Application of Microwave Sensing to Blade Health Monitoring

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Abstract

This paper discusses the application of microwave sensing to turbine airfoil health monitoring. The proposed microwave system operates at 6- and 24-GHz and is applicable to both blade tip-clearance and blade tip-timing measurements. One of the main advantages of microwave systems, compared to other technology such as capacitive or eddy current, is that it can be installed for long term operations in the harsh environment of the first turbine stages. The monitoring of blade tip-timing and tip-clearance pattern is useful for detecting abnormal blade behavior due to structural damage. Such a sensing system can also be used in actively maintaining optimal blade-to-casing clearance, thereby enhancing turbine efficiency. This paper presents blade tip-clearance pattern monitoring based on microwave measurements. First, a laboratory study shows the ability of the system to consistently measure tip clearance pattern. Then tip clearance pattern measurements from a real engine test are presented. While this paper presents results from system testing on tip clearance, it is expected that this study will be carried forward in the next phase to demonstrate tip-timing measurement and further, to show how such as system can form the basis for a more comprehensive health management system.

1. Introduction

Both aero gas turbines as well as stationary gas turbines are increasingly deploying blade health monitoring (BHM) systems that assess the health of airfoils by sensing the tip-clearance and the tip-timing of individual blades. BHM systems can estimate different parameters depending on the sophistication of the algorithms. Many academic papers have been written on this topic, but the real value of such technologies in solving the BHM problem is seen by the number of real world systems that have started employing the technology (Flotow, Mercadal & Tappert, 2000; Zielinski & Ziller, 2005; Hess, Frith & Suarez, 2006; Hess, 2007; Martin, Forry, Maier & Hansen, 2011).

Blades can fail because of the structural flaws that are caused by manufacturing defects or by impacts from external objects. Tip-clearance and tip-timing measurements can be used to detect these flaws. One relatively straightforward way of doing this is to establish a "baseline" pattern during the initial operation of the turbine and then assessing the "deviation" from this baseline. Because these patterns will change as the turbine loads, the algorithms will need compensation factors built into them, but these can be readily developed. For example, the effect of temperature can be accounted for by a simple additive term, as is shown in the paper. More sophisticated techniques involve the actual modeling of the vibration modes of the airfoil using physics-based techniques and then detecting deviations from expected behavior and basing the diagnostics on this. The former method is easier to implement but is not as powerful as the model-based method.

In either case, the key is to get a reliable and repeatable measurement system that can be depended on to deliver consistent measurement under noisy and harsh conditions.

Additionally, monitoring blade passage can be used to detect incipient damage to the rotor as well as aid in sophisticated clearance control. An SAE Aerospace Information Report, currently in preparation (2012), will provide a good overview of various uses of BHM. A specific sensor can only measure the instantaneous clearance between the airfoils and a specific location on the casing. With multiple sensors located around the circumference, a better estimate of the clearance can be obtained, which can be used for real-time clearance control. Structural failure, especially in the low pressure compressor, can occur due to foreign object damage (FOD). The BHM system can be used to detect FOD as well, possibly in concert with other diagnostic sensors such as accelerometers mounted close to the front of the turbine. Mounting two sensors in roughly the same radial location can help in detecting axial deflections that will allow blade twist to be estimated, again improving the ability to measure different failure mechanisms. Of course, these techniques come at the price of added system complexity and cost, so it has to be weighed carefully against the benefit.

This paper describes a system based on microwave technology that delivers a highly accurate and consistent measurement. This is demonstrated for blade clearance in this paper via experimental results. In particular, the ability of the sensor to detect blade length variations lower than a few tenths of millimeters is described. The detection of such variation can be used to detect blade fatigue cracks and thus, improve the maintenance scheduling. Combined with its harsh environment survivability, this detection capability offers a real opportunity to design reliable BHM systems (Woike, Abdul-Aziz & Bencic, 2010).

Section 2 gives a general description of the microwave sensor including its operating principle and its application to blade anomaly detection. BHM performance depends critically on the accuracy and consistency of the measurement system. This is described in Section 3. Finally, Section 4 describes experimental results from a test on an industrial gas turbine. This shows that the microwave sensor is capable of accurate and consistent measurement of tip–clearance pattern.

