milestone name | WP no. | Lead beneficiary | Delivery date from Annex I | Actual / Forecast delivery date | Status |
|---|---|---|---|---|---|---|
| MS1 | Laboratory testing complete | 2 | 1 | 14 | 14 | Achieved |
| MS2 | Design readiness for blade shroud modification | 3 | 1 | 14 | 14 | Achieved |
| MS3 | Design readiness for sensor installation | 3 | 1 | 14 | 14 | Achieved |
| MS4 | Full measurement system validated | 2 | 1 | 21 | 24 | Achieved |
| MS5 | Engine Test Completed | 5 | 1 | 44 | 46 | Achieved |

*Table 7: List of milestones*

## 1.6 Explanation of the use of the resources

The engineering effort was spread over the 5 project work packages as follows in person-month (PM):

- WP1: 3.3 PM - Project Manager and Project Administrators
- WP2: 8.8 PM - Microwave Engineers, Firmware Engineer, Technicians
- WP3: 7.1 PM - Mechanical Engineers, Firmware Engineer, Technicians
- WP4: 3.0 PM - Microwave Engineer, Firmware Engineer, Mechanical Engineer
- WP5: 8.5 PM - Microwave Engineer, Software Engineer, Application Engineer

**Total: 30.7 PM**

Table 8 provides the breakdown of the total project costs.

| Work Package | Item description | Amount in € | Explanations |
|---|---|---|---|
| | **Personnel direct costs** | **458’045.88** | Personnel costs based on actual hourly rate |
| 2, 3, 4 | - RTD | 260’369.31 | |
| 5 | - Demonstration | 138’627.29 | |
| 1 | - Management | 59’049.28 | |
| | **Subcontracting** | **0.00** | |
| 2 | **Other direct costs - RTD** | **110’929.27** | Consumables for spin rig (final blade mock-ups and other mechanical parts).<br>Software for algorithm development<br>Reference system for clearance measurement<br>4 channels Microwave electronics<br>4x 24GHz microwave probes |
| 5 | **Other direct costs – Dem.** | **9’448.19** | Durable equipment: Final microwave sensors delivered to MTU (4x 24GHz microwave probes and integral high temperature cables). |
| 1 | **Other direct costs – Mgt** | **16’296.10** | Travel costs for project reviews (RV2/RV3/RV4) and engine installation + test campaign (5 tests sequences) |
| | **Indirect costs** | **131’308.31** | |
| 2, 3, 4 | - RTD | 81’288.09 | |
| 5 | - Demonstration | 33’357.18 | |
| 1 | - Management | 16’663.04 | |
| | **TOTAL** | **726’027.75** | |

*Table 8: Personnel, subcontracting and other major cost items for MEGGITT SA (M1-M47)*

## 1.7 Potential impact and exploitation plan

### 1.7.1 Potential impact

In jet engine the running radial clearance between the rotor blades and surrounding casing should be as small as possible in both the compressor and turbine in order to minimize the airflow losses and increase their overall efficiency. By design, a minimum turbine tip seal gap shall be ensured such that it prevents mechanical contact between the rotating blades and the casing for the intended range of operation of the engine. However, due to different thermal expansion characteristics between the case and the rotor as well as the effect of centrifugal forces on the rotor, a safety margin has to be included in the design. For this reason larger running clearances than needed – the minimum clearances does not usually occur in steady state cruise condition, the major flight condition concerning the fuel consumption – are encountered.

A solution to minimize radial tip clearance and associated blade tip leakage for the different engine operation conditions is to add an active clearance control (ACC) system. Intensive research and development work has been carried out and nowadays all of the recent commercial turbofan engines in service have clearance control system. As a non-exhaustive list, the GE90, CFM56, RR Trent (500, 700, 1000 and XWB), PW4000, V2500 engines operated in large number are all equipped with some variants of thermal ACC systems. It was demonstrated and proven that this allows achieving considerable reduction in fuel consumption over the whole flight mission. A thermal ACC system takes benefit of the available cooling air used by design to keep the engine bearings, case and rotor below their maximum rated temperature and maximize their life time.

