Energy harvester duty cycle evaluation for railway vehicle health monitoring

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Abstract. The recent growth of the IoT (Internet of Things) technologies makes these connected devices suitable for monitoring and diagnostic in different applications. Through these devices, a wireless sensor network has become a smart solution for monitoring structures, vehicles, and other devices. Each node in the network can be placed in an inaccessible or unsafe location for human intervention and provide a real-time data stream, useful for the diagnostic and maintenance of the structure. In this context, the power node becomes a fundamental problem since the replacement of batteries is a disadvantage both for environmental disposal and for the related costs. Thus, the interest in the so-called AIOT (Autonomous Internet of Things) is growing, and the energy harvester generators can be a possible solution to this problem. In this scenario, an inductive linear generator having a non-symmetrical gravitational suspension is presented. The main characteristics of the generator and the magnetic suspension are introduced with the description of the Matlab/Simulink model that simulates the same behavior. In this work, a first study of the duty cycle of the generator to power a wireless sensor node for industrial application is presented as well. This study is carried out with a particular focus on the acceleration frequency evaluation of railway vehicles to better understand the possible effective power that can be extracted from the harvester. The relevance of this work lies in the fact that the generator sizing cannot be separated from the detailed knowledge of the energy source and of the sensing/monitoring system that must be powered.

1. Introduction

The growing spread of IoT (Internet of Things) and monitoring systems based on micro-electro-mechanical systems (MEMS) also encompass the railway system. Through these connected devices it is possible to have real-time information and data regarding the monitored vehicle or component. These new data offer the opportunity to have a new vision regarding the status of the monitored device providing information now accessible thanks to the rising of these technologies. With a continuous stream of data, it is possible to have knowledge regarding the health of the monitored system that can be crucial for the maintenance, safety, and design field. In fact, these data allow a better knowledge of the monitored system in its working condition, making it possible to the create algorithms of predictive maintenance and to improve the design phase. Moreover, these data can provide fundamental information regarding the working conditions condition and offer an evaluation concerning the safety and the durability of the monitored device. A wireless monitoring network allows a continuous stream of data but also has to comply with some strict characteristics to be a powerful instrument. All these systems should be characterized by a low power demand, a reduced size, a long-life cycle, and
wireless connection reliability. The reduced size is required to be easily placed in dangerous or hard-to-reach places and to prevent any interference with the regular functionning of the system monitored. Moreover, a solid wireless connection to the server and through nodes is mandatory to have a reliable network ad an affordable set of data. At last, a long lifetime is required to reduce the cost of maintenance and of battery replacement, which are the main reasons for low power demand. The batteries used in these networks become no more sustainable in terms of cost and for environmental disposal but also in terms of safety. The need of replacing a battery is the main drawback of these systems that have to be designed with the logic of 'place and forget'. Also, for freight vehicles, the design of these monitoring devices remains a challenge due to the lack of power onboard. This is also the reason why these devices still do not achieve a widespread diffusion and so the interest regarding the alternative methods of power supply is growing. In this contest, one of the possibilities is the use of energy harvester devices and the process of harvesting the energy losses in the environment.