2. Presentation of the Microwave Sensor

2.1. Microwave measurement principle

The microwave blade monitoring system presented here is based on a phase measurement principle. A continuous-wave microwave signal is generated in a microwave signal conditioning unit and transmitted through a coaxial cable to the probe (Figure 1). The probe is an antenna capable of transmitting the continuous-wave into the space between the casing and the bladed rotor. The probe also acts as a receiver and captures the emitted wave that is reflected back by the blade tip, which is measured by the electronics.

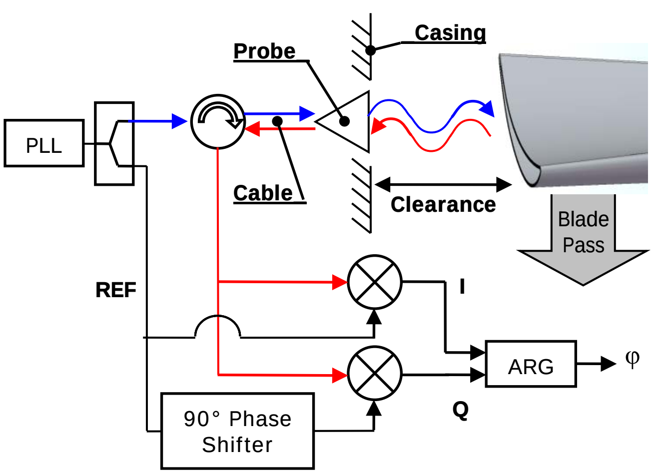

Figure 1. System architecture.

The microwave electronics generates a continuous-wave which is transmitted to the probe through a circulator. Then, the wave is reflected by the blade tips back to the circulator and to two RF mixers arranged in vector architecture. The in-phase and quadrature components of the reflected wave are extracted and digitalized before processing and phase calculation.

A vector mixer architecture is used to compare the received signal to an internal reference and to reconstruct a phase measurement. Basically, the phase between the transmitted and the reflected signals is proportional to the distance between the probe and the blade tips. The conversion between the measured phase φ and the associated clearance δ is given by Eq. (1) and depends on the wavelength λ of the microwave signal. Compared to other technologies, this relationship is linear and much easier to calibrate via sensitivity and offset corrections.

$$\delta = \frac{\varphi}{4\pi} \cdot \lambda \quad (1)$$

2.2. Probe and engine installation

The microwave probe is basically an antenna optimized to transmit at a defined frequency with a given bandwidth. This antenna is packaged into a hermetic sealed body with an integral mineral cable on its back. This probe construction is made with materials chosen for their high temperature survivability coupled with reliable long term operation in the harsh environment of gas turbines.

Two versions of the microwave system have been developed. The first one uses a frequency in the 6 GHz band and has a measurement range of 25 mm and a probe diameter of 14 mm (Figure 2). It is suited for large frame gas turbines. The second one uses a frequency in the 24GHz band for a measurement range of 6 mm and a probe diameter of 8.5 mm. It is preferably used with small blades from aviation or aero-derivative gas turbines.

Figure 2. Picture of the 6 GHz microwave probe.

The probe installation requires an opening through the casing such that the probe tip has a direct view of the rotor and its blade tips. A ceramic window on the probe tip allows the microwave signal to transmit to the blade. A retaining ring ensures that this ceramic window does not fall into the gas path. Depending on the engine construction, the integration is more or less complex. Normally, the installation in the turbine section has more constraints due to the high temperatures and to ensure proper sealing between several casing layers, which can move relatively, one to the other. Figure 3 shows an example of probe mounting in the turbine section of an aero engine with two casing layers. The probe tip is usually installed flush or recessed from the casing inner surface to ensure no contact with the blades even during a rub event.

