SINGLE BLADE TIP CLEARANCE MEASUREMENTS IN A TRANSIENT RIG

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1. ABSTRACT

The request to measure accurately radial and axial clearances has been intensified by the developments in high pressure compact turbomachinery. The blade tip gap is a vital parameter to characterize the turbine performance. The larger the tip clearance, the lower the turbine efficiency due to the increased loss associated with the hot jet flowing across the blade tip. Following the increasing demands in efficiency, these small clearances must be monitored to avoid mechanical rubbing. The appropriate design of control systems to adjust the turbine tip clearances requires a constant monitoring during the whole engine envelope. Although the blade clearance can be predicted in function of the RPM and thermal loads with numerical codes, tip clearance variability appears during the engine production.

This paper describes the complete implementation of a high-frequency capacitive sensor on the shroud of a large transonic turbine stage. The objective is the measurement of tip clearance of each blade. This high-pressure turbine is tested in a short duration facility with running times of less than 0.5 seconds, with temperature transients and accelerations. The calibration of the sensor is performed in situ. Preliminary results performed in a test bench at 1000 RPM together with the post processing procedure and uncertainty analysis are presented.

2. INTRODUCTION

Turbine leakage flows have a large impact on the whole machine performance, causing a decrease in efficiency that can reach 25 % of the stage total losses. Hence, it is necessary to minimize the gap between the blade tips and the casing. On the other hand, the clearances must be monitored to avoid any mechanical rubbing. Hence, it is necessary to balance the aerodynamic performance with the mechanical integrity. Several parameters alter the tip clearance, both the rise in rotational speed and temperature result in a reduction on the radial gap. Thermal transients of the engine result in dilatations and deformations of the rotor disk. The operating conditions in a HP turbine are very hostile. The sensor must be selected according to those harsh operating conditions. Furthermore, the sensor must be able to perform measurements at high frequency. Among all possible type of sensors the capacitive sensor seems to be the best suited, with a basic principle of operation, robust and reliable.

The novelty in the current project is the signal treatment. Previous methods presented restrictions in the band-width limitation, or in the distance between the electronic treatment unit and the probe. Thanks to the high processing velocity, the system presented here is able to resolve blade passing frequencies up to 55 kHz, while allowing a distance of 8 meters between the electronic and the probe without any loss of performance [1]. To calibrate the sensor, a complete set-up was designed and manufactured to be able to perform the calibration procedure on the HP turbine facility (in-situ) without any corrections due to an external calibration.

3. MODULATED CAPACITIVE PROBE

3.1 Probe

The probe comprises two coaxial conductive cylinders, separated by an electrical insulator, as displayed by Figure 1. The establishment of a voltage difference between the cylinders constitutes a capacitor. The capacitance Co is constant and depend of the material chosen for the insulation, it can be measured when no other object disturbs the electrical field. When a target enters into the electrical field, new capacitor is formed between the core and the new metal. The capacitance C(x) is a function of the distance between the target and the sensor. A second capacitor Cg(x) is formed between the target and the external electrode.

$$C_m = C_0 + \frac{(C_g(x) \,.\, C(x))}{(C_g(x) + C(x))}$$

Cg(x) can be neglected if the target (the rotor blade) and the external cylinder of the sensor are put at the same potential. In this way, the measured capacitance equation is simplified [2]: $C_m = C_0 + C(x)$

The operating scale depends of the central electrode diameter. As a rule of thumb one can assume that half of the diameter is the maximum clearance. The operating temperature of the selected probe is limited to 250°C, although there are capacitive probes able to withstand 1000°C.

