Different Configurations of a Reflective Intensity-Modulated Optical Sensor to Avoid Modal Noise in Tip-Clearance Measurements

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***Abstract*—Tip clearance is critical to the performance of rotating turbomachinery. The objective of this paper is to develop a non-contact sensor with a precision of 30 μm to measure tip clearance in a turbine rig assembled in a wind tunnel. To carry out the measurements, an optical sensor whose main component is a bundle of optical fibers is employed. We use four different configurations of this sensor, which are tested in two distinct turbines with the aim of minimizing the effect of the noise on the repeatability of the measurements. Each configuration serves to increase the precision until the required performance is achieved for the measurement of the tip clearance. Our results may be helpful to develop applications related to structural health monitoring or active clearance-control systems.**

***Index Terms*—Active clearance-control system, bundle of optical fibers, optical sensor, structural health monitoring, tip clearance, turbine.**

I. Introduction

THE gap existing between the blade tip and the casing of a turbine allows an air flow to pass through the turbine without generating any useful work [1]. This distance is known as tip clearance (TC) and it changes as a function of the revolutions of the turbine, becoming smaller as the rotational speed increases. TC also varies during the engine start-up and shutdown, so it is important to maintain a security interval. TC must be as short as possible to optimize the fuel consumption of the engine [2], minimizing leakage flow through this gap. Consequently, there is a growing interest in techniques that provide an accurate measurement of the TC. There are various kinds of non-optical sensors that could be used to measure TC, such as capacitive ones, eddy-current sensors and discharging probes. However, optical sensors can provide higher sensitivity, bandwidth and resolution, smaller size, non-contact measurements, easy acquisition of data for every blade of the turbine and, of course, immunity to electromagnetic interference. During the last few years, in collaboration with the *Aeronautical Technologies Center*, we have performed several TC measurements in turbine rigs using optical fiber sensors [3], [4]. The performance of all these sensors was evaluated firstly in our laboratory, taking measurements of a single blade, and later in a wind tunnel, taking measurements of the same blade in a turbine rig.

During the development of the first prototype of our reflective intensity-modulated optical sensor, the main problem that initially arose was the limited spatial precision of the measurement, which was due to the modal noise at the end of the bundle [5]. This noise appears when a light source of narrow bandwidth is used in combination with a multimode fiber [6]. The coherent light excites various modes that are guided in the fiber. Since the length of the fiber of the sensor is very short (3 meters), the equilibrium mode distribution (EMD) is not accomplished and the different propagation modes are not mixed [7]. As a consequence, the interference of these multiple propagating modes produces a random intensity distribution at the endface of the fiber, which is similar to a speckle noise pattern [8]. This pattern depends on the laser wavelength and bandwidth, on the fiber type (refractive index profile) and on its length.

The total intensity at the output of the fiber would be independent of the distribution given by the random interference pattern if the whole pattern were measured at the detector [9]. However, in practice, the elements of the sensor only gather a part of the total spot of light, so random changes in the collected interference pattern generate modal noise. These changes can be due to different causes, such as vibrations or a mechanical disturbance of the fiber or frequency instability of the source [10]. As a consequence, the intensity collected by the sensor fluctuates in spite of keeping the same distance to the target. This fact leads to repeatability problems in the measurement. The second source of noise is the speckle noise produced in the light reflected by the target surface and it also must be taken into account.

Manuscript received August 25, 2014; revised December 11, 2014; accepted January 23, 2015. Date of publication January 27, 2015; date of current version April 29, 2015. This work has been sponsored by the Ministerio de Economía y Competitividad (Spain) and FEDER funds under project TEC2012–37983-C03–01, the Gobierno Vasco/Eusko Jaurlaritza under projects IT664-13, ETORTEK14/13 and by the University of the Basque Country (UPV/EHU) through programs UFI11/16, US13/09 and EUSKAMPUS.

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Digital Object Identifier 10.1109/JLT.2015.2397473

The objective of this work is to design and develop an optical sensor for TC measurements with a precision of at least 30 μm. This is the worst acceptable resolution required by the *Aeronautical Technologies Center* for their tip-clearance measurements. In order to achieve this goal, the effect of both kinds of noises must be reduced.

