UDC: 681.2.08:53.08

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TEST AND VALIDATION OF A MICROWAVE TIP CLEARANCE SENSOR ON A 25MW GAS TURBINE ENGINE

Blade turbine monitoring is an important area of work for improvements in gas turbine operation. Blade tip clearance measurements offer improvement in engine efficiency by enabling active clearance control. However, this is a difficult measurement because of the harsh turbine environment. The high temperature microwave sensor presented in this paper is one of the most promising candidates for clearance measurement. It has been tested on the high pressure stage of a 25MW gas turbine engine during different operating modes. Moreover, the individual blade clearance measurement has been tested by using a rotor with ten shortened blades. The resulting measurement performance is very good in terms of precision and accuracy and show the efficacy of this measurement system.

Key words: *Gas turbine,sensor,tip clearance,microwave.*

Introduction

Blade tip clearance sensing is a key for future improvements of gas turbine design, operation and services [1]. A few sensing technologies exist at different maturity levels but at this time, no system is used as original equipment of an engine fleet. One of the main reasons is the harsh environment of the first stages of gas turbines in terms of temperature, pressure, vibration and the presence of combustion products. This environment limits long-term use of most candidate technologies.

Within this context, Meggitt Sensing System has developed a microwave system with high temperature probes that survive the engine environment [2]. Contrary to capacitive or eddy current technologies, the phase-based microwave system of Meggitt offers a raw measurement response which is naturally linear where the measured phase is proportional to the clearance as a portion of the wavelength. This fact is very important from a metrology standpoint and makes the system much more robust than others. Nevertheless, the only way to judge of the final measurement validity and quality is a real engine test as [3-4]. Within this purpose, an engine test campaign has been performed with the Meggitt microwave system in collaboration with the gas turbine company Zorya-Mashproekt. The high pressure turbine (HPT) stage of a DM80 engine (25MW rated output power) was instrumented with eight microwave sensors with clearance being monitored during different engine operating modes. This paper describes the different steps leading to the engine test as well as the obtained measurement results.

The operation of a blade tip clearance system within a gas turbine requires some operations such as engine modification for probe mounting, probe calibration, system configuration and installation. All these steps have to be performed consistently in order to achieve the desired measurement accuracy. The first step is a laboratory study performed by Meggitt in order to define the best system configuration corresponding to the target engine. For that, actual blades have been mounted on a precision test setup in order to ensure data a representative calibration environment [5]. Given the clearance range (0 to 4mm), the 24GHz version of the microwave system was chosen. This version of the system corresponds mainly to aeronautic or aero-derivative engines compared with the 6GHz version, which is designed for large frame gas turbines. During the laboratory study, the positioning of the probe with respect to the blade has been tuned in order to obtain the best measurement performance [6]. This step is necessary before the modification of the engine, which consists of drilling probe passage holes. Once the probe positioning and the engine modification have been defined, each one of the eight probes was individually calibrated by Meggitt.

The second important step performed before the engine test was the system and probe installation. When placed in the engine, the probes need to be positioned in the same location as defined during the laboratory study. Therefore, the probe actual probe recesses when installed in the engine (due to tolerance stack up) were measured and taken into account in order to correct the clearance measurements.

The objective of the engine test was to evaluate the Meggitt tip clearance microwave system in terms of measurement performance. Therefore, two types of results are considered. The first one is the consistency of measurement over different engine operation modes: start-up, power sweeping, hot restart and activation of a casing cooling system. The second type of validation results is the capacity of the system to measure individual blade clearances. In order to test this, the rotor was modified by shorting ten blades at different heights. Before presenting the engine test results, the first section of this paper will describe the microwave system and the associated measurement principle.Then, the laboratory study and the probe calibration will be presented. The system installation and the probe mounting will be detailed in the third section. Finally, the measurement results obtained during the engine test will be described in the last section.

1. Presentation of the sensor

The microwave high temperature blade tip clearance system developed by Meggitt is based on a phase measurement principle.The first industrialized version of the system was used for the test engine presented in this paper.

1.1. Microwave system overview

The measurement system uses high temperature microwave probes (figure 1). The dimensions of these probes are relatively small with an outer diameter of 8.5 mm. This small probe diameter minimizes the probe intrusion inside the engine.

Figure 1. Picture of the ten microwave high temperature probes used for the engine test. Eight probes were mounted in the engine and two probes were used as spare

In order to measure blade tip clearance, the probes are mounted through the engine casing such their sensor has adirect view of the blade tips.The sensor measures the distance between the blades tip and the probe. The probe is recessed into the ring segment and a conical opening is made around the probe tip (figure 2).

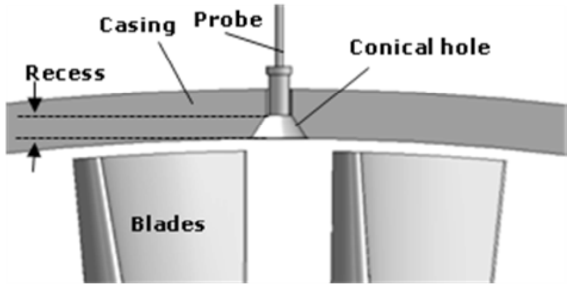

Figure 2. Probe installation into the engine. The probe is mounted toward the blades

The microwave system used for this engine test is composed of eight independent measurement channels operating at 24 GHz. Each channel is composed of a microwave probe installed in the engine, a microwave cable and an electronics cards pair (figure 3). The electronics cards are installed in a rack mounted inside a protective and thermally regulated enclosure located close to the engine. The microwave probes are connected to these electronics with one meter of integral high temperature cable and seven meters of medium temperature extension cable. Additionally to the microwaves channels, the speed signal of the high pressure rotor is provided to the system for synchronization.

