

A smart battery free system for wireless condition monitoring using piezoelectric energy harvester

Namanu Panayanthatta
Institut IMEP-LaHC,
univ. Grenoble Alpes, Univ. Savoie
Mont Blanc, CNRS, Grenoble INP*,
38000 GRENOBLE, FRANCE,
Namanu.panayanthatta@grenoble-
inp.org

Mario Costanza
FEMTO-ST,
UBFC,
25000 Besançon, France
mario.costanza@femto-st.fr

Skandar Basrour
TIMA,
University Grenoble Alpes, CNRS,
Grenoble INP
38000 Grenoble, France
skandar.basrour@univ-grenoble-
alpes.fr

Catherine Dehollain
Ecole Polytechnique Federale de
Lausanne,
1015 Lausanne, Switzerland
catherine.dehollain@epfl.ch

Giacomo Clementi
FEMTO-ST,
UBFC,
25000 Besançon, France
giacomo.clementi@femto-st.fr

Samuel Margueron
FEMTO-ST,
UBFC,
25000 Besançon, France
samuel.margueron@femto-st.fr

Edwige Bano
Institut IMEP-LaHC,
univ. Grenoble Alpes, Univ. Savoie
Mont Blanc, CNRS, Grenoble
INP*, IMEP-LaHC, 38000
GRENOBLE, FRANCE,
edwige.bano@grenoble-inp.fr

Roberto La Rosa
¹STMicroelectronics,
Stradale Primosole 50,
95121 Catania, Italy
²Ecole Polytechnique Federale de
Lausanne
roberto.larosa@st.com

Merieme Ouhabaz
FEMTO-ST,
UBFC,
25000 Besançon, France
merieme.ouhabaz@femto-st.fr

Ausrine Bartasyte
FEMTO-ST,
UBFC,
25000 Besançon, France
ausrine.bartasyte@femto-st.fr

Laurent Montes
Institut IMEP-LaHC,
univ. Grenoble Alpes, Univ. Savoie
Mont Blanc, CNRS, Grenoble
INP*, IMEP-LaHC, 38000
GRENOBLE, FRANCE,
laurent.montes@grenoble-inp.fr

Abstract— A machine failure is often characterized by a sudden increase in the vibration acceleration level. We propose a wireless and battery-free vibration sensor and a method for condition monitoring and predictive maintenance of vibrating objects such as machines and engines. The principal part of our system is a piezoelectric transducer that acts both as a vibration intensity sensor and in addition as an energy source for the sensor circuitry. Our system consists of a battery-free sensor attached to the monitored object that transmits vibration data to a remote Base Station (BS) wirelessly via Bluetooth Low Energy (BLE) beacons. The vibration data is interpreted remotely by the BS via time-domain readout by analyzing the advertising time T_{adv} of the beacons received by the BS, that can monitor the vibrations and can send a standby signal to the machines in case of emergent faults.

Keywords—piezoelectric, predictive maintenance, wireless vibration sensor, energy harvester, battery-free sensors

I. INTRODUCTION

Vibration during the operation of equipment and automotive motor engines (thermal or electric), is a common phenomenon. However, excessive vibration amplitude often indicate the deteriorating fault condition, which if not monitored, could lead to component failure or damage of the machine.[1] A suitable vibration monitoring technique is therefore required. Recently, battery free and self-powered vibration monitoring systems have received growing interest, as a result of advancements in IoT systems. [2,3] Our work