The first step to reduce noise was the attainment of a uniform intensity distribution at the output of the fiber to avoid random intensity patterns. For this purpose, three alternatives were tried. The first one was the employment of scramblers to mix and filter the modes [11], thereby shortening the necessary fiber length for EMD. The second one was the use of plastic optical fibers (POFs) whose coupling length is shorter than that of glass fibers [12], [13]. The last alternative was to use a single-mode glass fiber to illuminate the blades of the turbine [14]. Unlike previous works using a single-mode illuminating fiber [15], which use a mirror as target, in this paper we employ a turbine blade instead of the mirror, which gives an idea of the robustness of the sensor. We study the performance of a trifurcated bundle of optical fibers working in the back-slope region (region II, of negative slope). This region allows us to extend the linear range of our sensor to 4–5 mm, instead of the maximum of 1 mm achieved in previous works working in the front-slope region (region I, of positive slope). As we employ a trifurcated bundle instead of a bifurcated one, we can determine the distance to the target as the ratio of the optical intensities obtained in the receiving legs of the bundle, thus avoiding problems derived from fluctuations of the source or from changes in the reflectivity of the blades. Another novelty of the sensor is the use of asymmetric gain for the photodetectors to increase the sensor sensitivity, as explained in Section III.

The second step to reduce noise was the development of a new processing method of the TC measurements. Specifically, the results obtained at consecutive revolutions in a period of time of a minute were averaged to get a measurement with minimal noise.

In this paper, four different configurations of the optical sensor for measuring tip clearance are presented and evaluated. The general structure of the sensor and the specific characteristics of each configuration are explained in Section II. In Section III, measurements carried out on a wind tunnel for each configuration are presented and discussed. Finally, the conclusions are summarized in Section IV.

II. Methods

Even though sensors based on other techniques such as interferometry [16], [17] can achieve better accuracy, our reflective intensity optical sensor presents several advantages, such as simplicity, robustness, low cost and higher bandwidth. The main component of the sensor is a trifurcated bundle of optical fibers composed of one illuminating fiber and two rings of receiving fibers. The intensity of the reflected optical signal is collected by each ring as shown in Fig. 1. The distance is obtained as a quotient of the intensities of each of the rings in order to avoid the influence of the reflectivity of the blade surface or variations of the light source power [18], [19].

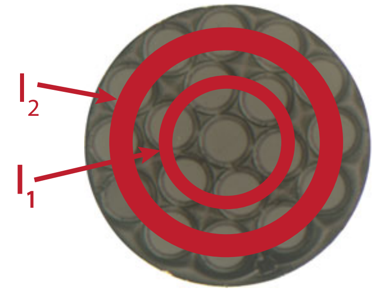

Fig. 1. Microscope view of the cross section of the common leg of the bundle. I_1 and I_2 represent the reflected intensities collected by the two rings of receiving fibers. The photodetectors produce the corresponding voltages V_1 and V_2 from these intensities.

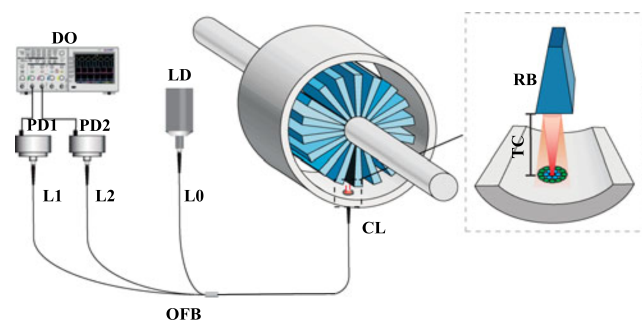

Fig. 2. DO: Digital Oscilloscope; PD1: Photodetector 1; PD2: Photodetector 2; OFB: Optical Fiber Bundle; LD: Laser Diode; TC: Tip Clearance; RB: Rotor Blade; L0: Leg 0; L1: Leg 1; L2: Leg 2; CL: Common Leg.