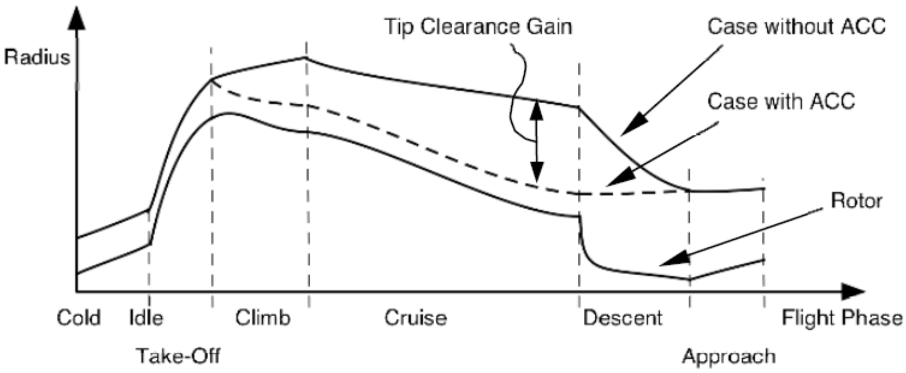


*Figure 22: HPT tip clearance change during the flight conditions of a commercial engine*[1]

The radial running clearance optimization methods currently used in commercial engines are all based on thermal actuation technology by using available cooling air from the HPC (High Pressure Compressor) or fan duct. A valve controls the airflow to modify the thermal state and thus the difference of radius between the casing and the rotor. Different systems are in service for clearance control which have different level of sophistication. The older and most common systems are controlling clearance on the turbine where the casing temperature is controlled to change its diameter size, such systems are commonly called HPTCC (High Pressure Turbine Clearance Control) or LPTCC for the low pressure turbine part. Some of the most advanced engines have also a control system of the HPC where it is the rotor temperature which is controlled.

[1] Figure from the book Systems of Commercial Turbofan Engines, An Introduction to Systems Functions from Andreas Linke-Diesinger, ISBN 978-3-540-73618-9

This contributed among other system improvements to the reduction of SFC and $CO_2$ emissions of the modern commercial engines. Those engines are able to meet the environmental regulation standards and feature lower fuel consumption than without clearance control system.

After decades of development and improvement of the thermal ACC systems, the potential to further reduce the radial running clearances is by directly measuring the blade tip clearance and provide this measurement as an input to the ACC system. However, it has been identified that the lack of a reliable and accurate non contact tip clearance sensor is one of the technological barriers to be overcome. Meggitt has developed such clearance sensor candidate based on microwave technology and improving the technology readiness level of this sensor is the scope of the MICMEST project.

The Microwave Clearance Measurement system developed in this project not only measured the radial running clearances of shrouded blades in low pressure turbine but the capability to measure the axial rotor displacement was added. The accuracy of the clearance measurement has been improved and verified on SAGE4 engine demonstrator. Overall the technology readiness assessment of the microwave clearance measurement system after SAGE4 engine test is still too far away for series application and to be integrated in the ACC of the LPT.

In addition, unfortunately the SAGE4 engine had not a dedicated active clearance control system for the LPT; it is a common system for both the HPT and LPT as by design it has only one control valve to regulate cooling air towards HPT and LPT. Therefore the ACC system is optimized for the HPT where it is the most critical. The LPT clearance modification achievable keeping a safety margin with the system is thus limited even using the feedback from tip clearance sensors. For this reason MTU decided not to integrate the microwave clearance measurement system as part of the closed-loop control system as it would not bring benefit in terms of LPT efficiency improvement. This would not be the case on other turbofan engines with a specific LPTCC and is only because of the SAGE4 engine demonstrator construction.

However, the gain in closed-loop ACC system based on cooling air seems to be limited as the response time is too slow and hence does not allow reducing significantly the safety margin. Mechanical ACC systems based on electrical or hydraulical power bear the highest potential compared to thermal ACC systems[2] of eliminating the clearance losses while only minor improvement can be made for thermal ACC systems. However those mechanical ACC systems have not been validated on demonstrator but the concepts studied led to 93% elimination of the tip clearance losses and to completely compensate any clearance deterioration over time in the LPT for a new engine. In comparison, a thermal ACC system also based on tip clearance sensor feedback can achieve 72% average tip clearance losses elimination and the current state-of-the-art thermal ACC systems eliminate about 56% on new engine compared to without any ACC system.

