Measurement of blade tip clearance and time of arrival in turbines using an optic sensor

J.M. Gil-García
Dept. of Electronic Technology
University College of Engineering of Vitoria-Gasteiz
University of the Basque Country UPV/EHU, Spain

I. García, J. Zubia
Dept. of Communications Engineering
Faculty of Engineering of Bilbao
University of the Basque Country UPV/EHU, Spain

G. Aranguren
Dept. of Electronic Technology
Faculty of Engineering of Bilbao
University of the Basque Country UPV/EHU, Spain

***Abstract* – Turbine blades suffer vibrations when they rotate inside a turbo machine. The measurement of those vibrations can indicate a problem in the working regime currently in use or can assess the quality of a manufactured rotating part. In order to evaluate the vibratory state of a spinning stage in a turbo machine, the measurement of the tip clearance and the time of arrival of the blades are computed. In this article the development of an electronic system based on an optic probe designed to measure those parameters will be introduced. An analog front end that will adapt the voltage coming from the sensor has been developed and an IP core has been synthesized to handle the digitalized signals from the analog front end. The IP core is embedded into an FPGA and will calculate the mentioned parameters for each blade before the following blade finishes passing in front of the sensor.**

Keywords- Tip clearence; time of arrival; blade; FPGA

I. INTRODUCTION

Blade monitoring can be employed to analyze the performance of different operation modes of a rotating turbine. One of the existing strategies to analyze the vibration state of a rotating part of a turbo machine are the so called blade-tip-timing (BTT) methods which are based on measuring accurately the time of arrival (ToA) of a blade [1]. The ToA is the time a blade tip passes in front of the sensor. This time is compared with the time it would have passed if no vibration was present in the turbine blade, so that blade vibration can be detected. BTT methods are indirect, as they extract the vibration state from the blades timing, and mainly based on non-intrusive sensors [2]. These sensors are easier to setup and they do not introduce any bias in the measurement as they do not interfere directly with the mechanical parts. They are also suitable to determine the ToA of each individual blade of the rotating engine.

Tip-clearance (TC) is the measurement of the gap between the tip of the blade and the casing of the engine. The smaller the TC is, the more efficient the engine will be, as the air flow going through that gap does not develop any work. Some benefits of more efficient engines are the reduction in fuel consumption or the extension of the useful life of the turbine due to the less demanding conditions required to be operated [3]. However, too tight TC values can jeopardize the integrity of the engine if the blades get in touch with the casing due to the deformation produced by the rotating regime the turbine is under. The measurement of the TC complements the analysis of the data obtained from the ToA study.

Several types of non intrusive sensors have been proposed in order to measure the TC and ToA parameters. Capacitive sensors have been widely used due to their rugged nature but they need to have conductive blades [4]. Microwave based sensors can benefit from their good performance in the presence of products of combustion [5]. Likewise, Eddy current sensors are immune to the debris produced in the core of the engine and can sense the state of the blade through the casing material which allows lower temperature measurement conditions [6]. Finally, optic sensors feature a very high dynamic range and can stand temperatures up to 700 ºC.

Section II will describe the components and operating principle of the optical sensor developed to obtain the signals used to calculate the ToA and TC parameters. In section III the features of the developed prototype will be described and in section IV the algorithms employed in this work will be explained. Section V will show the obtained results. Finally, in section VI conclusions will be summarized.

II. OPTIC SENSOR

An optic sensor composed of a trifurcated bundle of optical fibers has been developed and constructed to carry out the measurements [7]. The fibers are organized concentrically around a central fiber which drives the light to the probe end in order to illuminate the blade tip. The reflected intensity of light is collected by the two concentric rings of fibers composed of 6 and 12 fibers respectively. Each group of fibers conveys the light to one photodetector (PDA100A-EC manufactured by Thorlabs) to transform it into two analog signals, V_1 and V_2. Fig. 1 shows a capture of the photodetector voltages over an entire revolution rotating at 3400 rpm.