A laser module is utilized to couple light into the illuminating fiber. Its wavelength is 650 nm and it is manufactured with an SMA or an FC connector for easy coupling to the bundle. Two photodetectors convert the optical signals in each ring into voltages, which are acquired by an Agilent Technologies Infinium MSO9104A oscilloscope for post-processing. The sampling frequency for the acquisition is 250 ksamples/s. The arrangement of the sensor elements and the operation principle of the sensor are displayed in Fig. 2.

To perform the measurements were used two different turbines because the first one was available only for a short time. The following four configurations of the sensor were tested: bundle of glass fibers, bundle of glass fibers plus scrambler, bundle of POFs, and bundle of glass fibers with single-mode illuminating fiber. The results obtained employing the first alternative correspond to the third stage of a multistage turbine rig with 146 blades. Since it is the platform of the blade that is illuminated instead of the tip of the blade, the measured distance for this turbine was about 4–5 mm, or, equivalently, values of the TC between 2–3 mm (see Fig. 4).

To test the rest of configurations a one-stage rotor with 106 blades was used (see Fig. 3). As can be observed in Fig. 4, the blades of this rotor are completely different from those of the first rotor. In this case, the measurement requirements are much more demanding because the distance from the end of the probe to the platform is about 17–18 mm, corresponding to TC values of about 4–5 mm. Besides, the illuminated platform presents a steeper surface.

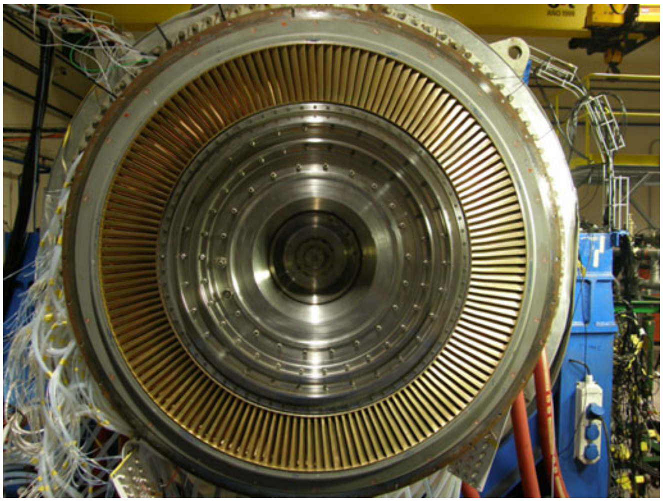

Fig. 3. Turbine rotor that was used to test the third and fourth sensor configurations, assembled in the wind tunnel.

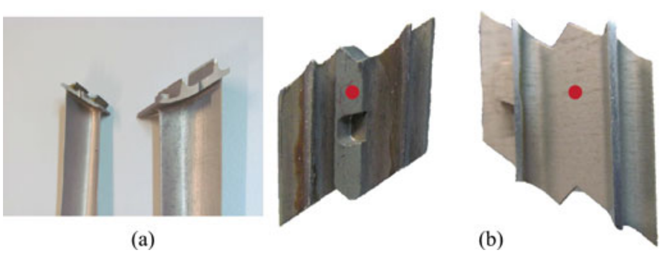

Fig. 4. (a) On the left, a blade profile corresponding to the first turbine of 146 blades, and on the right, the one corresponding to the second turbine of 106 blades. (b) Top view of both blades displaying the light spot for each blade.

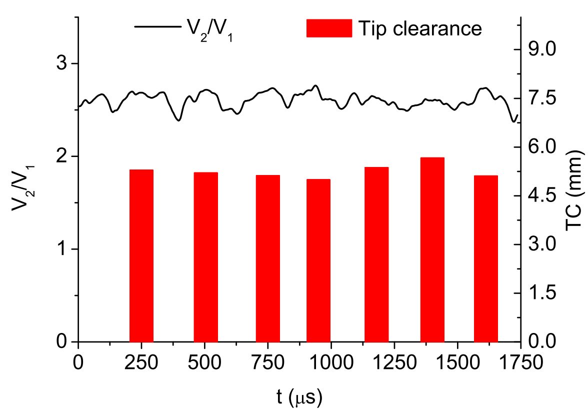

Fig. 5. Signal obtained at 2458 rpm as the quotient of the voltages V_1 and V_2 of the first and second photodetectors, respectively, by using a single-mode illuminating fiber. The value of the TC for each blade is represented by the amplitude of the bars.