The potential impact of an ACC system based on clearance measurement beside the reduction of fuel consumption is the compensation of deterioration losses due to single rub-in events and optimization of the different operating conditions during a flight mission. For modern turbofan engines, clearance measurement sensing coupled with improved ACC system is a serious candidate to reach the ICAO and European commitment to reduce the CO2 emissions of commercial air transport. However,

[2] Aircraft Engine Performance Improvement by Active Clearance Control in Low Pressure Turbines, Christian Knipser (ILA), Wolfgang Horn (MTU) and Stephan Staudacher (ILA), paper GT2009-59301, ASME Turbo Expo 2009: Power for Land, Sea, and Air, Orlando, Florida, USA

presently there are no tip clearance sensor on the market technologically ready to be used with an ACC system and the microwave clearance sensor as a potential candidate still need to be further validated and developed to be suitable. According to MTU recommendation, it is not suitable for being used in production low pressure turbines and MTU will certainly pursue other measurement techniques as alternatives to quantify rub-in for nearer term integration in next generation of LPT.

### 1.7.2 Exploitations plan and results

The work performed within the scope of the MICMEST project contributed to increase the TRL of the microwave clearance measurement system of shrouded blades but the objective to reach TRL6 with this project was not achieved.

In summary, all along the testing phase the system proved able to record measurements data with no sensor failures. In addition no degradation of the microwave sensors signal has been observed as expected following the validation of endurance test with previous DREAM project. In addition, the laboratory studies performed to improve the radial clearance measurement had a positive impact on the signals measured during the SAGE4 demonstrator test. Indeed, the ribs features used to achieve the measurement could be distinguished clearly with a signal to noise ratio of at least an order of magnitude better than with DREAM. Given those improvements, the blade detection was less uncertain despite the remaining technology gaps and the axial measurement could be provided.

There are still some remaining technology gaps to be addressed and solved before the microwave clearance measurement system is a suitable candidate for being part of a closed-loop controlled ACC system for series application and capability of flying.

The major technology gap is the calibration aspect and incomplete understanding of the physical model. Various improvements to make more robust, general and reliable the clearance measurement process have been discussed as possibility based on experience from this project. Among them the use of unwrapping and integration of time information appear the most important. Benefits can derive by using neural network as fitting tool to produce measure directly from raw IQ data, instead of the gradient descent approach.

Following this project, Meggitt plans to develop a physical model of microwave sensor including understanding of the electromagnetic interaction and how to filter out the undesired effects on the phase induced by multipath and near field effect. Then based on the model, this would allow simulating the sensor response according to the blade type and sensor surrounding geometry to reduce the experimentation required and more reliably test the algorithm robustness. The end goal would be to get rid of individual complex calibration process as performed currently. This is part of the exploitation plan to bring the microwave clearance measurement system to TRL6, hence closing the gap preventing to use tip clearance sensor as feedback for ACC system on commercial turbofan engines.

### 1.7.3 Main dissemination activities

Some major advances resulting from the project were presented at the joint PIWG (Propulsion Instrumentation Working Group)/EVI-GTI (European Virtual Institute for Gas Turbine Instrumentation) conference 2014 in Hasbrouck Heights (NJ), USA. The presentation was entitled “Advances in Microwave Tip Clearance Sensors”. The EVI-GTI and PIWG associations are regrouping major OEMs, end users (sensors manufacturers) and academic actors involved in the gas turbine instrumentation, both for aerospace and power generation applications. The presentation was made available to the conference attendees proceedings of this scientific and industrial event.

A very brief overview of the project objectives was also presented as part of the Clean Sky SAGE4 Demonstrator poster prepared for the exhibition at Paris for “Le Bourget” Air Show in 2013.

