Blade tip clearance measurement technology in gas turbines

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Abstract.
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. 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.

Key words: Microwave, Clearance, Gas turbine, Blade, Sensor.
Introduction.

One of the means of generating clean electric power is gas turbines, where carbon dioxide emissions are low, and gas turbines have a capacity of about 500 kW. In order that of the temperature of around 1600°C in some modern gas turbines [1], design techniques are required to design turbine components that can withstand this heat. One of these parts that are designed to withstand high temperatures is the microwave sensor [2].

The high temperature microwave sensor presented in this paper is one of the most promising candidates for clearance measurement. Blade tip clearance sensing is a key for future improvements of gas turbine design, operation and services [3]. Some sensing technologies are in development, Due to the following factors, temperature, pressure, vibration and the presence of combustion products. This environment limits the long-term use of most technologies. Within this context, Meggitt (a global turbine manufacturer) has developed the high temperature microwave sensor [4].

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. The only way to judge the quality of the final measurement is with a real drive test [5-6]. Within this purpose, the motor test drive as (fig.1) was carried out using a microwave system and the high pressure turbine (HPT) stage of the DM80 motor (rated output power 25 MW) was equipped with eight microwave sensors with clearance monitoring during different motor operating modes.

This paper describes the various steps that lead to testing the engine as well as the measurement results obtained. Operating the blade tip removal system inside a gas turbine requires some operations such as engine modification for probe installation, probe calibration, system configuration and installation.
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 [7]. This step is necessary before the modification of the engine.

Once the probe has been positioned and the actuator adjusted, each of the eight probes is individually calibrated. The second important step that was taken before testing the engine was the installation of the system and the probe. When placed in the actuator, the probes must be placed in the same location as determined during the laboratory study.

**Equipment used and work idea.**

The microwave system used for this engine test is composed of eight independent measurement channels operating at 24 GHz. Each channel is composed of measurement system uses high temperature microwave probes (fig.2). The dimensions of these probes are relatively small with an outer diameter of 8.5 mm, installed in the engine, a microwave cable and an electronics cards pair (fig.3), eight probes were installed around the high pressure turbine rotor and numbered by their dedicated probe port (fig.4), these probes are connected to a rack located next to the engine by using extension cables which are rated up to 200 °C. 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.

The microwave displacement measurement system has been developed, which is based on the continuous microwave signal generated by the electronics, which is sent by the probe and reflected by the tip of the blade back to the electronics. The
reflected signal is then compared to an internal reference in order to extract its phase and magnitude. Quadrature mixer architecture is used to extract the in phase and quadrature channels (baseband) from the microwave signal (fig.5).

**Laboratory study.**

The laboratory study and calibration of the probe were carried out using real blades and a representative model of the engine casing. During this study, the optimal position of the probe, in terms of cold axial position and orientation was determined in order to obtain the best measurement performance. The positioning parameters were used to perform the individual calibration of each probe dedicated to the motor test, and the measurement results obtained during the motor test will be described. Operation of blade tip removal systems, regardless of the technology used requires preliminary lab work. The main objectives are to choose the position of the probe in relation to the blades and to calibrate the individual probes. The final measurement performance is highly dependent on these two steps, which are discussed in this section.

In order to measure blade tip clearance, the probes are mounted through the engine casing such their sensor has a direct 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 (fig.6). The laboratory study is mainly done using a precision test setup with actual blades attached to its (fig.7). 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 (fig.8). Indeed, because of the polarization of the electromagnetic field generated by the probe, the probe angular orientation changes
The measurement response. The parameter to optimize is the consistency of measurement over the different axial positions seen by the probe during engine operation. 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 [8, 9]. 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, the optimal probe cold axial position and probe orientation obtained for this engine are given by (fig.9). After having chosen the cold axial position and the orientation of probes, as explained, 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 (fig.10). 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. (fig.11) shows each probe calibration curve.

![Graph](image1)

![Graph](image2)

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. 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 (fig.12).
Fig. (12) 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.

Fig. (13) 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.

Fig. (14) Average clearance trends for the eight probes on the second day of engine testing.
Fig. (15) Average clearance trends for the eight probes on the third day of engine testing during the fast engine output load decreasing and increasing event.

Fig. (16) Average clearance trends for the eight probes on the third day of engine testing during the slow increasing of output power load.

**Conclusion.**

The graphical analysis in figures (13) to (16) shows the results obtained. In (fig.13) 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 (fig.14), 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 1.1 mm.

Fig. (15) Shows a rapid load variation from 18MW 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 1.65mm 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.

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 behavior 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). Such detection can be used to track changes over time within individual clearance and detect potential blade crack and pending blade failure.
References.