When the turbine is rotating, the expected variations in the angle between the tip of the sensor and the blades are lower than 1°. According to the laboratory tests, if the changes in this angle are smaller than ±5°, the obtained differences in the tip clearance are smaller than 2%. Since the angular changes during our tests were lower than 1°, their effect was considered negligible.

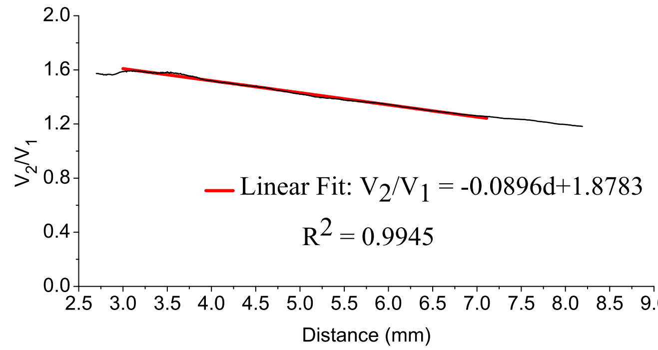

Fig. 6. Calibration curve for the first configuration of the sensor. The red line represents the fit of the calibration curve to a straight line in the range 3–7 mm.

Fig. 5 shows the signal obtained from the quotient of the voltages of the two photodetectors, together with the corresponding TC values for each blade, which are calculated at the corresponding peaks of the signal. The displayed results are obtained when the turbine is rotating at 2458 revolutions per minute (rpm), by using a single-mode illuminating fiber.

A. First Sensor Configuration

For the first configuration the FP-65 7FE-SMA laser module from *Laser Components* was used as source of light. The typical output power of this laser is 7 mW. The trifurcated bundle was manufactured by *Fiberguide Industries* using multimode glass optical fibers with a core diameter of 100 μm and a numerical aperture (NA) of 0.22. Two adjustable-gain photodetectors were chosen (PDA 100A-EC from *Thorlabs*). The gain of the transimpedance amplifier for both photodetectors was set at 0.75×10^4 V/A. Fig. 6 shows the calibration curve obtained in our laboratory for this configuration in a measurement range from 3 to 7 mm.

B. Second Sensor Configuration

The bundle in this second configuration is the same as the previous one, but a scrambler was placed between the laser module and the bundle to achieve a more uniform intensity distribution at the output of the fiber. The scrambler design consisted of two mandrels with a diameter of 42 mm separated by 3 mm from each other. A POF is wound around them following the instructions given in [20]. The mode scrambler is shown in Fig. 7.

The insertion losses of the scrambler are compensated by using a laser module of greater power (30 mW), namely the FP-SMA-650–30P from the same manufacturer as the one employed in the first configuration. The same photodetectors are used, but their gains are 0.75×10^5 V/A (first photodetector) and 2.38×10^5 V/A (second photodetector). This asymmetric gain of the photodetectors increases four times the sensitivity of the sensor with respect to a symmetric gain, as will be demonstrated in the next section. The calibration curve for the first turbine and for the same distance range as in the first configuration has been plotted in Fig. 8.

The improvement in the performance of the second sensor configuration is clearly seen in Table I. To characterize the

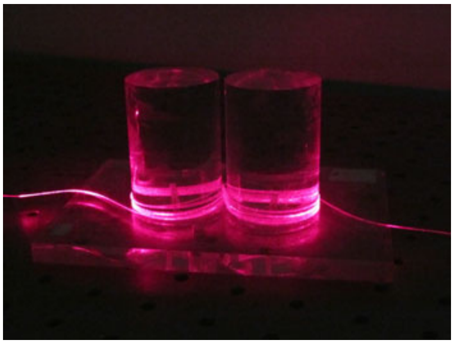

Fig. 7. Mode scrambler used in the second configuration of the tip clearance sensor.

