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A Dual-Purpose Device for Condition-Based Maintenance and Energy Harvesting in the Context of IIoT Applications

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Abstract— **This paper presents a dual-purpose device for condition-based maintenance (CBM) and for energy harvesting (EH) in IIoT applications. Vibration monitoring in industrial environments is a key indicator for predictive maintenance purposes and for energy harvesting. The paper includes the description of the hardware and software of a flexible platform that permits vibration measurements, vibration sensor calibration and energy harvesting testing. The vibration exciter included in the platform can be controlled by the output signal of a common signal generator. The platform also includes a differential temperature sensor that can gather additional data for CBM purposes. The final part of the paper includes experimental results of a vibration sensor under characterization and of the performance evaluation of a commercial EH module.**

Keywords— industrial internet of the things, condition-based maintenance, energy harvesting, industrial vibration measurements.

I. INTRODUCTION

In the recent past, it was common for industrial process maintenance management systems to not have sufficient data to predict critical equipment failures and the proper functioning of systems and equipment were dependent only on preventive and corrective maintenance tasks. Prolonged periods of inactivity of production systems, accumulated costs and the low efficiency of periodic maintenance routines result in exaggerated maintenance costs. Currently, the significant increase in digitalization and the reduction in costs associated with the implementation of intelligent instrumentation systems, based on the Industrial Internet of Things (IIoT), enable access to a large volume of data [1][2], changing the challenge from data availability to the ability to obtain crucial information for efficient management of production systems and processes. In the past, large volumes of data were discarded due to inability to process them in an efficient way. The existence of advanced processing techniques [3-4] makes possible to predict and avoid equipment faults and to provide, in real time, data to manage maintenance activity in an efficient and optimized way, allowing the implementation of proactive maintenance procedures that allow an increased reliability of production systems and a reduction of maintenance costs. By using advanced data analysis techniques, it is possible to take advantage of retrospective analyzes and to improve the quality of the information and knowledge that is obtained. In this context, a simple and well-known example of a CBM [5-8] application related with the monitoring of vibrations of rotating machines, used in industrial applications, is presented. Machine absence of imbalances, misalignments, gaps, among others, would

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mean that there would be no causes for vibrations to take place. Obviously, in practice, this does not happen, and vibrations then appear frequently. A well-designed project will result in a machine with vibration and noise levels that are normally quite low. However, throughout the life of the machine, the clamping legs become loose, the components deform, appearing machine misalignments and imbalances. All these factors will contribute to an increase in vibrations that can cause resonances and increased load on the bearings. Thus, vibrations amplitudes and frequencies are essential indicators of the operating conditions of the machines being these indicators easily obtained through frequency analysis of the vibration signals [9-10]. From another perspective, energy harvesting based on vibration has registered a huge development since the 90s. Nowadays, it is possible to harvest higher levels of electrical energy by utilizing smart materials [11-12] and implementing various energy harvesting strategies. Thus, particularly in industrial environments, vibration is a seductive energy source to power small devices such as the ones used in IIoT that include sensing and elementary processing capabilities which are placed in remote locations that need power supply solutions to ensure their functionality and ability to transmit wireless data [13-14].

II. SYSTEM DESCRIPTION

Figure 1 represents the hardware block diagram of the proposed vibration testing platform that contains five main blocks, namely: a vibration source; a vibration sensor pair that includes a vibration reference sensor and the vibration sensor under test; a power harvesting module; a differential temperature sensor, that can be used to detect an excessive temperature variations of the device under test, and a low-cost ESP 32 microcontroller.

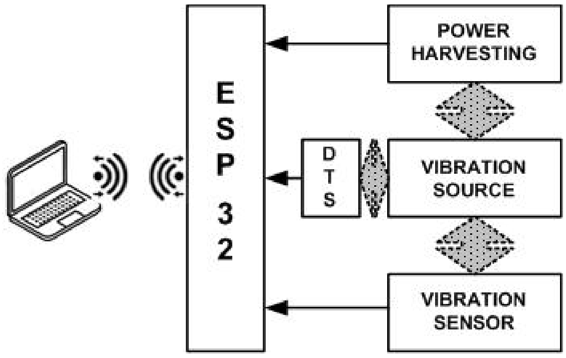


Fig. 1. Block diagram of the proposed vibration testing platform (DTS- differential temperature sensor).