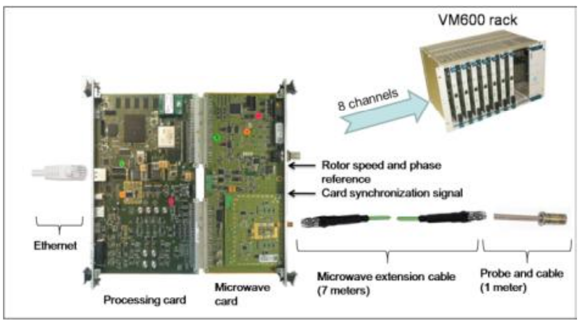

Figure 3. System architecture. All electronics cards are mounted in a VM600 rack

The raw signal acquisition scheme is based on periodic snapshots every second. Each snapshot catches exactly one rotor revolution by being synchronized with the rotor speed signal. The sensors are not making measurements in-between acquisitions and during this time the signal processing is performed. Therefore, each sensor provides atip clearance update of the rotor's blades every second.

1.2. Measurement principle

The microwave displacement measurement system was originally developed and patented at Georgia Tech in 2001[3]. It is based on a continuous-wave microwave signal which is generated by the electronics, transmitted by the probe and reflected by the blade tip back to the electronics. The reflected signal is then compared to an internal reference in order to extract its phase and magnitude. A quadrature mixer architecture is used to extract the inphase and quadrature channels (baseband) from the microwave signal (figure 4). Therefore, the obtained phase is directly related to the clearance even if specific signal processing is necessary to remove the phase contribution of the cable.

The conversion between the measured phase and the associated clearance is given by Equation 1 and depends on the wavelength λ. Nevertheless, it requires a calibration map which depends on probe sensitivity, blade tip geometry and installation parameters such as probe installation recess in order to make the absolute clearance measurement.

$$\delta = \frac{\varphi'}{4\pi} \cdot \frac{c}{T} \quad \text{and} \quad \delta' = f_{cor}(\delta)$$

Equation 1: Calculation of the clearance with respect to the measured phase φ, the wavelength λ and the calibration map f_{cal}.

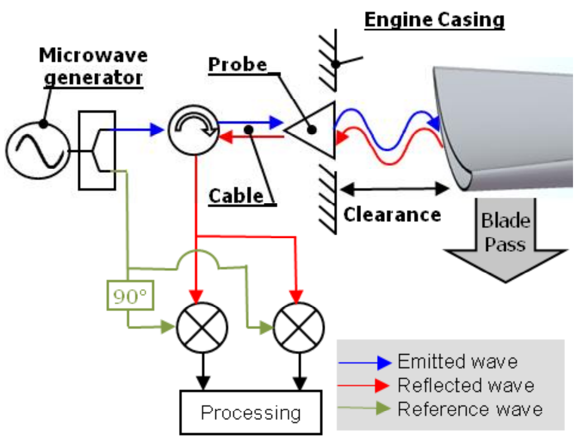

Figure 4. Electronics architecture. The microwave generator emits a signal which is transmitted to the probe through a circulator. Then, the wave is reflected by the blade tip back to the circulator and to the two mixers. The inphase and quadrature components of the reflected wave are extracted and digitalized before processing

2. Laboratory study

Operation of blade tip clearance systems, independently of the used technology, requires preliminary laboratory work. The main goals are the choice of probe positioning with respect to the blades and the individual probes calibration. Final measurement performance greatly depends on these two steps, which are discussed in this section. The laboratory study is mainly done by using a precision test setup with actual blades mounted on it (figure 5).

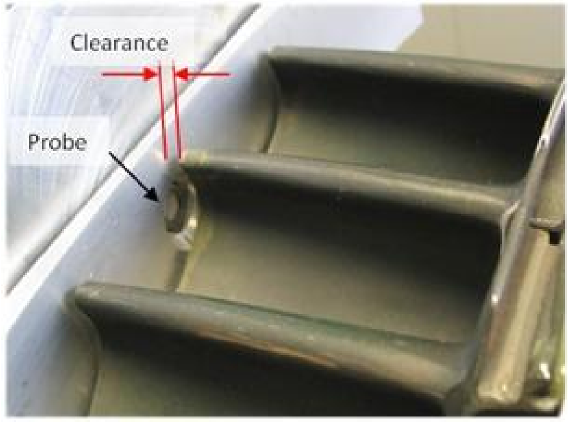

Figure 5. Laboratory mounting used for test and probe calibration. Three actual blades are mounted and moved in the same arc motion as the engine. The probe is mounted through an engine casing mockup, which reproduces the actual engine radius and the actual probe port shape. Clearance is automatically controlled and corresponds to the absolute distance between blade tip and casing.

2.1. Choice of probe positioning

Measurement performance depends on the geometry of the target in front of the probe. Even if the blade geometry is fixed, the relative axial position of the probe to the blade as well as its angular orientation can be tuned to improve performance (figure 6). Indeed, because of the polarization of the electromagnetic field generated by the probe, the probe angular orientation changes the measurement response.

