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AFRICAN RAILWAY CENTER OF EXCELLENCE

Determining the Optimum Parameters of an Energy harvesting system using simulation

A Thesis in Rolling Stock Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Railway Engineering

By

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The undersigned have examined the thesis entitled '**Determining the Optimum Parameters of an Energy harvesting system using simulation'** presented by **Akello Fiona Mercy**, a candidate for the degree of **Master of Science in Railway Engineering (Rolling Stock)** and hereby certify that it is worthy of acceptance.

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I certify that research work titled "Determining the Optimum Parameters of an Energy harvesting system using simulation" is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged / referred.

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Akello Fiona Mercy

ABSTRACT

Ethiopia has a small percentage of its population accessing electricity with some energy utilized by the transportation sector, also there are frequent power outages at the Addis Ababa Light Rail Transit Services which takes a long while to return. From this former statement, it is clear that demand for energy is high and there is too much dependability on the current energy source. The aim of this study is to simulate an energy harvesting system using vibration from the track using a two degree of freedom oscillator. Secondary data was collected, then a damped Mass-spring-two degree of freedom oscillator was modeled and the energy harvested from the system simulated. This oscillator produces mechanical energy to power signaling and communication equipment of the railway line. The optimum parameters of the energy harvester were determined; the mass of 1 kg, a spring stiffness of 0.12 N/m and a damping coefficient of 5.5Ns/m. The cumulative mechanical power harvested by Addis Ababa Light Rail Transit's lowest speed was calculated to be $8.06\,W$. The damped two-degree-of-freedom oscillator produces higher mechanical energy, therefore meeting the energy demand of the signaling and communication equipment.

Key words: *Electricity, energy harvested, vibration, mechanical energy, two degree of freedom oscillator*

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LIST OF ABBREVIATIONS

AALRT - Addis Ababa Light Rail Train

SDOF - Single-degree-of-freedom

2DOF – Two-degree-of-freedom

OLE – Overhead Line ElectricficationS

MEMS – Micro-electromechanical systems

PZT - Lead Zicronate Titanate

PVDF - polyvinylidenefluoride

TPLS – Traction Power Line System

EW – East – West

NS – North South

EP – Electric Power

V – Volts

W – Watts

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CHAPTER 1

1.1 Introduction

In Africa, the population growth is higher than the rate of electricity growth which poses a need to increase energy exploitation [1]. In addition, the rate of electrification has increased in many developing countries, even though most low-income African countries lag far behind [2]. Energy is among the 17 sustainable development goals for 2030, with a target of universal access to , reliable, affordable, and modern energy services by 2030 [3].

1.1.1 Power Transmission

Large amounts of electricity generated at a power station (hundreds of MW) are transported over a long distance (hundreds of kilometers) to load centers to provide electricity to consumers using transmission towers and transmission line.

The government of Ethiopia has a vision of transforming from a developing country to a middle-income country by 2025 under its latest Growth and Transformation Plan (GTP). The current GTP goal is to increase the electricity generation capacity to 35000 MW by 2037 with the current generation capacity at 4800 MW from solar, wind, geothermal and hydroelectric sources [4].

An overhead line is made up of one or more overhead wires which carry electricity whose source is feeder stations. The feeder stations are usually fed from a high-voltage electrical grid of 132kV in Ethiopia which is stepped down to 15kV for Addis Ababa Light Rail Train overhead line electrification. This voltage is further stepped down to 400 V for the signaling and communication equipment.

Figure 1. 1 : Transmission lines [5]

Overhead contact line system has the principal function to make contact through electrical wires or conductor rails with a sliding current collector, to supply electrical energy to railway vehicles. For this reason, it is frequently named Overhead Contact Line System [6]. The contact line is considered to include insulators and these are classed as being part of the electrical system in contact with high voltages. Overhead contact line systems include:

- Supporting structures, foundations, and any other components whose function is to align and support, hold and insulate the contact wire and conductors.
- All overhead contact line conductors and wiring, including the catenary wire, contact wire, return current conductors, earthed conductors, lightning protection conductors, feeder and parallel feeder lines if these are installed on the same supporting structures.

- Switchgear equipment, monitoring and protective equipment installed on the same supporting structure as the lines.

Overhead line equipment consists of a large number of standardized components. Most of this equipment is there to achieve the primary aims of overhead line designers: minimizing wear of the system, and maintaining the contact wire as stationary as possible so that power can flow uninterrupted to the train. To achieve this, the contact wire is tensioned between support structures in such a way that it can withstand deflection by high winds and extreme temperatures. This ensures that the current passes to the train in all weather, even at high speed [6].

The contact wire is suspended from vertical cables called droppers that are supported by a longitudinal cable called the catenary. The catenary and contact wire span between support structures –either masts or frames–which are normally spaced approximately 50m apart (although there is some flexibility in spacing). The wires themselves are normally about 1500m long and tensioned at either end. To ensure no loss of power to the pantograph, adjoining sections of wire overlap for about 180m.

In designing the supporting structures, the most important engineering consideration is the effect of high winds, both along and across the tracks. The supports are made sufficiently stiff so that they do not deflect enough to impair current collection. The contact wire also runs in a zig-zag path above the track to avoid wearing a groove in the pantograph. The zig-zag -known as the ‘stagger’ -is generally achieved by the use of ‘pull-off’ arms attached to the support structures [6]. Figure 1.2 and 1.3 show how the overhead line runs above the track, with details of each part.

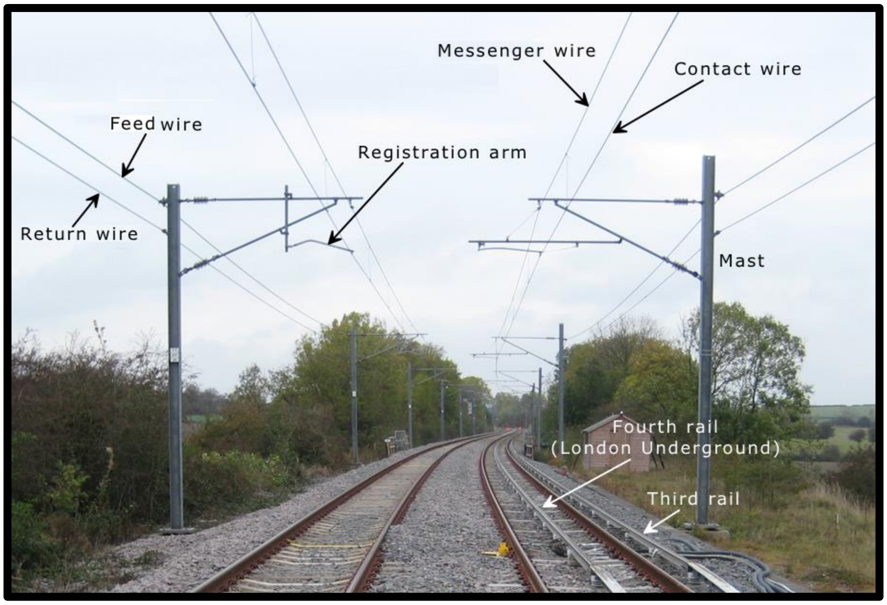

Figure 1. 2: Overhead line components in detail [7]

Figure 1. 3: Showing movement of overhead line on train [8]

The pantograph is a device used by trains to collect necessary current from power supply systems, through the contact line. This collector device presses against the underside of the lowest wire of an overhead line system, the contact wire. The current collector of the pantograph is conductive and the current will flow to the train or tram and back to the feeder station through the steel wheels on running rails [7].

There are four stages of power supply to trains by overhead line electrification (OLE);

1) Power generation
2) Power transmission (National Grid)
3) Power feeding
4) Power collection

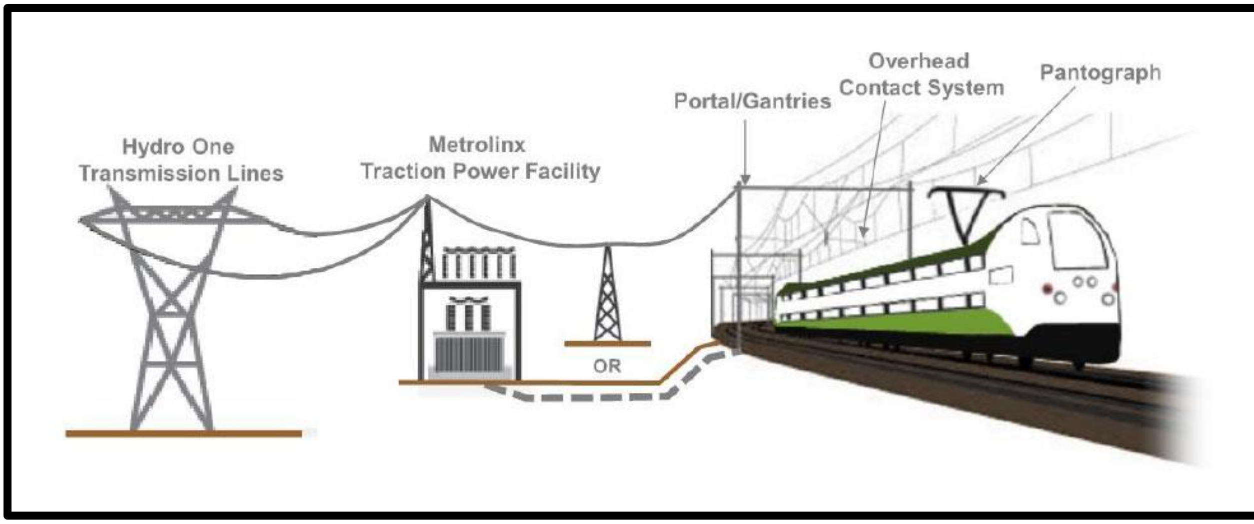

Figure 1. 4: Four stages of power supply to trains by overhead line electrification (OLE) [10]

Figure 1. 5: Overhead line electrification [11]

Figure 1.5 shows the arrangement of the overhead electrification above the tracks having turn outs and switching points.

Figure 1.6 shows the Traction Power Line System loop of power flow of the East-West line and the North South line from the Air Insulated Substation (Switching); Ayat EP Substation, EW 22 EP Substation, Kality EP Substation and NS 27 EP Substation, to the traction substation for rectification. This rectified power is used for traction of the trains. It is called loop-in and loop-out because, in case one substation is not operational, the others substations can operate the trains since the substations are inter-looped. In summary, one Air Insulated Substation can supply all the substations incase the other is non-operational.