In turn, figure 2 depicts a general view of the vibration platform that includes a vibration exciter, including the devices under test that are on its top, a charge amplifier, a power amplifier, a digital multimeter, a spectrum analyzer and a laptop. Some important specifications of the components used to implement the proposed vibration testing platform include: a reference and certified piezoelectric accelerometer B&K type 4370 [15], with a sensitivity of 998 pC/(m/s^2) and a flat frequency range that extends between 0.1 and 4800 Hz ; a vibration exciter, B&K type 4808 [16] with a force rating of 112 N sine peak, a first axial resonance frequency of 10 kHz and a maximum displacement of 12.7 mm; a charge amplifier, B&K type 2635 [17], with a maximum sensitivity of 10 V/pC and a set of built-in integrators for displacement and velocity measurements; a power amplifier, B&K type 2712 [18], with a maximum output power of 180 VA into a 0.8 Ω resistor load, an output voltage capacity of 12 V RMS in a frequency range that extends between DC and 15 kHz, and a piezoelectric EH module, Midé type V25W [19], whose main specifications include a maximum piezo strain of 800 micro-strain and a maximum tip-to-tip displacement of 0.15 in.. The vibration sensor chosen for testing purposes [20] can detect vibrations in a wide frequency range that extends from 10 Hz up to 15 kHz, through the effective conversion of vibrations to electrical signal by utilizing a proprietary optimized piezo ceramic material and an original vibration amplifying design. Its ability to detect even the faintest levels of vibration throughout a large sensing bandwidth makes it ideal for predictive maintenance and process control operations in industrial IIoT application scenarios. Regarding the EH module, it is important to underline that it includes two electrically isolated piezo wafers with independent wiring connections, enabling a series or parallel wafers' association, and using an adjustable natural frequency set-up adjusted by a variable tunning mass. The differential temperature sensor is based on two digital temperature sensors [21] that have an absolute accuracy of ± 0.7 °C, a linear output error lower than 0.2 °C and a resolution better than 0.005 °C. The output signal of these sensors is a square wave with a well-defined temperature-dependent duty cycle modulated by temperature which enables an easy A/D conversion of the temperature signal. Figure 3 depicts a detailed view of the vibration platform with the main elements of its moving parts.

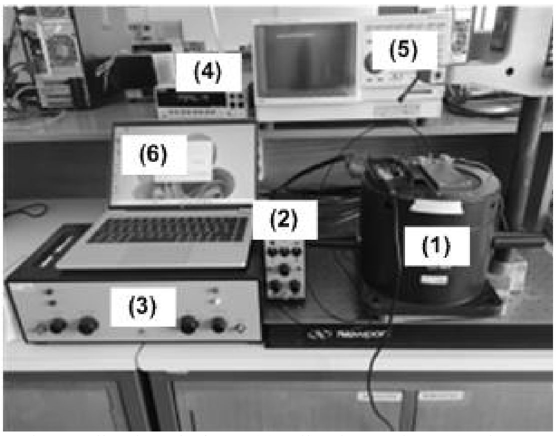


Fig. 2. Vibration platform: (1)- vibration exciter; (2)- charge amplifier; (3)- power amplifier; (4)- digital multimeter; (5)- spectrum analyzer and (6)- laptop.

The microcontroller device is an ESP32 that uses a Tensilica Xtensa 32-bit LX6 microprocessor that includes two 12-bit SAR A/D converters, supporting a total of eighteen measurement channels, assuring an embedded Wi-Fi and Bluetooth wireless connectivity. The software part of the virtual instrument is implemented by a laptop that runs a LabVIEW program. The main tasks developed by the LabVIEW program include system configuration and control, data acquisition and data processing, storage of measurement data and the implementation of a user friendly interface.