In literature, there are many research works regarding the design and study of the energy harvester devices in the railway field. In particular, the applications and the characteristics of these devices can be summarized in different ways. For example, in the comprehensive reviews from Bernal et al. [1], Pan et al. [2] and Hosseinkhani et al. [3] the authors focus on the different monitoring systems, dividing them on th bais of how they are powered and what they measure and monitor. In the work of Bosso et al. [4] a comprehensive review of energy harvester used in the railway field is reported, where they classify the energy harvester used energy harvester on the basis of the type. Another classification method is based on the location in which the devices are mounted, as proposed by Chunsheng et al.[5]. The ones mounted on-board are generally composed by an accelerometer, gyroscope, noise sensors, GPS, and temperature sensor and they are used to provide a continuous monitoring system with real-time detection of defects, track irregularities, vehicle dynamic, location, and speed. The other ones are mounted around the track for wheel profile monitoring, wheel impact, and bogie performance evaluation. The main drawback of these systems is the fact that they provide information only in that specific location of the track. From our research group, two possible monitoring systems are proposed, one presented in the work of Aimar et al.[6],[7], which is followed in this work, and followed in this work and the other presented in Bosso et al.[8]. So, in this paper, it will be shown an onboad monitoring system and the prototype realization of an energy harvester for its power supply. In section 2 the description of the numerical model of the energy harvester is proposed with details on the integration in the system of the experimental nonlinear stiffness and the comparison with the experimental measurements. Then in section 3, the monitoring system is described with all its components and the heatmaps and plots of the measured data are presented in section 3.1. Then the evaluation of the load cycle on the energy harvester computed through the experimental data is explained in section 4. The same section shows the of the power the power obtained from the harvester if it is excited with the load curve computed with 5 days of activity. In the last section 5, the duty cycle design for this kind of harvester is presented.

2. Mathematical Model
Roundy and al. [9] propose basic principles of the functionality of vibration energy harvester. These generators consist of a seismic mass $m$ attached with spring and viscous damper to a moving base inside a box (on the left of Figure 1). The analytic model is a 1 d.o.f mass-spring-damper system. The moving magnet has a relative motion $z$ with respect to the base, which receives an imposed displacement $y$. The vibratory external source makes the seismic mass move out of phase with respect to the box. This relative motion between the mass and the base can drive a suitable transducer to generate electrical energy. Like all inertial devices, the harvester must be set in vibration to generate electrical power.
Figure 1: on the left, the model of the harvester with reference system, on the right the electromagnetic force

The magnetic interaction within the two magnets can be studied as a non-linear magnetic spring and the experimental and fitting curve of the elastic force obtained from the suspension is shown on the right of Figure 1. The static measures are carried out by placing different calibrated masses on the moving magnet with a supporting beam having a plate on the top for the application of these masses. By processing these measures, it is possible to find the numerical fit of the elastic force and then compute the stiffness curve to insert it in the numerical model. The equation of motion can be written in terms of the relative motion, considering the starting position as the equilibrium of the magnet, when its weight is equal to the repulsive magnetic force. Thus, the absolute motion coordinate of the moving magnet $x$ is related to the static equilibrium condition of the moving magnet $x_0$.

\[
m \ddot{x} + c_{tot}(\dot{x} - \dot{y}) + k(x - y) = 0 \quad (1)
\]

\[
z = x - y \quad (2)
\]

\[
m \ddot{z} + c_{tot} \dot{z} + kz = -m \ddot{y} \quad (3)
\]

\[
\ddot{y} = -\omega^2 y_0 \sin(\omega t) = -Y_0 \sin(\omega t) \quad (4)
\]

Then the form to introduce this equation in Matlab Simulink is:

\[
\ddot{z} = -\frac{c_{tot}}{m} \dot{z} - k \frac{z}{m} + Y_0 \sin(\omega t) \quad (5)
\]

Where:

- $m$ is the mass of the moving magnet
- $c_{tot}$ is the sum of viscous damping $c_{vis}$ and the magnetic damping $c_{mag}$
- $k$ is the magnetic non-linear stiffness
- $Y_0$ is the acceleration amplitude, in this case it is sinusoidal
- $\omega$ is the excitation frequency
Figure 2 below shows the complete Simulink model and the blocks that are circled in blue are the most characterizing ones and are explained in Table 1. In detail, about the block used in the numerical simulation, the ones blue circled are reported in Table 1.