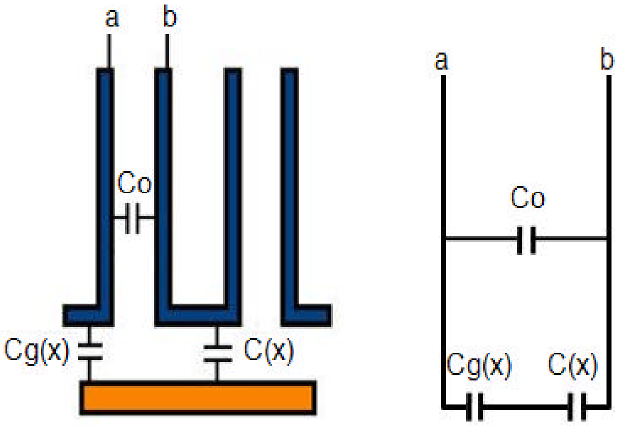

Figure 1. Working principle of the capacitive probe

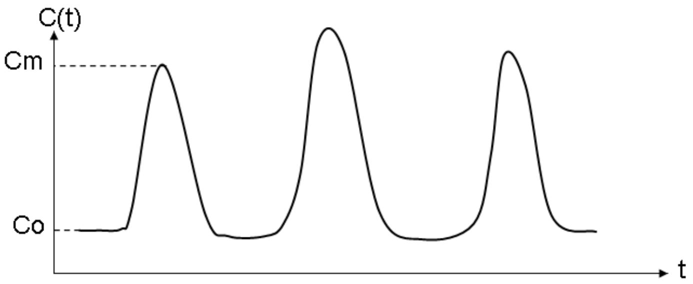

Figure 2. Capacity variations due to a blade passing

Figure 3. Capacitive probe picture

3.2 Acquisition chain and amplifier unit

The measurement chain is composed by a capacitive probe, and an amplifying electronic unit fed by a DC power supply. The probe is located into the rotor casing and is directly connected to an amplifier stage. The amplifier unit provides a high-frequency signal (60 MHz) to the sensor. The large frequency band is obtained thanks to the use of modern FPGA technology, allowing measurements at very high frequency in Femto-Farat range. When the metallic blade passes near the probe the high-frequency signal is modulated. The comparison between the raw high-frequency signal and the probe-modulated output allows the derivation of the blade clearance. This function is realized thanks to a fast Field Programmable Gate Array (FPGA). The feedback loop via the Digital-Analog-Converter provides wide range of compensation for the disturbing change of the probe capacity. The conversion into the amplification has 10 bits of resolution; hence the theoretical resolution of the device is 1/1024 of the span selected for the testing. But the effective resolution is reduced by the influence of noise and the residual errors due to the filtering. An integrated auto calibration function allows temperature compensations. The measuring signal is linearised via cubic splines and converted into blade clearance in real time. The output of the system is sent to both a data acquisition system and an oscilloscope.