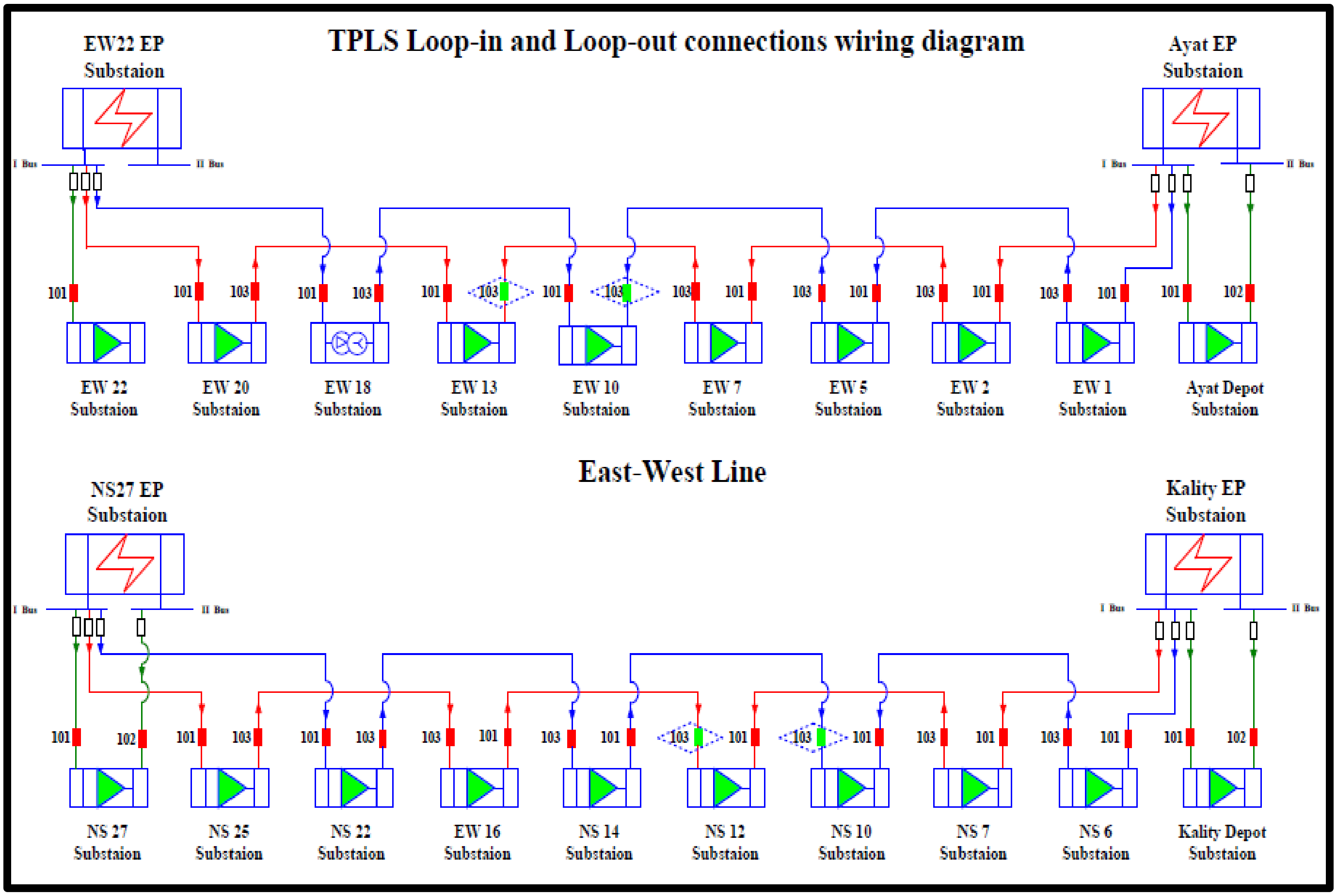

Figure 1. 6: Flow of power through each substation of AALRT

In Ethiopia 42.90% of the population have access to electricity with 6.11% of this electricity from fossil fuel. Cleaner, cheaper and more sustainable energy resources are substituting traditional fossil fuel [8]. Sustainable energy systems have become common in recent years with the optimal utilization of the renewable energy resources of Africa calling for a continent-wide increase in energy access inorder to uplift the continent’s socio-economy [9]. Some of the sustainable energy sources include; wind energy, solar energy, energy from ambient conditions (vibration, human), geothermal energy, hydropower and many others.

Energy harvesting which is used to harness energy from ambient conditions has increased in the recent few decades from sources such as mechanical vibration, wind, magnetic fields, sound, light, temperature gradients and water currents. Energy harvesters convert any type of energy to electrical energy [10]. There are sources of energy that generate large scale electrical energy like wind power plants, thermal power plants, and hydroelectric power plants [11].

The above-mentioned supply homes, cities and industries. However, many other energy sources can generate small amounts of electricity that can power electronic devices like calculators, way side monitoring sensors and many others. Kinetic energy is a great potential energy source due to its presence in every environment. It's a mechanical phenomenon due to movement with vibrational energy being one of the kinetic energy sources.

There is a possibility of generating power by tapping this energy using a mass spring damper system (oscillator). A comprehensive investigation on this topic was recently presented by the authors (Gatti *et al*), where energy was harvested from the track-side vibration, induced by the passage of a train , as a specific practical application of time-limited excitation, where there is only significant vibration input for the duration of the train passage [12]. A single degree of freedom oscillator was investigated by [12] to find the maximum available energy that could be potentially harvested from a passing train. Using an acceleration time history of vertical vibration measured on a sleeper during the passage of an Inter-city 125 train in the United Kingdom, passing at a speed of about 195 km/h, the optimum mechanical parameters of a linear energy harvesting device are determined. A numerical and analytical study was done, it was found that the maximum energy that could be harvested per unit mass of the oscillator is about 0.25 J/kg at a frequency of about 17 Hz.

Therefore, this technology is modified by making the oscillator a two degree of freedom system. Kinetic energy from moving trains is used to generate electricity which can be used for powering signaling and communication equipment of the railway line. Furthermore, this design offers pollution free power generation, low mechanical friction losses, low budget electricity production and its maintenance would be easy.

Energy harvesting has been done before by various authors who used different harvesting mechanisms like piezoelectric materials, electromagnetic mechanism and many others. However, these technologies' output power is low, mechanical friction is a challenge, air drag is increased by wind turbines and no researcher has harvested energy from moving trains using a two degree of freedom oscillator.

Even though, the Single degree of freedom oscillator has been done on the railway network to harness vibration kinetic energy and convert it to electricity, it has not been done using the second degree of freedom system on the rail track.

The aim of this study is to simulate an energy harvesting system using vibration from the track. The first objective is to model the energy harvester as a damped Mass-spring-two degree of freedom oscillator. The second objective is to do a sensitivity analysis of the technical parameters and the third objective is to determine the energy harvested from the system.

1.2 Problem statement

Electricity is inadequate in Ethiopia with 42.9% of the whole population (104,957,438) accessing electricity. Ethiopia has a final energy consumption of around 40,000 GWh [13]. 4 % of the energy is consumed by transport sector of which railway is one of them with 66.1MW used by Addis Ababa Light Rail Train (AALRT) from the national grid [14]. There are also frequent power black outs at Addis Ababa Light Rail Train (AALRT) with a duration of about 6 hours for power to get back on during the black-out [15].

In addition, global warming has led to the need for new sources of energy. It is very important to generate extra power using a sustainable source which does not injure or pollute the environment while meeting the high demand for energy.

1.3 Main Objective

To simulate an energy harvesting system using vibration from the track

1.4 Specific objectives

I. To model the energy harvester as a damped Mass-spring-two degree of freedom oscillator.

II. To do a sensitivity analysis of the technical parameters

III. To determine the energy harvested from the second degree of freedom oscillator.

1.5 Research Questions

I. What is the model of the energy harvester?

II. Which technical parameters directly affect the energy harvested?

III. How much energy is harvested by the second degree of freedom oscillator?

1.6 Delimitation

This research has been limited to the simulation of an energy harvesting system using vibration from the track, with the objective of modeling the energy harvester as a damped Mass-spring-two degree of freedom oscillator, doing a sensitivity analysis of the technical parameters and determine the energy harvested from the second degree of freedom oscillator. This paper does not cover the cost review of the technology. However, it was briefly described in the introduction. In this dissertation, the conversion of mechanical energy to electrical energy is not considered. Rather, the optimum mechanical parameters of the device are sought by assuming that the electrical energy harvested is equal to the mechanical energy dissipated. Storage of the harvested energy and fabrication of the prototype is also not be covered.

CHAPTER 2 LITERATURE REVIEW

This literature review will contain researches and studies on the current energy harvesting techniques that are in use today on railway like piezoelectric, electromagnetic and wind energy harvesters. There will be coverage on the single degree of freedom oscillator whose technology has been modified for use in the railway system.

Energy harvesting has become of increasing interest in the past few decades and research paper numbers have risen in the last few years [16]. There has been an advance in micro-energy harvesting from sources such as: vibration (mechanical energy) whose electromechanical transducers can be; electromagnetic, wind turbines, electrostatic, or piezoelectric [17]-[22]. Electromagnetic use electromagnetic transducers. Also, Momentum and Thermal are generated by radioactive reactions into Pressure gradients, electrical energy, Solar and light, Micro water flow (e.g. faucet), and Biological [16].

Several energy harvestings for railway are developed with mainly two mechanisms used to convert mechanical energy to electrical which include; piezoelectric and electromagnetic principles [20], [21].

Some other mechanisms like electrostatic energy harvesters have been developed as well. Electrostatic energy harvesters are made up of two conductive plates which move relative to each other and are electrically separated by a gap, filled with air or a dielectric material. This harvester works in two modes; a voltage constrained mode and charge-constrained mode [22]. The charge-constrained mode keeps the charge constant using a capacitor. Distance change between the two plates causes the voltage to change. The voltage-constrained mode keeps the voltage between the two plates constant with charge increasing with decrease in distance between the plates. The advantages of using electrostatic transducers is due to the fact that they are able to generate moderate levels of energy without the use of different materials, and they are compatible with micro electromechanical systems (MEMS) [23]. The disadvantage of electrostatic transducers is that it can only work when the capacitor is pre-charged [24]. The figure 2.1 shows different types of electrostatic energy harvester configurations.

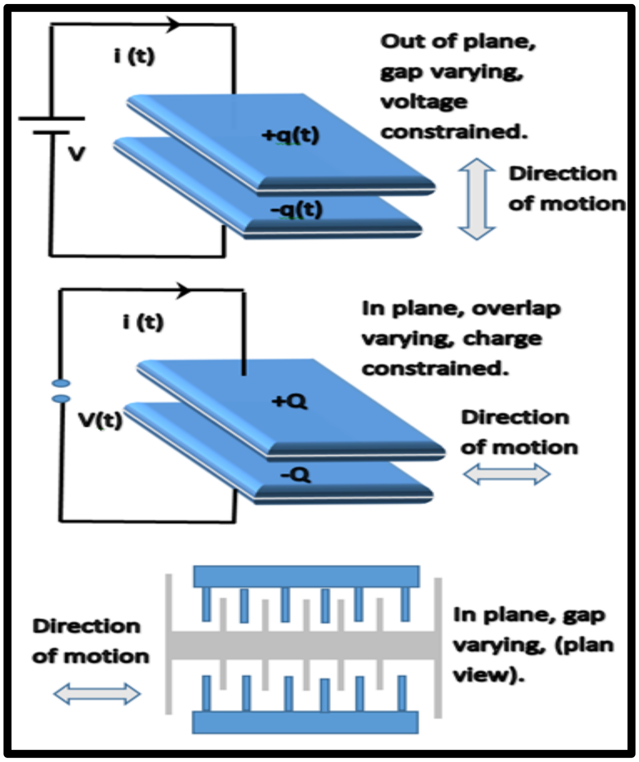

Figure 2. 1: Different Electrostatic Energy harvester Configurations by [25]

Several piezoelectric materials have been used, with the most popular material used in transduction processes being Lead Zicronate Titanate (PZT) along with the polymer material polyvinylidenefluoride (PVDF) [26]. PZT is preferable because of its abundant vibration accessibility and high piezoelectric constants [27].

According to Song *et al*, a piezoelectric converter based cantilever beam was proposed, which generates 19.64 mW when 8 permanent magnets were added as tip mass on the cantilever for an operating commercial high speed Korean train with a speed greater than 300km/hr [28]. Nelson *et al* [29] placed another type of piezoelectric converter on the bottom of the rail track. This system used a piezoelectric film and harvested 1mW of power. A tuned vibrational harvester that recovers 10-50mW of energy was developed by a British company Perpetuum Ltd [30]. Investigation of energy harvesting from train vibrations for low power wireless sensors was done by the French national railway system [31]. Piezoelectric transducers are devices able to generate a voltage, between 3 to 10 V, without requiring a pre-charge to work [32], [33]. Piezoelectric materials are, however, very sensitive to temperature, and therefore need to be applied in environment with limited temperature variability [34]. If piezoelectric materials are subject to high temperatures, they can become de-polarized and inoperative. Generally piezoelectric converters produce a current that is not compatible in microelectronics, but have a high voltage generated compared to electromagnetic converters [35].

