BLADE TIP CLEARANCE AND BLADE VIBRATION MEASUREMENTS USING A MAGNETORESISTIVE SENSOR

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ABSTRACT

A Blade Tip Timing (BTT) system enables the measurement of turbomachinery blade vibrations by means of contactless sensors mounted in the casing. In addition, the so-called Blade Tip Clearance (BTC) measurement system ensures the monitoring of the existing running gaps between the blade tip and the casing.

This paper focuses on the results achieved so far using a novel magnetoresistive sensor for simultaneous BTT and BTC measurements.

Several prototypes of the probe have been realized and tested. Measurements of clearance are possible with an uncertainty of U = ± 22 µm (20:1) within a gap range [1 ÷ 1.5] mm, in line with the commonly used probes.

In terms of measurement of vibration, a dedicated calibration bench for any type of BTT and BTC probe was realized. Experimental investigations are presented.

The magnetoresistive sensor has low manufacturing costs and the metrological characteristics fulfill the requirements of industrial instrumentation standards.

NOMENCLATURE

BTC	Blade Tip Clearance
BTT	Blade Tip Timing
CT	Calibration Tower
DAS	Data Acquisition System
I	Current
M	Magnetic Field
OPR	Once Per Revolution signal
SNR	Signal to Noise Ratio
θ	Theta: angle between the Magnetic Field and Current vectors
U_{95}	Expanded Uncertainty
V	Voltage

INTRODUCTION

The blade tip clearance and the vibration of the blades play a fundamental role in the design and development of any turbomachine. For instance, the efficiency of the rotor can be improved by minimizing the distance between the blade tip and the casing in order to reduce leakage flows. However, during operation the tip clearance changes due to mechanical loads and varying temperature and pressure conditions inside the turbomachine. To prevent a fatal damage, an accurate online monitoring system is therefore mandatory for optimized and safe operations. The so-called blade tip clearance (BTC) measurement systems are based on non-contact probes sensitive to the distance between the passing blade tip and the casing. As reported by Lattime and Bruce (2004), a typical sensor for such applications requires an accuracy of about 25 µm. In addition, all turbomachinery blades and components experience vibrations during their operation. This is due to several sources like: mistuning, pressure distortions, flutter, stall and surge; as explained more in

detail by Brouckaert (2007). Unfortunately this undesirable structural motion affects fatigue life, performance and integrity. For more than half a century, vibration measurements have been performed by installing strain gauges on the blades and using telemetry to transmit the signals. The blade tip timing (BTT) technique, is currently adopted by all manufacturers as a replacement for the classical strain gauge technique because of its non-intrusive character. The aim of a BTT measurement system is to evaluate the time at which a point on a rotating blade tip passes a stationary reference. In the absence of any structural vibration, the blade arrival time would depend only on the rotational speed of the blade. When the blade is vibrating, the arrival time will also depend on the amplitude, frequency and phase of the vibration. Hence, the blade motion can, in theory, be determined from the arrival data.

Many different sensing principles have been utilized for tip clearance and tip timing measurements. A summary of them and of their performance was given by Chana (2007). Optical probes are largely used thanks to the fast response and the very small spot size. For instance, they have been used as reference with respect to other sensor types (Cardwell et al, 2007), to validate a new tip-timing technique in the work of Gallego-Garrido et al (2007) and Heath and Imregun (1996), to realize a novel laser doppler system (Pfister et al, 2006) or in comparison with the consolidated strain gauge technique, e.g. Andrenelli et al (1991),(1992), and Nava et al (1994). Nevertheless, optical probes suffer from low tolerance to debris (Häusler et al, 1999). Due to the hostile turbomachinery environment, capacitive sensors are also often employed, because they are small and robust. Zielinski and Ziller (2005), described a capacitance based tip timing system currently used at MTU. Furthermore, eddy current probes provide about the same accuracy as capacitive sensors with the advantage of measuring through non-ferromagnetic casing walls. Nevertheless, the sensor response strongly depends on the thickness and the material of the casing and blades. For instance, Terpay (1999) patented a shielded Eddy Current probe. Finally, applications can be found also with microwave (e.g. Wagner et al, 1998), ultrasound probes (Tagashira et al.1997) and pressure sensors (Belsterling, 1971). Nevertheless, the wave propagation strongly depends on the temperature, pressure and relative speed of the air in the gap between blade tip and turbine casing. Pressure sensors have a low signal to noise ratio.