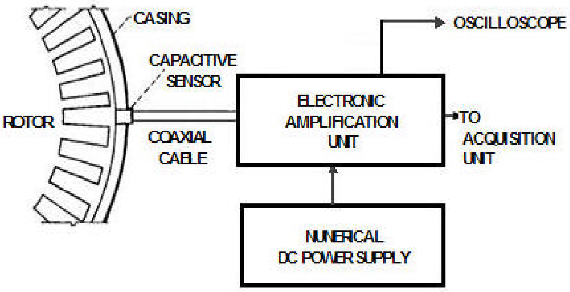

Figure 4. Acquisition chain diagram

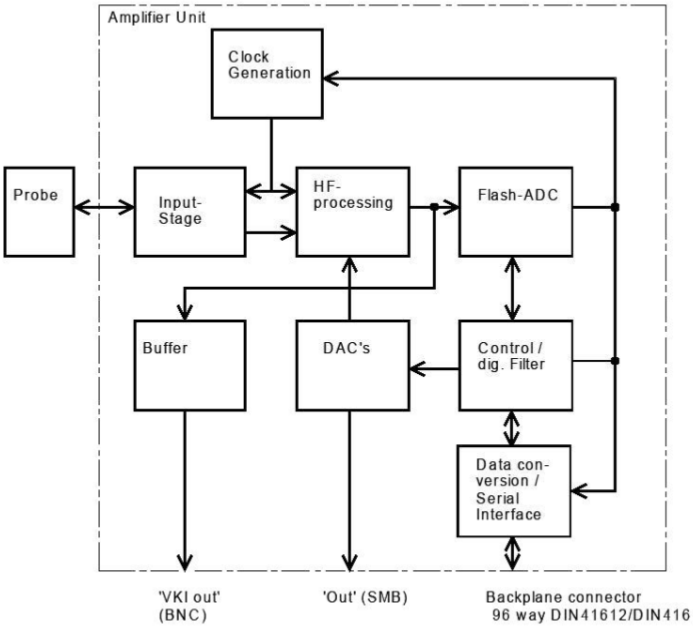

Figure 6. Diagram of the amplification unit

3.3 Required time resolution

To determine the necessary cut-off frequency of the ideal sensor, analytical were performed. For our particular application into the HP turbine facility, we have a rotor disk with 64 blades (pitch 34 mm) rotating at 6500 RPM, namely 6933 blades per second will be observed by the probe. The blade passage is 144 µs, and during 30 µs there is a step-wise signal. Figure 7 indicate that even with a cut off frequency of 60 kHz there is not enough frequency to resolve the step. One needs high frequency levels, around 1 MHz to properly resolve the step, please note that the current system has an internal cut-off frequency of about 4 MHz. At 1 MHz a blade width of 7 mm, implies that the number of samples per blade passage is about 30.

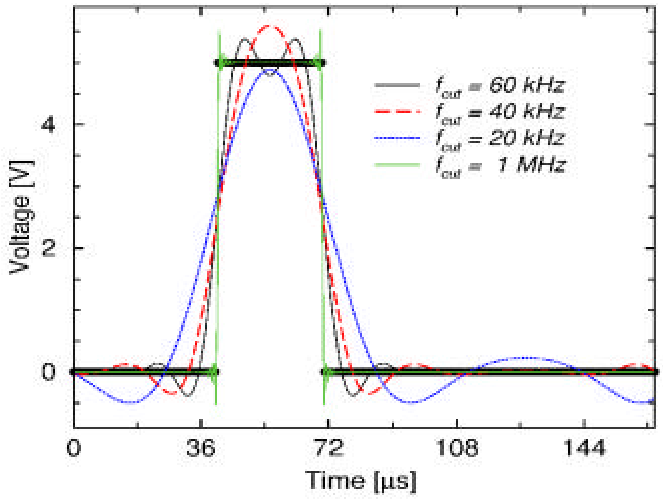

Figure 7. Cut-off frequency

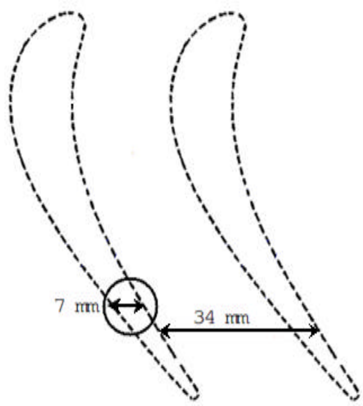

Figure 8. Blade pitch

4. EXPERIMENTAL APPARATUS

4.1 Description of the compression turbine rig

The compression tube facility (CT3) is a short duration wind tunnel able to simulate the conditions encountered in a high pressure turbine stage. With a diameter of nearly 800 mm, the CT3 is the world largest short-duration compression tube facility. This facility allows measuring several parameters in rotation like the static pressure, the total pressure and the heat transfer. Figure 9 presents the main components of the CT3. The test section is located in between the two reservoirs: the upstream cylinder and the downstream dump tank. In this way, the Reynolds number can be adjusted. Initially, the shutter valve is closed and isolates the test section from the upstream cylindrical reservoir. The free light piston is at the rear of the upstream reservoir that is set at a given pressure at ambient temperature. Vacuum is set in the downstream dump tank (~30 mbar). The turbine is spun-up to almost its design speed. When the test starts, high pressure air (240 bars) is admitted in the back of the upstream cylinder trough sonic throats that control the incoming mass flow. The piston starts to slide and a quasi-isentropic compression of the air is performed downstream of the piston. When the desired value of pressure is reached, the fast opening valve is opened. A blowdown of hot gas takes place over a 'cold' turbine simulating in this way heat transfer to the blades and endwalls. Before opening the shutter valve, the rotor is spun up to 6500 RPM thanks to a power turbine. The test duration on this facility is about 50 ms and during 40 ms, the parameters are kept constant. During the test the rotational velocity increase up to 6900 RPM, that cause a growing of the disk due to the heating combined with the centrifugal forces [3].