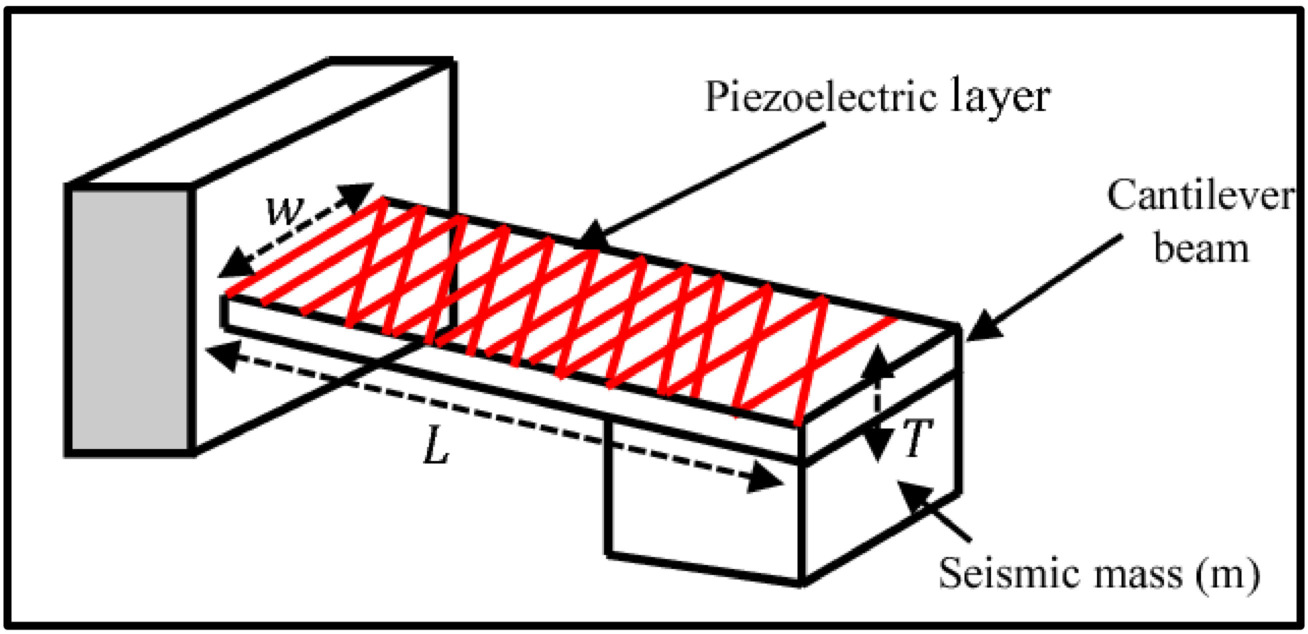

Figure 2. 2: Illustration of a piezoelectric harvester by [18]

Some other research based on the development of vibration converter based on electromagnetic principle. An electromagnetic converter was used by [36], which was placed near the rail and once the train passed, energy would be generated through the coil fixed near the rail. Nelson *et al* harvested an average power of 0.22 Watts using an electromagnetic harvester [37]. Hart *et al* developed a gear and rack mechanism, which maintains the rotational motion of the generator using roller clutches and a flywheel [38]. Also, an average power of 0.1mW is generated if discs and spherical magnets have the same polarization and 0.65mW is generated if discs and spherical magnets have opposite polarization in, where a spherical magnet and spiral coil are placed around a central disc magnet [38]. Bradai *et al* used an electromagnetic vibration converter to generate 10 mW maximum output power and an average power of 1.2volts [39]. However, these converters output a very low voltage with power up to 140mW in low frequency vibration applications, while high frequency applications can output more than 2W [31]. Figure 2.3 illustrates the arrangement of an electromagnetic energy harvester.

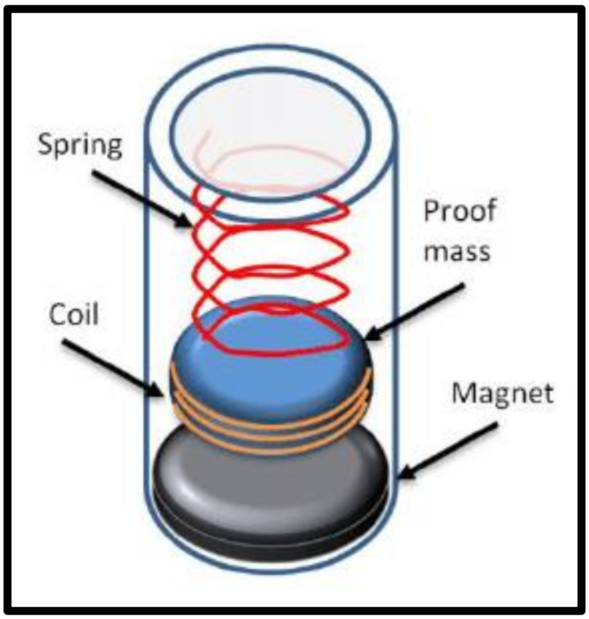

Figure 2. 3: Schematic of a traditional electromagnetic energy harvester [32]

For both the piezoelectric and electromagnetic energy harvesting techniques, there is a challenge of low power scavenged used for low power applications and mechanical component friction.

To improve the power output, some authors like Penamalli and Phillips *et al* developed electromagnetic railway track harvesters which use the rack and pinion design [40], [41]. These have a feature of converting bidirectional linear motion into unidirectional rotational motion. It reduced the negative effects of motion inertia and impact forces in harvester components. Therefore, improving harvester reliability and lifetime. This design still had a challenge of the generator producing an intermittent pulse like power output and operating at erratic speeds which resulted into mechanical wear and impulse stresses [40]–[42].

In order to prevent the draw backs of the rack pinion system due to large inertia, a mechanical motion rectifier system was developed [43]. It has been applied in regenerative shock absorbers, wave energy converter and animal tracking energy harvesting [44], [45]. The mechanical motion Rectifier has potential to power major railroad equipment and infrastructure but its mechanical efficiency is still less than ideal due to mechanical component friction [46].

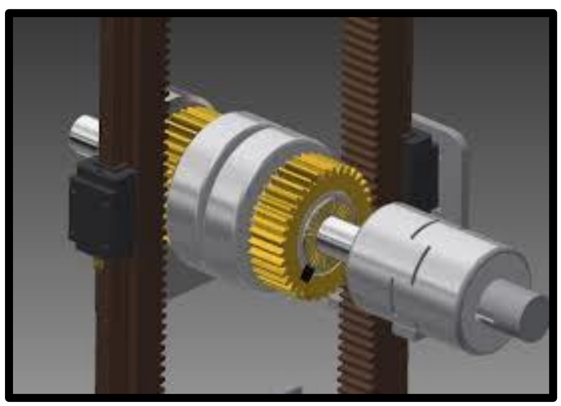

Figure 2. 4: Illustration of a Mechanical Motion Rectifier by [38]

Furthermore, wind energy harvesting from moving trains has been done by [47]. Wind turbines were installed over the train roof and tested. Some of the challenges faced are additional air drag created by the mounted turbine over the train roof, intermittent power generation and dramatic change in practical aspects such as ambient temperature, air density, and altitude. Figure 2.5 shows the details of a wind turbine mounted at the top of the train to harvest wind energy as the train moves.

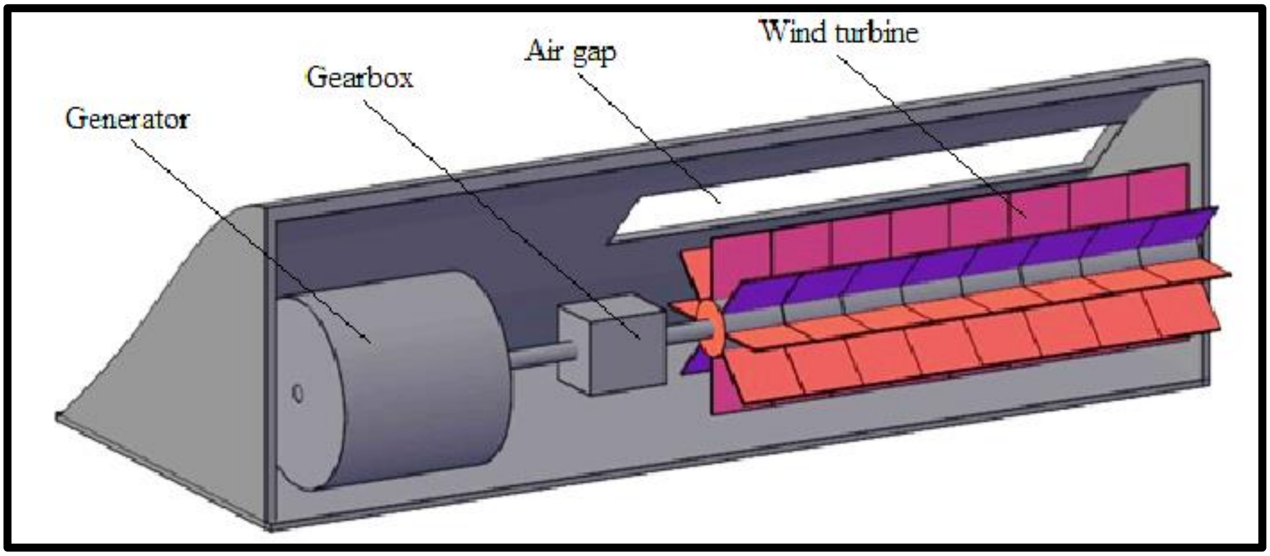

Figure 2. 5: Illustration of wind energy harvesting by [51]

All the above energy harvesting techniques have been developed and used on railway, however, the second degree of freedom oscillator has not been developed. Studies have been done on many types of oscillators for energy harvesting, thou the most common It is a simple system in which the undamped natural frequency is tuned to the excitation frequency [48]. The optimum operational condition of a single degree of freedom to scavenge the maximum amount of energy was investigated using a mathematical model for an energy harvesting device considering steady-state excitation [49]. An assumption was made that the power harvested is the same as the power absorbed by the damper [50]. This SDOF oscillator demonstrated how generators extract energy from environmental vibrating sources.

Another researcher [12], investigated how much energy can be harvested from the vertical vibration of the track due to a passing train using a single linear energy harvesting device. indicate how much energy can be potentially harvested from a typical train pass by. It was found that the harvester should be tuned to a frequency at which the vertical acceleration is the greatest, and this corresponds to one of the train-load frequencies.

It is from these principles that the second degree of freedom oscillator was developed. Therefore, harnessing the vibration kinetic energy from the moving trains and converting it into power. This second degree of freedom oscillator is used to generate more mechanical energy than the SDOF oscillator.

CHAPTER 3 METHODOLGY

3.1 Collection of vibration data

3.1.1 Railway Vibration

Vibrations betide due to the wheel/rail interaction and they can be subdivided as trainload excitation, also known as quasi-static excitation, roughness excitation, flat wheel and others, known as dynamic excitation [49]. [51] compared the quasi-static and dynamic excitation, and showed that the quasi-static is dominant at low frequencies (between 25 to 50 Hz, depending on the train speed) and generates high levels of vibration on the sleepers. Dynamic excitations are dominant at higher frequencies (higher than 25 to 50 Hz depending on the train speed) due to the roughness between the wheel/rail interactions. In a numerical prediction, [52] obtained similar results for sleeper vibration and also showed that the quasi-static deflection is only dominant in very low frequencies for ground vibration close to the track. Regarding the quasi-static excitation, [53] showed that the dominant frequencies from trainload vibrations are integer multiples of the train speed, V, divided by the carriage length, L, and n as number of oscillations;

$$f = \frac{n\,V}{L} \qquad \text{3.1}$$

Secondary data of the Inter- city 125 train at a speed of 195km/h was collected. The secondary data was in figure form (data_figure) shown in Appendix B (3) from which data was read in Matlab [12]. The Acceleration signal of the vertical displacement of the sleeper and time variable data were obtained as Shown in figure 3.1.

The characteristics of the Inter- city 125 train were obtained, the characteristics of the vibration were obtained from the acceleration signal and amplitude spectrum graph.

3.1.2 Vibration Characteristics of an Inter- city 125 train

The sleeper's vertical acceleration was measured at Steventon on the Great Western Main Line in the UK as an Inter- city 125 train at a speed of 195 km/h (54.2 m/s) passed by. The track consists of continuously welded rail attached by spring clips and supported via rubber pads on concrete monoblock sleepers in ballast. The train consists of two diesel power cars, one at each end, with seven passenger coaches between them. Each vehicle is supported by four wheel-sets arranged in two bogies, each of which has a wheelbase of 2.6 m. The power cars are about 18 m long, while the passenger coaches are about 23 m long. Seven seconds of data were recorded at a sampling frequency of 1 kHz as the train passed by, and the resulting acceleration signal is shown in Figure 3.1 [12]. According to Figure 3.1, the train induces vibration of the track for about 4 seconds, that is, from 1.5 seconds to 5.5 seconds.