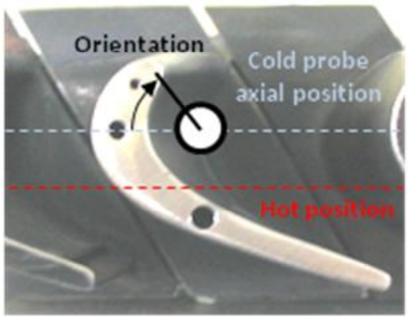

Figure 6. Probe positioning. Usually, the cold probe axial position can be chosen during the installation within a given range. This position has to be chosen by considering the axial shift of the rotor which will set the probe in its hot position during the engine operation. Moreover the angular orientation of the probe can also be tuned

The parameter to optimize is the consistency of measurement over the different axial positions seen by the probe during engine operation (figure 6). Indeed, spatial filtering effects can generate measurement errors if the blades are moving axially relatively to the probe. These errors are usually characterized by using the precision test setup and can be minimized by tuning the probe cold build position and the probe orientation [6]. The optimal probe cold axial position and probe orientation obtained for this engine are given by figure 7.

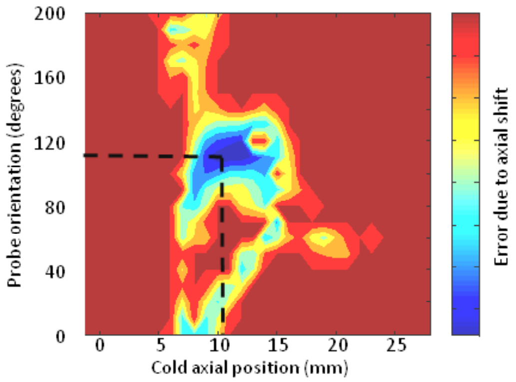

Figure 7. Optimization of probe positioning. The measurement error due to the axial shift is computed for different combination of orientation and cold axial position. It shows an optimum for 10 mm of cold position and 110 degrees of orientation

2.2. Individual probe calibration

After having chosen the cold axial position and the orientation of probes, as explained in the previous section, the individual calibration of each probe is performed. This calibration is required to remove the systematic errors that come from blade geometry and probe manufacturing variability. Probe calibration is made by using the precision test setup. Several measurements are made at different clearances in order to record the system response (figure 8). Moreover, the probe axial position is also randomly swept from the cold position to the hot position in order to make the calibration consistent over the full axial range. The error due to the rotor axial shift has been estimated during probe calibration to be within ±0.2 mm.

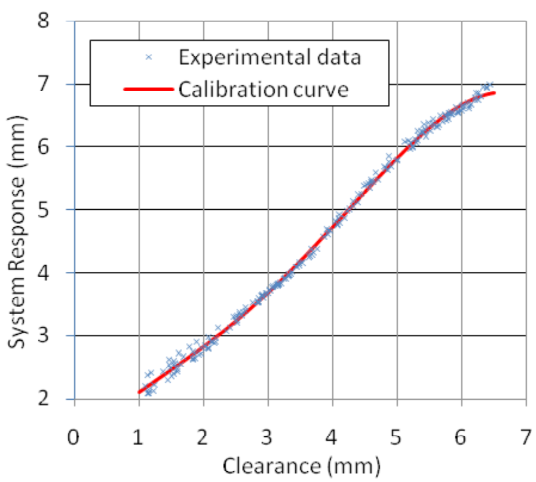

Figure 8. Example calibration one. The experimental data points show that the system response is not perfectly linear and have to be corrected by the calibration map. The spread of measurement corresponds at the same time to axial shift effect and to random noise

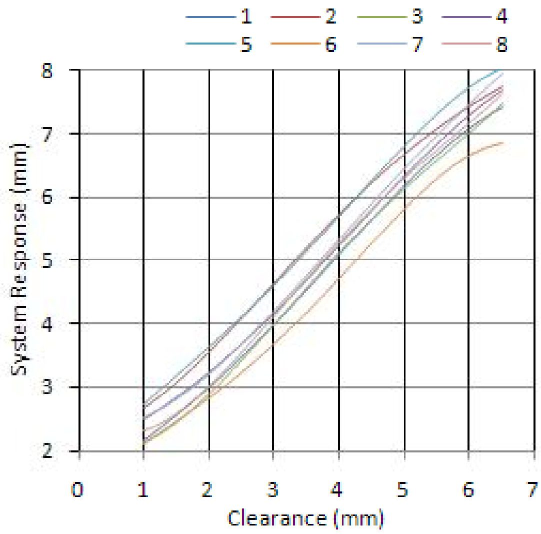

Figure 9. Individual calibration curves of the different probes. Even if the general shape is comparable, there are some offset differences

Figure 9 shows each probe calibration curve, which are slightly different mainly in term of offsets. These offsets come from the probe manufacturing variability. That is the reason why an individual calibration is currently required for absolute clearance measurement. Nevertheless, a common calibration is possible but would require a zeroing process while the probes are mounted on the engine.

2.3. Conclusion on laboratory study

The laboratory study has been performed by using real blades and a representative mock-up of the engine casing. During this study, the optimal probe positioning, in terms of cold built axial position and orientation, has been defined in order to get the best measurement performance. These positioning parameters have been used to make the individual calibration of each probe dedicated to the engine test.