introduces a battery-free system to implement failure detection based on measuring acceleration and its deviation from nominal values of non-defective parts. Recent developments in micro and nanoelectronics have led to miniaturization of vibration monitoring devices. These devices must operate remotely and wirelessly with power requirements in the order of several microwatts. [4,5] Most of the vibration sensors are located at places that are difficult to reach and their frequent battery replacement would imply a costly maintenance issue. Although microscale ambient energy harvesters may not be able to provide the power for continuous operation of Wireless Sensor Network (WSN), it is sufficient to power these nodes in an intermittent manner. Therefore, the WSN needs to be designed smartly with low power consumption while awake, and negligible power consumption during sleep mode. Typical self-powered WSN nodes used for condition monitoring are powered by a battery, thus needing replacement from time to time. [6] In this work, we present a system that replaces the battery with a capacitor powered by a lead-free Piezoelectric Energy Harvester (PEH) made from Lithium Niobate [7,8] of area 1cm^2 and thickness $500\ \mu\text{m}$. The remote sensor and BS implement a BLE communication scheme, which is self-starting and fully autonomous. The BS implements a condition monitoring algorithm, for the remote fault detection. The paper is arranged as follows: Section II describes the system; Section III reveals the setup and the results and section IV describes the major conclusions of this work.

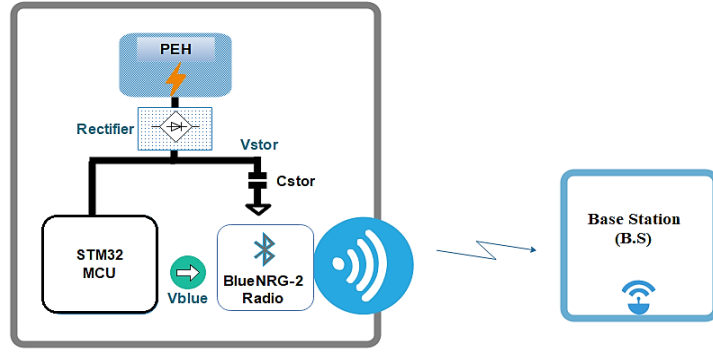


Figure 1: schematic of the vibration sensor

II. SYSTEM DESCRIPTION

As illustrated in Fig 1, the vibration sensor consists of a PEH for power supply, and rectification system (full bridge), a capacitor (220 μ F) for energy storage, STM32L0 microcontroller for voltage monitoring, and a BlueNRG-2 BLE radio. [4] The size, geometry, and mechanical stress of the PEH have been optimized using Finite Element Simulations. [7] The sensor node can be connected wirelessly to a BS that performs data processing and continuous data transfer to the cloud. BLE is used as the communication standard because of its low power consumption and the compatibility and ease of BLE use in portable devices to communicate with the WSNs. The sensor node is designed to transmit beacons intermittently, and thus the radio is shut down after every transmission to minimize the overall energy consumption. The total power consumed by wireless sensor device P_{WSN} in each cycle can be characterized by the power consumed by its components and their processes and expressed as:

$$P_{WSN} = P_{SB} + P_{MCU} + P_S + P_{TX} \quad (1)$$

where P_{SB} is the standby power consumption, P_{MCU} is the power consumed by the processor unit, P_S (0 in our case) is the power consumed by the sensor, and P_{TX} is the power consumed by the BLE transmission section respectively. The peculiarity and advantage of this system are that the PEH plays the dual-role of energy harvester that supplies the power to the whole system and also acts as a vibrational sensor. The monitoring of the input vibration is realized by measuring the time between successive beacons, also known as advertising time ($t_{adv} = t_C - t_A$), emitted by the wireless sensor radio to the BS as shown in Figure 2.

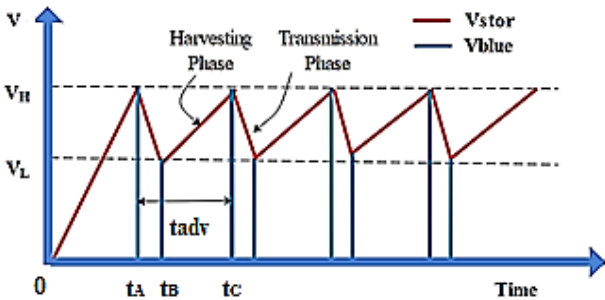


Figure 2: Typical time evolution of V_{stor} and V_{blue} , showing the harvesting and transmission phases