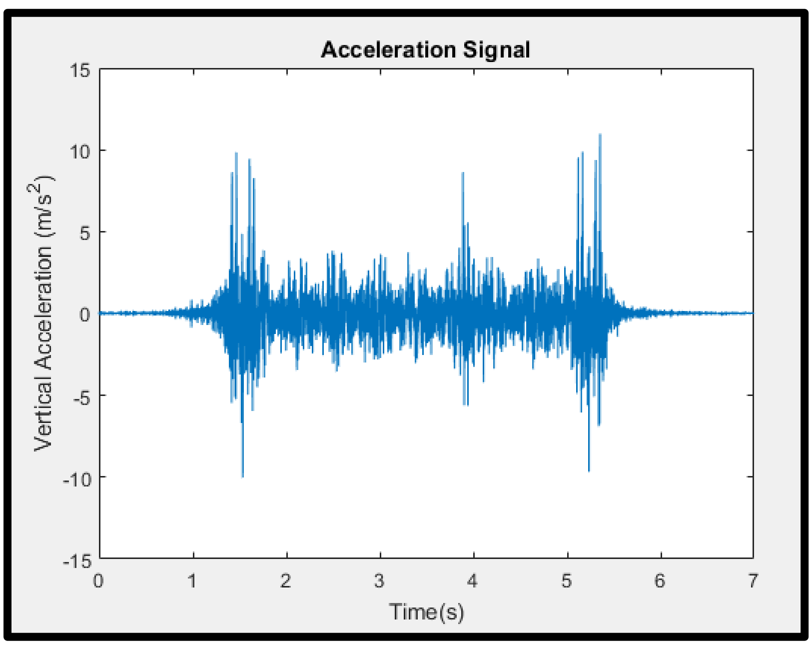

Figure 3. 1: Measured vertical acceleration of a sleeper as an Inter-city 125 train passes

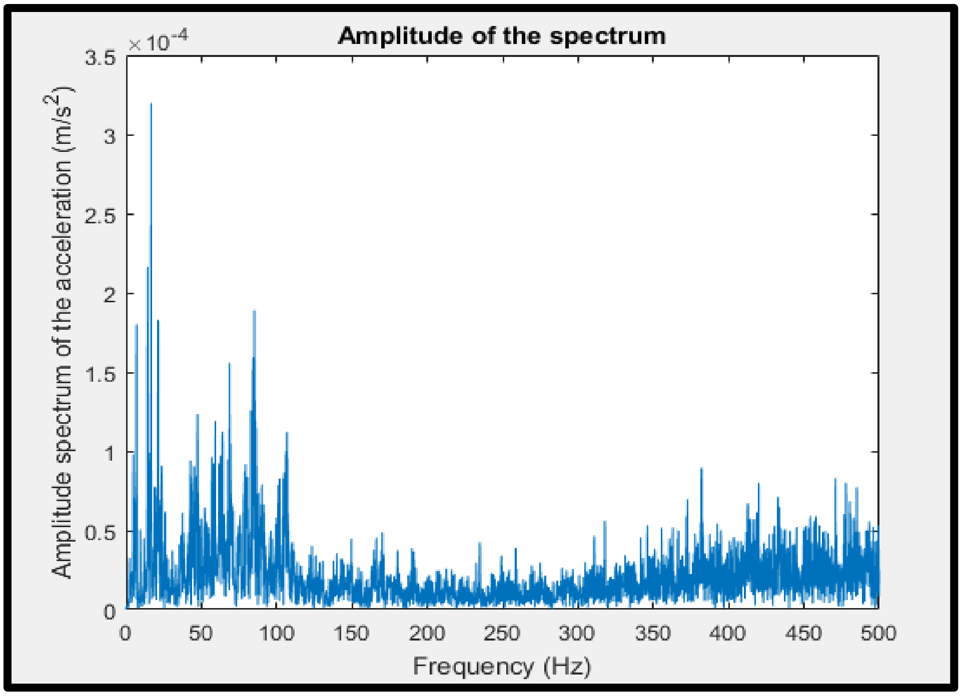

Figure 3. 2: Amplitude spectrum of the sleeper acceleration

From figure 3.2 the amplitude spectrum of the sleeper acceleration shows the dominant frequencies, in which the most significant amount of energy can be harvested can be seen. The dominant frequencies, corresponding to the highest peaks are at about 7.14 Hz, 14.29Hz, 16.57Hz, and 21.29Hz.

3.2 Modeling the Energy Harvester as a damped Two Degree of Freedom Oscillator

The energy harvester is a two degree of freedom mass-spring-damper oscillator enclosed in a rigid housing. This Oscillator is placed under the sleeper from which the vibrating base transmits vertical vibration to the seismic mass through the spring and damper. The schematic representation of the Energy Harvester is shown in figure 3.3.

Assumption

- The vibration of the energy harvesting device does not affect the vibration of the sleeper.

- The energy harvested is the same as the energy dissipated by the damper, therefore identifying the ideal upper limit case where no mechanical loss is considered.
- Electrical energy harvested is equal to the mechanical energy dissipated

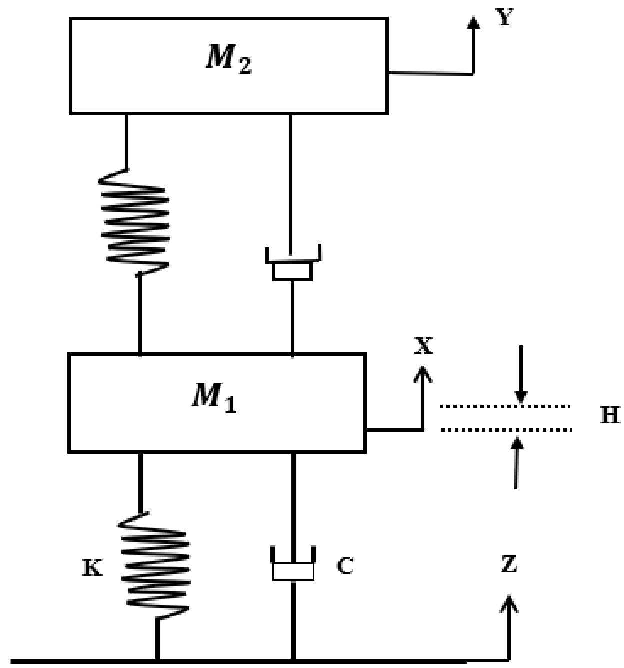

Figure 3. 3: Model of a two degree of freedom, damped spring- mass system

Where;

M_1 and M_2 are masses

K is the spring stiffness

C is the damping coefficient

X, Y, Z are the displacements of mass 1, mass 2 and the casing respectively

H is the relative displacement of the energy harvester

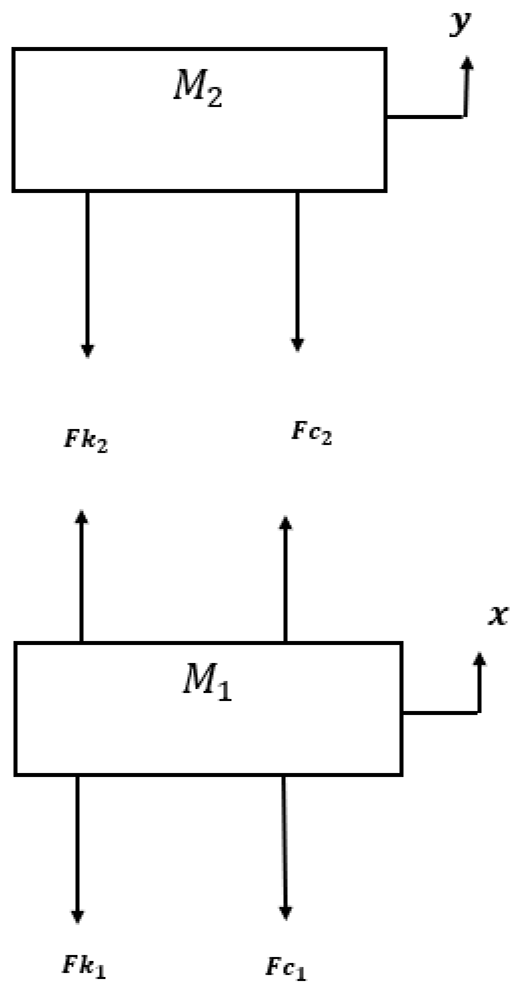

Figure 3. 4: Free body diagram of the mass-spring-damper system

Assume a linear spring and damper system with x=0, y=0, when the system is in static equilibrium (allows gravity to be neglected).

$\sum F$ = ma ……………………………………………………………………………………...3.1

Mass 1

Fk_1+ Fc_1 - Fk_2 - Fc_2 = $M_1\ddot{x}$ ………………………………………………………………...3.2

$Fk_1 = k_1(x - z)$ …………………………………………………………………………....3.3

$Fc_1 = c_1(\dot{x} - \dot{z})$ ……………………………………………………………………...… 3.4

$Fk_2 = k_2(y - x)$……………………………………………………………………………………….3.5

$Fc_2 = \ c_2(\dot{y} - \dot{x})$ ……………………………………………………………………………………3.6

Mass 2

- Fk_2 - Fc_2 = $M_2\ddot{y}$ ……………………………………………………………………………3.7

3.2.1 Equation of Motion of the system

The derivation of the equations is based upon a Newtonian approach, as the Newton´s Second Law is applied to the free body diagram. The equation of motion is shown in equation (3.8 and 3.9) from newton's second law of motion. This equation is solved using state space equation in Matlab to get the maximum relative displacement of the two degree of freedom oscillator with an input of force (F0) described in the code in appendix A (4), the input force (F0) is made up of some variables; spring 1 stiffness, damping coefficient of damper 1, velocity and displacement of the input vertical signal of the sleeper in figure 3.1. The velocity of the signal is found using cumulative trapezoidal integration of the input acceleration signal in figure 3.1. Likewise, the displacement of the input signal is found using cumulative trapezoidal integration of the input velocity signal. State space simply converts the equation to first degree. The input force (F0) is put into the state space equation. The relative mass displacement of the two degree of freedom oscillator is obtained from the state space equations. Detailed code of finding maximum relative mass displacement is in appendix A (4).

After substituting equations 3.3, 3.4, 3.5 and 3.6 in to 3.2 and 3.7, the equations of motion of the energy harvester can be written as,

$m_1\ddot{x} + (c_1 + c_2)\dot{x} + (k_1 + k_2)x - k_2y - c_2\dot{y} = k_1z + c_1\dot{z}$ …………………………………..3.8

$m_1\ddot{y} + k_2y + c_1\dot{y} - c_1\dot{x} - k_2x = 0$ …………………………………………………………...3.9

Using State space;

x=x_1……………………………………………………………………………………3.10

$\dot{x}_1 = x_2$……………………………………………………………………………………3.11

$\dot{x}_2 = \frac{-(k_1+k_2)}{m_1} x_1(t) - \frac{(c_1+c_2)}{m_1} x_2$ (t) + $\frac{k_2}{m_1} x_3(t)$ + $\frac{c_2}{m_1} x_4$ (t) + $\frac{F}{m_1}$……………………………..3.12

y = x_3…………………………………………………………………………………..3.13

$\dot{x}_3 = x_4$ ……………………………………………………………………………….3.14

F= $k_1 z + c_1 \dot{z}$…………………………………………………………………...3.15

$\dot{x}_4$= $\frac{k_2}{m_2} x_1(t)$ + $\frac{c_2}{m_2} x_2(t)$ - $\frac{k_2}{m_2} x_3(t)$ - $\frac{c_2}{m_2} x_4(t)$…………………………………………………3.16

$$\begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{Bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ \frac{-(k_1+k_2)}{m_1} & \frac{-(c_1+c_2)}{m_1} & \frac{k_2}{m_1} & \frac{c_1}{m_1} \\ 0 & 0 & 0 & 1 \\ \frac{k_2}{m_2} & \frac{c_2}{m_2} & -\frac{k_2}{m_2} & -\frac{c_2}{m_2} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{m_1} \\ 0 \\ 0 \end{bmatrix} F(t) \quad \text{……………………….3.17}$$

For state space equations in the form;

$\dot{X}(t) = A.x(t) + B.u(t)$………………………………………………………………... 3.18

$y(t) = C.x(t) + D.u(t)$ ……………………………………………………………..3.19

We obtain;

$$\begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{Bmatrix} = A \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + B \begin{bmatrix} F \\ 0 \end{bmatrix} \quad \text{…………………………………………………………....3.20}$$

$$y = C \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + D \begin{bmatrix} F \\ 0 \end{bmatrix} \quad \text{.......... 3.21}$$

A, B, C, D are the respective matrices of the mechanical system defined as follows;

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ \frac{-(k_1+k_2)}{m_1} & \frac{-(c_1+c_2)}{m_1} & \frac{k_2}{m_1} & \frac{c_1}{m_1} \\ 0 & 0 & 0 & 1 \\ \frac{k_2}{m_2} & \frac{c_2}{m_2} & -\frac{k_2}{m_2} & -\frac{c_2}{m_2} \end{bmatrix} \quad \text{.......... 3.22}$$

$$B = \begin{bmatrix} 0 \\ \frac{1}{m_1} \\ 0 \\ 0 \end{bmatrix} \quad \text{.......... 3.23}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \quad \text{.......... 3.24}$$

$$D = [\,0\,] \quad \text{.......... 3.25}$$

Where;

k is the spring stiffness

c_1 *and* c_2 are the damping coefficients

m_1 *and* m_2 are the masses of the energy harvester

F is the input force from the sleeper vibration (z being the displacement due to vibration and $\dot{z}$ being the velocity of the vibration)

The above state space equation is solved in Matlab to find the relative displacement of the mass system.

Finding the relative displacement of the mass system using the 30km/h speed of AALRT in Matlab; the state space is written using a Matlab code in appendix A (4), the displacement is found then the amplitude of the displacement is found using the code (Amplitude y). All the parameters of the oscillator have to be optimum,

3.3 Simulation of the Energy Harvested from the 2DOF Oscillator

The energy simulated is mechanical energy from which electrical energy can be converted and used to supply the axle counters.