# 2 USE AND DISSEMINATION OF FOREGROUND

## 2.1 Section A

MICMEST project did not lead to the publication of scientific papers. Some major advances resulting from the project were presented at the joint PIWG (Propulsion Instrumentation Working Group)/EVI-GTI (European Virtual Institute for Gas Turbine Instrumentation) conference 2014 in Hasbrouck Heights (NJ), USA.

**LIST OF DISSEMINATION ACTIVITIES**

| NO. | Type of activities | Authors | Title | Date/Period | Place | Type of audience | Size of audience | Countries addressed |
|---|---|---|---|---|---|---|---|---|
| 1 | Conference: Joint PIWG/EVI-GTI conference 2014 | J. Geisheimer, G. Giner, B. Pichon | Advances in Microwave Tip Clearance Sensors | 20-24 October 2014 | Hasbrouck Heights, NJ (USA) | Gas turbine instrumentation community (industry (OEMs, end-users) and academics) | Approx. 130 | All countries |
| 2 | Exhibition - Paris Le Bourget Air Show | D. Kwapisz, B. Pichon | Clean Sky - SAGE 4 Demonstrator | 21 June 2013 | Paris (France) | Scientific community (higher education, Research) - Industry - Civil society - Medias | >1000 | All countries |

## 2.2 Section B

The Foreground resulting from MICMEST did not lead to new patent applications. However, the work carried out in the project made use of Background IP already protected by a number of Meggitt's patents.

| Type of Exploitable Foreground | Exploitable foreground | Confidential | Foreseen embargo dated | Exploitable product(s) or measure(s) | Sector(s) of application | Timetable, commercial or any other use | Patents or other IPR exploitation (licences) | Owner & Other Beneficiary(s) involved |
|---|---|---|---|---|---|---|---|---|
| General advancement of knowledge | *Contactless combined measurement of axial displacement and radial clearance* | *NO* | | *Shrouded blade tip clearance and axial rotor displacement* | H51.1.0<br>H51.2.1 | *2018 and beyond* | *Yes (existing prior to MICMEST project)* | *Meggitt (owner)*<br>*MTU* |
| General advancement of knowledge | *Spin rig* | *NO* | | *Laboratory rig* | H51.1.0<br>H51.2.1 | *2016 and beyond but for laboratory purpose* | *No* | *Meggitt (owner)* |
| General advancement of knowledge | *Improvement of measurement accuracy* | *NO* | | *Microwave clearance measurement system* | H51.1.0<br>H51.2.1 | *2018 and beyond* | *Yes (existing prior to MICMEST project)* | *Meggitt (owner)*<br>*MTU* |
| General advancement of knowledge | *Use of neuronal network and Kalmann filter technique to improve measurement* | *NO* | | *Microwave clearance measurement system* | H51.1.0<br>H51.2.1 | *2018 and beyond* | *No* | *Meggitt (owner)*<br>*MTU* |

The Exploitable foreground can be summarized as:

- Development of new measurement capability with the microwave clearance measurement system
- Improvement of the measurement accuracy with shrouded blades tip
- Construction of a new laboratory spin rig for concept test, validation and calibration
- Development of advanced signal processing and algorithms

The combined measurement of tip clearance and rotor axial position of shrouded blades using Microwave clearance measurement system was developed. The measurement accuracy could be improved as a result of the very detailed study conducted to perform this combined measurement. The purpose is to provide reliable, accurate and more information with one sensor that can be used by the engine active clearance control system.

A laboratory spin rig was built and used actively with the MICMEST project to validate and calibrate the microwave clearance measurement system. This rig features a full rotor with blades and surrounding case and reproduces as close as possible the key mechanical features of the SAGE4 engine demonstrator LPT important for the microwave sensor. The modular construction of this spin rig makes it usable for other development projects of the microwave clearance sensor or other type of sensors. It has been exploited for tip timing investigations and plans to add probe heating capability are under study.