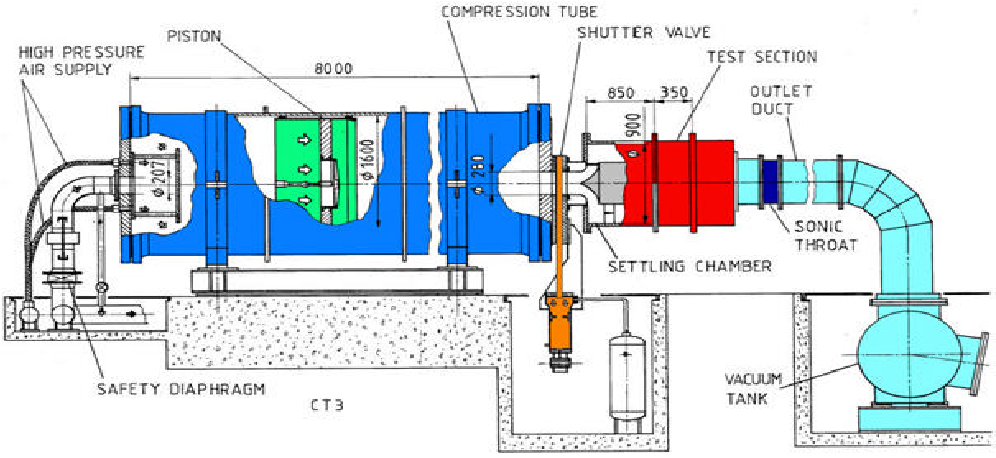

Figure 9. General view of the HP turbine test rig

4.2 Simplified test rig

Prior to the installation of the sensor on the transient HP turbine facility, preliminary calibration tests were performed on a lathe (Figure 10). A wheel with twelve teeth was designed, mounted on a shaft and clamped into the chuck of the lathe on one side and on the tailstock on the other side. The sensor is located into the tool rest that allowing to control his displacement with a resolution of 0.01 mm. Due to internal electronic settings the lower limit o the blade passing frequency is about 160 Hz and the maximum limit is about 55 kHz.

Tests were performed at 1000 RPM that corresponded to a blade passage frequency of 200 Hz. The sampling frequency is 400 kHz. The sensor was moved at different distances from the wheel to perform the measurements and also to obtain the calibration curve. The operating scale of the sensor is included between 0.3 and 2 mm.

