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Characterizing and Optimizing Piezo Harvesters for Train Interiors

Milan Saliya Nikolaos Kouvelas R. Venkatesha Prasad Niels Hokke
Embedded and Networked Systems Group, Delft University of Technology, The Netherlands, N.Kouvelas@tudelft.nl

***Abstract*—Internet of Things (IoT) has created a niche in the last decade. We are in the midst of an unprecedented growth of automation and smart systems, driven by the miniaturization of sensing and computing & communication technologies. Even though battery technology has grown to a large extent, it is still not possible to power these sensors for long, especially in situations where sensors need to provide data at a higher frequency, which drains the batteries fast. Thus, recently researchers are looking into various means of self-powered sensing systems that harvest energy from the ambiance. In this paper, we characterize and optimize a piezoelectric energy harvesting device consisting of a cantilever beam, which is suitable for self-powered Wireless Sensor Network (WSN) nodes in the rail transport networks. The integrated unimorph-piezoelectric sensor harvests energy from ambient vibration. We attune the harvester parameters to the low range of ambient vibration frequencies and demonstrate an experimental model to validate the results of our setup. Vibration frequency and amplitude are measured by performing real experiments inside trains on the routes of the Dutch and German railway network. Each harvester provides 0.72μJ to 0.19mJ per hour depending on the vibration. Multiple of them can be utilized as secondary energy sources inside trains to measure the ambient vibration while harvesting to make it a perpetually powered sensor.**

***Index Terms*—piezoelectric (PZT) harvester, vibration sensor**

I. INTRODUCTION

The demand is increasing for smart systems that monitor different ambient parameters through IoT devices. Such parameters include temperature, humidity, motion detection, ambient vibration, etc. Further, IoT devices are widely considered in public transport, such as the railway industry, to improve predictive maintenance, scheduling, system capacity, safety, and to reduce life-cycle costs as well as to enhance the passenger experience. However, these networks draw a considerable amount of power per device that can be heavily reduced as recent works have shown [1] [2]. In general, batteries and/or wires have been widely used to supply power to these devices, making their features restricted. Batteries have a limited life cycle and eventually need to be replaced. Moreover, they are non-ecological, and their disposal produces a large carbon footprint. The wired solutions restrict the flexibility and reliability of the sensor nodes as it requires continuous maintenance, which can be time-consuming and cost-intensive. Therefore, powering the nodes by harvested energy from the ambiance will be more than useful and it will also allow perpetual powering of the devices. In this paper, we focus on vibration harvesters inside trains generating electrical energy from vibration as a source of kinetic energy. The most prevalent techniques to harvest electrical energy from vibrations involve electrostatic, electromagnetic, and piezoelectric harvesters [3]. However, as the device size decreases, the amount of energy that can be harvested with electrostatic or electromagnetic techniques becomes too small. In such small scales, vibration energy can be vital. Piezoelectricity is popular for detecting these vibrations and hence is a viable energy scavenging source [4]. However, leveraging vibrations in the interiors of trains to harvest energy is not trivial, because the predictability of the generated energy by vibrations is limited. This hinders the design of a mechanism of maximum power generation.

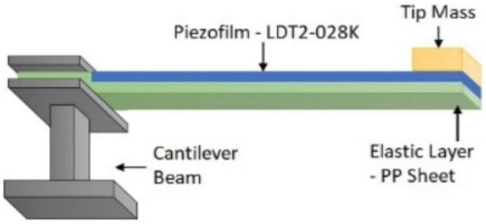

Fig. 1: Cantilever beam structure of piezoelectric generator with proof mass at its free end.