This paper describes a novel sensor for simultaneous blade vibration and clearance measurements, based on magnetoresistive sensing elements (Holman, 2004). This technology has already been applied in a steam turbine by Prochazka and Vanek, (2010). Recently Brouckaert et al (2012) and Tomassini et al (2014) published a comparison between the magnetoresistive technology and the optical and capacitive probes. High temporal and position resolutions have been demonstrated, in line with the performance of the other sensors. In addition, the magnetoresistive elements present advantages like: small dimension, fast rise time, low manufacturing costs and tolerance to debris. Consequently, the application of magnetoresistive based principles in turbomachinery testing opens new perspectives for future developments.

SENSOR DESIGN

Magnetoresistivity is the ability of a material, like a Permalloy thin film, to change resistance under the influence of a magnetic field (Holman, 2004). The sensing element is shown in Figure 1 left. I is the current, M is an external magnetic field and θ is the angle between them; a change in theta, the direction of the magnetic field, results in a variation of the output signal of the sensing element. By placing a Permalloy element beside a permanent magnet, a system sensitive to the variation of magnetic field, is created. Hence, if a ferromagnetic object (like a blade) passes in front of it (Figure 1 right), there will be a distortion of the magnetic field, therefore a variation in the output signal.

During the design and development of the novel probe, different configurations of the two components (chip-magnet) have been investigated. For the same $\Delta\theta$, the output signal amplitude

changes with the magnet position, shape and strength. In order to maximize the SNR, a preliminary optimization of the sensor components layout has been performed.

Finally, two sensor prototypes have been realized: an analogue and a digital one (Figure 2). The former is made of a cylindrical permanent magnet placed beside the magnetoresistive chip. The digital probe has a Schmitt trigger on the sensing element output. The casing of the two probes is made of an 8 mm outer diameter Brass/Aluminium pipe, with the sensing element placed at the top. A length of 40 mm or less can be achieved.

A detailed characterization of the sensors has been performed in a dedicated test bench by Tomassini et al (2014). Interesting results have been pointed out: fast rise time (about 20ns), high signal repeatability and cheap technology.

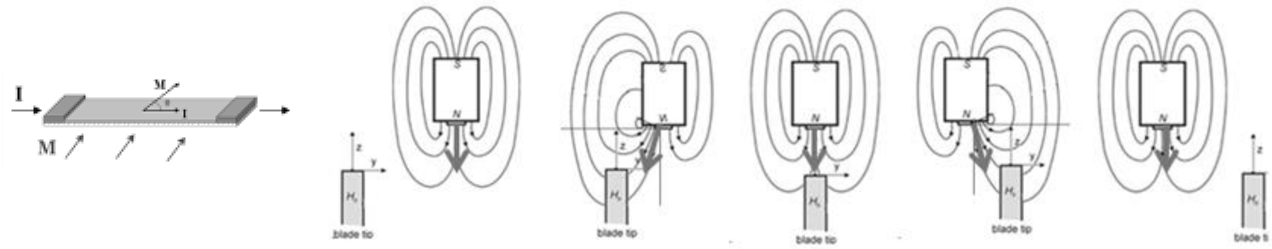

Figure 1. (Left) Permalloy film; (right) sensor measurement principle.