3.3.1 Existing Model

The base excited 2DOF system shown in figure 13 is considered, whose equation of motion is shown in equation 3.8 and 3.9.

The energy harvested at time te [12];

$E(te) = \int_0^{te} F_d dz$ ……………………………………………………………………..3.26

But $\dot{z}\, dt = dz \; and \; F_d = C\dot{z}$ ……………………………………………………………..3.27

Substituting 3.27 into 3.26 yields the energy harvested at period te, hence equation 3.28

$E(te) = \int_0^{te} c\, \dot{z}^2\, dt$ ……………………………………………………………………..3.28

Where;

C is the damping coefficient

$\dot{z}$ is the input signal velocity

From figure 15 it can be seen that the train induces vibrations from approximately 1.5 s to about 5.5 s, so that the input duration can be considered to be approximately 4 s. Therefore, t_e as in Matlab code is 4 seconds.

3.3.2 Effect of Damping coefficient on Energy Harvested

After the mass relative displacement of the system has been found, the equation 3.26 of energy harvested is formulated in Matlab as shown in the code in appendix A (1). The energy harvested is found for the respective damping coefficient range (0.5Ns/m to 5.5Ns/m) [12]. A graph of energy harvested against natural frequency is plotted to see the effect of damping coefficient on energy harvested.

3.3.2 Effect of Spring Stiffness on Energy Harvested

The whole procedure of finding energy harvested is repeated with a spring stiffness range of 0.12N/m, 1.2N/m, 5N/m, and 10N/m. A graph of energy harvested against natural frequency is plotted to see the effect of spring stiffness on energy harvested. Matlab code found in appendix A (2)

3.3.3 Effect of Mass on Energy Harvested

The whole procedure of finding energy harvested is repeated with a mass range of 0.5kg, 1kg, 1.5kg, and 2kg. A graph of energy harvested against natural frequency is plotted to see the effect of mass on energy harvested. Matlab code found in appendix A (3).

3.3.4 Energy harvesters within 1km and 10km of a railway line

Energy harvesters that can be placed within 1km;

1 rail is 25m with 16 sleepers

1km = 1000m

1km = $^{1000}/_{25}$ rails

1km = 40 rails

Total length of the train

Power cars = 18m long

Passenger coaches = 23m long

Total length of train = (18×2) + (23×7) = 197m

How many sections will the train pass in 1km = 1000/197 = 5.1 sections

Therefore, a minimum of 5 energy harvesters were put in 1km, assuming the train is moving at the same speed of 195km/h.

Position of the energy harvester;

$^{40\ rails}/_{5}$ = 8 rails

Therefore, the energy harvester will be placed every after 8 rails.

How many sections will the train pass in 10km = (5.1×10) = 51sections

Therefore, 51 energy harvesters were put in 10km, assuming the train is moving at the same speed of 195km/h.

In summary, to get the minimum number of energy harvesters to be placed in 1km.

How many sections will the train pass in 1km = $\frac{1000\ m}{Total\ length\ of\ train\ (m)}$ = Number of sections

The number of sections is equivalent to the number of energy harvesters you can place in 1km.

CHAPTER 4 RESULTS AND DISCUSSION

4.2 Model of the Two-degree-of-freedom oscillator (Energy Harvester)

According to the schematic representation of a 2 DOF oscillator, the model has two masses each of displacement x and y respectively, supported by springs and damping elements represented by standard symbols whose properties are represented by k and c in the case of suspension stiffness and damping respectively.

The acceleration signal shown in figure 3.1 is considered to be the base input to the energy harvesting device shown in figure 3.3 which is a 2 DOF mass-spring-damper system encased in a rigid housing. The maximum relative displacement of the mass is limited to H, which is the relative displacement between the mass 1 and the casing. The optimum mass relative displacement is shown in figure 4.1. The displacement starts increasing gradually from 5 Hz to 19.5 Hz frequency and there after destabilizes. The optimum mass relative displacement whose magnitude is 0.43 m happens at 19.14 Hz frequency as shown in figure 4.1.

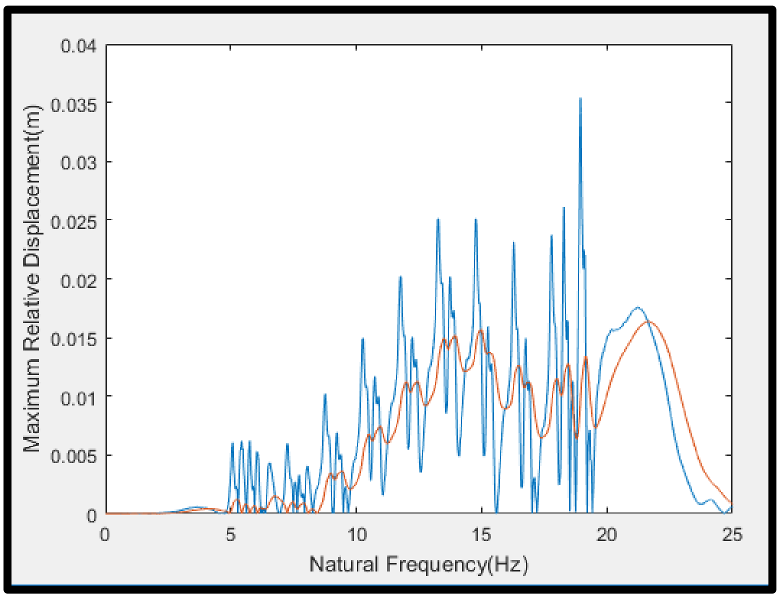

Figure 4. 1: Optimum mass relative displacement

4.3 Simulation

4.3.1 Sensitivity Analysis

The effect of damping coefficient, mass and spring stiffness was checked. According to figure 4.2, it was found that the most effective damping coefficient resulting in the highest energy harvested is 5.5 Ns/m. It can also be observed the highest energy harvested takes place at the 19.14 Hz natural frequency. During the calculation of the optimum energy harvested, 5.5 damping coefficient shall be used. In addition, energy is harvested at a reasonable amount from 10 Hz to 19.27 Hz at intervals, with 1.61 Hz being the largest interval before the energy diminishes to zero, it remains at zero for 0.63 Hz after every interval.

According to figure 4.3, the higher the spring stiffness, the higher the energy harvested, in this case, 10N/m being the highest spring stiffness. Its observed that there is no energy harvested from 0 Hz to 10 Hz. Also, a significant amount of energy is harvested from 11.67 Hz to 19.27 Hz, there after diminishing to zero, where it stays constant at zero. Given the damping coefficient and a natural frequency at an instant, the spring stiffness can be calculated using equation 4.1.

$$c = 2\,\varepsilon\,\sqrt{km} \quad \text{..........} 4.1$$

Where;

c is damping coefficient

ε is damping ratio

k is spring stiffness

m is mass

According to figure 4.4, the mass 1, 1.5, and 2 have the same energy harvested, with mass 0.5 having a higher energy harvested. The natural frequency at which energy harvested is highest is 19.14 Hz and the lowest natural frequency is 7.643 Hz. After the sensitivity analysis is done, the maximum relative displacement is plotted in figure 4.1 and the optimum energy harvested is plotted in figure 4.5. It is observed that the highest energy is harvested at 19.14 Hz with a value of 1.362 kJ. There is no energy harvested after 19.59 Hz.