In this paper, we characterize vibration harvesting using piezoelectric cantilever and evaluate it in real-case scenarios inside trains. The piezoelectric sensor is characterized based on the detected resonant frequency and vibration level inside the chair car of the train. We provide a complete design, setup, and evaluation of piezoelectric vibration harvesting sensors. The scavenged energy of our harvesters can be stored in supercapacitors of batteryless and wireless sensors inside trains, and used to wake-up these sensors from sleep in order to transmit several packets per hour, before turning to sleep-state again. This step is a simple extension of our work here which is out of the scope of this paper. Specifically, our contributions are the following:

1) We characterize the vibration sensitivity depending on the moving frequency and acceleration inside trains.
2) Based on our measurements, we design and calibrate a piezoelectric generator and highlight the frequencies which maximize the power output, under different acceleration values and harvesting configurations.
3) We provide results by measurements from experiments on multiple train-routes in the Netherlands and Germany.

II. METHODOLOGY

A piezoelectric sensor is made of piezoelectric ceramics and crystal materials. It is primarily used to measure changes in force as well as pressure, acceleration, temperature, and strain by converting them to electrical charges [5]. The charges get separated due to an applied strain in the material, called the piezoelectric effect. This effect can be derived by the equations in Strain-Charge form [6] [7]. The majority of

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TABLE I: Physical and geometric properties of materials.

Materials	Density [kg/m^3]	Young's Modulus [Gpa]	H [μm]	B [mm]	L [mm]
PEZ film with electrode	7800	66	147	16	77
Lamination Layer (Mylar)	1390	5.1	28	16	77
Elastic Layer (PP Sheet)	830	1.1	1000	16	77

piezoelectric generators that have been fabricated and tested use some variation of lead zirconate titanate (PZT), because its large piezoelectric coefficient and dielectric constant allows generating more power for a given input acceleration [7] [8] [9]. In this paper, we provide the measurement and test done with a laminated piezo sensor manufactured by 'TE Connectivity'. There are three layers in the film, the upper layer is a protective coating, the middle layer is the piezo film itself, and the bottom layer is polyester laminate [10].

Piezosensor Characterization. The majority of piezoelectric generators use a beam structure with one end free and the other fixed, so the slope and deflection at that end become zero; these are known as cantilever beams. Fig. 1 represents the structural overview of the cantilever beam used for measurements. The piezo-film is kept on the elastic layer, and the tip-mass is added at the free end to increase the strain of piezo-film. The physical properties of the material are mentioned in Table I. The generator needs to be designed to work at the resonance frequency of the environment to generate the maximum output power. Therefore, the optimal frequency of the energy harvester may vary according to the specific application and the environment in which it is designed to operate [11]. The first-order resonant frequency of the cantilever can be adjusted by keeping a mass on the free end of the cantilever [12] [13]. The resonant frequency can be calculated either using 'Euler-Bernoulli' beam equations or by a first-order spring-mass system with corresponding stiffness and effective mass [7], [14]. The mass weight is calculated as shown in Eq. 1 utilizing physical properties and geometric parameters of materials used in the cantilever beam, including the piezoelement, as mentioned in Table I.

$$T_m = \frac{3E_T B H^3}{L^3 \omega^2}, \tag{1}$$

where T_m is Tip Mass, E_T is Young's Modulus, B the total breadth, H the total thickness, L the total length, and $\omega = 2\pi f$. Fig. 2 shows that the calculated mass weight using Eq. 1 at the tip of the cantilever decreases rapidly with the increase of first-order resonant frequency. This helps to optimize the tip mass weight to increase efficiency of energy harvesting for different detected frequencies based on the applications.

III. IMPLEMENTATION RESULTS

In this work, we first analyze the results from vibration inside the railway coach, and then use them to find the optimum resonant frequency and the acceleration level for our harvester.

Train Measurements. Train measurements are taken with 'Arduino Uno' using accelerometer. The device is kept inside 3D printed boxes on different positions in the railway coach (leg room, work table, side surface) to find the most preferable position with higher vibration in the train, as seen in Fig. 3. The measurements have been taken from multiple routes in the Netherlands and Germany but due to space limitations we highlight here only the most relevant route from the Netherlands. As seen in Fig. 4, the detected frequency is between 60 Hz to 80 Hz with a peak at 67.83 Hz. The vertical displacement is on average ±2 m/s^2. The above values of frequency are used as a reference to calculate the tip mass weight (6.5 gm) as per Eq. 1.