![Simulink model of the energy harvester](image)

**Table 1: Main Simulink blocks**

| N  | Type                      | Description                                                                 |
|----|---------------------------|----------------------------------------------------------------------------|
| 1  | Sine Wave                 | Excitation with $Y_0$ amplitude and $\omega$ frequency                      |
| 2  | 1-D Lookup Table          | Electromagnetic coefficient-moving magnet displacement relation             |
| 3  | Matlab Function           | Stiffness-moving magnet displacement relation                                |

The results obtained by comparing the numerical simulation results with the experimental ones are promising in terms of Frequency Response Function (FRF). Despite some slight differences in the matching resonant frequency and in the amplitude, a good comparison is obtained, as can be seen in Figure 3. It is important to notice that these differences are very reduced, the maximum difference of the peak resonance is about 0.3 Hz. The height difference in the peak is mainly due to the modelling of the friction damping in the model. Experimental tests show a non-linear behavior of this parameter, as the variation of the damping coefficient obtained from the logarithmic decrements is significant. In fact, the variation of the damping coefficient obtained from the logarithmic decrements was huge. This is because of inaccuracies in the realization of the tube causing more friction when the magnet is close to the equilibrium position. Also, there is a dependence of the damping coefficient on the moving magnet speed. When the magnet moves faster and widely during resonance, the damping is at its minimum.
value vice versa when the magnet oscillates away from resonance the damping is higher. In this first phase of the study, it is chosen not to implement the non-linearity of the damping friction and it is introduced as a constant value. Then, it is verified that this simplification does not affect heavily the obtained results. A future step of this work is to introduce this nonlinearity to complete the model. More details about these developments are presented in the work of Russo et al. [10].

Figure 3: Experimental and numerical FRF’s plot

3. The monitoring device
The monitored device developed by our research group [6] is build with these main components that are summarized in the table below:

| N | Components             | Description                  |
|---|------------------------|------------------------------|
| 1 | Microprocessor         | ATmega2560                   |
| 2 | Triaxial Accelerometer | 16 g                         |
| 3 | Memory                 | μSD Card                     |
| 4 | GPS module             | position of the system       |
| 5 | Temperature Sensor     |                              |
| 6 | Differential pressure sensors |                        |

Table 2: Hardware components description

The data acquisition system is based on a micro-controller ATmega2560, which is an embedded software and firmware developed entirely by our research group. Through the GPS it
is possible to have fundamental information regarding the position and the velocity of the train. The GPS signal is sampled with a frequency of 1 Hz. In case of no GPS signal (e.g. inside the railway galleries), the monitoring system keeps sampling the other parameters. In particular, the monitored data are the accelerations in the x-y-z directions, the temperature, and the pressure. All these parameters are sampled at 200 Hz and then the RMS, minimum and maximum value of the acceleration are computed every second and saved on the sd memory. The accelerometer measures allow to have a better understanding of the vehicle dynamics and to detect potential impacts. Going into detail, the z-axis accelerations provide important information on the wheel-rail track interaction; the x-axis, the longitudinal one, is crucial during the braking operations and the y-axis is the lateral one. Moreover, the vertical acceleration values represent an excellent basis for the correct design of an energy harvester device [11] as presented in this work. The temperature sensor is used to monitor the temperature of the brake block. The sensor is glued into a small groove cast iron brake block and it has a range temperature from -50°C to 500°C, enabling high temperature measures during braking. The pressure sensor, with a range of 0 to 7 bar, is placed on the same attachment points used during the periodical brake test after the laboratory calibration.

3.1. Heatmap of the data monitored
The data obtained from the GPS can be used to plot the real path of the train knowing latitude and longitude. The heatmaps allow to highlight, through a color graduated scale, the trend along the path of a certain data. In particular, the quantities of interest are the altitude, the speed, and the temperature to run a cross analysis for train braking monitoring. Below are reported, as an example, the data obtained during the 9 August 2020 between 9:00 and 14:00.

From the heatmaps, it is possible to see that the speed remains almost constant along all the routes and around 100 km/h. The duration of stops along the way can be obtained by crossing the GPS data with the respective instants of time.