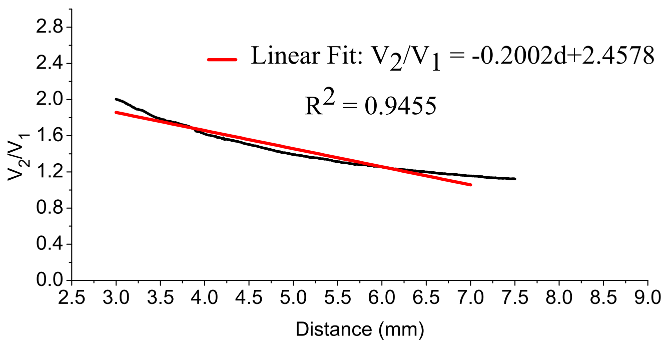

Fig. 8. Calibration curve and its linear fit for the second sensor configuration.

TABLE I
SENSITIVITY AND PRECISION OBTAINED IN OUR LABORATORY FOR THE FIRST AND SECOND SENSOR CONFIGURATION

Configuration	Sensitivity (mm^{-1})	Precision (μm)
1st Sensor Configuration	0.0896	141
2nd Sensor Configuration	0.2002	51

sensor performance we use two parameters: the sensitivity and the precision of the sensor. The sensitivity is defined as the derivative of the quotient of the voltage of each ring of receiving fibers with respect to the distance to the target, or, equivalently, the slope of the calibration curve. The precision in each sensor configuration is calculated by repeating three times a set of measurements increasing the displacement in steps of 25 μm in the whole range. The M-ILS250CC Linear Stage from Newport is used for this purpose. The minimum possible step (minimum incremental motion) using this stage would be 1 μm. The precision in the whole range is estimated as the average of the standard deviations of a set of three measurements carried out for each displacement. Due to the asymmetric gain of the photodetectors, for the second configuration, the sensitivity is more than twice the sensitivity of the first configuration. Besides, the precision is almost three times better, because of the mode mixing achieved by the scrambler. Unfortunately, we could not test this configuration on the turbines because they were not available for the time this configuration was ready.

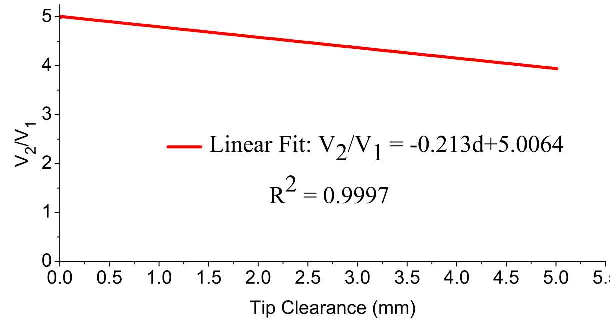

Fig. 9. Calibration curve and its linear fit for the third sensor configuration.

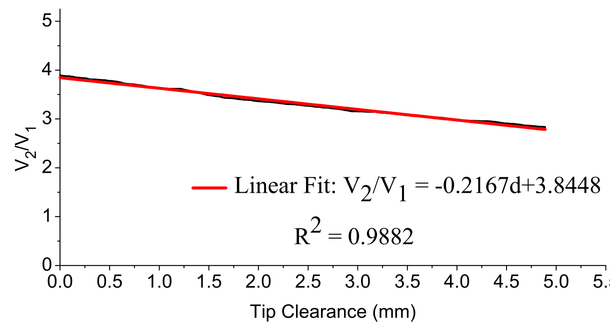

Fig. 10. Calibration curve and its linear fit for the fourth sensor configuration

C. Third Sensor Configuration

Since the profile of blades of the second turbine imposes a different calibration set-up with respect to the first and second configurations, now we will change the format of the calibration curves. Specifically, in the third and fourth configurations the x axis will represent the TC value instead of the total measured distance.