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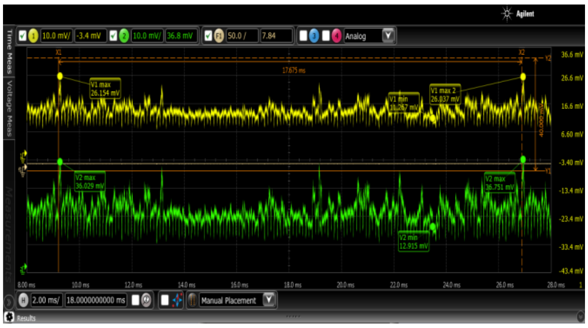

Figure 1. Sensor output capture over one revolution

Both voltages depend on the fluctuation of the light source, the losses in the fiber transmission and the variations of the reflection properties of the blade tip surface. All these effects can be cancelled out by dividing V_2 by V_1 and that quotient will be function of the distance between the blade tip and the sensor end. After a process of calibration and characterization of the sensor, a linear fit equation valid over a limited range of interest can be obtained, where there is a proportional relationship between the TC and the quotient of the voltages.

The calculation of the ToA involves only one of the two signals. It is required to locate correctly the minimum where it is considered that one blade has just passed and the next one is arriving. As only one voltage is used, the signal is prone to be sensitive to all mentioned factors and a very irregular voltage with several minima between the limits of the blade has to be processed.

Following these principles, a sensor was designed, implemented and tested at the Aeronautical Technology Center (CTA) facilities in a turbine rig with a 146-blade rotor. Output signals provided by the optical sensor for 84 different working points of the turbine were acquired during these tests, each at a different combination of rotation speed, temperature, pressure, etc... Fig. 2 shows the obtained calibration curve of the sensor (black), the linear fit of the calibration curve in the range of 3 to 7 mm. (red) and the signals of the photodetector 1 (green) and photodetector 2 (orange) during the calibration process. The calculated linear fit is represented in (1) and shows a coefficient of determination R^2 of 0.9945 over the considered range.

$$V_2/V_1 = -0.08969 \cdot d + 1.8783 \qquad (1)$$

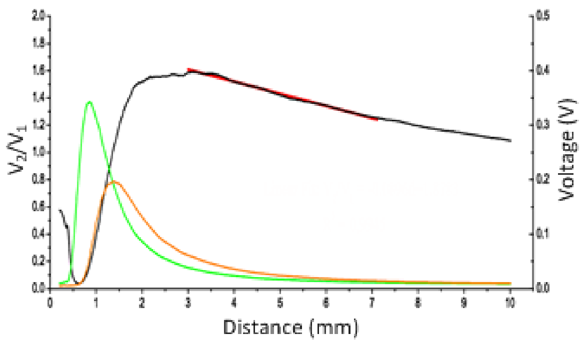

Figure 2. Calibration curve of the optical sensor.

The signals were originally acquired by a high speed digital oscilloscope and stored to be processed later in a personal computer.

The calculated TC values were compared with the results obtained by the discharging probe usually employed at CTA in TC measurement and the highest difference found was of 2.22 % in the worst case.

After several improvements and new developments carried out on the sensor, accuracy up to 24 µm. has been reported [8].

III. MEASUREMENT SYSTEM

In order to be able to immediately process and obtain the TC and ToA of each blade without PC, an electronic system has been developed. It has been divided into two boards: the first one in an analog front end and deals with the adaptation of the single ended 30 mV output signal of the photodetector to the input of a dual channel 16-bit digital to analog converter. The second board is a KC-705 commercial FPGA development board from Xilinx featuring a Kintex family part. The connection of both elements is accomplished through a low-pin count FPGA Mezzanine Card (FMC) connector. Fig. 3 shows an image of the connection of both boards.

A. *Analog front end*

Fig. 4 represents a simplified block diagram of the analog front end. The core of the board is a 1.8 V AD9650 16-bit dual channel analog to digital converter with differential inputs in the range of 2.7 Vpp and programmable CMOS or LVDS outputs. Several aspects of its performance, like the output code format, the delay of the clock out signal, power saving modes, or the transitory output of test patterns to verify the signal integrity of the board, can be configured via a SPI bus. It is clocked by a programmable voltage controlled oscillator (Si570) which frequency can be modified from 10 MHz to 945 MHz commanded by an I2C bus.

The maximum working frequency of the AD converter is 25 MHz which can handle the 2.4 MHz maximum bandwidth of the photodetector. The use of a variable frequency oscillator gives flexibility to the system.

Figure 3. Analog front end plugged in the KC705 development board.