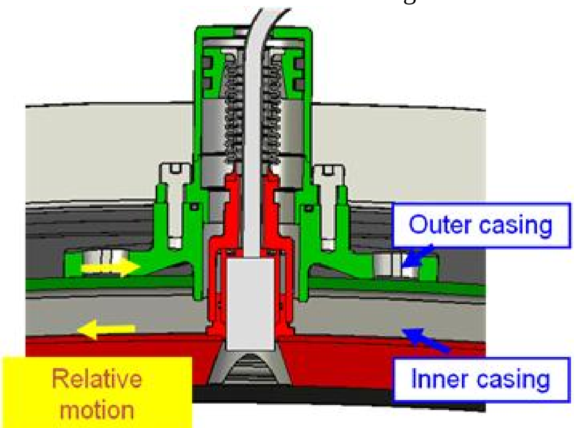

Figure 3. Probe mounting on the turbine.

The important parameter for the probe installation is the position of the probe relative to the blade tips as the probe measures what is directly underneath it. It is not always possible to install the probe at a desired location due to piping or mechanical constraints. Typically, the rotor moves axially due to thermal dilatation and aerodynamic forces and therefore the blade tips move in the axial direction with respect to the fix casing. This is normally known and taken into account during probe mounting.

2.3. Microwave tip clearance measurement output

The microwave blade tip clearance system presented in this paper does not provide continuous blade profile waveform output proportional to the measured distance like a laser, eddy current or capacitance probes. The amount of data becomes quickly important in the case of continuous blade profile measurement and has to be reduced to be exploitable for blade health monitoring. Therefore, data reduction is used by the mean of an algorithm detecting each individual blade within the microwave measurement and extracting only one tip clearance value for each blade. These calculated tip clearance values correspond to the minimum distance between the individual blade tips and the probe. The sensor then provides a digital array with one tip clearance measurement δ_i per blade. The array of tip clearance measurements over a full rotor revolution is called the blade clearance pattern.

2.4. The centered blade clearance pattern and its application to health monitoring

The monitoring of the individual blade tip clearances δ_i provides useful information on abnormal blade elongation due to cracks and thus, can be used for health monitoring purposes. Nevertheless, abnormal blade elongation must be differentiated from normal elongations due to temperature or centrifugal forces Eq. (2).

$$\delta_i = \delta_i^c + \delta^{\text{temperature}} + \delta^{\text{centrifugal}} \qquad (2)$$

The main hypothesis that can be done on abnormal elongation is that it affects only one particular blade while global elongations affect all the blades of the rotor. Given a relative high number of blades, the mean clearance should not be affected by the abnormal elongation of one particular blade. In this case, the centered blade clearance pattern $\{\delta_1^c, \ldots, \delta_i^c, \ldots, \delta_N^c\}$ defined by Eq. (3) can be used as baseline. Any deviation from this baseline can be used as metric for blade crack detection (Figure 4).

$$\delta_i^c = \delta_i - \frac{1}{N}\sum_{j=1}^{N} \delta_j \qquad (3)$$

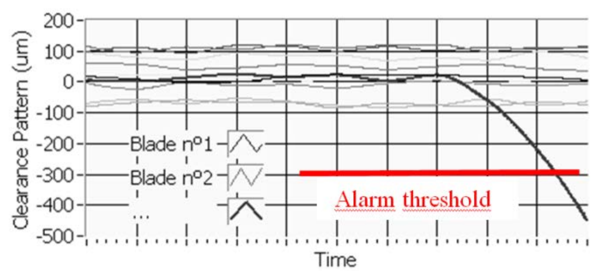

Figure 4. Principle of crack detection based on clearance pattern monitoring. If the centered clearance of one particular blade passes above a given threshold, an alarm can be generated.

Such a detection strategy requires that an abnormal blade elongation can be detected without any ambiguity due to measurement errors. Therefore, it is necessary to validate that the clearance pattern can be consistently measured by the sensor system. This point is discussed in the next section.