3. Engine installation of the microwave system

Eight probes were installed around the single HPT stage of a DM80 test engine (figure 10). This engine is equipped with a tip clearance control system at the HPT with the microwave clearance system being used to characterize the efficiency.

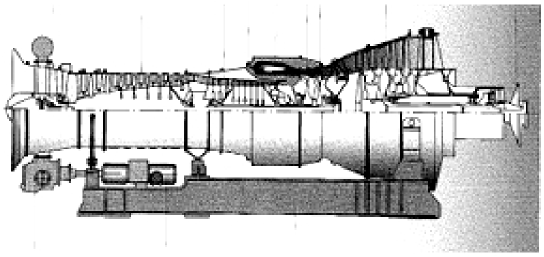

Figure 10. DM80 engine schematic from Zorya-Mashproekt documentation. This engine has 3 spools: 9 stages low pressure compressor with a single low pressure turbine stage, 9 stages high pressure compressor with a single high pressure turbine, a four stage free power turbine providing 25 MW power to a generator

3.1. Microwave system installation overview

In order to ensure a good reading of the engine casing deformation; eight probes were installed around the high pressure turbine rotor and numbered by their dedicated probe port (figure 11). These probes are connected to a rack located next to the engine by using extension cables which are rated up to 200 °C.

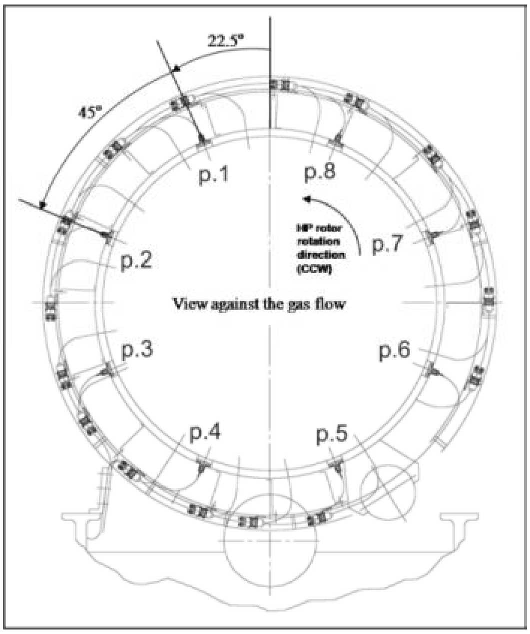

Figure 11. Mounting diagram of the eight microwave probes on the stage high pressure turbine of the DM80 engine. The view is from the exhaust and the rotor turns counter clockwise

3.2. Probe holder design

The probe is clamped into the probe holder at a given orientation maintained by a pin. The probe holder is screwed into the upper ring segment from the outside of the casing. The final recess of the probe tip inside the ring segment is set by an adjustment washer. An annulus between the probe tip and hole in the ring segment allow compressor pressurized cooling air to circulate around the probe tip and reduce the probe heating that would occur with direct contact of the gas path.

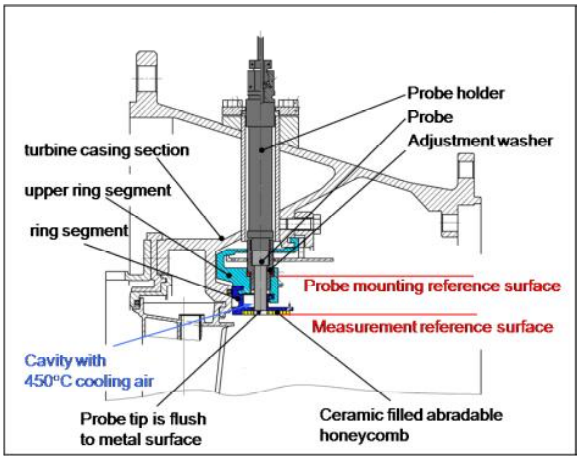

Figure 12. Drawing of the microwave high temperature probe holder design and its mounting on the DM80 engine port. The probe mounting is referenced to the upper ring segment while the blade tip clearance zero is the surface of the ring segment

3.3. Discussion on probe referencing in the engine

The measurement given by the probes is the distance between the probe and the blades whereas the distance of interest is the one between the blade and the honeycomb ring segment surface. The individual laboratory calibration of the probes was done by Meggitt with a fixed recess. Any deviation from this recess used for probe calibration results in an absolute clearance offset in the final measurement.

The probe mounting was done with the engine partially assembled when the high pressure turbine rotor was not yet mounted, allowing the measurement of the probe recess. For each probe, the difference between the recess measured during laboratory calibration and during engine installation was used to correct the absolute clearance measurement (figure 13).

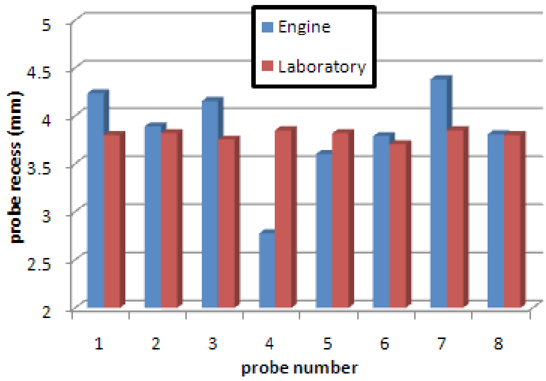

Figure 13. Probe recess measured during the laboratory calibration and the engine installation. The difference between them is taken into account as a clearance offset for final measurement

A perfect absolute clearance measurement is difficult to achieve because of the mechanical tolerance stack up from the laboratory mounting and the engine one. This is why is it highly recommended to perform a zeroing with regards to an actual mechanical measurement. Unfortunately, this actual mechanical measurement was not conducted during this engine test and there are still uncertainties with the absolute measurement provided by the microwave system.