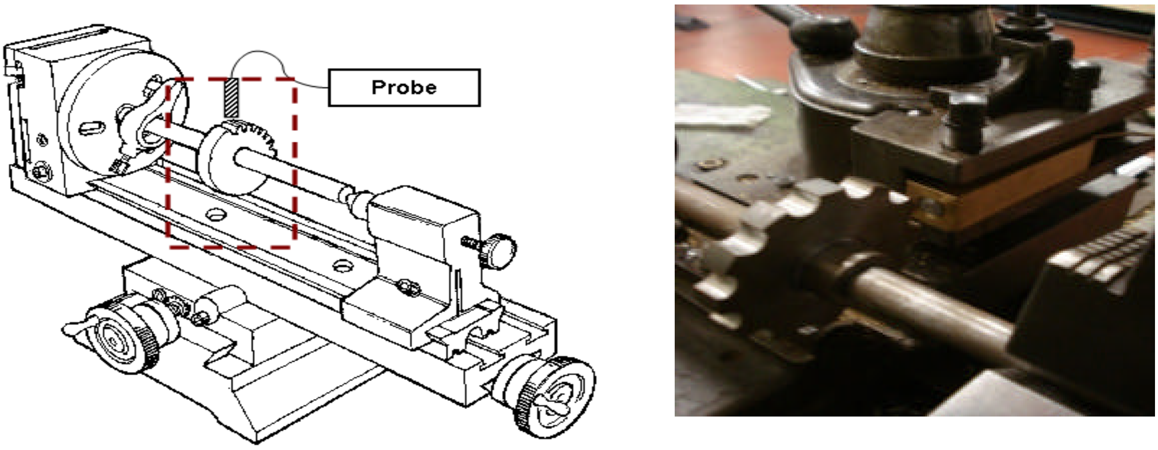

Figure 10. Pictures of the test bench

4.3 Implementation into the turbine rig

Figure 11 shows all pieces that were designed and manufactured to perform the calibration in situ on the CT3. The sensor is mounted and fixed in an extension screw. This screw is passing through the external casing and the rotor shroud of the CT3. In screwing this device, the sensor is moving radialy to perform the calibration. The maximum blade tip clearance is measured thanks to two wearing gauges that provide the reference value at the beginning of the calibration procedure. A system composed of a micrometric screw measure the displacement of the extension screw. With this system, it is possible to adapt the measuring span of the sensor to work with the minimal gap as possible in order to minimize the error on the measurement. Three positions distant of 120 degrees were planned around the CT3's casing. This system will allow the determination of the rotor eccentricity, vibrations and acceleration.