New signal processing concepts were developed and used to improve the measurement. They will be integrated to the generic microwave tip clearance system also to measure non-shrouded blades. It has been highlighted that before taking full advantage of the neuronal network, further research is needed to built an accurate model and understand the physics of the microwave electromagnetic interaction between the blade, casing and sensor antenna. Also further study if neuronal network can be used in a system certified on an aircraft and what would be the work to be able to certify such system.

## 3 REPORT ON SOCIETAL IMPLICATIONS

## A General Information

**Grant Agreement Number**
307866

**Title of Project**
Development of a Microwave Clearance Measurement System for Low Pressure Turbines

**Name and Title of Coordinator**
Meggitt SA represented by Bertrand Pichon, Applied Research & Technology Manager

## B Ethics

| | |
|---|---|
| **1. Did your project undergo an Ethics Review (and/or Screening)?** | ***No*** |
| **2. Please indicate whether your project involved any of the following issues (tick box)** | |
| **RESEARCH ON HUMANS** | |
| • Did the project involve children? | No |
| • Did the project involve patients? | No |
| • Did the project involve persons not able to give consent? | No |
| • Did the project involve adult healthy volunteers? | No |
| • Did the project involve Human genetic material? | No |
| • Did the project involve Human biological samples? | No |
| • Did the project involve Human data collection? | No |
| **RESEARCH ON HUMAN EMBRYO/FOETUS** | |
| • Did the project involve Human Embryos? | No |
| • Did the project involve Human Foetal Tissue / Cells? | No |
| • Did the project involve Human Embryonic Stem Cells (hESCs)? | No |
| • Did the project on human Embryonic Stem Cells involve cells in culture? | No |
| • Did the project on human Embryonic Stem Cells involve the derivation of cells from Embryos? | No |
| **PRIVACY** | |
| • Did the project involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)? | No |
| • Did the project involve tracking the location or observation of people? | No |
| **RESEARCH ON ANIMALS** | |
| • Did the project involve research on animals? | No |
| • Were those animals transgenic small laboratory animals? | No |
| • Were those animals transgenic farm animals? | No |
| • Were those animals cloned farm animals? | No |
| • Were those animals non-human primates? | No |
| **RESEARCH INVOLVING DEVELOPING COUNTRIES** | |
| • Did the project involve the use of local resources (genetic, animal, plant etc)? | No |
| • Was the project of benefit to local community (capacity building, access to healthcare, education etc)? | No |
| **DUAL USE** | |
| • Research having direct military use | No |
| • Research having the potential for terrorist abuse | No |

## C Workforce Statistics

**3. Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).**

| Type of Position | Number of Women | Number of Men |
|---|---|---|
| Scientific Coordinator | 0 | 2 |
| Work package leaders | 0 | 2 |
| Experienced researchers (i.e. PhD holders) | 1 | 8 |
| PhD Students | 0 | 0 |
| Other (Technicians) | 0 | 5 |

| | |
|---|---|
| **4. How many additional researchers (in companies and universities) were recruited specifically for this project?** | **0** |
| Of which, indicate the number of men: | |

## D Gender Aspects

| | | |
|---|---|---|
| **5. Did you carry out specific Gender Equality Actions under the project?** | No | |

**6. Which of the following actions did you carry out and how effective were they?** Not applicable

| | Not at all effective | | | | Very effective |
|---|---|---|---|---|---|
| ❑ Design and implement an equal opportunity policy | ○ | ○ | ○ | ○ | ○ |
| ❑ Set targets to achieve a gender balance in the workforce | ○ | ○ | ○ | ○ | ○ |
| ❑ Organise conferences and workshops on gender | ○ | ○ | ○ | ○ | ○ |
| ❑ Actions to improve work-life balance | ○ | ○ | ○ | ○ | ○ |
| ○ Other: | | | | | |

**7. Was there a gender dimension associated with the research content – i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?** No

## E Synergies with Science Education

**8. Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)?** No

**9. Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?** No

## F Interdisciplinarity

**10. Which disciplines (see list below) are involved in your project?**

- ○ Main discipline: 2
- ○ Associated disciplines: 2.2 ; 2.3

## G Engaging with Civil society and policy makers

**11a Did your project engage with societal actors beyond the research community?** *(if 'No', go to Question 14)* No

**11b If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)?**

- ○ No
- ○ Yes- in determining what research should be performed
- ○ Yes - in implementing the research
- ○ Yes, in communicating /disseminating / using the results of the project