4. Engine clearance measurements

4.1. Results summary

The microwave system was able to measure clearance correctly during the different test phases. The measured valued are consistent probe to probe and with the expected engine behaviours. Three different engine phases were monitored: sweeping of engine power, hot restart and utilization of an active clearance control system.

4.2. General trends

The general trends for the entire engine test are presented in Figure 14 through Figure 17. The first figure shows the ignition of the engine from idle to 1MW of output power. The mean clearance varies from 2.4 mm to 1.9 mm during this start-up. During the second day of testing (figure 15), clearance decreases from 1.9 mm at 3.1 MW to 1.3 mm at 19.1 MW. Therefore, the total clearance variation from the cold state to the hottest state is about 1.1mm.

Figure 16 shows a rapid load variation from 18 MW to 1 MW.The tip clearance increases from 1.31 mm to 1.33 mm immediately after the load decreasing and reach the value 1.65 mm after 13.5 min. The total increasing of the clearance is 0,34 mm. After this rapid load decreasing, the load is increasing up to 19.3 MW. The clearance quickly goes from 1.65 mm to 1.60 mm and reaches the value of 1.43 mm after 5 min. The total decreasing of clearance is 0.22 mm.

Fast load increasing-decreasing shows that the tip clearance is not overlapped and is sufficient for normal operation in load range from 1 to 19 MW, and after measured results extrapolation, up to 25 MW.

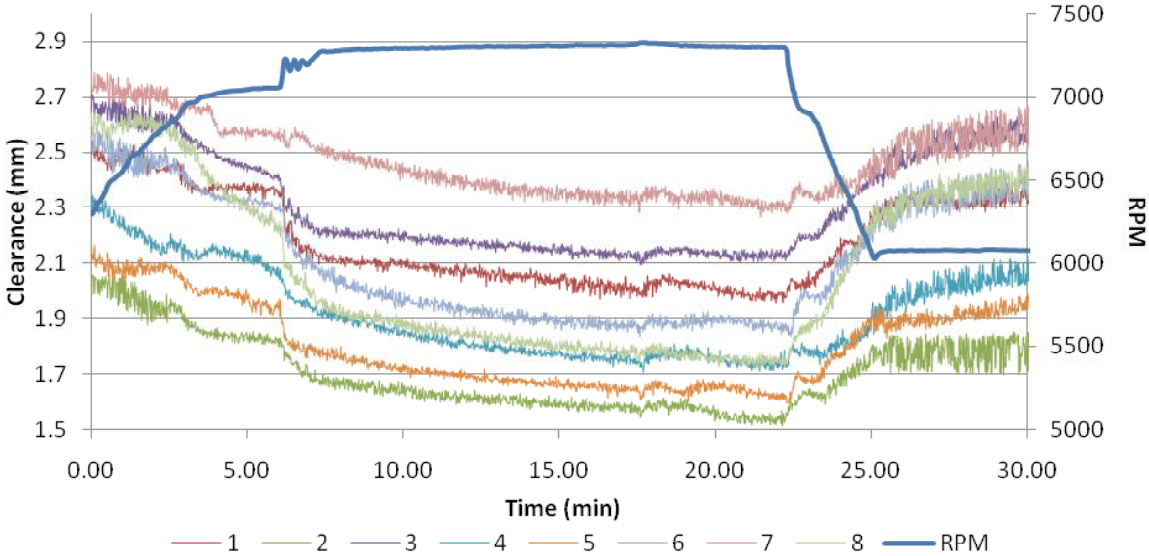

Figure 14. Average clearance trends for the eight probes on the first day of engine testing. Short engine test mainly to check microwave system after its installation. The engine was brought to idle and then to 1 MW output power synchronized with the grid