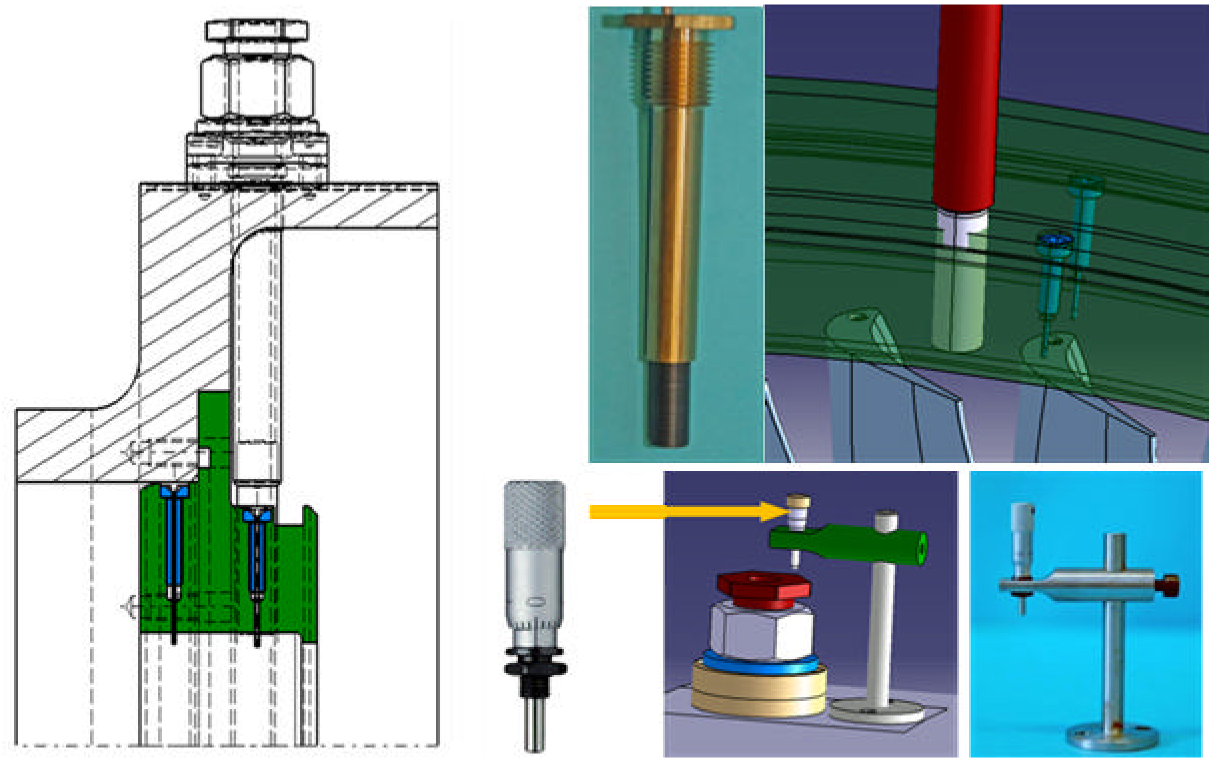

Figure 11. Views of the calibration system

5. RESULTS AND DISCUSSION

A Matlab program was realized to obtain the calibration curve. The program delivers each single blade height and can compare the evolution of a blade height in the time. The signal is filtered at ten times the main frequency using a numerical Matlab filter. The program computes also the mean value (‘a’ on the Figure 13) of all the data acquired. This thereshold levl is used to recognize the upper and lower parts of a wave. From ‘i’ to ‘j’ , the minimum value is acquired. From ‘j’ to ‘r’ the maximum value is acquired. In this way, all the maximum values are known for each blade passage.

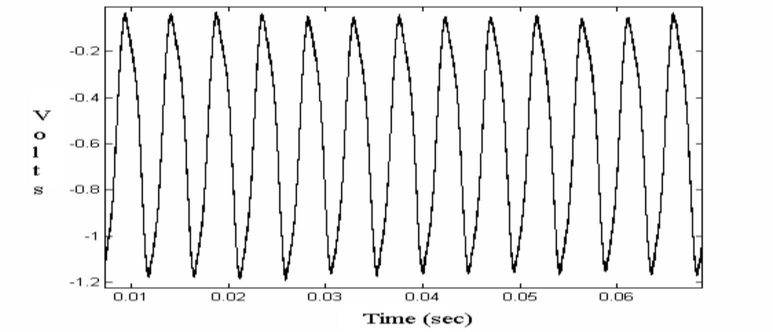

Figure 12. Signal output

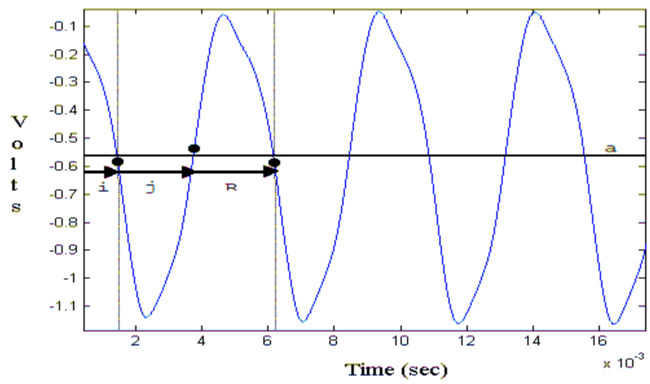

Figure 13. Filtered signal output and post processing procedure

The results obtained thanks to the post processing program allow constructing the calibration curve. This curve is exponential to fit with the physical phenomenon. $C = \frac{\varepsilon_o \cdot \varepsilon_r \cdot S}{x}$

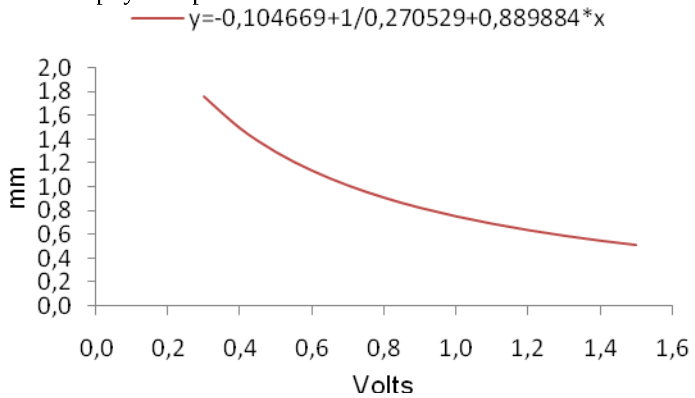

Figure 14. Calibration curve.