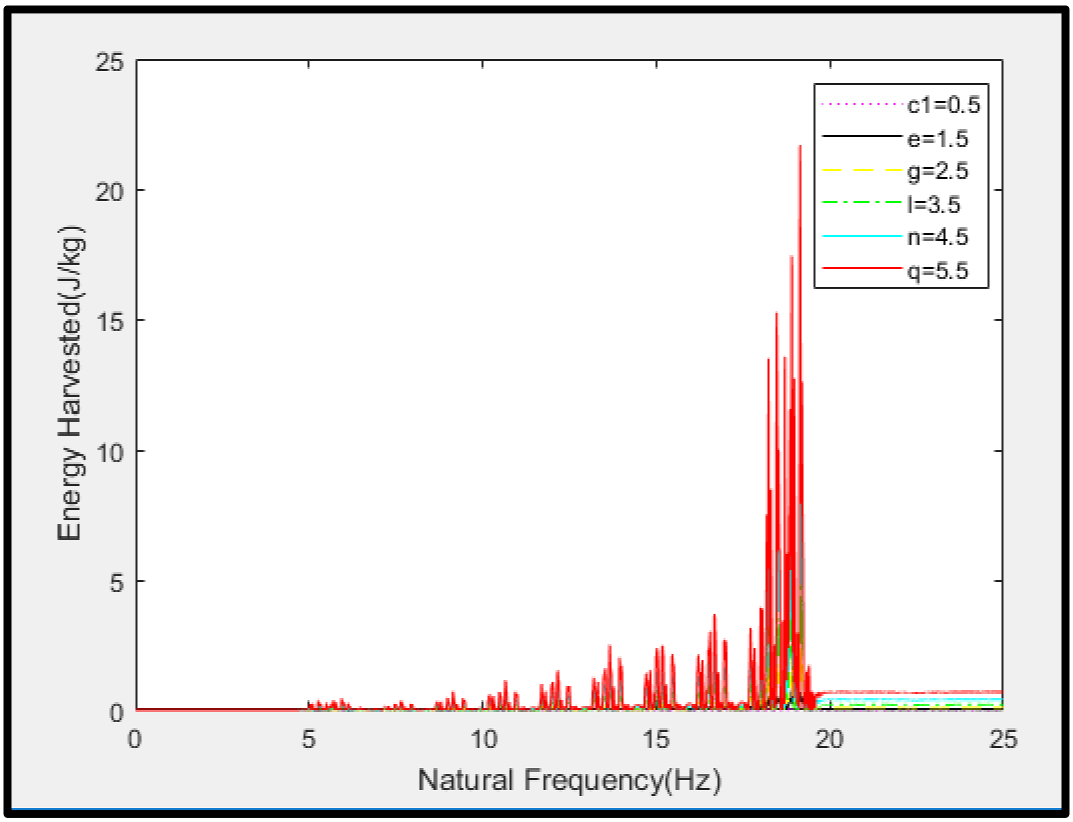

Figure 4. 2: Energy harvested with respective to different damping coefficients

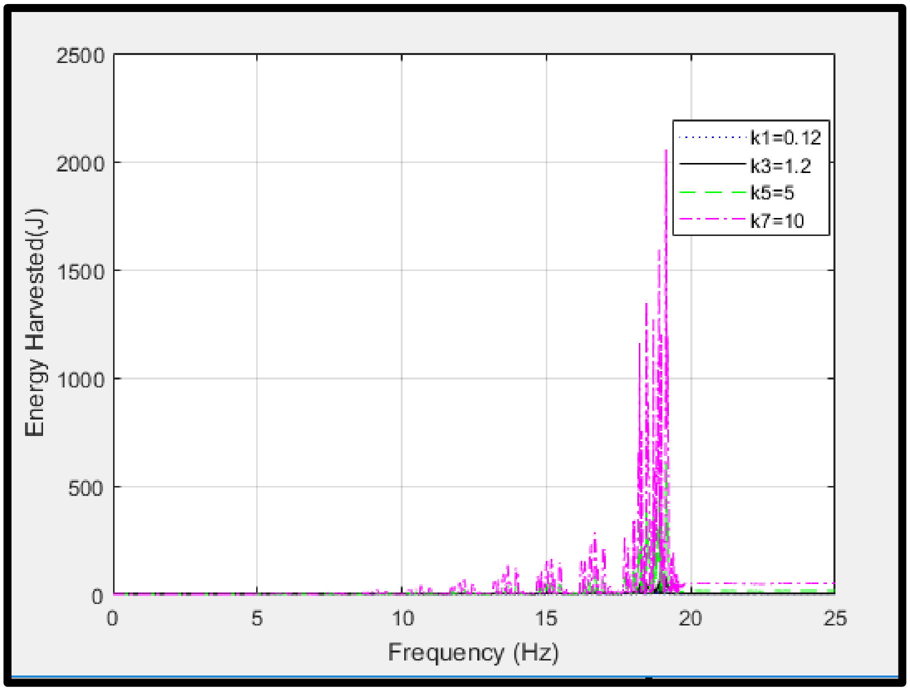

Figure 4. 3: Effect of spring stiffness on Energy harvested

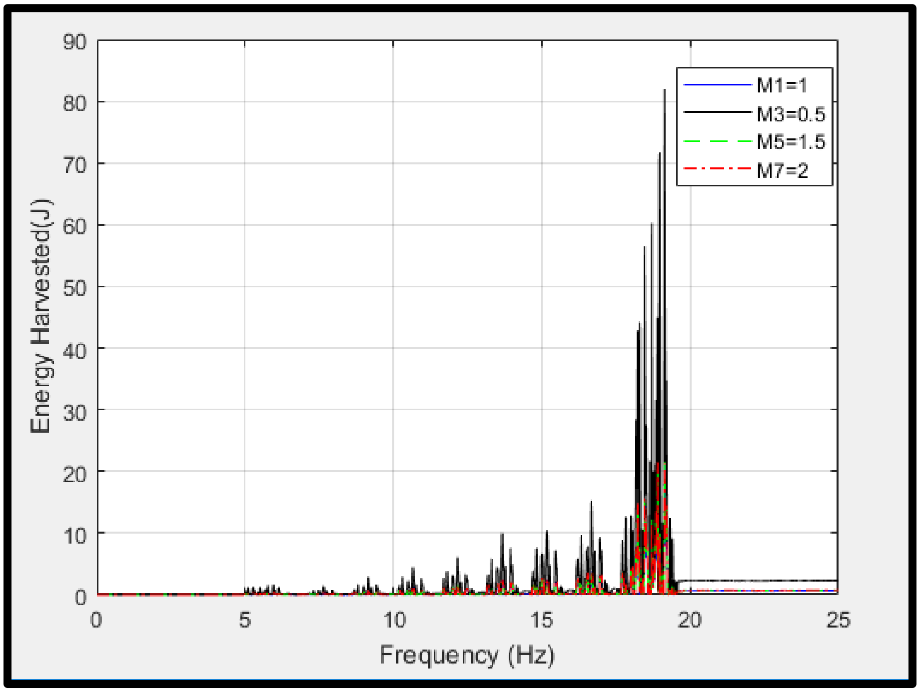

Figure 4. 4: Effect of Mass on Energy harvested

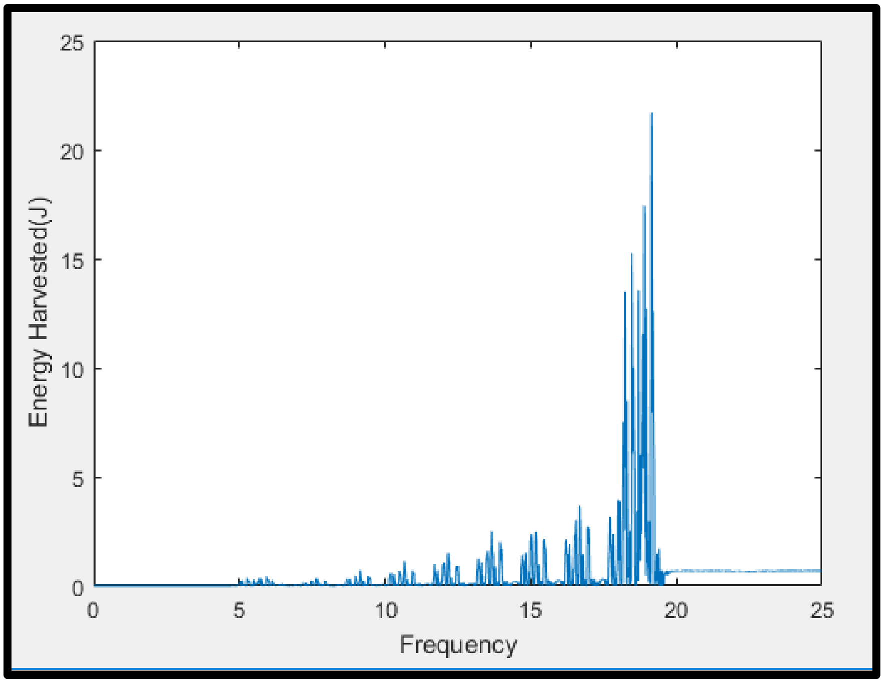

Figure 4. 5: Optimum energy harvested

4.3.2 Cumulative Energy Harvested

According to figure 4.6, the lowest natural frequency which marks the beginning of energy harvested is 7.643Hz. A Matlab code in appendix A (6) was used to calculate the cumulative energy harvested for different speeds. The energy harvested for the respective speeds was got from the Matlab code in appendix A (6). Optimum parameters such as mass of 1kg because it's the beginning of the energy harvested being equal to any size of mass, spring stiffness as used by Bradai *et al* and damping coefficient of 5.5 Ns/m as it has the highest energy harvested from the sensitivity analysis. The higher the speed, the higher the power generated. Its observed that at 195km/h, the highest energy is 21.68 J, at 120 km/h, the highest energy is 8.211 J, at 80 km/h, the highest energy is 3.649 J, at 70 km/h, the highest energy is 2.794 J, at 60 km/h, the highest energy is 2.053 J, at 50 km/h, the highest energy is 1.426 J, at 30 km/h, the highest energy is 0.8644 J. All the respective highest energies happen at 19.14 Hz.

Cumulative Energy Harvested at 195 km/h: 1.362e+03 J

Power harvested = $\frac{\text{Cumulative Energy Harvested}}{4}$ J/s

Power harvested = $\frac{1.362e+03}{4}$ J/s

Power harvested = 340.5 W

In table 1, the cumulative energy harvested at different speeds is used to calculate the respective power generated for the Inter-city 125 train, Addis Ababa-Djibouti train and AALRT at their maximum and minimum operation speeds.

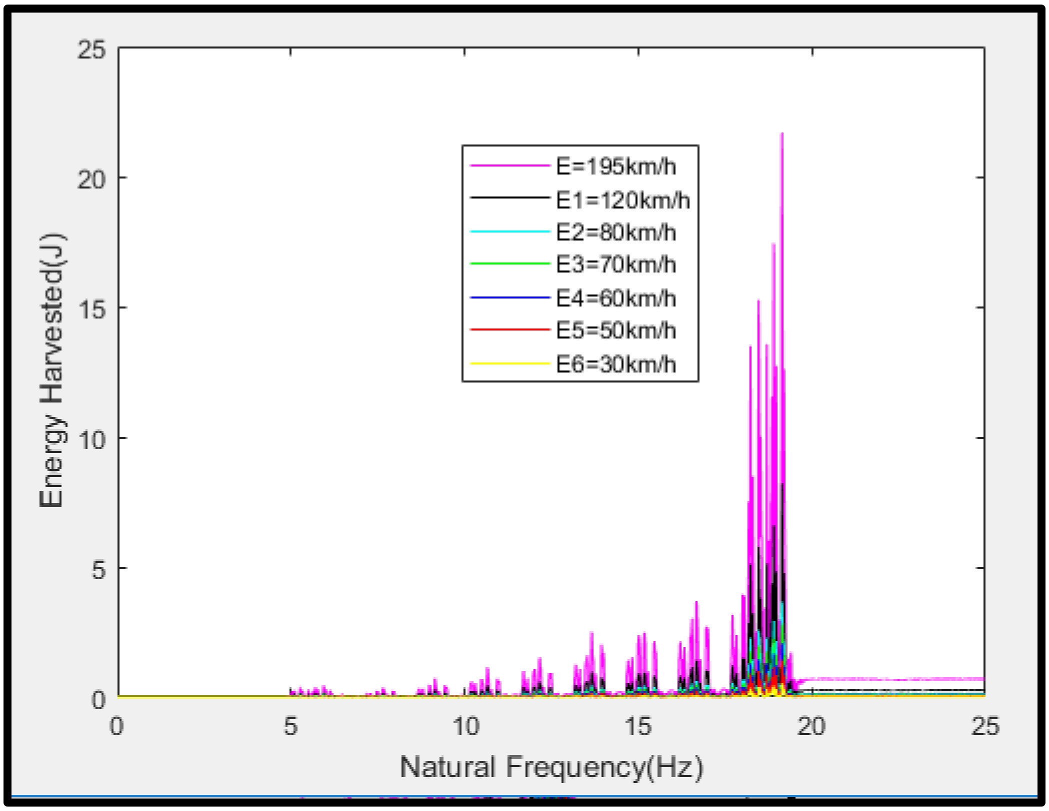

Figure 4. 6: Energy harvested at different speeds

Table 4- 1: Cumulative power harvested by the different speeds of the train

Railway	Speed	Highest Energy	Power Generated
Inter- city 125 train	195km/h	21.68 J	$\frac{1.3620e+03}{4} = 340.5\ W$
Addis Ababa-Djibouti Train	Max: 120km/h	8.211 J	$\frac{515.78}{4} = 128.9\ W$
	Min: 70km/h	2.794 J	$\frac{175.5}{4} = 43.9\ W$
AALRT	Max: 70km/h	2.794 J	$\frac{175.5}{4} = 43.9\ W$
	Min: 30km/h	0.8644 J	$\frac{32.24}{4} = 8.06\ W$

Table 4- 2:Power requirements of some track side equipment at AALRT

	Axle counter	Level Crossing	Point Machine	Signal Lights
Power Requirements	20W	110 W	380 - 400V	220V

Some Communication and Signaling Equipment are shown and discussed below;

A: Axle counter

Each axle counter requires 20 Watts, operating typically at 24V $\pm$ 5% DC. There are 313 axle counters in the whole AALRT. Figure 4.7 shows the placement position of the axle counter on the AALRT track, which is between the sleepers on the rail.

Figure 4. 7: Axle counter on the track

B: Level Crossing

Level crossings require 110Watts, operating at 220 V AC at 0.5 Amps peak current. Figure 4.8 shows a level crossing at Kality. It consists of signal lights, balises before the road. the signal crossing between the rail line and road network traffic.

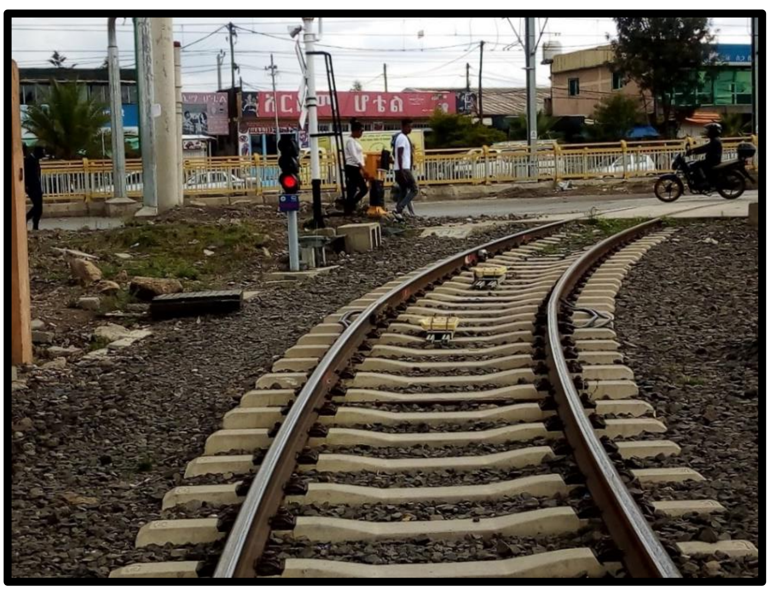

Figure 4. 8: Level crossing at AALRT Kality

C: Point Machine

Operates between 380 – 400 V. Figure 4.9 and 4.10 show point machines which are used to coordinate the balises to determine the color displayed at the traffic lights to guide the train driver either to proceed (green), wait (yellow) or stop (red).