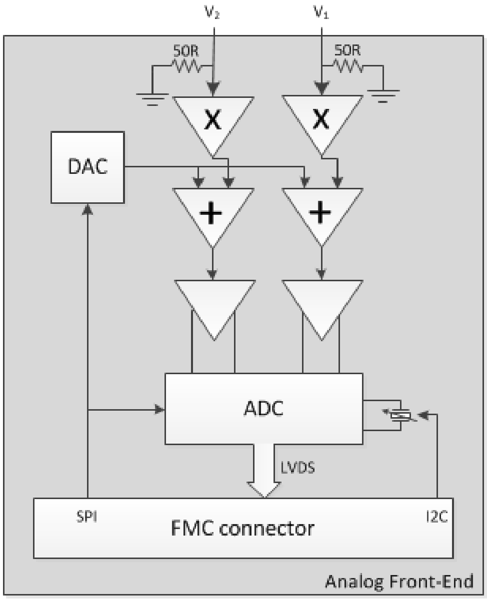

Figure 4 Analog front end simplified block diagram

The photodetector output is single ended with an output impedance of 50 Ω. The output voltage is unipolar with a maximum value of around 30 mV. To take advantage of the maximum differential input range allowable by the AD converter, an amplifier and a level shifter with a programmable offset are also included. A 16-bit digital to analog converter (MAX5441) controlled by a SPI bus provides the desired level of DC. The level can be dynamically adjusted to avoid saturation by supervising the over-range outputs of the ADC. The conversion from single ended to differential to drive the AD input is carried out by a low distortion differential ADC driver (ADA4938).

Some glue logic to adapt the different voltage interfaces has also been required.

B. *TC and ToA processor IP core description*

The detection of the ToA and the calculation of TC have been implemented in a core written in VHDL. It offers an interface to a post-processor system based on control and configuration registers and a dual port memory where the ToA and TC values of the current experiment can be read for any of the blades in the turbine. The implemented memory capacity is 2048 x 32 and can store information for up to 253 blades as each blade occupies 8 positions. The synthesized post-processor has been a Microblaze core which is in charge of configuring the analog front end, monitoring and evaluating the results. It is also feasible to insert an additional core between the TC and ToA processor IP core and the Microblaze to apply and speed up any BTT algorithm. Sharing the FPGA with the developed core, some other cores such as GPIO's, I2C and SPI cores, have been used to configure and enable the analog front end.

The core could be instantiated as many times as required in order to process the inputs if more sensors were installed in the rig, as long as more analog channels and LVDS inputs in the FPGA are provided. The synthesis tools reported the utilization of logic of the core in the FPGA (XC7K325T) is less than 1 %.

IV. ALGORITHMS

A. *Measurement of time of arrival*

The moment of change of blade is determined by a minimum voltage that need to be distinguished from the other local minima present along the travelling of the blade in front of the optical probe. Fig. 5 represents a real voltage measured by the photodetector (red) and when it is decided that a new blade is present (*ToA_detect* in green). Two counters are employed. The signal is continuously searched for a new minimum. When found, the counter *min_ctr* is set to 0. Meanwhile, the *counter* is running since the last blade was detected. The local minimum is considered a new blade detection if it reaches a *limit* value or if it is minimum for one fourth of the current ToA value. In both cases, the ToA value gets updated with the subtraction of *min_ctr* from *counter* and the algorithm stops searching for another minimum for three quarters of the current ToA value.

The algorithm needs some iterations until it founds the correct ToA for a given set point. For the experiment where the image of Fig. 5 has been taken, it was needed 126 blades to find the proper ToA. This represents less than one revolution of the 146 blades rotating part. Fig. 7 represents the first detections and the detections after the algorithm successfully finds the ToA.

B. *Measurement of tip clearence*

Fig. 6 shows a block diagram of the implemented core. The TC is obtained from the quotient calculated by the divider using 16-bit arithmetic. The divider is tuned to take advantage of the fact that the quotient of the V_1 and V_2 signals will be between 1.2 and 1.4 for the analyzed signals and the test sensor. The divider needs 16 clock cycles to obtain the quotient and then the "Tip clearance" block calculates the TC every clock using the linear fit (1). The "Memory Controller" block checks that value over the blade passing period and keeps track of the minimum one. When the "Time of Arrival" block asserts the *ToA_detect* signal indicating the detection of change of blade, the "Memory Controller" block stores the current value in the corresponding memory position.

The core also keeps track of the maximum and minimum values in case they were interesting to implement alarms.