3. Laboratory Evaluation of Clearance Pattern Measurement

3.1. Problem Description

Blade elongations due to mechanical cracks are about a few tenths of a millimeter (Dyke, 2011). In order to be able to detect these abnormal elongations, the measurement uncertainty on tip-clearance has to be lower than the elongation itself. This elongation has to be consistently differentiable over the different engine conditions. The purpose of this laboratory evaluation is to validate that the microwave system can detect blade elongations of a few tenths of a millimeter. For that, two types of test campaign are realized. The first one is done on a precision test setup which can accurately position the blades relative to the probe. For this test, five blade mockups are mounted and the clearance pattern is characterized at different nominal clearance. The goal is to validate the consistency of the tip-clearance pattern measurements over a given range of nominal clearance. The second type of validation is realized on a spinning setup with forty blade mockups mounted on a rotor. The goal is to characterize precision and accuracy of clearance pattern measurement with a test bench representative of an engine. Both test campaigns use the 24GHz version of the microwave system and a laser sensor for reference measurements.

3.2. Reference measurements with a laser sensor

In order to correctly assess the clearance pattern measurement realized with the microwave system, a laser sensor is used for reference measurements. The five blade-mockups are mounted on the precision test setup – as described in Kwapisz, Hafner, and Queloz (2010) – and then scanned by a laser sensor (Figure 5).

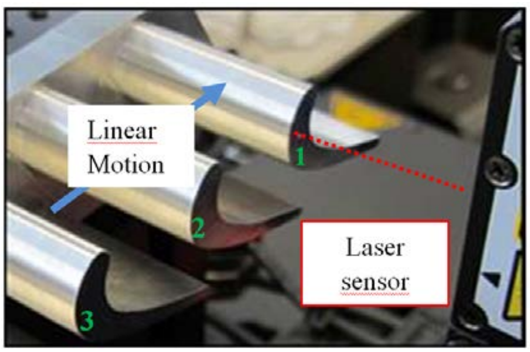

Figure 5. The exact blade profile is measured by a laser sensor with an accuracy of 6µm.

The blade clearance profile measured by the laser sensor is given in Figure 6.

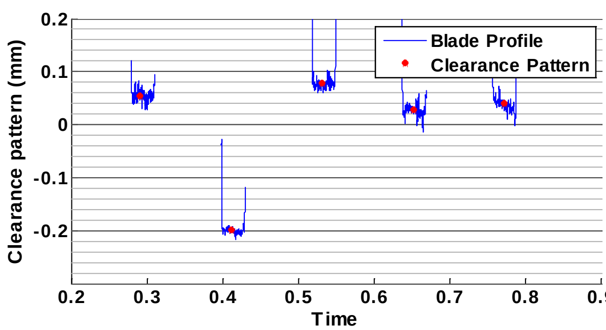

Figure 6. Actual tip clearance profile and associated pattern measured with the laser sensor. Longest blade is about 250µm ahead the other ones.

To be compared with microwave measurements, the clearance pattern is directly extracted from the profile by taking the median value of each blade tip profile. The individual blade clearances are within 60µm except for a longest blade which is 250µm ahead.

3.3. Measurement with the microwave sensor

The microwave sensor is installed on the precision test setup with the probe oriented toward the blade tip (Figure 7). The nominal clearance between the probe tip and the blade tips is set to 1mm and the blade tip clearance pattern measured by the microwave system.

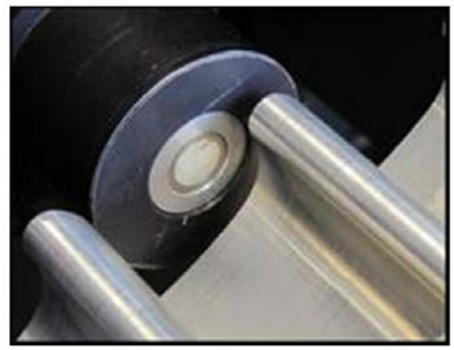

Figure 7. The 24GHz probe installed in front of the blades.

In order to compare the measurement made by the microwave system with the reference measurement made with the laser system, both measurements are made without any dismounting. Therefore, it is possible to make a direct comparison between both systems.

This first measurement shows that the microwave system correctly measured the clearance pattern with small errors of about 50µm maximum (Figure 8). The longest blade is clearly differentiable. This result has been obtained for a nominal clearance of 1mm and has to be confirmed for the entire clearance range of variation, purpose of the next section.