For the third configuration, the employed laser module and the asymmetric-gain photodetectors are the same ones as those described in the second configuration, but the bundle was manufactured by *FiberTech Optica* using POFs of 240 μm of core diameter and $\mathrm{NA} = 0.5$. The calibration curve is shown in Fig. 9 for a TC range from 0 to 5 mm.The disadvantage of this configuration is the much lower operating temperature of POFs as compared to glass fibers. The bundle of POFs has a maximum operating temperature of 60 °C, whereas our bundles of glass fibers can work at temperatures up to 350 °C. The reason for that low operating temperature is not the POF itself, but it is related to the glue used to assemble the bundle. This temperature constraint will be solved in a future prototype using an adhesive that can stand higher temperatures.

D. Fourth Sensor Configuration

In this configuration the bundle is also manufactured using glass fibers from *Fiberguide Industries*, but now a single-mode fiber is used as illuminating fiber to eliminate the modal noise. The receiving fibers are the same as in the first configuration. The single-mode fiber has a core diameter of 4.3 μm and $\mathrm{NA} = 0.12$. A pigtailed laser module with an output power of 20 mW (HSML-0660–20-FC from *Frankfurt Laser Company*) was used

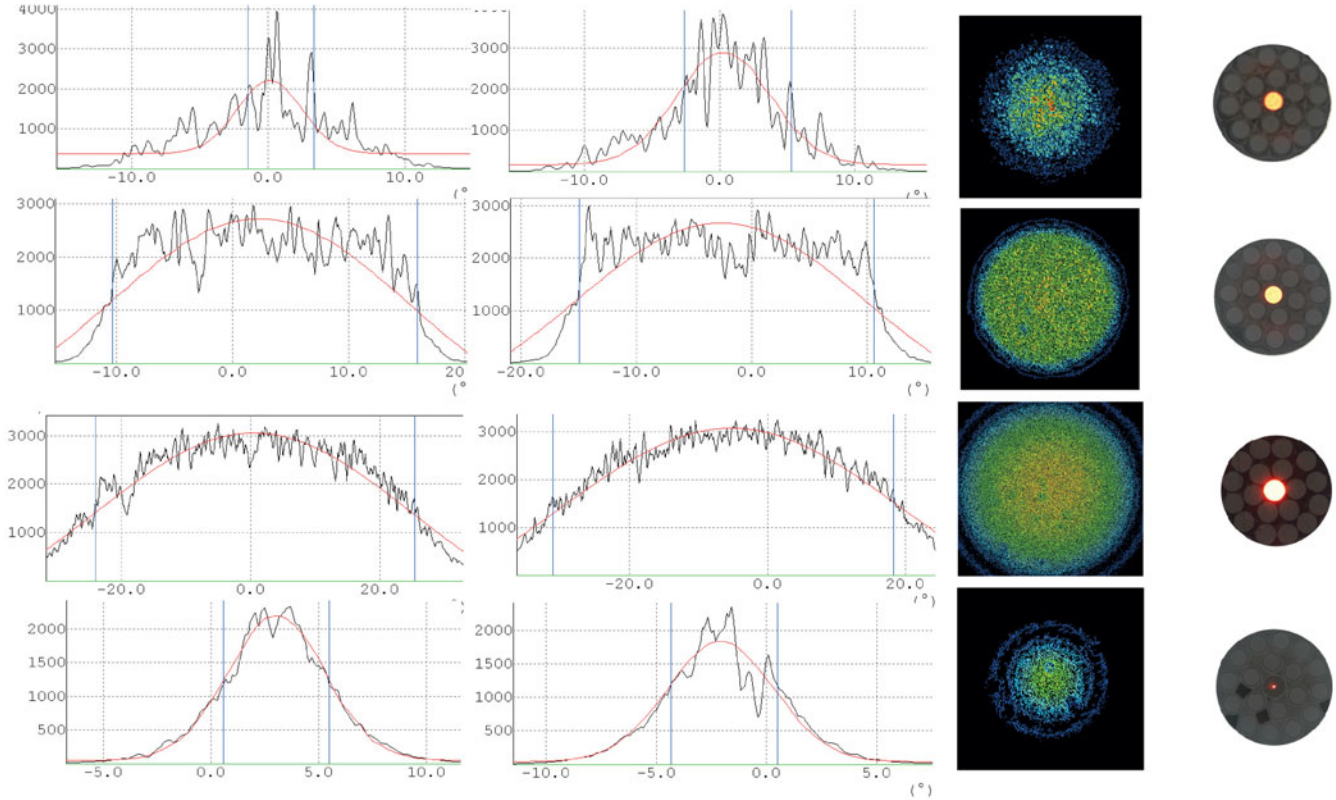

Fig. 11. Output power distribution in two perpendicular planes and 2D representations for the first, second, third and fourth sensor configurations, respectively. The common leg of the bundles is also shown. The total diameter of the bundles for all configurations is 660 μm, except for the POF bundle whose diameter is 1280 μm.

to couple light into the illuminating fiber. Asymmetric-gain photodetectors were adopted again, obtaining the calibration curve shown in Fig. 10 for the same range of TC values as in the third sensor configuration.

The output power distributions of all the configurations can be observed in Fig. 11. The power distributions are measured in the far field using the laser beam profiler LEPAS-12 from *Hamamatsu*. In this figure, a significant reduction in modal noise with respect to the first configuration can be observed, due to a greater uniformity of the output power pattern.

TABLE II
COMPARISON OF THE SENSITIVITY AND PRECISION FOR THE THIRD AND FOURTH SENSOR CONFIGURATIONS WITH SYMMETRIC AND ASYMMETRIC GAINS IN THE PHOTODETECTORS

Configuration	Sensitivity (mm^{-1})	Precision (μm)