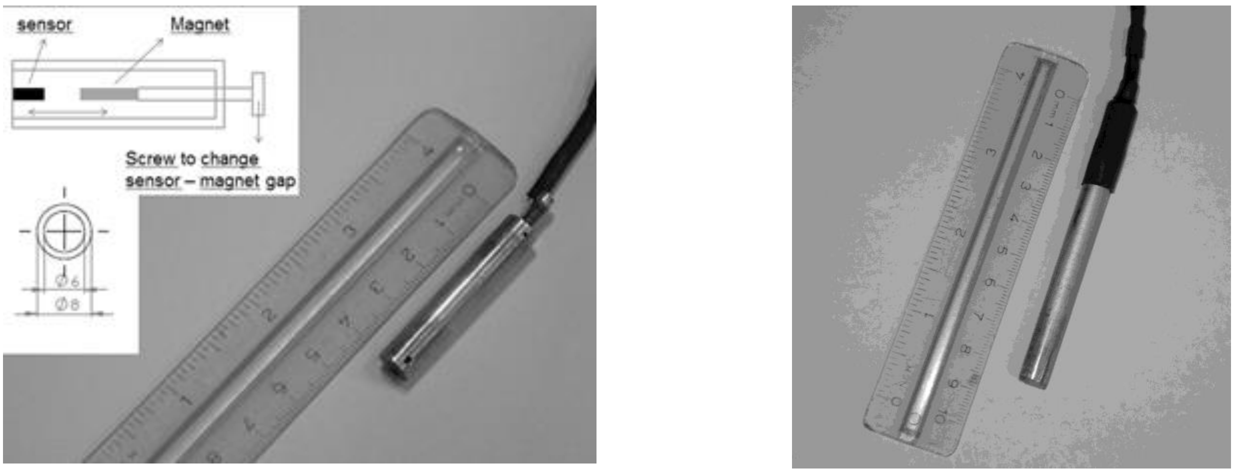

Figure 2. The magnetoresistive sensors: (left) analogue sensor; (right) digital sensor.

CLEARANCE MEASUREMENTS

This paragraph reports the experimental investigations on clearance measurements. Every time a blade is passing in front of the sensor, a pulse is generated. The amplitude of the output signal is sensitive to variations of the gap between a passing blade tip and the sensor head. Static and dynamic tests have focused on this phenomenon to retrieve the calibration curve.

Static test: setup and methodology

The passage of a blade in front of the sensor at different gaps was studied in a static test bench. As shown in Figure 3, a blade was mounted in a rotary slider with a resolution of 1°, facing the Magnetoresistive sensor installed in a linear slider with a resolution of 10 µm. The sensor axis was aligned with the blade axis at 0° on the rotary slider. The blade passage was discretized and studied in the angular range [-20 + 20]° with an angular step of 2°. The measurements were repeated for different gaps (sensor head-blade tip): [0.5 – 1 – 1.5]mm. At every fixed position, the mean DC signal was acquired and represents one point of the fitting curves shown in Figure 4.

The passage of the blade was also investigated using an electromagnet. In comparison to a permanent magnet, this configuration gives more flexibility for applications with different materials

and better results in terms of SNR, using a dedicated and optimized electromagnet. As shown in Figure 3 right, a commercial coil was used at this preliminary stage. The aim of the test with this configuration was to validate the possibility of using a general electromagnet. The passage of the blade has been repeated at gaps of 1 and 1.5mm and for different voltages of the electromagnet power supply.

Results

Figure 4 shows the typical pulses observed at the blade passage. The plot on the left is related to the configuration chip-permanent magnet at different clearances and the configuration chip-electromagnet at 1mm and 1.5mm, at 12V power supply, namely: "1mm12VEM" and "1.5mm12VEM". The graph on the right shows the output signal of the blade passage at 1mm by changing the electromagnet supply voltage.

The variation of the blade tip clearance implies a signal amplitude variation: the bigger the gap, the smaller the peak to peak value. An interesting aspect to point out is that, whatever the clearance is, all signals pass through a common point at 0 Volt. This behavior is of fundamental importance for Tip Timing measurements. Concerning the pulses obtained with the electromagnet, the amplitudes are lower because the generated magnetic field was weaker than the permanent one. Moreover, the pulses do not cross the x axis exactly at 0° because there was a misalignment between the blade, the free chip and the generated magnetic field.

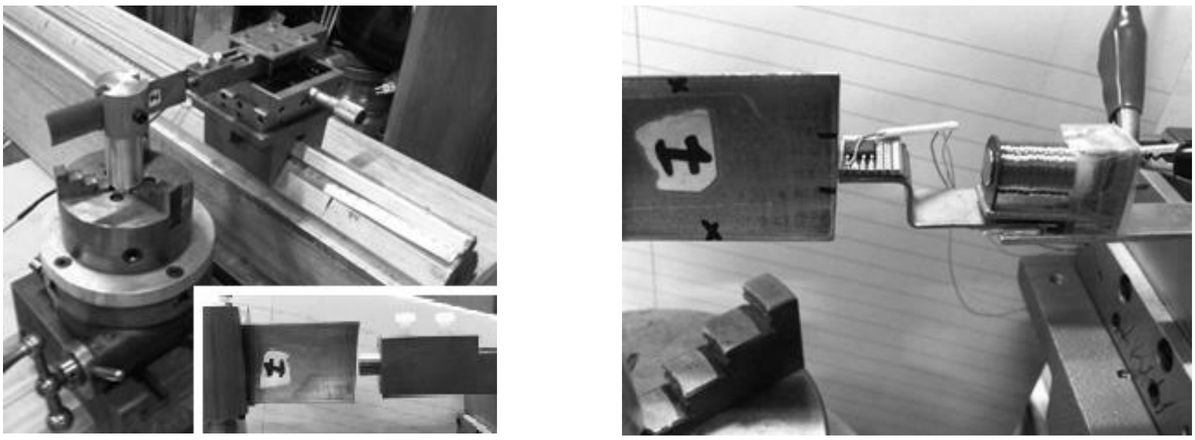

Figure 3. (Left) the static test bench; (right) the test with an electromagnet.