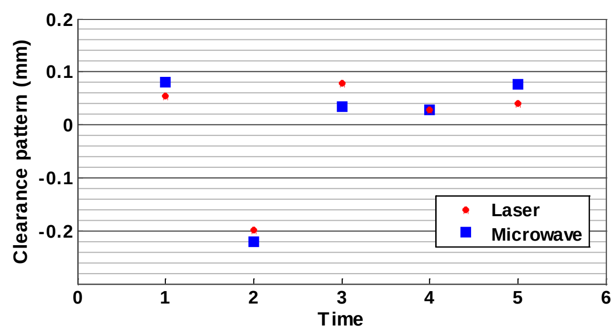

Figure 8. Direct comparison between laser measurement and microwave measurement.

3.4. Consistency of pattern measurement over the clearance range of variation

Blade tip clearance measurement is difficult for the different technologies in competition: capacitive, inductive or microwave sensors. The main reason is that the sensor behavior greatly depends on the nominal sensing distance because of the non-linearity of the physical laws that are involved. In the case of microwave sensing, clearance measurement is based on phase measurement with a linear relationship between phase and clearance (Eq. 1). Therefore, the calibration of such sensor is relatively easy and consists only on sensitivity and offset correction. Nevertheless, the beam width is relatively large and spatial filtering effects can generates measurement errors (Holst, 2005). This is why the correctness of clearance pattern measurement has to be validated over the full clearance range. This validation is the purpose of this section.

Regarding the blade geometry, which corresponds to aero-derivative turbine, the clearance does not likely exceed 3mm. For safety purposes, the minimum clearance that can be set on the test bench is 1mm. Therefore, a set of clearance pattern measurement is performed with a nominal clearance that varies from 1mm to 3mm by step of 0.05mm. Figure 9 shows the clearance response of the five individual blades. The longest one consistently gives a shorter clearance over the full clearance range. The longest blade gives a consistent offset of about 250µm over the full nominal range. This result shows that measurement uncertainties are small enough to enable the differentiation of blade elongation of a few tenths of a millimeter.

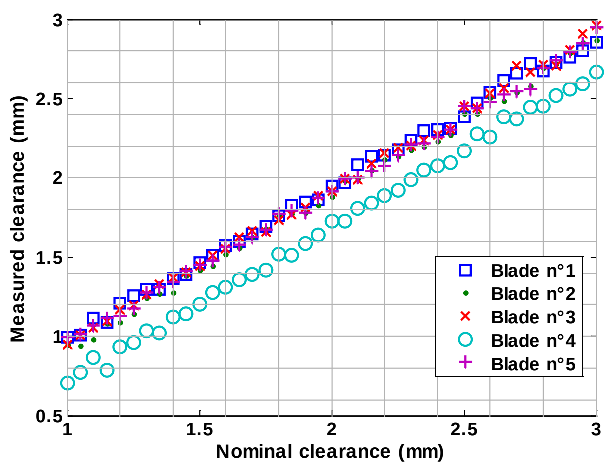

Figure 9. The clearances measured by the microwave system with respect to the nominal one.

Typically, a strategy of blade health monitoring, based on blade elongation measurement, requires that the measurement uncertainties be lower than the elongation to detect. To characterize the measurement uncertainties, the blade clearance pattern is computed from each set of measurements between 1mm and 3mm and then compared to each other. Thereby, the uncertainty range on pattern measurement can be estimated as described by Figure 10. It shows that the measurement variability (between the first and the last deciles) on pattern measurement is about ±40µm. The first and last deciles are represented by the boxes. The median is represented by the line inside the box. The minimal and maximal values are represented by the lines. This results has been obtained without any averaging and thus, takes into account both precision and accuracy aspects. They are also consistent with the reference measurements and enable the differentiation of the longest blade over the entire clearance range.

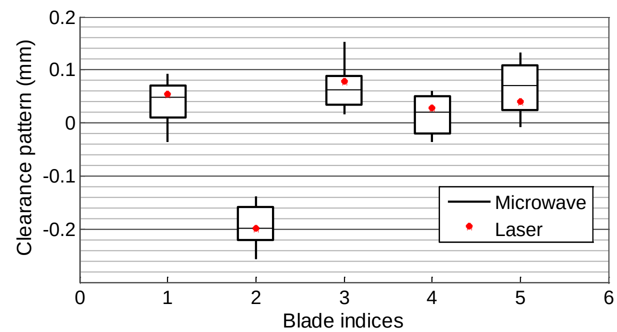

Figure 10. Variability range of blade clearance pattern measured between 1 and 3mm.