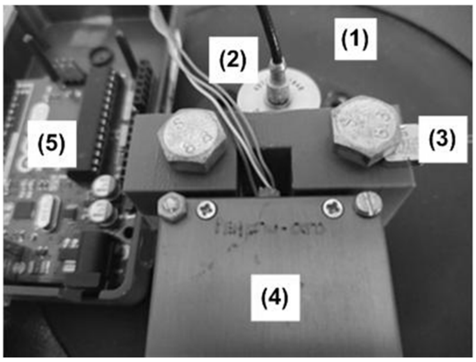
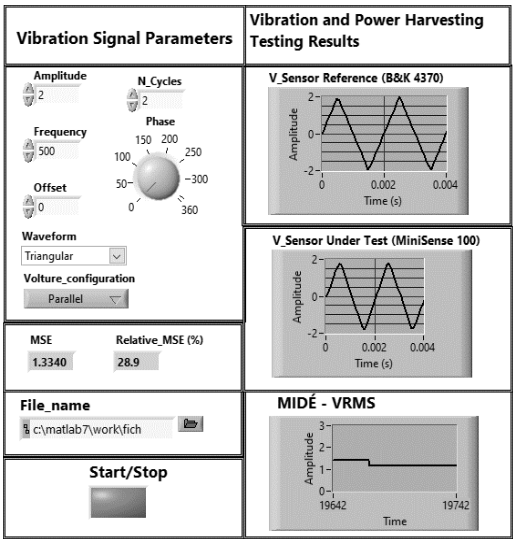


Fig. 3. Hardware details of the vibration platform: (1)- vibration exciter; (2) reference vibration sensor; (3)- vibration sensor under test; (4) energy harvesting module; (5)- signal conditioning.

Experimental Results

To demonstrate the capabilities of the implemented system, this section includes two testing examples that can be supported by the proposed testing platform. One example concerns the calibration of a vibration sensor, and the other example concerns the performance evaluation of an EH module. Figure 4 represents the front panel of the virtual instrument that was developed to interface the vibration platform. On the left side of the figure the user can define the characteristics of the vibration signal, used for testing purposes, and the right side, of the same figure, displays the testing results that are obtained when is used a low-cost vibration sensor [22] and a commercial EH module [19]. The vibration control signal, used for testing purposes, has an amplitude of 2 V, a frequency equal to 500 Hz and a triangular waveform. Due to the bandwidth limitations of the vibration sensor under test, the distortion results, relatively to the reference vibration sensor, in terms of mean square error, corresponds to a distortion coefficient equal to 28.9 %. This is an expected value due to the specifications, namely, the bandwidth limitations, of the vibration sensor under test. It is important to refer that the error, previously referred, is evaluated to the amplitude of the vibration signal used for testing results.

The EH test result, represented in the lower graph, on the right side, of figure 4, is obtained with a parallel configuration of the two electrically isolated piezo wafers of the EH module. In this test, the AC voltage at the terminals of the piezoelectric generator is in a first stage converted by a DC voltage rectifier circuit and a decade of resistances is used to vary the EH circuit load. In this way, it is possible to easily evaluate the open circuit voltage, the short circuit current and the maximum power point (MPP) of the EH module, as a function of the load resistance for different amplitudes, frequencies, and spectral contents of the vibration source. As an example, figure 5 represents the experimental results that were obtained for the peak-to-peak open circuit voltage as a function of the maximum acceleration associated with a sinusoidal vibration signal of 50 Hz.



Amplitude: 2
N_Cycles: 2
Frequency: 500
Offset: 0
Waveform: Triangular
Volture_configuration: Parallel
MSE: 1.3340
Relative_MSE (%): 28.9
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Fig. 4. Front panel of the virtual instruments that was used to perform vibration sensors and energy harvesting tests.

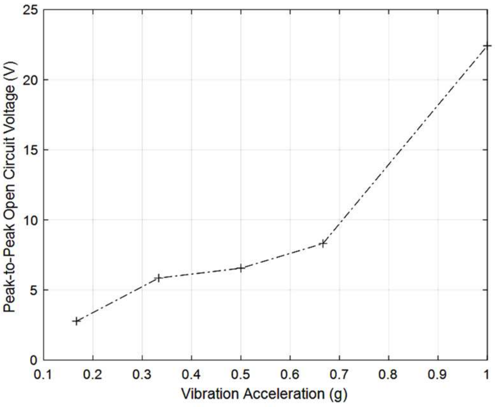

Fig. 5. Harvesting module open circuit voltage as a function of vibration signal acceleration (50 Hz).

III. CONCLUSIONS

This paper presents a vibration platform that can be used for testing and calibration of vibration sensors and for evaluating the performance of energy harvesting (EH) modules. The same vibration signal is simultaneously applied to a reference vibration sensor, used for calibration purposes, to a vibration sensor, under test, and to an EH module. A commercial signal generator, without any special requirements, can be used to generate a signal whose frequency, amplitude and waveform are easily adjusted according to specific applications' requirements. A virtual instrument was developed to interface the vibration platform and the experimental results that were obtained validated the theoretical expectations.

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