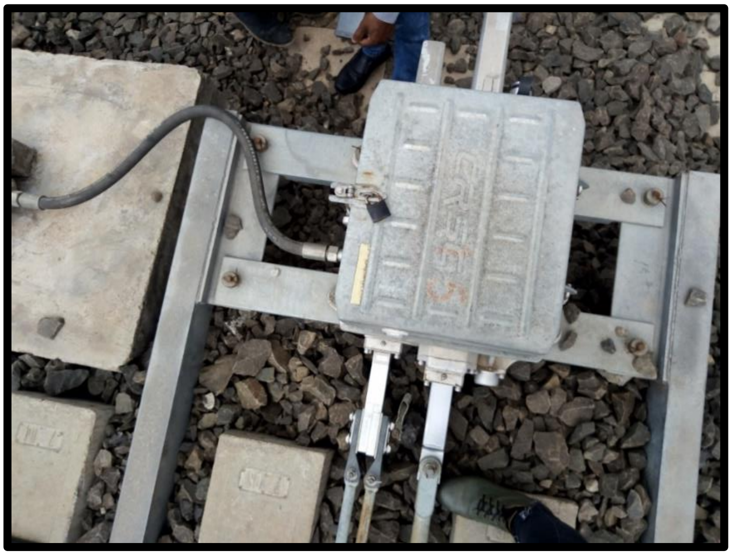

Figure 4. 9: Point machine top view

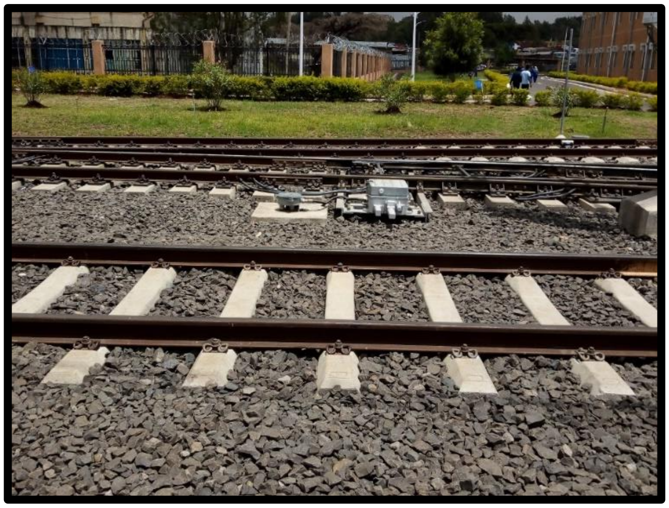

Figure 4. 10: Point machine at AALRT Kality Depot

D: Signal lights

Operate at 220 V. Figure 4.11 shows a signal light which warns the driver if there is train in the next section. These are generally important for safe traffic control on a railway line.

Figure 4. 11: Signal light at AALRT Kality Depot

Other track side equipment

Equipment shown in figure 4.12 is a Euro balise at Kality used to detect trains in a block on the line. Its also a safety equipment to prevent accidents on a railway line.

Figure 4. 12: Euro Balise at AALRT Kality Depot

4.3.3 Total Power Consumption of Communication and Signaling Equipment

Depot

The data below was collected from the Kality Depot so as to calculate the power consumption of the communication and signaling equipment at the Kality depot.

Table 4- 3: Central Signal at control Center

Central Signal at control Center (Amps)	34.40	34.36	34.39	34.38 (Average Current)

Power consumption of communication and signaling equipment at Depot = (34.38 × 400) W = 13.752 kW

Main line

The following data was collected from the Kality power substation;

Table 4- 4: Central Signal at control Center

Power supply of communication Equipment (Amps)	3.048	2.98	3.02	2.88	2.982 (Average Current)

Table 4- 5: Power supply of signal at main line

	I_1	I_2	I_3	Average Current
Power supply of signal (Amps)	8.06	7.68	8.00	7.913
	7.80	7.66	8.02	7.827
	7.86	8.02	7.84	7.907
	Overall Average Current = 7.88			

The above main line data was collected for one substation, so finding the power consumption of communication and signaling equipment of the 20 substations, the power consumption of the Kality substation is multiplied by 20.

Power consumption of the communication and signaling equipment of the Kality Substation

$= \{(2.982 \times 400) + (7.88 \times 400)\}$ W

= 4.345 kW

Power consumption of the communication and signaling equipment of the main line

$= (4.345 \times 20)$ kW

= 86.896 kW

Total power consumption of the communication and signaling equipment of AALRT

$= (86.896 + 13.752)$ kW

= 100.65 kW

4.3.4 Power Contribution of the 2DOF Oscillator

The normal operating speed of trains at AALRT is 30km/h whose energy harvested from the 2DOF oscillator is $8.06\ W$.

1 oscillator gives 8.06 W

Number of oscillators to meet the total power consumption of the communication and signaling equipment of AALRT

$= \left(\frac{100.65 \times 1000}{8.06}\right) oscillators$

$= 12487.6 \approx 12488\ oscillators$

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Table 5- 1: Comparison of the SDOF and 2DOF oscillator parameters

Speed = 195km/h		
Oscillator Parameters	**SDOF**	**2DOF**
Maximum energy harvested [J]	0.2595	21.68
Natural Frequency [Hz]	16.57	19.14
Relative Displacement [mm]	5.056	35.45

In conclusion, a 2DOF energy Oscillator was modeled from the vibration of a passing train to power the axle counter equipment at AALRT substations. The effect of damping coefficient, spring stiffness and mass of the oscillator was investigated. It was found that the most effective damping coefficient resulting in the highest energy harvested is 5.5 Ns/m. It is observed that as the spring stiffness increases, the rate at which energy is harvested also increases, this can be attributed to the two DOF being employed in the study. Any mass from 1 kg and above has the same energy harvested, while any mass below gives a higher energy harvested. The relative displacement was found to be 35.45 mm. The natural frequency at which energy harvested is highest is 19.14 Hz and the lowest natural frequency is 7.643 Hz. It can be found that a 2DOF energy oscillator can harvest up to $8.06\,W$ for AALRT's lowest speed. It takes 12488 oscillators to meet the total power consumption of the communication and signaling equipment of AALRT main line and Kality depot.

From the above stated findings, the 2DOF oscillator harvests a higher mechanical energy than the SDOF oscillator. This 2DOF oscillator meets the energy demand of some way side equipment i.e. the communication and signaling equipment.

The limitations during the course of my research has been;

- Lack of available data from the AALRT
- Inadequate finances and time for the research
- Lack of available software

5.2 Recommendations

Future work should be done to investigate the performance of an energy harvester using a nonlinear two degree of freedom mass spring-damper system. Formulate an algorithm of calculating the energy harvested using a multi-degree of freedom oscillator. Finally, investigation of how much electrical energy can be harvested and stored from the 2DOF oscillator.