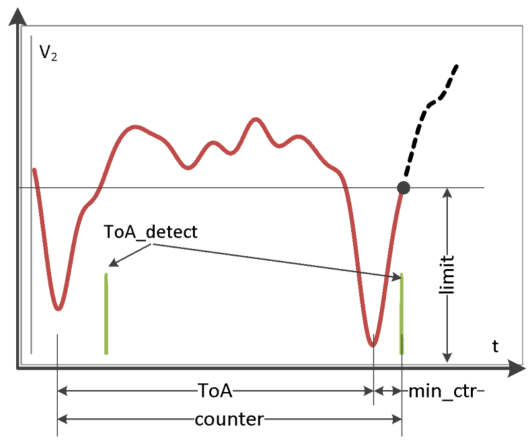

Figure 5 Reflected light waveform and ToA determination point

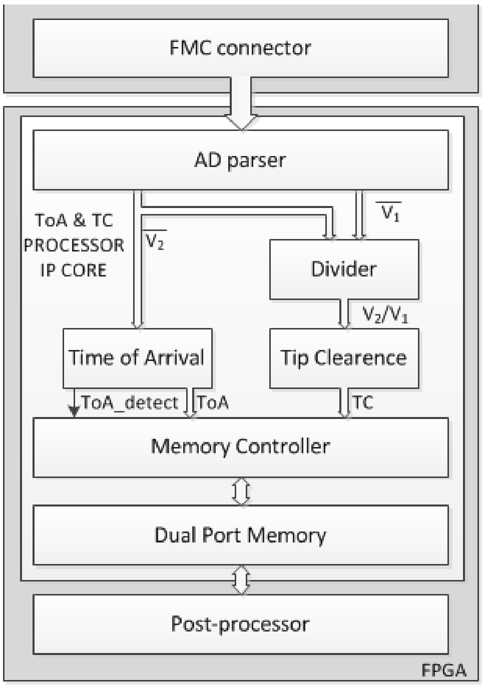

Figure 6 TC & ToA processor core block diagram

V. RESULTS

To assess the algorithm, recorded data from the experiments conducted at CTA's wind tunnel have been employed. Fig. 7 represents the real samples of V_1 and V_2, the first false detections and the detections after the algorithm successfully finds the ToA. The middle samples have been omitted for clarity.

The processing time depends on which of the two conditions is first met. In the worst case, when a slow rising slope defines the detection of a blade, it takes one fourth of ToA to detect the change of blade. An additional 1.44 µs (at 25 MHz ADC clock) from the assertion of the *ToA_detect* signal are needed to update all values and have them available at the dual port memory. Namely, before the current blade ends passing in front of the sensor, the parameters of the previous blade are already calculated.

The use of logic of the FPGA by the TC and ToA processor core is negligible and can be implemented easily in smaller FPGAs.

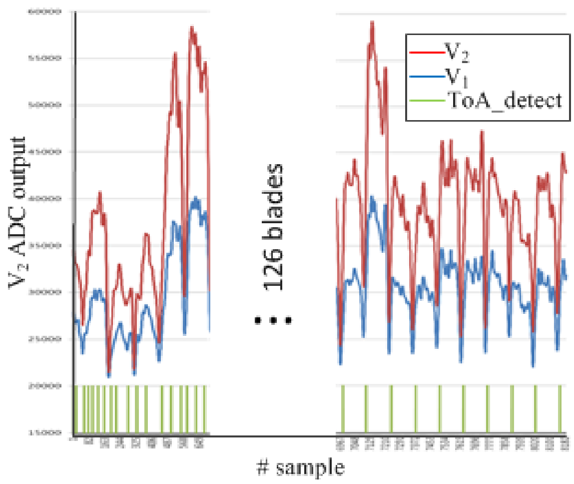

Figure 7 Convergence of the algorithm

VI. CONCLUSIONS

A prototype to measure the TC and ToA of a bladed assembly based on an optic sensor has been developed.

An IP core has been developed to obtain the TC and ToA values almost instantly. The core can be implemented in parallel with other cores if processing more than one sensor is required.

The TC and ToA processor IP core can be used as a pre-processor for a BTT system processor hardware implementation.

The developed prototype is not robust enough to be embedded into a system but it can be used for testing bladed assemblies in test wind tunnels of bladed assemblies. A self-contained electronic system integrating the mentioned devices is being developed to be used in laboratory test benches or on-board systems.

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