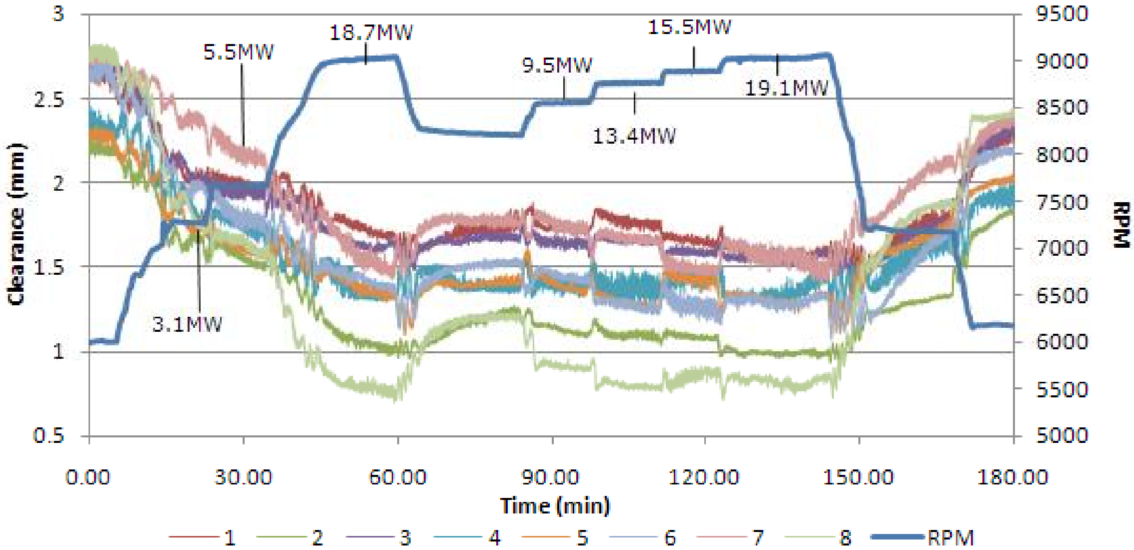

Figure 15. Average clearance trends for the eight probes on the second day of engine testing

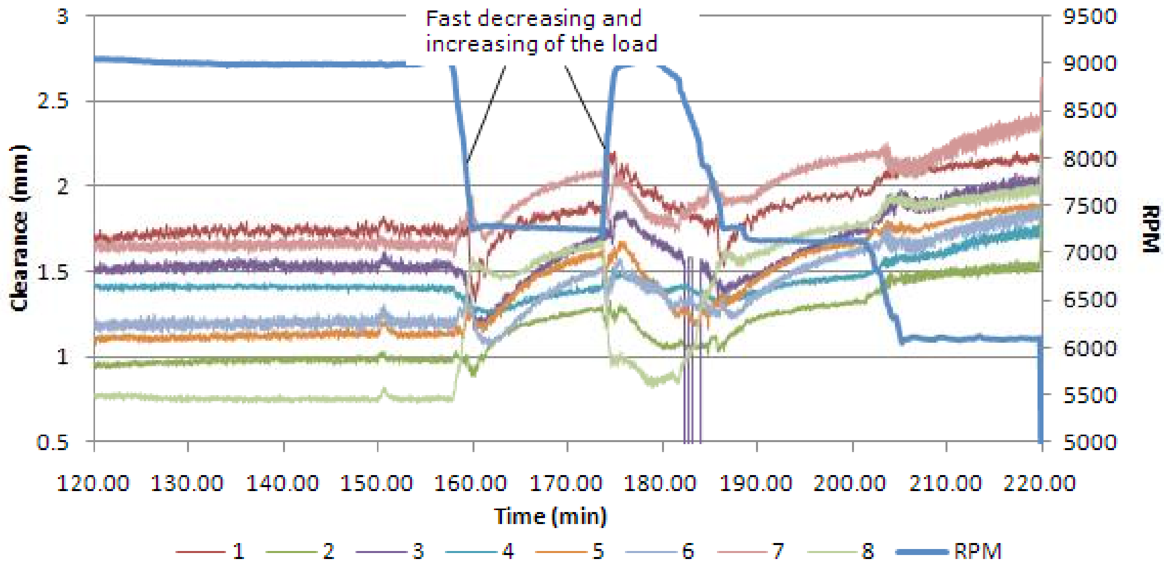

Figure 16. Average clearance trends for the eight probes on the third day of engine testing during the fast engine output load decreasing and increasing event

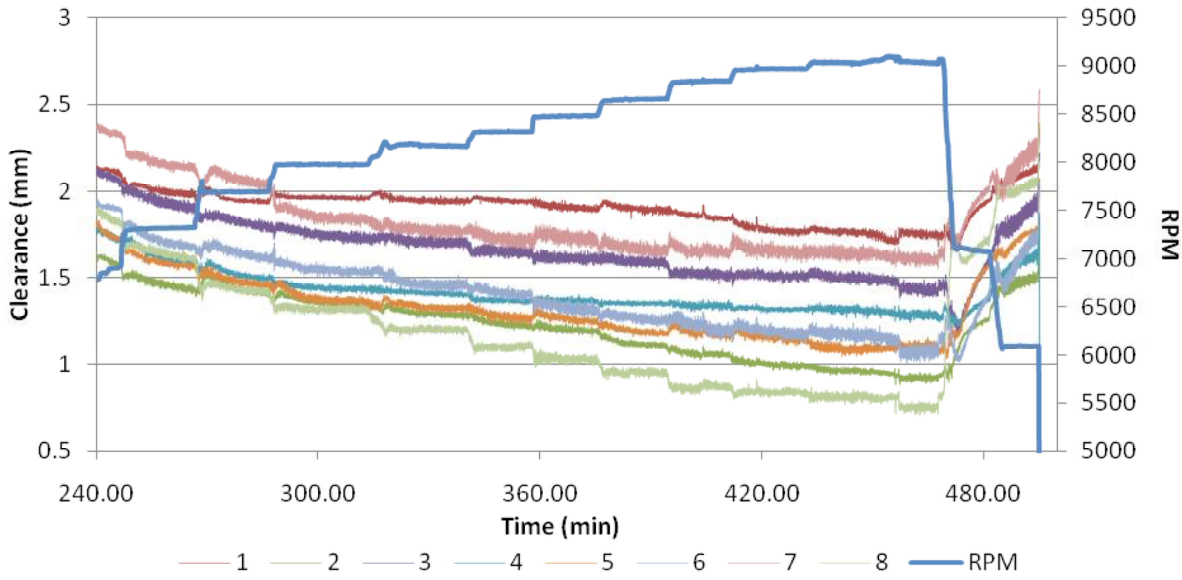

Figure 17. Average clearance trends for the eight probes on the third day of engine testing during the slow increasing of output power load