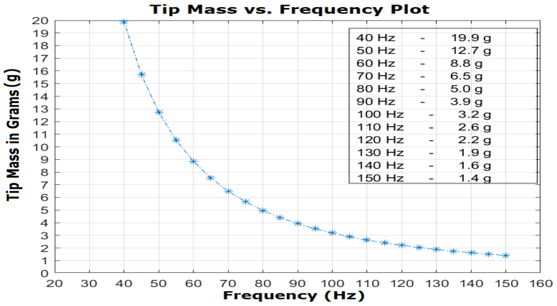

Fig. 2: Characterizing of tip-mass weight versus first-order resonant frequencies.

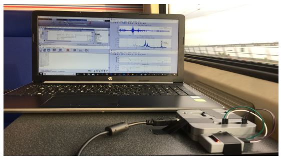

Fig. 3: Measurement setup on the table inside the train.

Energy Harvesting. In this work, we calibrate the vibration generator and measure the harvested energy with the proposed cantilever structure using an oscilloscope. The block diagram in Fig. 5 presents the measurement setup and the signal chain of the generator. Fig. 6 shows the measurement setup in a lab environment where speaker woofer is considered as vibration generator, which is driven with continuous

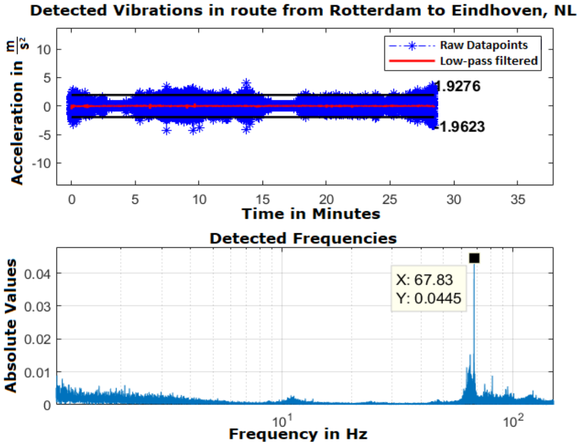

Fig. 4: Measurement taken on the route of Rotterdam to Eindhoven, the Netherlands.

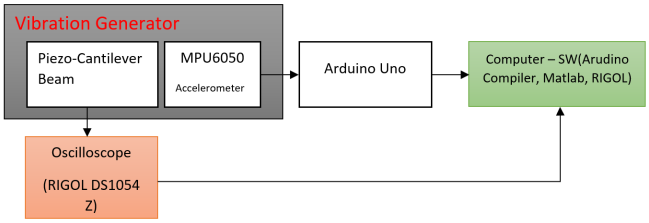

Fig. 5: Block diagram of the setup in lab environment.

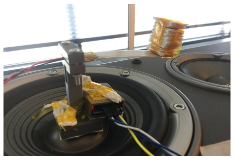

Fig. 6: Cantilever beam (6.5gm tip mass at free end).

sinusoidal frequency ranging from 40 Hz to 100 Hz to cover a wide frequency spectrum from the railway data. The 3-D modelled cantilever beam integrated with piezofilm in unimorph structure is kept on the woofer. The MPU is also kept on the beam to measure and calibrate the vibration frequency and vertical acceleration. RMS voltage V_{RMS} can be calculated from from the measured voltage at different acceleration and frequencies using oscilloscope and the continuous power P_c can be calculated as $P_c = V_{RMS}^2/R_t$ where R_t is a total resistance, in our case $1.01\,\mathrm{M\Omega}$. Respectively, the energy $E_h = P_c \cdot t$, where t is $3600s$ considering generated energy per hour. Fig. 7 shows that the speaker woofer is calibrated with $\pm 2\,\mathrm{m}/s^2$ with tolerance of 1% in the frequency range of 40 Hz - 100 Hz. Fig. 8 presents that the maximum harvested energy with 6.5gm of tip mass at $\pm 2\,\mathrm{m}/s^2$ is approximately 0.72 µJ/hour at the resonance frequency of 70 Hz. Decreased vertical displacement leads to relatively less generated energy. Fig. 9 presents the harvested energy for different acceleration values, e.g., vibration with $\pm 19.5\,\mathrm{m}/s^2$ can offer harvested energy of 0.19mJ/hour at the resonance frequency of 70 Hz. This amount of energy is enough for each sensor inside a train to be triggered from sleep mode and transmit 3 times per hour at -5 dBm reaching 9 meters distance, assuming 20 b packets with 3.4 ms transmission time.