4. Load diagram
The vertical acceleration data allows the definition of the excitation input of the energy harvester. The RMS value of the vertical acceleration, along the y axis, it is to count the number of peaks in a certain range and how often these are repeated in a daily data set. Through this approach it is possible to elaborate the load diagram which shows how many times a certain range of peaks acceleration is repeated in a time period. The process is shown in Figure 5, where at the top the peaks counting for day 09-08-20 is reported as an example. The same process is followed for all the other days that are analyzed. Subsequently, by means of the load diagram it is possible to transform the random acceleration signal in a sum of sinusoidal waves with amplitude values equal to the corresponding peaks range of the diagram and a temporal extension equal to the ratio between the number of cycles in which that amplitude occurs and the total number of cycles. The excitation frequency was considered equal to the resonance frequency of the energy harvester (3.5 Hz), which is the optimum working condition of the device.

Once this sinusoidal input is introduced in the Simulink model of the energy harvester, it is possible to evaluate the electrical quantities of the system and the output power, as it is shown in Figure 7. The obtained RMS value of power is compared with respect to the power generated by the mathematical model of the harvester excited by a sinusoidal with a constant amplitude equal to 0.4 g and a resonance frequency of 3.5 Hz. This point of comparison is the maximum theoretical power that can be generated by the model with the chosen sinusoidal excitation input. The load resistance and the number of turns used as a comparison are the optimal ones of the configuration that produces the maximum theoretical power.
Figure 4: Altitude, speed and velocity heatmaps

The Table 3 below shows the effective RMS power that can be obtained from the 5 days chosen and the theoretical RMS power described before. From these two parameters, it is possible to have a first estimation of the harvester efficiency during a working cycle.

| Day       | Effective RMS Energy at 3.5 Hz [mWh] | Ideal RMS Energy [mWh] | Efficiency |
|-----------|-------------------------------------|------------------------|------------|
| 09-08-20  | 30.5                                | 50                     | 61%        |
| 13-08-20  | 20                                  | 50                     | 40%        |
| 04-09-20  | 20.4                                | 50                     | 41%        |
| 06-09-20  | 17.4                                | 50                     | 35%        |
| 16-09-20  | 10.5                                | 50                     | 21%        |

Table 3: Energy comparison of five examples days

To have a better knowledge of what happens moving around the resonant frequency, the RMS power at 2.5 Hz and 4.5 Hz is computed as well. As expected, the efficiency of the harvester continues to decrease. The asymmetric decreasing of the efficiency is due to the non-linearity of the device. The stiffness characteristic has a softening behavior, which leads to a sudden drop of the power when the frequency decreases from the resonance. On the contrary, when the excitation frequency has greater values than the resonance, the output power decreases more slowly. Finally, the efficiency is evaluated comparing again the effective output power with the theoretical one in terms of RMS value. The Table 4 below shows the obtained energy values for
Figure 5: Peaks of vertical RMS acceleration, Load diagram and sum of sinusoidal with proportion obtained from he load diagram

Table 4: Energy obtained around the resonant frequency

| Day     | RMS energy 2.5 Hz [mWh] | RMS energy 3.5 Hz [mWh] | RMS energy 4.5 Hz [mWh] |
|---------|-------------------------|-------------------------|-------------------------|
| 09-08-20 | 3.1                     | 30.5                    | 11.7                    |
| 13-08-20 | 4.1                     | 20                      | 10.1                    |
| 04-09-20 | 2.7                     | 20.4                    | 9.2                     |
| 06-09-20 | 1.7                     | 17.4                    | 7                       |
| 16-09-20 | 0.9                     | 10.5                    | 3.9                     |