When the capacitor voltage V_{stor} reaches the highest value V_H , the system turns to the transmission phase, where the microcontroller supplies the BLE through one of its General-Purpose Input/Output (GPIO) pins. Soon after the transmission phase ($t_B - t_A$), when the voltage drops to the lowest values, the microcontroller shuts down the BLE radio, turns in sleep mode, and the whole system returns to the energy harvesting phase ($t_C - t_B$). The sensor works on the principle that the time delay between two successive beacons depends on the input acceleration of the PEH. The values of V_L and V_H are chosen such that the voltage never exceeds the rated maximum (3.6V) and a minimum supply voltage (1.6V) of the STM32L0 microcontroller. During the harvesting phase, the harvested power $P_{harvested}$ varies quadratically with the power of two of the acceleration a_{cc} :

$$P_{harvested} = K_{acc} \cdot a_{cc}^2 \quad (2)$$

The harvested energy $E_{harvested}$ in the capacitor during the energy harvesting phase is a constant that depends on the capacitor value C_{stor} and the fixed voltage value V_L and V_H . The time interval between two successive beacons is called the advertising time t_{adv} . $E_{harvested}$ is related to $P_{harvested}$ and the time that it takes to charge that is nearly the same as the advertising time, between two beacons, since $(t_C - t_B) \gg (t_B - t_A)$.

$$P_{harvested} \approx \frac{E_{harvested}}{t_{adv}} \quad (3)$$

Due to this approximation, $P_{harvested}$ is slightly overestimated. The communication between the sensor and the base station is made through Bluetooth wireless beacons. From (2) and (3), it is possible to estimate acceleration a_{cc} in terms of t_{adv} as:

$$a_{cc} \approx \frac{S_v}{\sqrt{t_{adv}}} \quad (4)$$

where, the constant S_v is the calibration constant and is determined from inverse of slope of the calibration curve, as described in Figure 3d. Equation (4) can be implemented in the embedded firmware of the BS so that the acceleration a_{cc_BS} can be remotely and indirectly measured at the BS that can measure t_{adv} from the received beacons.