3.5. Measurement on a spinning setup

The validation of clearance pattern measurement is difficult to realize on a real engine in operation because of the lack of reference sensors that can survive the associated harsh conditions. In this case, the obtained measurements are difficult to interpret in term of accuracy and precision because the actual clearance pattern variations due to vibration and thermal expansion are unknown. That is why; a set of laboratory measurements has been realized on a spinning test bench with a reference laser sensor (Figure 11). It enables the direct comparison of microwave measurement with a reference sensor and helps the characterization of measurement performance.

The spinning test bench is based on a 500mm diameter rotor. Forty blades are mounted on the rotor and the tip-clearance of each individual blade can be tuned by using a dedicated sliding mechanical fixture. In order to evaluate the performance of the microwave sensor, the blades are set in order to get a rich clearance pattern. This pattern has been measured by a laser sensor for further comparison with the microwave system (Figure 12). This measurement was very stable with a standard-deviation lower than 10µm which indicates the absence of undesirable vibrations.

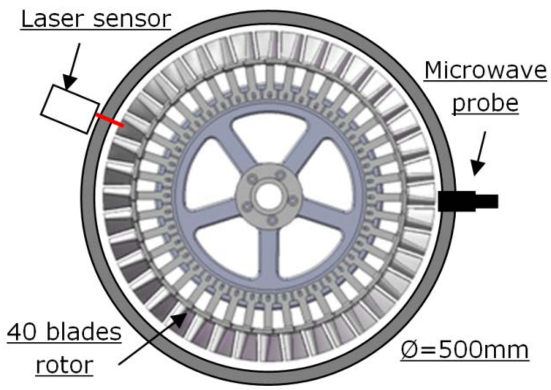

Figure 11. Joint measurement of the clearance pattern with the microwave and laser sensors on a spinning test bench.

The blade tip-clearance pattern has been measured by the microwave system over five hundred revolutions. Figure 12 shows the obtained results in term of median, extrema, first and last deciles. Basically, the clearance pattern measured by the microwave system accurately fits with the reference laser measurements. The precision of the microwave system obtained during this test corresponds to an uncertainty range of ±50µm (between the first and the last deciles). It is consistent with the precision of ±40µm obtained with the precision test setup (Section 3.4). This precision can be greatly improved by filtering the output of the sensor and by taking into account the tradeoff between precision and measurement bandwidth.

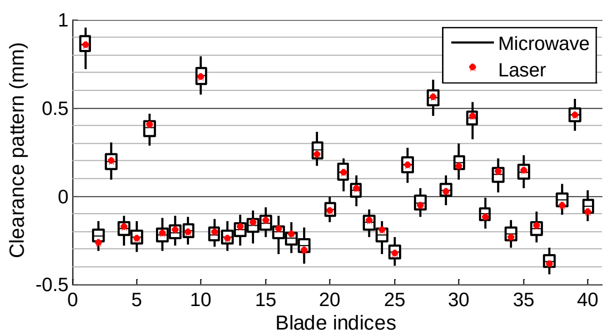

Figure 12: Measurement of the blade clearance pattern by the microwave system.

The correlation graph of Figure 13 is obtained by plotting the blade pattern measured by the laser sensor versus the averaged pattern found by the microwave system. The obtained correlation coefficient is higher than 0.99 which validates the linearity of the microwave measurement. The residual deviation is about 17µm. This result demonstrates that microwave measurement can be used to reliably detect clearance variation lower than 100µm.