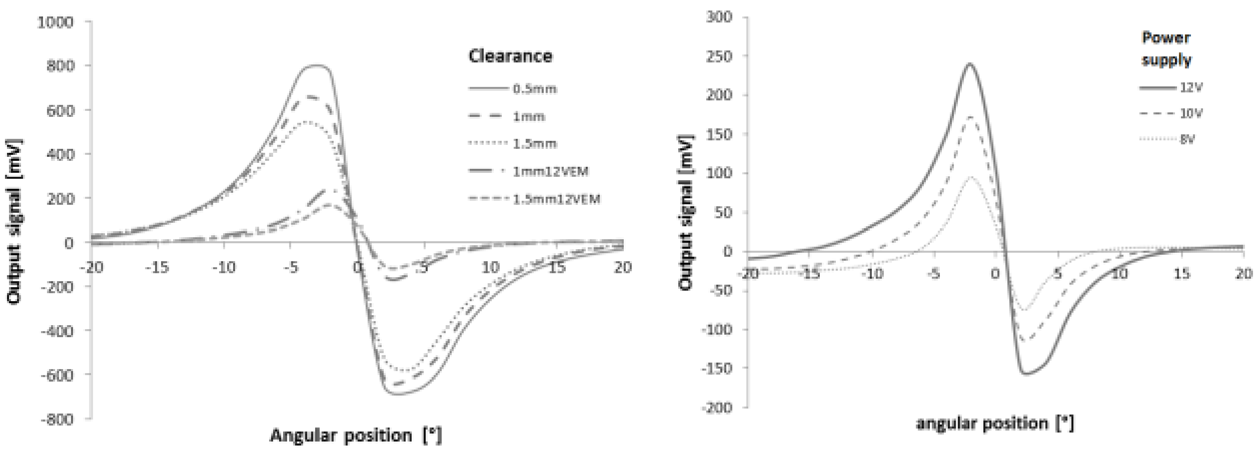

Figure 4. (Left) blade passage pulse at different clearances - (right) blade passage pulse at 1mm clearance for different supply voltages of the electromagnet.

Dynamic test: setup and methodology

To investigate the presence of significant dynamic effects, the sensor was installed in the VKI R2 compressor rig (Figure 5). It is a high speed compressor driven by a 185kW DC motor. The rotational speed can vary up to 10,000 rpm. It is a single stage axial compressor with a 400 mm tip diameter test section. The rotor is composed of 24 subsonic blades of the NACA 65 family; the hub radius is 100 mm. The stator is composed of 30 blades. The probes are inserted at four circumferential locations, every 90°.

The analogue sensor was installed in the calibration tower of Figure 5. The latter is equipped with a comparator to monitor the displacement of the sensor (resolution 0,01mm) and it is mounted in one of the four instrumentation access windows of the compressor casing.

The passage of one of the 24 rotor blades was extracted and studied for three velocities v = [1000 - 3000 - 5000] rpm and for different gaps in the range g = [1 – 1.5] mm with a step of 0.1mm. The gaps were changed moving the sensor by means of the CT. For every combination velocity-gap (v,g), the machine was kept at fixed speed, the sensor held at the desired gap and 30 revolutions were acquired. The mean value among the 30 maximum blade pulse values was extracted and it corresponds to "$V_{max}(v,g)$". For instance, $V_{max}(1000,1.2)$ is the mean maximum peak value acquired at 1000 rpm and 1.2 mm clearance. The V_{max} values were normalized according to (1). The resulting points were plotted together and fitted with a linear function. The resulting calibration curve of the sensor for clearance measurements is reported in Figure 6. It also shows the 30 maximum peak values acquired at 1000 rpm and 1.2mm gap.

$$\boldsymbol{VNorm = \frac{V_{max}(v,g) - V_{min}}{V_{max} - V_{min}}} \qquad (1)$$