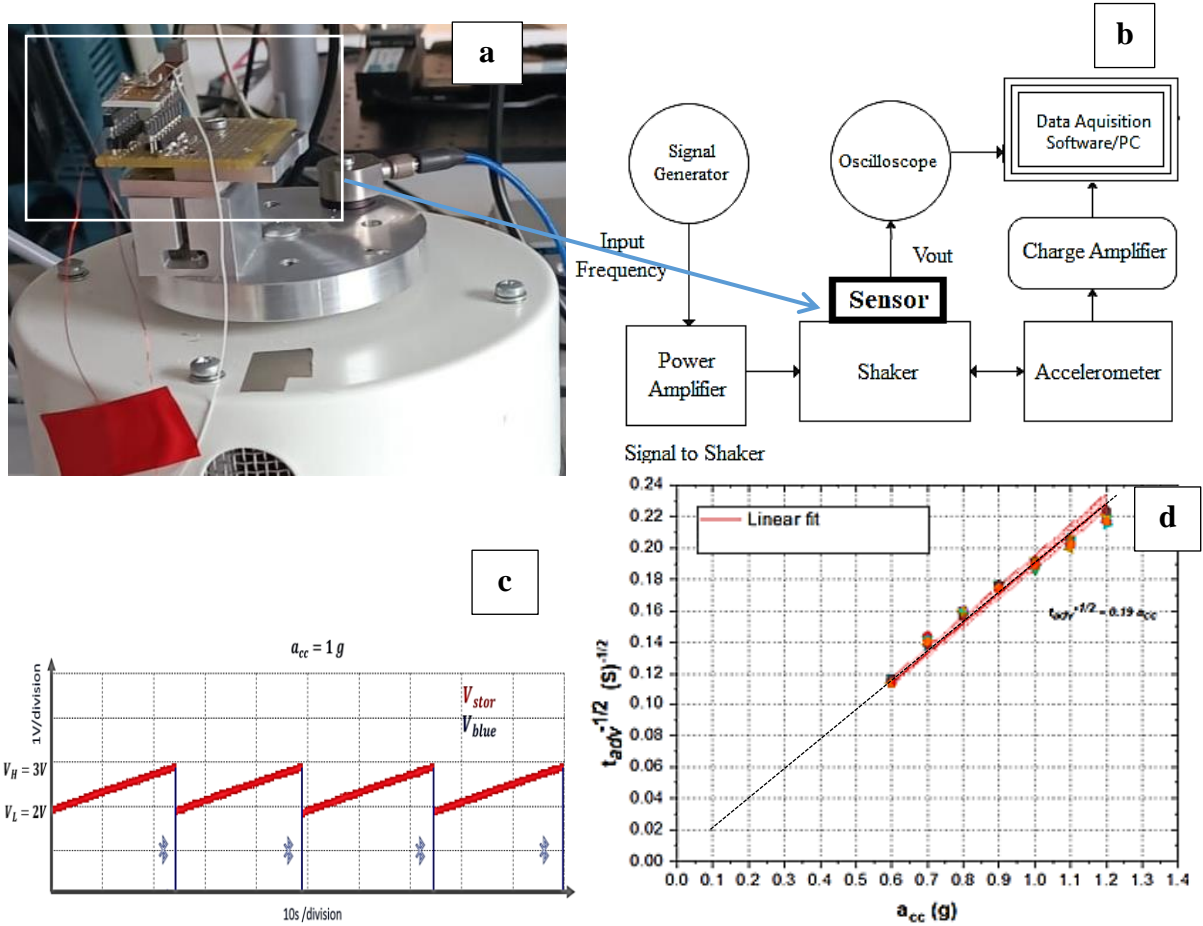


Figure 3: (a) shaker setup with the PEH for measurement (b) experimental setup schematic (c) experimental measurement of advertising time for $a_{cc} = 1g$ (d) Calibration curve displaying the advertising time t_{adv} vs input acceleration a_{cc} with linear fit of the experimental measurement data with $1/Sv = 0.19 \text{ m}^{-1} \cdot \text{s}^{1.5}$

III. RESULTS AND DISCUSSION

As shown in Figure 3c, the voltage V_{stor} across C_{stor} toggles between set values of $V_L = 2V$ and $V_H = 3V$. The advertising time t_{adv} can be determined from the intervals between two Bluetooth beacons as identified from V_{blue} . The t_{adv} at $1g$ acceleration is determined to be $\sim 25s$ at $1g$ input acceleration as in Figure 3c. The sensor characterization in terms of Limit of Detection (LoD) and sensitivity in response to the vibrational acceleration has been carried out at room temperature in the air ambient as shown in Figure 3 (a, b). The vibration sensor, positioned on the shaker as in figure 3a, has been subjected to various vibration levels with the acceleration $a_{cc, in}$ varying in the range $[0.6 \text{ g} - 1.2 \text{ g}]$. Figure 3b reveals how the time t_{adv} decreases with the increase of the acceleration a_{cc} in agreement with equation 4.

The test measurements unveil that it is possible to measure remotely and wirelessly at the BS. Sv , the calibration constant is determined to be $5.25 \text{ m} \cdot \text{s}^{-1.5}$ from inverse of the slope of the calibration curve (Figure 3d). The measurement results within the range of acceleration $[0.6-1.2 \text{ g}]$ are repeatable with an error consistently below 11%, measured over different tests. The BS can therefore receive beacons from wireless vibration sensor node, placed on the vibrating parts of machines under