**11c In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?**

**12. Did you engage with government / public bodies or policy makers (including international organisations)**

- ○ No
- ○ Yes- in framing the research agenda
- ○ Yes - in implementing the research agenda
- ○ Yes, in communicating /disseminating / using the results of the project

**13a Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?**

- ○ Yes – as a **primary** objective (please indicate areas below- multiple answers possible)
- ○ Yes – as a **secondary** objective (please indicate areas below - multiple answer possible)
- ○ No

**13b If Yes, in which fields?**

| | | | | | |
|---|---|---|---|---|---|
| Agriculture<br>Audiovisual and Media<br>Budget<br>Competition<br>Consumers<br>Culture<br>Customs<br>Development Economic and Monetary Affairs<br>Education, Training, Youth<br>Employment and Social Affairs | | Energy<br>Enlargement<br>Enterprise<br>Environment<br>External Relations<br>External Trade<br>Fisheries and Maritime Affairs<br>Food Safety<br>Foreign and Security Policy<br>Fraud<br>Humanitarian aid | | Human rights<br>Information Society<br>Institutional affairs<br>Internal Market<br>Justice, freedom and security<br>Public Health<br>Regional Policy<br>Research and Innovation<br>Space<br>Taxation<br>Transport | |


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**13c If Yes, at which level?**

- ○ Local / regional levels
- ○ National level
- ○ European level
- ○ International level

## H Use and dissemination

| | |
|---|---|
| **14. How many Articles were published/accepted for publication in peer-reviewed journals?** | 0 (1 conference proceeding was published) |
| **To how many of these is open access provided?** | 0 |
| **How many of these are published in open access journals?** | |
| **How many of these are published in open repositories?** | |
| **To how many of these is open access not provided?** | 0 |
| **Please check all applicable reasons for not providing open access:** | |
| X publisher's licensing agreement would not permit publishing in a repository<br>❑ no suitable repository available<br>❑ no suitable open access journal available<br>❑ no funds available to publish in an open access journal<br>❑ lack of time and resources<br>❑ lack of information on open access<br>❑ other: …………… | |
| **15. How many new patent applications ('priority filings') have been made?** *("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).* | 0 |

| | | |
|---|---|---|
| **16. Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).** | Trademark | 0 |
| | Registered design | 0 |
| | Other | 0 |

| | |
|---|---|
| **17. How many spin-off companies were created / are planned as a direct result of the project?** | 0 |
| ***Indicate the approximate number of additional jobs in these companies:*** | N/A |

**18. Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:**

| | | |
|---|---|---|
| ❑ Increase in employment, or | | In small & medium-sized enterprises |
| ❑ Safeguard employment, or | | **In large companies** |
| ❑ Decrease in employment, | | None of the above / not relevant to the project |
| X Difficult to estimate / not possible to quantify | | |

| | |
|---|---|
| **19. For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (*FTE = one person working fulltime for a year*) jobs:** | |


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| | |
|---|---|
| Difficult to estimate / not possible to quantify | X |

## I Media and Communication to the general public

**20. As part of the project, were any of the beneficiaries professionals in communication or media relations?**

○ Yes X No

**21. As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?**

○ Yes X No

**22 Which of the following have been used to communicate information about your project to the general public, or have resulted from your project?**

| | | |
|---|---|---|
| ❑ Press Release | | Coverage in specialist press |
| ❑ Media briefing | | Coverage in general (non-specialist) press |
| ❑ TV coverage / report | | Coverage in national press |
| ❑ Radio coverage / report | | Coverage in international press |
| ❑ Brochures /posters / flyers | | Website for the general public / internet |
| ❑ DVD /Film /Multimedia | | **Event targeting general public (festival, conference, exhibition, science café)** |

**23 In which languages are the information products for the general public produced?**

| | | |
|---|---|---|
| ❑ Language of the coordinator | | **X English** |
| ❑ Other language(s) | | |



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