Where:
$V_{max}(v,g)$ = the maximum peak value, for the combination velocity-gap (v,g);
V_{max} = the maximum among all the values $V_{max}(v,g)$;
V_{min} = the minimum among all the values $V_{max}(v,g)$;

<u>*Uncertainty analysis*</u>

The expanded uncertainty U_{95} is defined as (for further details see Dieck, 2007):

$$\boldsymbol{U_{95} = \pm 2\left[b^2 + {S_X}^2\right]^{1/2}} \qquad (2)$$

Where:
b = the systematic component of the uncertainty;
S_X = the standard deviation of the calibration data, defined as (3) – [S_X = 0.0096 mm];

$$\boldsymbol{S_X = \left[\frac{\sum_{i=1}^{N}(X_i - \bar{X})^2}{N-K}\right]^{1/2}} \qquad (3)$$

Where:
X_i = the *i*th data point used to calculate the calibration line fit;
$\boldsymbol{\bar{X}}$ = the average of the calibration data;
N = the number of data points used to calculate S_X - [6 gaps, 3 velocities = 18 points];
K = the number of curve fit coefficients [K=1];

In this case, the systematic component of the uncertainty was given a uniform distribution. Therefore, the value of b was taken as the comparator resolution (0.01mm) divided by the root mean square of 3 (e.g. Castrup and Castrup, 2010).

The resulting expanded uncertainty is: $U_{95} = \pm 22\ \mu m$ (20:1) within the range [1 ÷ 1.5] mm of gap range.

Results

A good repeatability was seen in the static and dynamic tests reported. The clearance can be measured with reference to the maximum value of the sensor signal peak. No significant dynamic effects were observed. Moreover, the accuracy of the new magnetoresistive probe is in line with the main types of sensors often used in BTC systems (Lattime and Bruce, 2004).

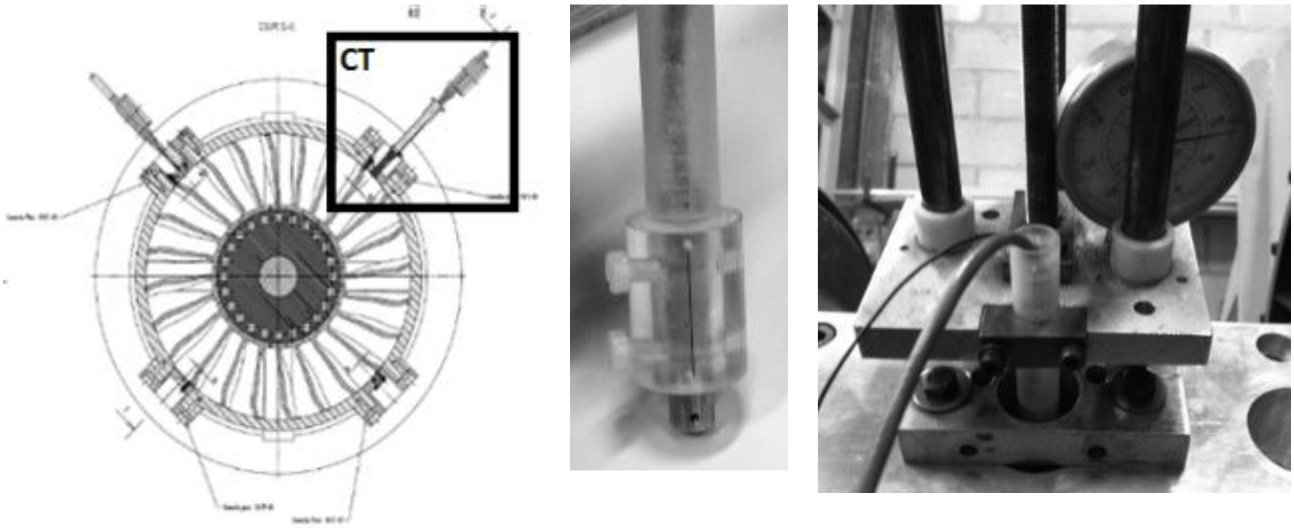

Figure 5. (Left) the VKI R2 compressor rig – (middle) the sensor support - (right) the calibration tower.