From this evaluation it is possible to point out the importance of a correct design of the harvester. It is necessary to provide a wide range for a wide range of the FRF spectrum so that the efficiency of the harvester remains constant in a wide range of excitation frequencies. Moreover, the duty cycle of the energy harvester should be evaluated. This parameter has become an essential part of the designing phase in order to obtain an efficient energy harvester. Real devices in working conditions always have accelerations or input excitation that are different from the laboratory one and it is mandatory to know how much power the device can effectively generate during its working operation. This concept will be explained in detail in the next
5. Duty cycle: cycle type and application range
The generator sizing cannot be separated from the detailed knowledge of the sensing/monitoring system that must be powered. The activity of design and dimensioning of the generator must be supported by complete information about the characteristics of the overall autonomous system including its frequency of data transmission, its powering demand during the acquisition data phase and the transmission one, etc. Moreover, it is important to consider the powering request of all the components between the transducer and the sensor. Usually, the following functional blocks can be identified (see Figure 8): current rectifier, charge reservoir (storage battery), one or more sensing devices (sensors), the transceiver device.

In almost every case, the energy generated by the harvester is stored in batteries or supercapacitors before use, requiring a preliminary conversion of the alternate current produced by the harvester in continuous current. The charge storing is an expensive activity in terms of energetic efficiency. However, it is often necessary due to some reasons: firstly, to provide continuous supply also in case of irregular power generation; secondly, to reach the prescribed energy threshold needed to supply the utilizer. The energy produced by the harvester and stored in the battery can be used for supplying only when the minimum charge threshold is reached; this lower level of the battery charge is imposed by the energetic demand of the utilizers. Similarly, the time interval when the power flows from the battery to the utilizer must be calculated to know the consumed energy in time unit. The mentioned constraints are considered in defining the duty cycle of the self-powered system and in Figure 9 is represented.
Figure 7: Efficiency plot obtained at 2.5 Hz, 3.5 Hz and 4.5 Hz

Figure 8: Energy harvester functional blocks

a typical working schematic duty cycle.

Figure 9: Transmission duty cycle

In general, during the design phase of a self-powered monitoring system, it is mandatory to consider the application in which the systems must work. It is important to define how and what the system must measure and how often it must send the data to the server. This global analysis allow to have a complete understanding of the system that needs to be monitored. The working time (T) of the harvester device and its transmission time period (t) must be evaluated. For the purpose of a long-lasting autonomous device, the ratio between these two quantities should be minor than 1. The time in which the harvester reaches power level has to be greater than the time in which the power is requested. In this case, it is possible to have a harvester
with a power output magnitude of mW and working for a long period. While, if continuous or more frequent information is required to be sent to the server, the ratio between the two time characteristics tends to 1. In this case, a more powerful energy harvester with output power magnitude of W has to be designed To have a better understanding of this concept see Figure 10). In conclusion, this ratio has to be a fundamental parameter to be consider during the study of an energy harvester. The definition of the duty cycle becomes one of the early phases of the designing process that allows obtain a prototype suitable for the application desired.

6. Discussion
This paper shows the evaluation of an energy harvester power generation in working conditions. The analysis is carried out firstly by the realization thanks to the first realization of a numerical model that simulates the real behavior of a prototype energy harvester. The model is built in Matlab/Simulink environment and leading to a good superimposition of numerical and experimental results. Also, a brief description of the monitoring board design by our research group is described in order to understand the cause of the excitation of the harvester mounted on a rail freight car. Then, the heatmaps of the data obtained from the monitoring device are presented and the vertical acceleration is processed to compute the load diagram. In this way, it was possible to build a sinusoidal wave with power content equivalent to the random excitation accelerations. Five days of train working are analyzed, in which the GPS coordinates are recorded. This process allows to have a raw evaluation of the efficiency of the energy harvester design during a real working operation. This phase is fundamental because it points out the necessity to design a harvester that presents a wider peak in the FRF in order to generate more power also when the resonance is not reached. The non-linearity of the harvester causes the generated power to rapidly drop when the frequency decreases from the resonance (softening stiffness), while it decreases slowly at higher frequencies. Finally, the duty cycle concept is introduced and its importance in the early design phase to understand the necessity of the definition of a duty cycle also in the early design phase to understand how much power has to be generated and if the energy harvester solution is suitable for the application.

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