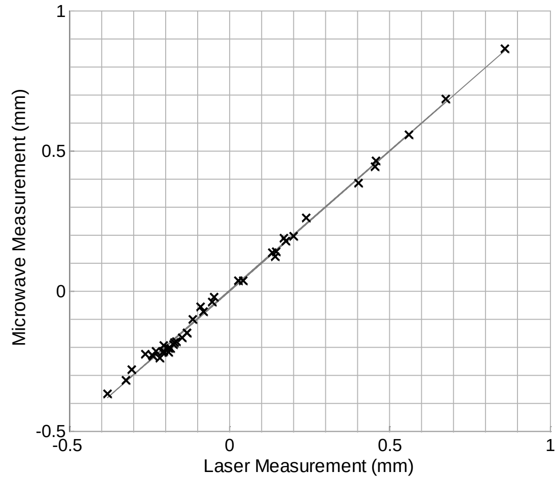

Figure 13: Correlation graph between microwave measurement and laser measurement. Each data point corresponds to one particular blade.

3.6. Conclusion on laboratory study

The ability of the microwave sensor to adequately measure tip-clearance patterns has been evaluated through different laboratory tests. The first one, realized on a precision test setup, has showed that the tip-clearance pattern can be consistently measured over the clearance range 1-3mm with a measurement variability of ±40µm. A second test has been realized with a spinning test bench and the obtained results are consistent with a measurement variability of ±50µm. This measurement uncertainty mainly comes from electronics noise and depends on system configuration. For example, it could be improved by using higher performance cables or by applying filtering strategies to the sensor output. On the other hand, the accuracy on pattern measurement is very good with residual errors about 17µm on the measurement realized with the spinning test bench.

4. Blade Pattern Measurement Realized on a Real Engine

4.1. Presentation of data

The microwave sensor has been evaluated through an engine test performed in 2011 on a 25MW turbine (Kwapisz, Hafner, Spitsyn, Mykhaylov & Berezhnoy, 2011). The purpose of this test was the validation of tip clearance measurement but an additional objective was to evaluate the ability of the system to measure the tip-clearance pattern. For that purpose, ten blades of the rotor had been shortened by a few tenths of a millimeter. The measurement of the blade clearance pattern has been performed during different engine operating states. This section presents an analysis of measurement variability related to the clearance pattern measurement with real engine data.

4.2. Raw measurement analysis

In order to compare the measurement performance obtained during the engine test with laboratory measurement, the data are analyzed without any filtering (Figure 14). Basically, the ten shorter blades can be easily differentiated during the different engine operating states. In term of precision and variability, the measurements are consistent with the laboratory study and show a variability of ±60μm. Nevertheless, the precision can be improved by filtering the clearance measurement outputs as described in the next section.

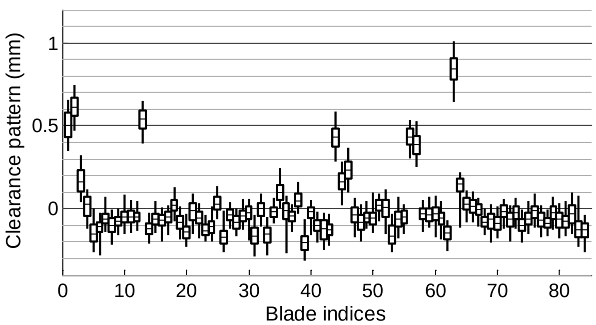

Figure 14: Variability range of blade clearance pattern computed over the whole engine test represented by extrema, first and last deciles and median.

4.3. Filtered measurement analysis

Detection of abnormal blade elongation requires a clearance pattern measurement with uncertainties lower than the elongation to detect. The measurement noise can be reduced by adequate filtering but there is a tradeoff between noise reduction and detection bandwidth. During the engine test, the measurement rate was 0.5 Hz. In order to reduce noise, a median filter with a window size of 20 samples is applied to the raw clearance measurements. In this configuration, the filtering leads to a minimal detection delay of 40s. Nevertheless, during this engine test, the measurement rate was not optimized and can be greatly improved for blade health monitoring applications.

The blade pattern has been computed for the whole engine test after having filtered the clearance outputs. The variation ranges are computed and shown by Figure 15. It is interesting to note that the variability of the blade tip-clearance pattern was not uniformly improved by the filtering. Some blades present a very small variability, lower than ±20μm, while other blades still have a variability of ±60μm. Indeed, the pattern variation comprises both measurement uncertainties and actual blade length variations. During this particular engine test, rotor speed and output power were not constant and the blades were subject to different temperature and load constraints. Because of small structural or mounting differences of the blades, the blade clearance pattern is not necessarily constant over all engine conditions. Typically, the BHM system has to detect abnormal variation, due to crack, among these normal variations.