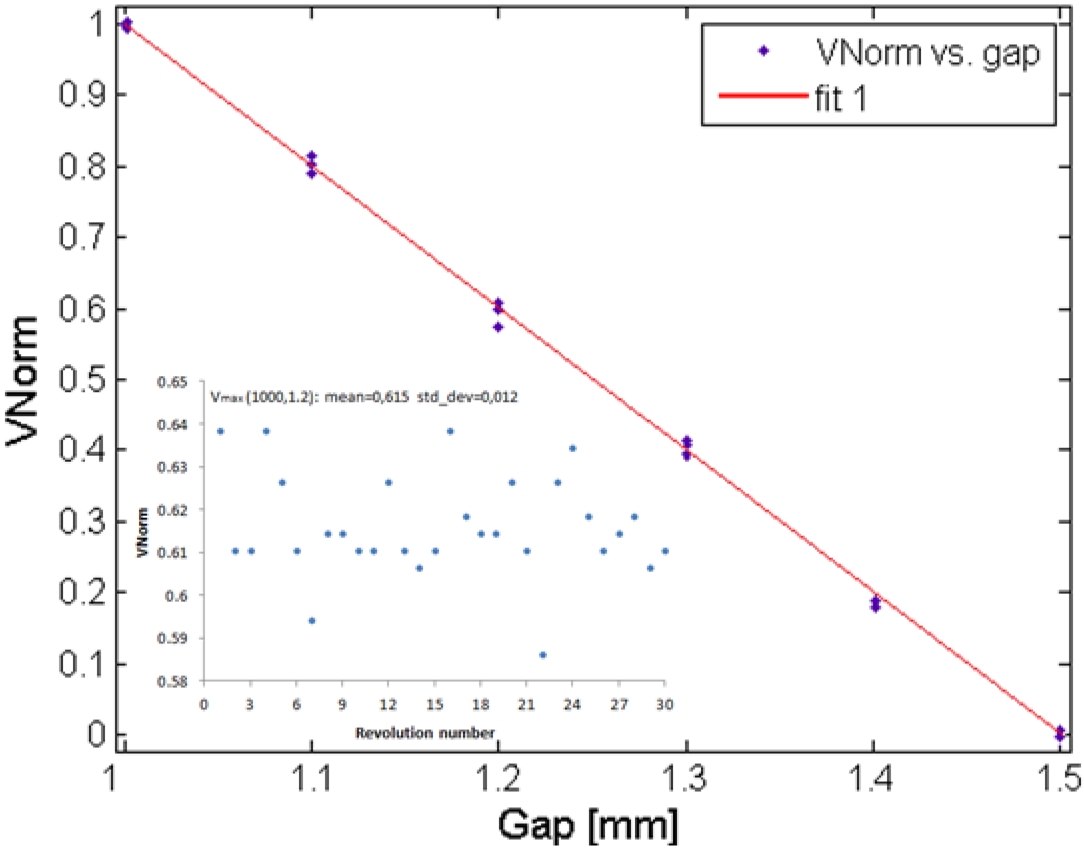

Figure 6. The calibration curve for clearance measurements.

VIBRATION MEASUREMENTS

To develop and test the whole instrumentation for vibration measurement, a dedicated calibration bench for BTT probes was designed. It is based on the idea of the blade motion decomposition presented by Rossi and Brouckaert (2012). Instead of having a rotating and vibrating blade and fixed casing sensors, the new method consists in letting one sensor vibrate at known frequency and amplitude, while non-vibrating blades are kept in rotation. As a result, the acquired data have a vibration content that is imposed by the probe displacements. It is monitored with good accuracy and can be used as reference. To realize the test bench (Figure 7), an aluminium rotor disk with 24 shaped, equally spaced and non-vibrating blades was built. To ensure the non-vibrating condition, every blade is a small insert mounted in a shaped hole of the disk and fixed with a screw. An electric motor is connected to the rotor and a protection frame closes everything for safety reasons. In addition, a shaker driven by a sinusoidal signal generator was connected to the linear slider of the BTT probe. In this way, the sensor recorded the blade passages and had one degree of freedom: the linear motion. The latter was monitored by an accurate displacement sensor. This paragraph reports the results of the measurement of a vibration event during a speed transient.

Test setup and methodology

A vibration event was imposed to the BTT probe while acquiring the data of the speed transient of Figure 7 right. The passage of the 24 “non-vibrating” blades was acquired at the sampling frequency of 32 MHz. The reference vibration was the BTT probe displacement: imposed and kept constant at 60Hz and 0.35mm amplitude, from about the 6^{th} to the 14^{th} second. The OPR signal was taken at the shaft.