4.3. Noise Characterization

The results presented in the previous section are not filtered and contain random noise that comes from electronics. The amount of noise is generally a problem on tip clearance system such as those that use capacitive measurements. It directly impacts the filtering strategy which has to fulfil at the same time the needs of accuracy and bandwidth. In this section, an estimation of the noise levels obtained during the engine test is presented. It is based on the assumption that the actual variations of clearance are located in the low frequencies and the noise is white. Indeed, the radial clearance typically changes relatively slowly within seconds as they are driven mainly by thermal change of the different engine components such as the rotor, blades and stator casing. Therefore, the noise is separated from the signal by using a filter with a cut-off frequency set at 0.01 Hz for a measurement frequency of 1 Hz (figure 18).

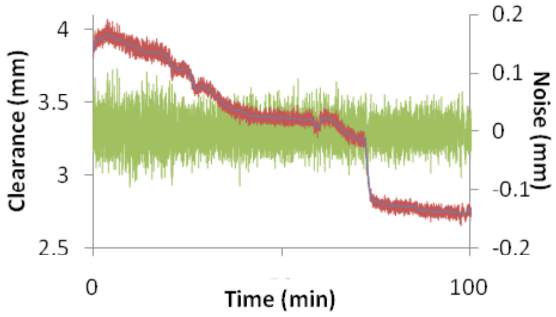

Figure 18. Estimation of noise based on frequencies separation

Once the noise is separated from the signal, it is characterized in terms of spectrum, standard deviation and 99th percentile. The spectrum (figure 19) does not show any specific frequency content and be considered white. Standard deviations and 99th percentile have been computed for all sensors and are summarize by (figure 20).

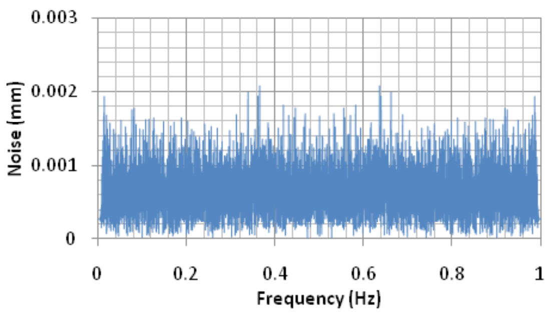

Figure 19. Spectrum of the noise, it shows the noise can be considered white

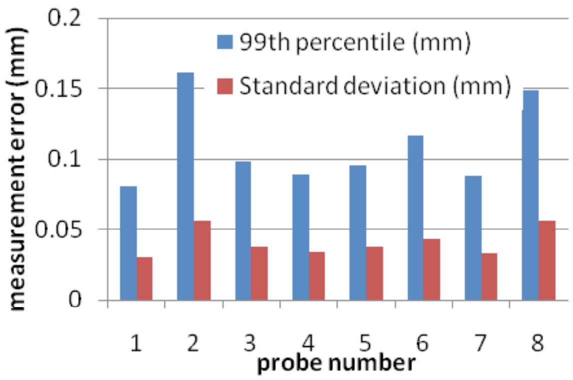

Figure 20. Standard deviation and 99th percentile of noise measured for the eight sensors. Results are within the same order of magnitude for all probe and consistent with a Gaussian distribution

4.4. Individual clearance measurement

One of the objectives of this engine test is to confirm that the microwave system is able to correctly measure individual blade tip clearance.It is important in terms of technology demonstration but also in terms of application. Indeed, individual clearance measurement are necessary to get the minimal clearance which corresponds to the blade that will rub the casing first. Moreover, one of the applications of tip clearance measurement is the detection of blade crack by tracking a quick change with the blade size.

In order to evaluate system performance for individual clearance measurement, ten blades of the rotor were shortened at different heights up to one millimetre shorter. Theses shortened blades are located at different angular positions on the rotor which gives a recognisable pattern. This pattern has been measured and averaged for all sensors as shown by figure 21. The shorter blades can be easily differentiated and correspond to the actual modification realized on the engine. Nevertheless, some differences appear between the sensors which arise from two areas. The first reason is calibration imperfection which generates measurement sensitivity variations. In other terms, a clearance difference between two blades is seen smaller or larger depending on the sensor. As example, the sensor n°8 generally measured higher clearance differences than the other sensors (see figure 21). Independently of scaling factor which comes from calibration, a residual variability of about 0.1mm remains. This second type of difference is typically a systematic measurement error which could come from the probe sensitivity to small differences on blade tip geometry. Indeed, microwave measurement corresponds to an integration of the waves reflected on almost the entire surface of the blade tip in front of the probe. Small difference between blade surface such cooling holes, can be seen differently by the probes and generate small clearance pattern differences.