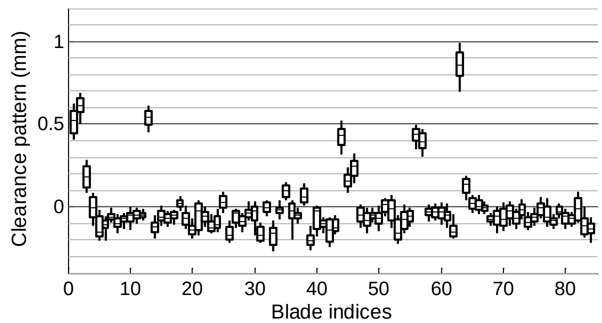

Figure 15: Variability range of blade clearance pattern computed over the whole engine test represented by extrema, first and last deciles and median.

4.4. Conclusion on engine test data

The purpose of the engine test was not the validation of blade crack detection based on microwave sensing. The primary goal was the validation of the absolute clearance measurement. Nevertheless, a side results was the measurement of the blade clearance pattern over different engine conditions. Basically, it shows that the variation of the blade clearance pattern is about ±60μm without any filtering. This range comprises both measurement uncertainties and actual blade elongation. It has been improved by filtering and the obtain results show residual variability which are likely due to actual clearance variations. Basically, in order to assess the feasibility of blade health monitoring based on microwave measurement, three metrics are important. The first one is the blade elongation threshold that indicates a crack long enough that turbine control action needs to be taken. The second one is the normal blade elongation discrepancy from which a crack effect has to be differentiated. The last one is the measurement performance of the sensing system that monitors the blades. This last metric has been evaluated in this paper but the feasibility analysis of such BHM system requires additional knowledge on blade elongation.

5. CONCLUSION

Blade health monitoring offers real opportunities to improve gas turbine operation and to reduce maintenance costs. Different strategies and system architectures can be envisaged but one of the keys points is to obtain reliable and accurate sensor package. Due to the harsh environment in the hot section, only a few sensing technologies are capable of blade monitoring in this area. In this domain, the microwave sensor has real advantages as it is capable of accurate temperature measurements while withstanding temperatures near the turbine inlet. This paper has described the tracking of the blade clearance pattern as one way of using this technology for blade health monitoring. This paper shows how to deal with variability that comes from measurement errors but also from real blade elongation discrepancies. This last point is very important and leads to physics-based diagnostic techniques. In addition to blade clearance measurement, the microwave system is capable of time-of-arrival measurements. This type of measurement is currently under evaluation and will certainly provide rich information for blades health monitoring. In conclusion, the microwave sensor provides a sound basis for future diagnostic systems in term of measurement performance and sensor operability.

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BIOGRAPHIES

David Kwapisz is research engineer at Meggitt Sensing Systems since 2008. He is responsible for technology and testing aspect of microwave sensing. He received a M.Sc. degree in 2005 from Ecole Supérieure des Techniques Aéronautiques et de Construction Automobile (Paris) and a Ph.D degree in Automatic Control in 2008 from Université de Limoges.

Michaël Hafner is product manager at Meggitt Sensing Systems since 2010. He is in charge of the microwave tip clearance and tip timing products for the Energy market. He received a Mechatronics M.Sc. degree in 2006 from the Swiss Federal Institute of Technology.

Ravi Rajamani joined Meggitt PLC in 2011 as an Engineering Director, responsible, in part, for Integrated Vehicle Health Management (IVHM) strategy. Ravi has a BTech from IIT Delhi, an MS from IISc, Bangalore, and a PhD (EE) from the University of Minnesota. Before his current position, Ravi worked at General Electric and at United Technologies primarily in the area of gas turbine controls and diagnostics. He is active within SAE's Engine Health Management (E-32) and Integrated Vehicle Health Management (HM-1) committees.