test, and exercise predictive maintenance or fault detection by simply measuring the advertising time t_{adv} of the received beacons as shown in Figure 4a,b. For long-term predictive diagnosis of machines, the wireless vibration sensor node can be embedded in specific mechanical parts that require regular maintenance as bearings, gears, conveyors, turbines, shafts, valves, and the like. When a mechanical fault happens, there is a sudden increase in the rate of change in the detected acceleration amplitude at the BS. The instantaneous rate (K_r) can be monitored by the BS, by measuring the vibration accelerations at two successive time intervals as:

$$\text{Rate } (K_r) = \frac{a_{cc}(t_2) - a_{cc}(t_1)}{(t_2 - t_1)} \quad (5)$$

where, $a_{cc}(t_2)$ and $a_{cc}(t_1)$ are the amplitudes of accelerations at time intervals t_2 and t_1 . The base station calculates the instantaneous rate K_r , and can send interrupt or standby signals to the machine control. Also, alarm signals can be initiated to the user if the rate is above a critical threshold K_c of machine failure, as shown in Figure 4.

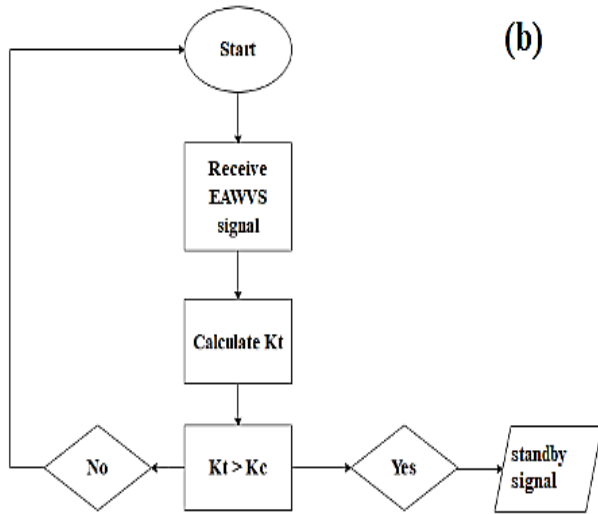
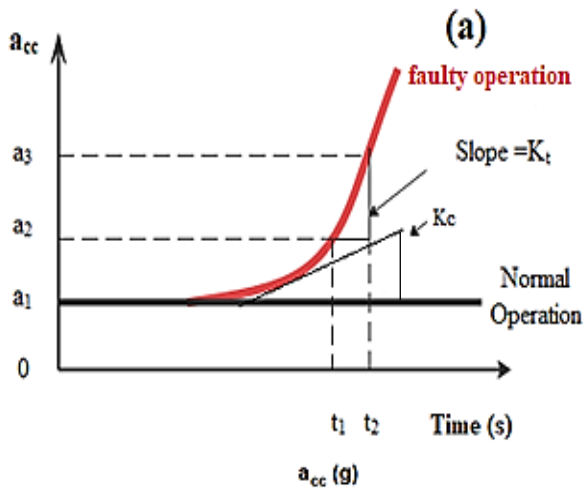


Figure 4: (a) Example of an increase in acceleration between time t_1 and t_2 (b) Application scenario algorithm of the predictive maintenance with wireless vibration sensor

In addition, less complicated algorithms such as limiting the machine operation to a critical acceleration threshold to prevent the machine failure, can be implemented. The LoD of the system, is only determined by the standby power consumption of the system ($<5\mu W$), and can further be improved by improving the design of the harvester, and thereby improving the energy density per unit area.