3rd Symmetric Gain	0.0526	59
3rd Asymmetric Gain	0.213	36
4th Symmetric Gain	0.0448	61
4th Asymmetric Gain	0.2167	15

III. RESULTS

Prior to the analysis of the results for each configuration, it is important to underline the improvement on the performance of the sensor owing to the asymmetric gain of the photodetectors. The increase in the gain of the second photodetector serves to obtain a quotient V_2/V_1 that is much higher than in a symmetrical configuration. This higher quotient yields a steeper calibration curve, so the sensitivity of the sensor is increased. To assess this improvement, the experimentally obtained sensitivities and precisions of the third and fourth sensor configurations are compared for the two cases of using symmetric and asymmetric gains. As can be observed in Table II, the asymmetric gain provides values of the sensitivity more than four times higher than in the case of symmetric gain. Regarding the precision of the sensor, it is also clearly improved with the use of asymmetric gain.

The way in which the signals are acquired and processed to determine the TC values in each rotor revolution were explained in our previous works [3]. The only difference is that, to obtain the TC for each working point during these tests, the acquisition lasts for one minute and the final value is calculated averaging the minimum clearance for each revolution in this interval. This averaging cancels the effect of noises, thus increasing the performance of the sensor.

For the first sensor configuration, although many points were tested, only five different working points will be compared. This is because only five of them correspond to the same revolutions per minute, so this set of five working points will allow us to assess the sensor performance. Since the duration of each working point of the turbine was very short, the corresponding TC measurement could not be repeated more than once in each test session. However, we carried out a second TC measurement

TABLE III
FIRST SENSOR CONFIGURATION RESULTS

rpm	TC (mm)		σ (μm)
3148	2.89	2.832	41
3390	2.896	2.844	37
4359	2.829	2.811	13
4601	2.812	2.805	5
4843	2.831	2.799	22
$\sigma_{\rm lab}$ 141 μm		$\sigma_{\rm TC}$ 24 μm	

TABLE IV
THIRD SENSOR CONFIGURATION RESULTS

rpm	TC (mm)		σ (μm)
1664	4.594	4.564	22
1898	4.539	4.498	29
1898	4.545	4.52	18
2242	4.506	4.485	15
2811	4.500	4.476	18
3059	4.498	4.429	48
$\sigma_{\rm lab}$ 33 μm		$\sigma_{\rm TC}$ 25 μm	