From the acquired data, the blade tip displacement samples have been calculated according to (4):

$$\boldsymbol{S_{ir} = V_{tip} * \Delta TOA} \tag{4}$$

Where:
S_{ir} = the measured displacement sample of the blade “i” (i=1…24), at the revolution “r”;
V_{tip} = the blade tip velocity calculated from the OPR signal;
ΔTOA = the measured variation of the time of arrival of the blade pulse compared to the OPR one;

As demonstrated by Heath and Imregun (1998), by using only one sensor, synchronous vibrations cannot be monitored with good accuracy. Improvements on this aspect can be achieved by installing a second sensor in a different position. Nevertheless, the long term objective of this preliminary investigation is to end with an universal calibration bench for further investigations on uncertainty analysis related to tip-timing measurements. Efforts are focused on improving the detection and quantification of the different sources of errors in the BTT measurements chain, by knowing the imposed vibration and the measured one. Developments are still needed, but in the author’s opinion, the reported results show good potential.

Results

The individual displacement samples of blade 1 measured in function of time are reported in Figure 8. The presence of a vibration event is evident considering the measured amplitudes. Moreover, Figure 9 shows a detail of a comparison between the reference vibration signal and the measured samples in front of blade 1. The latter are plotted as dots and they fit very well the curve of the imposed displacement, showing a good agreement between the two. Finally, as reported by Watkins et al.(1985) and by Kurkov and Dicus (1978), all the samples can be taken into account and fast Fourier transformed. This process is done by means of consecutive Fourier transforms of sub-sets of the measured samples, because the sampling frequency of the measured vibration is changing with

the speed along a transient. The result is the so-called Zplot of Figure 7, where the x axis and y axis represent the speed and the frequency, while the amplitudes are plotted in color. The measured amplitude resulted lower because the measured displacement samples were Fourier transformed without filtering and fitting. The aim is to detect and to quantify the errors between the measured samples and the imposed vibration. Anyway, further investigations are still needed to discern all the quantitative values.
The preliminary experimental campaign performed with the calibration bench has highlighted the importance of some fundamental parameters in the measurement chain. The results are strongly affected by the sampling frequency of the data acquisition system, the SNR of the sensor signal and the processing method adopted. Further investigations on the sources of errors and the measurement uncertainty are ongoing.