IV. CONCLUSIONS

In this work we proposed a novel battery free system for condition monitoring of and predictive maintenance of vibrating objects such as machines and engines. The proposed system composed of lead-free piezoelectric energy harvester, voltage monitoring circuit and BLE radio could detect the input vibration as low as 0.6 g. Experimental tests have shown that the wireless vibration sensor and BS system can deliver repeatable and accurate sensing functionality with less than 11% maximum error, consistently over different tests. The BS upon receiving beacons from one or more

wireless vibration sensor nodes, placed on the vibrating parts of machines under test, exercise predictive maintenance or fault detection by simply measuring the advertising time t_{adv} of the received beacons. This feature therefore involves less complicated electronics at the sensor side, than analog architectures and therefore lower energy consumption, compared to similar condition monitoring sensors [10], which is key for energy-autonomous systems. Therefore, using the proposed algorithm, the BS, can send interrupt or standby signals to the machine control upon by estimating the rate K_t . Also, alarm signals can be initiated to the user if the rate is above a critical threshold K_c of machine failure. The sensor is light compact, occupying an area of 2cm X 2cm. Thus, the proposed novel sensor system for condition monitoring provides a maintenance-free, install and-forget approach, thanks to the unnecessary for an external power source, making it ideal for use in industrial application.

ACKNOWLEDGMENT

This project has received funding from European Union's Horizon 2020 research and innovation program under grant agreement No 722496. We also thank FMNT (Federation Micro Nano Technologies) who supported part of the work.

REFERENCES

- [1] T. Du, X. Zuo, F. Dong, S. Li, A. E Mtui, Y. Zou, & M. Xu, A Self-Powered and Highly Accurate Vibration Sensor Based on Bouncing-Ball Triboelectric Nanogenerator for Intelligent Ship Machinery Monitoring, *Micromachines*, 12(2), 218, (2021).
- [2] H. Fu, J. Rao, M. S. Harb & S. Theodossiades, Ultrasonic wireless power links for battery-free condition monitoring in metallic enclosures, *Ultrasonics*, 114, 106395, (2021).
- [3] G. Loubet, A. Takacs, E. Gardner, De A. Luca, F. Udrea, & D. Dragomirescu, LoRaWAN battery-free wireless sensors network designed for structural health monitoring in the construction domain, *Sensors*, 19(7), 1510, (2019).
- [4] N. Panayanthatta, G. Clementi, M. Ouhabaz, M. Costanza S. Margueron, A. Bartaszyte, S. Basrour, E. Bano, L. Montes, C. Dehollain, R. La Rosa, A Self-Powered and Battery-Free Vibrational Energy to Time Converter for Wireless Vibration Monitoring, *Sensors*, 21(22), 7503, (2021).
- [5] N. Panayanthatta, R. La Rosa, C. Trigona, E. Bano, and L. Montes, Optimization of the geometry of MEMS Piezoelectric Energy Harvester cantilevers, *COMSOL conference Europe 2020*.
- [6] M. Gao, P. Wang, Y. Wang & L. Yao, Self-powered ZigBee wireless sensor nodes for railway condition monitoring, *IEEE Transactions on Intelligent Transportation Systems*, 19(3), 900-909, (2017).
- [7] G. Clementi, M. Ouhabaz, S. Margueron, M. A. Suarez, F. Bassignot, L. Gauthier-Manuel, D. Belharet, B. Dulmet, A. Bartaszyte, *Applied Physics Letters*, 119, 013904, (2021).
- [8] G. Clementi, S. Margueron, G. Lombardi, M. A. Suarez, E. Lebrasseur, S. Ballandras, J. Imbaud, F. Lardet-Vieudrin, L. Gauthier-Manuel, B. Dulmet, M. Lallart, A. Bartaszyte, *Mechanical Systems and Signal Processing*, 149, 107171, (2021).
- [9] N. Panayanthatta, L. Montes, E. Bano, C. Trigona, and R. La Rosa, Three terminal piezoelectric energy harvester based on novel MPPT design, *19th International Conference on Micro and Nanotechnology for Power Generation and Energy Conversion Applications (PowerMEMS)*, Krakow, Poland, Dec. 2019, pp. 1-7, (2019).
- [10] J. Doolan Fernandes, F. E. Carvalho Souza, G. G. Cipriano Manicoba, A. O. Salazar, & J. A. De Paiva, Wireless monitoring of induction machine rotor physical variables, *Sensors*, 17(11), 2660, (2017).