TABLE V
FOURTH SENSOR CONFIGURATION RESULTS

rpm	Session 1		Session 2		σ (μm)
	TC1 (mm)	TC2 (mm)	TC1 (mm)	TC2 (mm)	
2458	4.552	4.552	4.542	4.551	5
2730	4.495	4.498	4.472	4.476	13
3054	4.433	4.441	4.382	4.392	3
3475	4.369	4.375	4.307	4.315	35
3749	4.338	4.324	4.257	4.252	45
4310	4.282	4.277	4.210	4.201	43
	$\sigma_{\rm lab}$ 24 μm			$\sigma_{\rm TC}$ 28 μm	

in another session several days later. The TC values obtained for each working point are shown in Table III. The precision achieved in the laboratory ($\sigma_{\rm lab}$) was 141 μm. To calculate the precision for the TC measurements of the turbine ($\sigma_{\rm TC}$), the standard deviation (σ) of our two measurements for each working point was evaluated. The precision of the sensor was calculated from the average of all deviations, and the value obtained was 24 μm. This value is much lower than the aforementioned $\sigma_{\rm lab}$ thanks to the high number of TC values averaged in the processing of the acquired signals to avoid the influence of the noise. Even though the advancement is significant, the processing cannot completely remove the effect of noise. It is interesting to remark that the results indicate that there are some wrong values in the measurements. As was mentioned before, TC values decrease when the rpm of the turbine increases. However, the second and fifth working points for the first set of measurements do not fulfill this requirement, so these must be incorrect values. In the third column of Table III, corresponding to the second set of measurements, the second value from the top also must be wrong, for the same reason, i.e. the effect of the noise was not completely canceled.

Regarding the third configuration, six working points were analyzed. Identical working points were measured in two different sessions separated by three days, and the corresponding TC values are shown in Table IV.

The precision obtained in the wind tunnel for this configuration of the sensor was 25 μm, improving the one obtained in our laboratory. Although the measurement conditions in the second turbine are much more complicated than in the first one, the results confirm that the performance of the third configuration of the sensor is satisfactory anyway, since all working points exhibit a correct behavior and the sensor satisfies the required precision of 30 μm.

In the case of the fourth configuration, six working points were used again to assess the performance of the sensor. The points were acquired in two different sessions separated by five days. In these tests, the working points were stable for longer time than in the rest of the measurements carried out for the other configurations. Therefore, it was possible to carry out two measurements separated by five minutes in the time that the working point was stable (TC1 and TC2). The results obtained for the fourth configuration are presented in Table V.

The precision obtained for this configuration was 28 μm, i.e. very similar to the laboratory value (24 μm). As in the previous configuration, the measurements of all working points present a correct behavior. The precision is a bit worse than the precision of the third configuration, but it must be due to the fact that the rpm of this measurements are higher, which induce greater amplitudes in blade vibrations leading to larger deviations in the measurements.

IV. CONCLUSION

Four different configurations of the sensor to measure TC in turbines have been tested and evaluated. Except for the second configuration that could not be tested on the wind tunnel, all of them show a measurement uncertainty that fulfills the initial requirement of 30 μm. The first sensor configuration has proved to be less satisfactory than the other ones, since several working points yielded incorrect behavior. The third configuration presents the best precision. However, its important disadvantage is that the POF bundle has a maximum operating temperature of 60 °C, restricting the possibilities of the measurements. The fourth configuration shows good results in all working points and the maximum operating temperature is 350 °C, so this is the configuration that has the best characteristics for TC measurements. This sensor has a great potential not only to perform TC measurements, but also to satisfy the requirements of active clearance control systems. It can also serve to develop applications in the field of structural health monitoring, by evaluating the vibration amplitude of the turbine blades using tip-timing methods in order to detect any damage on them. For instance, the *Aeronautical Technologies Center* will use three sensors circumferentially equidistributed to obtain the TC of a rotating disk of a real aircraft engine. The objective is to assess its behavior at different rotational speeds. The sensors will provide useful information about the vibration of the disk and the eccentricity of the shaft, which will allow to improve the design of the disk.

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