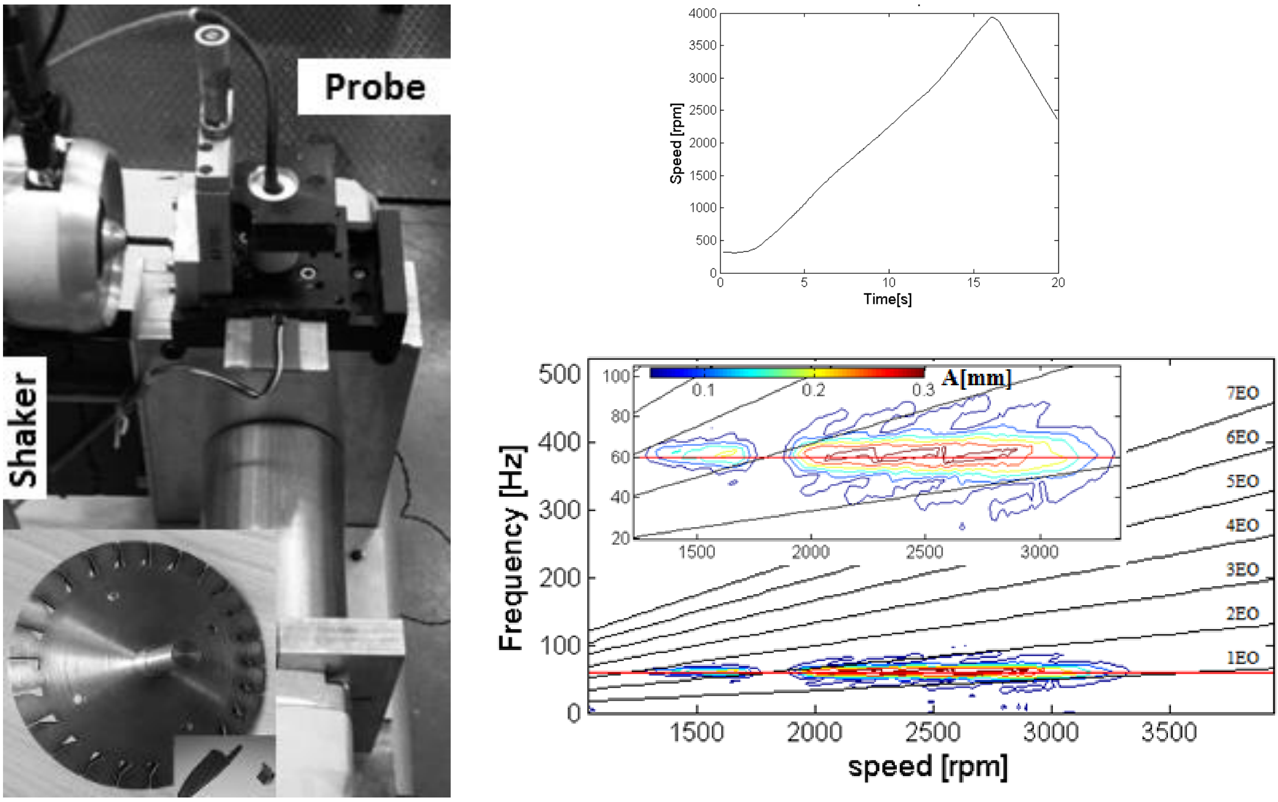

Figure 7. (Left) the calibration bench; (right) the speed transient and the Zplot.

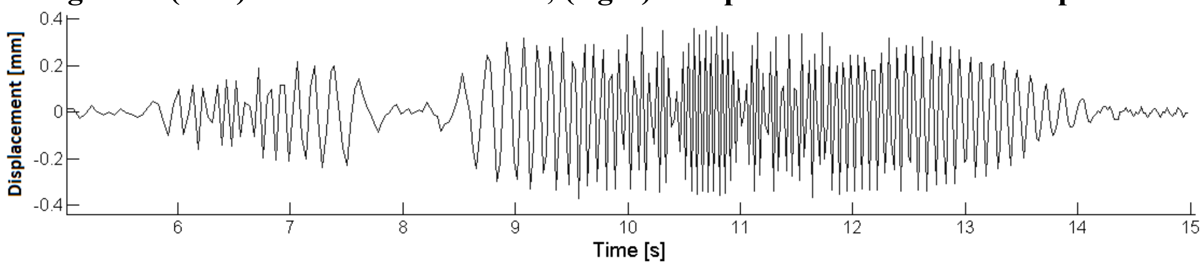

Figure 8. A detail of the measured displacement samples of one blade.

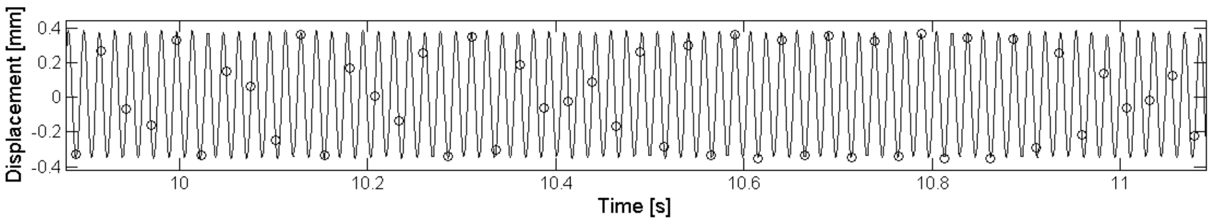

Figure 9. A zoom on the imposed (line) and measured displacements (dots).

CONCLUSIONS

A magnetoresistive probe for BTT and BTC systems was designed and tested. The sensor principle is based on the variation of the direction of the magnetic field. Several prototypes were realized and characterized during static and dynamic tests. Measurements of clearance are possible with an uncertainty of: $U_{95} = \pm 22$ µm (20:1) within the gap range [1 ÷ 1.5] mm; comparable to other commonly used sensors. Measurements of blade vibrations were performed in a dedicated calibration bench. A vibration event at 60hz and 0.35mm amplitude was measured during a speed transient up to about 4000rpm. In addition, the calibration bench based on the blade motion decomposition, represents an innovative testing and optimization tool for any BTT system. The advantage of knowing the imposed vibration ensures a better identification of the measurement errors in the whole measurement chain. Parameters like the sampling frequency, the SNR and the processing method play a fundamental role in the system accuracy and they can be optimized according to the specific application.

Finally, the use of the magnetoresistive probe in turbomachinery testing presents several advantages: low manufacturing costs, small dimensions, fast signal rise time, tolerance to debris, and high accuracy. Therefore, the novel probe has a great potential for the development of a simultaneous BTT and BTC measurement system.

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