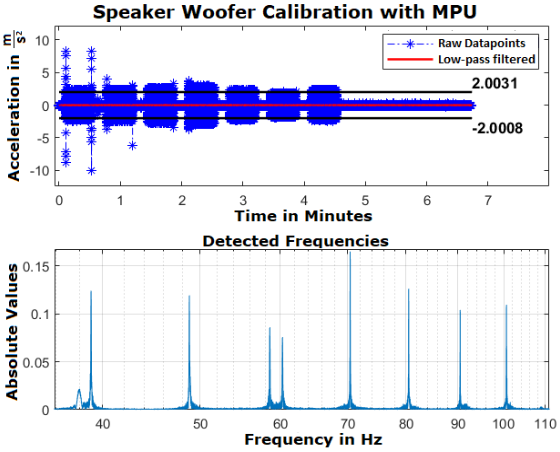

Fig. 7: Calibrated speaker woofer at $\pm 2\,\mathrm{m}/s^2$ and 40 Hz-100 Hz.

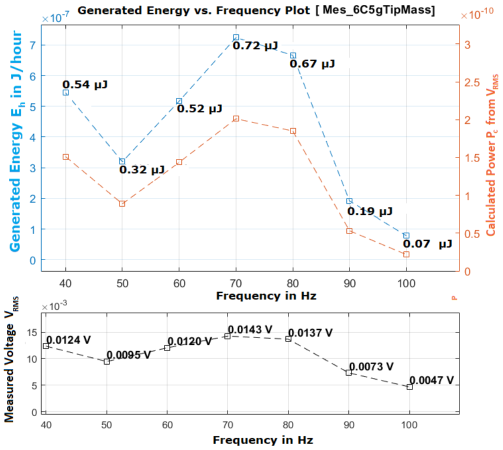

Fig. 8: Harvested energy (6.5gm tip mass at free end).

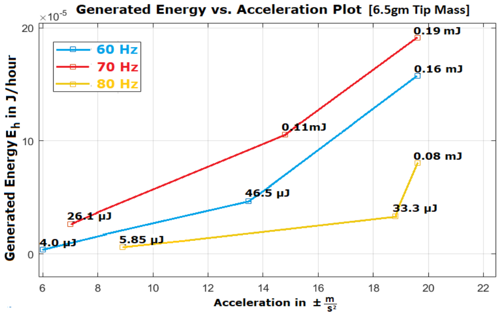

Fig. 9: Harvested energy with 6.5 gm tip mass at different acceleration values.

IV. CONCLUSION

The vibration measured inside chair cars of trains can be used as a secondary means of energy for wireless sensor networks. The results confirm that characterizing the harvester behavior with tip mass can maximize energy harvesting, but is limited to a particular frequency range. The harvested energy with cantilever reaches up to 0.72µJ per hour. Further, exposing the harvester to $\pm 19.5\,\mathrm{m}/s^2$ vibration generates about 0.2 mJ/hour. This is sufficient to transmit a few packets per hour without batteries perpetually. The proposed methodology can offer higher amounts of scavenged energy if implemented on the railway trails or where the sensor is subjected to a higher amount of vibration, which is the subject of our future research. Finally, to optimize the harvester for any frequency we will model the cantilever beam with tip excitation using additional magnet mechanism, according to *et. al.* [13].

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