The analysis of the repeatability of the signals provides a good estimate of the random error. This error grows with increasing the gap; it is therefore wise to work with the minimal gap during the test in order to minimize the error. The maximum error is about 25 µm at the end of the sensor operating scale.

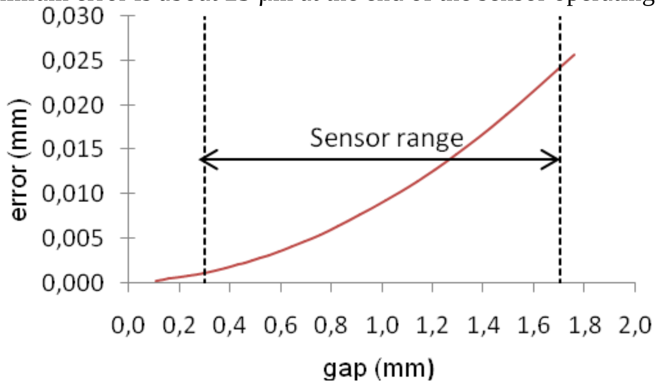

Figure 15. Random uncertainty curve

Figure 16-top presents the tooth height measured with a comparator (at 0 RPM), whilst Figure 16-bottom shows the results obtained with the capacitive sensor in 4 independent turns each color represents a different test). It is interesting to observe a high repeatability, with a dispersion of less than 13 µm. It is observed that the results of both figures are very similar. The oscillation obtained on the results measured by the capacitive sensor is the same that the oscillation measured by the mechanical device. This deviation is due to the precision of the machining device.

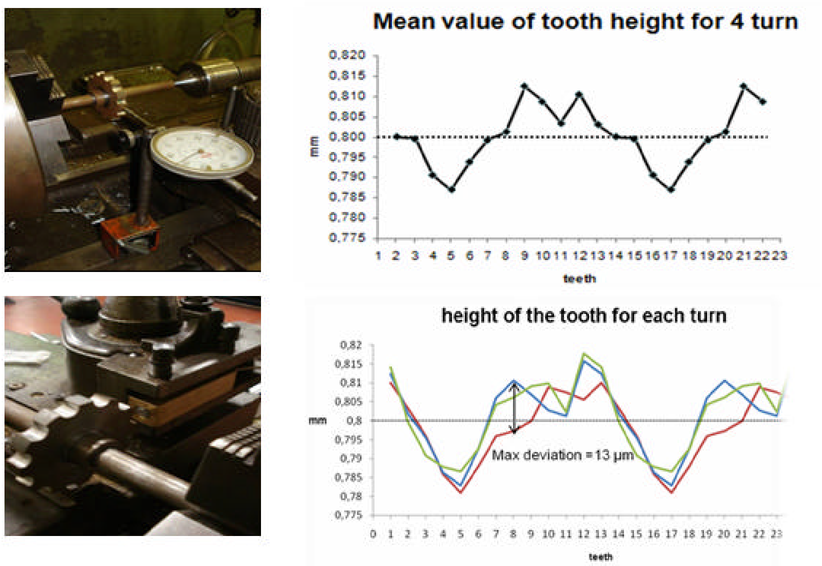

Figure 16. Mechanical measurement results versus capacitive probe results

6. CONCLUSIONS

Based on a thorough analysis of various tip clearance sensors a capacitive probe was selected due to its large cut-off frequency. The calibration system has been designed and manufactured in order to perform calibrations in situ. A post processing program was created to extract each blade clearance and to construct the calibration curve. Thanks to a new technique of signal treatment, the blade tip clearance system allows measuring the blade height with a very high precision. The maximum error is about 25µm and the end of the sensor operating scale. This error can be minimized if the sensor range is well adjusted. Thanks to the high sampling frequency of the acquisition system the tip of each blade can be observed. Finally, the blade tip clearance system is able to evolve in order to measure the eccentricity of the rotor and the balance of this one. The time response of the system is about 1 µs allowing future research on tip-timing and rotor acceleration measurements.

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