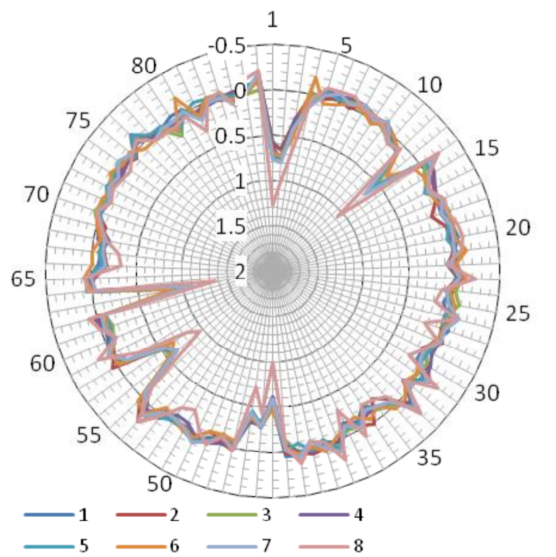

Figure 21. Averaged blade patterns measured by the eight sensors. Blade patterns correspond to the individual clearance relative to the mean one and the unit is in millimeters

In addition to cross-sensors clearance pattern comparison, it is interesting to looks at the evolution of a pattern measured by one sensor over a test period. As an example figure 22 shows the minimal and maximal values of individual clearance measured by one particular sensor. It shows pattern variation lower than 0.25 mm. This pattern variation can be explained by rotor vibrations, differential blade expansion with temperature and centrifugal forces, or measurement errors.

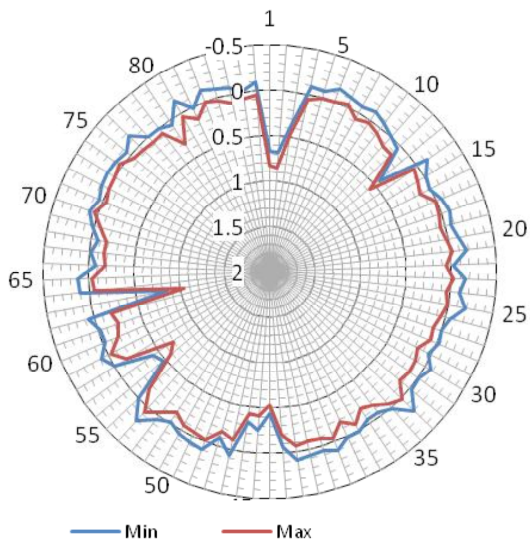

Figure 22. Lower and upper limits of the pattern measured by one particular probe over the entire period of test. The unit shown on the graph is in millimeters

Conclusion

Blade tip clearance measurement is a difficult measurement because of the harsh turbine environment. Many technologies are used for engine development and testing but no technology has been successfully adopted for long term monitoring over the life of the engine. The challenge is to find a technology that is suitable for long term, high temperature operation but that can also provide accurate and reliable measurement.The tip clearance microwave system of Meggitt is based on high temperature probe design and on a measurement principle robust to the effect of temperature and contaminants. The engine test presented in this paper has demonstrated the operability of the system in terms of probe mounting, calibration and system installation. The clearance measurements obtained during this test are within the range of expected values and directly usable for test engineers. The data has been used to correctly characterize the engine behaviour during normal operation and load variations. HPT blade tip clearance influences highly on the performance of the stage. Obtained results of the tip clearance measurements at different operation modes show the possibility of HPT stage performance increasing on 1.5-2.0% with gas-turbine engine performance increasing on 0.2-0.25% (absolute). Moreover, individual blade monitoring has been demonstrated with the ten shorter blades of the rotor correctly detected by the microwave system. Such detection can be used to track changes over time within individual clearance and detect potential blade crack and pending blade failure.

The results obtained during the engine test are very promising. Nevertheless, they will be completed with a follow-on engine test. More specially, low rotor speed measurements of a hot restart after an emergency stop have to be made to complete the range of situations to test. Long term test campaigns are also recommended to evaluate the stability of the system and the aging of the probe in a real turbine.

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Испытание и проверка сверхвысокочастотного датчика контроля зазоров кромок лопаток на газотурбинном двигателе мощностью 25 МВт

Контроль зазоров между кромками лопаток турбины является важной частью работы, направленной на улучшение рабочих характеристик двигателя, прежде всего, на повышение характеристик его эффективности. Измерения подобного типа являются чрезвычайно сложными. Представляемый датчик является одним из наиболее надежных приборов своего класса, обеспечивающих подобные измерения. Испытания датчика проводились в условиях высокого давления на разных режимах работы двигателя. Кроме того, были проведены испытания на измерение зазоров отдельных лопаток. С этой целью был использован ротор, имеющий десять укороченных лопаток. Полученные результаты имеют высокий уровень точности, что демонстрирует эффективность данной измерительной системы.

Ключевые слова: *газотурбинный, датчик, зазор кромки, сверхвысокочастотный.*

Випробування і перевірка надвисокочастотного датчика контролю зазорів кромок лопаток на газотурбінному двигуні потужністю 25 МВт

Контроль зазорів між кромками лопаток турбіни є важливою частиною роботи, спрямованої на поліпшення робочих характеристик двигуна, насамперед, на підвищення характеристик його ефективності. Виміри подібного типу є надзвичайно складними. Датчик, що представляється, є одним з найбільш надійних приладів свого класу, що забезпечує подібні виміри. Випробування датчика проводилися в умовах високого тиску на різних режимах роботи двигуна. Крім того, було проведено випробування на вимір зазорів окремих лопаток. З цією метою був використаний ротор, що має десять укорочених лопаток. Отримані результати мають високий рівень точності, що демонструє ефективність даної вимірювальної системи.

Ключові слова: *газотурбінний, датчик, зазор кромки, надвисокочастотний.*