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APPENDIX A: CODES IN MATLAB

1. **Code for finding Energy Harvested with a range of Damping coefficient.**

```
% Finding Energy Harvested with respective to different damping
% coefficients
M1=1; % Mass
M2=1;
c1=0.5
c2=c1;
k1=0.12;
k2=0.12;
te =0:0.00057143:4;

fig = gcf; % Obtaining Acceleration signal data of vertical
displacement of a sleeper from data_figure
axObjs = fig.Children;
dataObjs = axObjs.Children;
t= dataObjs(1).XData;
u= dataObjs(1).YData;

% velocity of the acceleration signal
velocity=cumtrapz(u,t);
```

```
zdot=velocity;

% Displacement of the acceleration signal
displacement=cumtrapz(velocity,t);
z=displacement;

F0=(k1.*z)+(c1.*zdot);
N=4;
A=[zeros(N/4)  eye(N/4)  zeros(N/4)  zeros(N/4);-M1\(k1+k2)  -
M1\(2.*c1)  M1\k2  M1\c1;  zeros(N/4)  zeros(N/4)  zeros(N/4)
eye(N/4);M2\k2 M2\c1 -M2\k2 -M2\c1];
B=[zeros(N/4);inv(M1);zeros(N/4);zeros(N/4)];
C=[zeros(N/4)   ones(N/4)   zeros(N/4)   zeros(N/4);zeros(N/4)
zeros(N/4) zeros(N/4) ones(N/4)];
D=0;
sys=ss(A,B,C,D);

z0=[0 0 0 0];
y=lsim(sys,F0,t,z0); % F0,t define the input signal. y is the
mass relative displacement.
b1=abs(y(:,1));
S1=c1.*(y(:,1).^2);  %  Finding  the  energy  harvested  from
formula.
E1=cumtrapz(S1,te);
```

```
%  second
M1=1;   % Mass
M2=1;
d=1;
c2=d;
k1=0.12;
k2=0.12;
F1=(k1.*z)+(d.*zdot);
N=4;
A=[zeros(N/4)  eye(N/4)  zeros(N/4)  zeros(N/4);-M1\(k1+k2)  -
M1\(2.*d)  M1\k2  M1\d;  zeros(N/4)  zeros(N/4)  zeros(N/4)
eye(N/4);M2\k2 M2\d -M2\k2 -M2\d];
B=[zeros(N/4);inv(M1);zeros(N/4);zeros(N/4)];
C=[zeros(N/4)  ones(N/4)  zeros(N/4)  zeros(N/4);zeros(N/4)
zeros(N/4) zeros(N/4) ones(N/4)];
D=0;
sys=ss(A,B,C,D);

z0=[0 0 0 0];
y1=lsim(sys,F1,t,z0);  % u,t define the input signal. y is the
mass relative displacement.
b2=abs(y1(:,1));
```

```
S2=d.*(y1(:,1).^2);     % Finding the energy harvested from
formula.
E2=cumtrapz(S2,te);


% Third
M1=1;   % Mass
M2=1;
e=1.5; % Damping coefficient
c2=e;
k1=0.12; % Spring stiffness
k2=0.12;
F2=(k1.*z)+(e.*zdot);
N=4;
A=[zeros(N/4)  eye(N/4)  zeros(N/4)  zeros(N/4);-M1\(k1+k2)  -
M1\(2.*d)  M1\k2  M1\d;  zeros(N/4)  zeros(N/4)  zeros(N/4)
eye(N/4);M2\k2 M2\d -M2\k2 -M2\d];
B=[zeros(N/4);inv(M1);zeros(N/4);zeros(N/4)];
C=[zeros(N/4)  ones(N/4)  zeros(N/4)  zeros(N/4);zeros(N/4)
zeros(N/4) zeros(N/4) ones(N/4)];
D=0;
sys=ss(A,B,C,D);


z0=[0 0 0 0];
```

```
y2=lsim(sys,F2,t,z0);  % u,t define the input signal. y is the
mass relative displacement.
b3=abs(y2(:,1));
S3=e.*(y2(:,1).^2);    % Finding the energy harvested from
formula.
E3=cumtrapz(S3,te);


% forth
M1=1;    % Mass
M2=1;
f=2;     % damping coefficient
c2=f; % damping coefficient
k1=0.12;
k2=0.12;
F3=(k1.*z)+(f.*zdot);
N=4;
A=[zeros(N/4)  eye(N/4)  zeros(N/4)  zeros(N/4);-M1\(k1+k2)  -
M1\(2.*f)  M1\k2  M1\f;  zeros(N/4)  zeros(N/4)  zeros(N/4)
eye(N/4);M2\k2 M2\f -M2\k2 -M2\f];
B=[zeros(N/4);inv(M1);zeros(N/4);zeros(N/4)];
C=[zeros(N/4)  ones(N/4)  zeros(N/4)  zeros(N/4);zeros(N/4)
zeros(N/4) zeros(N/4) ones(N/4)];
D=0;
sys=ss(A,B,C,D);
```

```
z0=[0 0 0 0];
y3=lsim(sys,F3,t,z0)   % u,t define the input signal. y is the
mass relative displacement.
b4=abs(y3(:,1));
S4=f.*(y3(:,1).^2);    % Finding the energy harvested from
formula.
E4=cumtrapz(S4,te);

% fifth
M1=1;   % Mass
M2=1;
g=2.5;  % damping coefficient
c2=g; % damping coefficient
k1=0.12;
k2=0.12;
F4=(k1.*z)+(g.*zdot);
N=4;
A=[zeros(N/4)  eye(N/4)  zeros(N/4)  zeros(N/4);-M1\(k1+k2)  -
M1\(2.*g)  M1\k2  M1\g;  zeros(N/4)  zeros(N/4)  zeros(N/4)
eye(N/4);M2\k2 M2\g -M2\k2 -M2\g];
B=[zeros(N/4);inv(M1);zeros(N/4);zeros(N/4)];
C=[zeros(N/4)  ones(N/4)  zeros(N/4)  zeros(N/4);zeros(N/4)
zeros(N/4)  zeros(N/4) ones(N/4)];
```

```
D=0;
sys=ss(A,B,C,D);

z0=[0 0 0 0];
y4=lsim(sys,F4,t,z0);   % u,t define the input signal. y is the mass relative displacement.
b5=abs(y4(:,1));
% plot(t,b5);
S5=g.*(y4(:,1).^2);    % Finding the energy harvested from formula.
E5=cumtrapz(S5,te);

% sixth
M1=1;   % Mass
M2=1;
h=3; % damping coefficient
c2=h; % damping coefficient
k1=0.12;
k2=0.12;
F5=(k1.*z)+(h.*zdot);
N=4;
A=[zeros(N/4) eye(N/4) zeros(N/4) zeros(N/4);-M1\(k1+k2) -M1\(2.*h) M1\k2 M1\h; zeros(N/4) zeros(N/4) zeros(N/4) eye(N/4);M2\k2 M2\h -M2\k2 -M2\h];
```

```
B=[zeros(N/4);inv(M1);zeros(N/4);zeros(N/4)];
C=[zeros(N/4)   ones(N/4)   zeros(N/4)   zeros(N/4);zeros(N/4)
zeros(N/4) zeros(N/4) ones(N/4)];
D=0;
sys=ss(A,B,C,D);

z0=[0 0 0 0];
y5=lsim(sys,F5,t,z0);   % u,t define the input signal. y is the
mass relative displacement.
b6=abs(y5(:,1));
S6=h.*(y5(:,1).^2);    %  Finding  the  energy  harvested  from
formula.
E6=cumtrapz(S6,te);

% seventh
M1=1;   % Mass
M2=1;
l=3.5;  % damping coefficient
c2=1; % damping coefficient
k1=0.12;
k2=0.12;
F6=(k1.*z)+(l.*zdot);
N=4;
```

```
A=[zeros(N/4)  eye(N/4)  zeros(N/4)  zeros(N/4);-M1\(k1+k2)  -
M1\(2.*l)  M1\k2  M1\l;  zeros(N/4)  zeros(N/4)  zeros(N/4)
eye(N/4);M2\k2 M2\l -M2\k2 -M2\l];
B=[zeros(N/4);inv(M1);zeros(N/4);zeros(N/4)];
C=[zeros(N/4)  ones(N/4)  zeros(N/4)  zeros(N/4);zeros(N/4)
zeros(N/4) zeros(N/4) ones(N/4)];
D=0;
sys=ss(A,B,C,D);


z0=[0 0 0 0];
y6=lsim(sys,F6,t,z0);  % u,t define the input signal. y is the
mass relative displacement.
b7=abs(y6(:,1));
S7=l.*(y6(:,1).^2);   % Finding the energy harvested from
formula.
E7=cumtrapz(S7,te);


% eigth
M1=1;   % Mass
M2=1;
m=4;  % damping coefficient
c2=m; % damping coefficient
k1=0.12;
k2=0.12;
```

```
F7=(k1.*z)+(m.*zdot);
N=4;
A=[zeros(N/4)  eye(N/4)  zeros(N/4)  zeros(N/4);-M1\(k1+k2)  -
M1\(2.*m)  M1\k2  M1\m;  zeros(N/4)  zeros(N/4)  zeros(N/4)
eye(N/4);M2\k2 M2\m -M2\k2 -M2\m];
B=[zeros(N/4);inv(M1);zeros(N/4);zeros(N/4)];
C=[zeros(N/4)  ones(N/4)  zeros(N/4)  zeros(N/4);zeros(N/4)
zeros(N/4) zeros(N/4) ones(N/4)];
D=0;
sys=ss(A,B,C,D);

z0=[0 0 0 0];
y7=lsim(sys,F7,t,z0);  % u,t define the input signal. y is the
mass relative displacement.
b8=abs(y7(:,1));
S8=m.*(y7(:,1).^2);  % Finding the energy harvested from
formula.
E8=cumtrapz(S8,te);

% ninth
M1=1;  % Mass
M2=1;
n=4.5;  % damping coefficient
c2=n; % damping coefficient
```

```
k1=0.12;

k2=0.12;

F8=(k1.*z)+(n.*zdot);

N=4;

A=[zeros(N/4)  eye(N/4)  zeros(N/4)  zeros(N/4);-M1\(k1+k2)  -
M1\(2.*n)  M1\k2  M1\n;  zeros(N/4)  zeros(N/4)  zeros(N/4)
eye(N/4);M2\k2 M2\n -M2\k2 -M2\n];

B=[zeros(N/4);inv(M1);zeros(N/4);zeros(N/4)];

C=[zeros(N/4)  ones(N/4)  zeros(N/4)  zeros(N/4);zeros(N/4)
zeros(N/4) zeros(N/4) ones(N/4)];

D=0;

sys=ss(A,B,C,D);


z0=[0 0 0 0];

y8=lsim(sys,F8,t,z0);   % u,t define the input signal. y is the
mass relative displacement.

b9=abs(y8(:,1));

S9=n.*(y8(:,1).^2);    % Finding the energy harvested from
formula.

E9=cumtrapz(S9,te);


% tenth

M1=1;   % Mass

M2=1;
```

```
p=5;  % damping coefficient
c2=p; % damping coefficient
k1=0.12;
k2=0.12;
F9=(k1.*z)+(p.*zdot);
N=4;
A=[zeros(N/4)  eye(N/4)  zeros(N/4)  zeros(N/4);-M1\(k1+k2)  -
M1\(2.*p)  M1\k2  M1\p;  zeros(N/4)  zeros(N/4)  zeros(N/4)
eye(N/4);M2\k2 M2\p -M2\k2 -M2\p];
B=[zeros(N/4);inv(M1);zeros(N/4);zeros(N/4)];
C=[zeros(N/4)  ones(N/4)  zeros(N/4)  zeros(N/4);zeros(N/4)
zeros(N/4) zeros(N/4) ones(N/4)];
D=0;
sys=ss(A,B,C,D);

z0=[0 0 0 0];
y9=lsim(sys,F9,t,z0);  % u,t define the input signal. y is the
mass relative displacement.
b10=abs(y9(:,1));
S10=p.*(y9(:,1).^2);   % Finding the energy harvested from
formula.
E10=cumtrapz(S10,te);

% eleventh
```

```
M1=1;    % Mass
M2=1;
q=5.5;  % damping coefficient
c2=q; % damping coefficient
k1=0.12;
k2=0.12;
F10=(k1.*z)+(q.*zdot);
N=4;
A=[zeros(N/4)  eye(N/4)  zeros(N/4)  zeros(N/4);-M1\(k1+k2)  -
M1\(2.*q)  M1\k2  M1\q;  zeros(N/4)  zeros(N/4)  zeros(N/4)
eye(N/4);M2\k2 M2\q -M2\k2 -M2\q];
B=[zeros(N/4);inv(M1);zeros(N/4);zeros(N/4)];
C=[zeros(N/4)   ones(N/4)   zeros(N/4)   zeros(N/4);zeros(N/4)
zeros(N/4) zeros(N/4) ones(N/4)];
D=0;
sys=ss(A,B,C,D);


z0=[0 0 0 0];
y10=lsim(sys,F10,t,z0);    % u,t define the input signal. y is
the mass relative displacement.
b11=abs(y10(:,1));
S11=q.*(y10(:,1).^2);    % Finding the energy harvested from
formula.
E11=cumtrapz(S11,te);
```

```
wn=0:0.0035714286:25;
plot(wn,(abs(E1)),'DisplayName','c1',....
'color','m',...
'linestyle',':')
hold on
% plot(t,(abs(y1(:,1))),'DisplayName','d')
plot(wn,(abs(E3)),'DisplayName','e',...
 'color','k',...
'linestyle','-')
% plot(t,(abs(y3(:,1))),'DisplayName','f')
plot(wn,(abs(E5)),'DisplayName','g',...
 'color','y',...
'linestyle','--')
% plot(t,(abs(y5(:,1))),'DisplayName','h')
plot(wn,(abs(E7)),'DisplayName','l',...
    'color','g',...
'linestyle','-.')
% plot(t,(abs(y7(:,1))),'DisplayName','m')
plot(wn,(abs(E9)),'DisplayName','n',...
    'color','c',...
'linestyle','-')
% plot(t,(abs(y9(:,1))),'DisplayName','p')
plot(wn,(abs(E11)),'DisplayName','q',...
```

```
    'color','r',...
'linestyle','-')
hold off
legend('c1=0.5','e=1.5','g=2.5','l=3.5','n=4.5','q=5.5')
xlabel('Natural Frequency(Hz)')
ylabel('Energy Harvested(J/kg)')
```

2. Code for checking the effect of spring stiffness on energy harvested.

```
% Checking Effect of Spring stiffness on energy harvested

fig = gcf;

axObjs = fig.Children;

dataObjs = axObjs.Children;

t= dataObjs(1).XData;

u= dataObjs(1).YData;

te =0:0.00057143:4;


% velocity of the acceleration signal

velocity=cumtrapz(u,t);

zdot=velocity;


% Displacement of the acceleration signal

displacement=cumtrapz(velocity,t);

z=displacement;

M1=1;    % Mass

M2=1;

q=5.5;  % damping coefficient

c2=q; % damping coefficient

k1=0.12;

k2=0.12;

F10=(k1.*z)+(q.*zdot);

N=4;
```

```
A=[zeros(N/4)  eye(N/4)  zeros(N/4)  zeros(N/4);-M1\(k1+k2)  -
M1\(2.*q)  M1\k2  M1\q;  zeros(N/4)  zeros(N/4)  zeros(N/4)
eye(N/4);M2\k2 M2\q -M2\k2 -M2\q];
B=[zeros(N/4);inv(M1);zeros(N/4);zeros(N/4)];
C=[zeros(N/4)  ones(N/4)  zeros(N/4)  zeros(N/4);zeros(N/4)
zeros(N/4) zeros(N/4) ones(N/4)];
D=0;
sys=ss(A,B,C,D);

z0=[0 0 0 0];
y1=lsim(sys,F10,t,z0);   % u,t define the input signal. y is
the mass relative displacement.
b1=abs(y1(:,1));
% plot(t,b6);
S1=q.*(y1(:,1).^2);   % Finding the energy harvested from
formula.
E1=cumtrapz(S1,t);

% second
k3=1.2;
k4=1.2;
F11=(k3.*z)+(q.*zdot);
N=4;
```

```
A=[zeros(N/4) eye(N/4) zeros(N/4) zeros(N/4);-M1\(k3+k4) -
M1\(2.*q) M1\k4 M1\q; zeros(N/4) zeros(N/4) zeros(N/4)
eye(N/4);M2\k4 M2\q -M2\k4 -M2\q];
B=[zeros(N/4);inv(M1);zeros(N/4);zeros(N/4)];
C=[zeros(N/4) ones(N/4) zeros(N/4) zeros(N/4);zeros(N/4)
zeros(N/4) zeros(N/4) ones(N/4)];
D=0;
sys=ss(A,B,C,D);

z0=[0 0 0 0];
y2=lsim(sys,F11,t,z0);    % u,t define the input signal. y is
the mass relative displacement.
b2=abs(y2(:,1));
% plot(t,b6);
S2=q.*(y2(:,1).^2);    % Finding the energy harvested from
formula.
E2=cumtrapz(S2,t);

% Third
k5=5;
k6=5;
F12=(k5.*z)+(q.*zdot);
N=4;
```

```
A=[zeros(N/4) eye(N/4) zeros(N/4) zeros(N/4);-M1\(k5+k6) -
M1\(2.*q) M1\k6 M1\q; zeros(N/4) zeros(N/4) zeros(N/4)
eye(N/4);M2\k6 M2\q -M2\k6 -M2\q];
B=[zeros(N/4);inv(M1);zeros(N/4);zeros(N/4)];
C=[zeros(N/4) ones(N/4) zeros(N/4) zeros(N/4);zeros(N/4)
zeros(N/4) zeros(N/4) ones(N/4)];
D=0;
sys=ss(A,B,C,D);

z0=[0 0 0 0];
y3=lsim(sys,F12,t,z0);   % u,t define the input signal. y is
the mass relative displacement.
b3=abs(y3(:,1));
% plot(t,b6);
S3=q.*(y3(:,1).^2);   % Finding the energy harvested from
formula.
E3=cumtrapz(S3,t);

% Fourth
k7=10;
k8=10;
F13=(k7.*z)+(q.*zdot);
N=4;
```

```
A=[zeros(N/4) eye(N/4) zeros(N/4) zeros(N/4);-M1\(k7+k8) -
M1\(2.*q) M1\k8 M1\q; zeros(N/4) zeros(N/4) zeros(N/4)
eye(N/4);M2\k8 M2\q -M2\k8 -M2\q];
B=[zeros(N/4);inv(M1);zeros(N/4);zeros(N/4)];
C=[zeros(N/4) ones(N/4) zeros(N/4) zeros(N/4);zeros(N/4)
zeros(N/4) zeros(N/4) ones(N/4)];
D=0;
sys=ss(A,B,C,D);


z0=[0 0 0 0];
y4=lsim(sys,F13,t,z0);    % u,t define the input signal. y is
the mass relative displacement.
b4=abs(y4(:,1));
S4=q.*(y4(:,1).^2);    % Finding the energy harvested from
formula.
E4=cumtrapz(S4,t);
wn=0:0.0035714286:25;
plot(wn,(abs(E1)),'DisplayName','k1',....
'color','b',...
'linestyle',':')
hold on
plot(wn,(abs(E2)),'DisplayName','k3',...
 'color','k',...
'linestyle','-')
```

```
plot(wn,(abs(E3)),'DisplayName','k5',...
 'color','g',...
'linestyle','--')
plot(wn,(abs(E4)),'DisplayName','k7',...
    'color','m',...
'linestyle','-.')
hold off
legend('k1=0.12','k3=1.2','k5=5','k7=10')
grid
xlabel('Frequency (Hz)')
ylabel('Energy Harvested(J)')
```

3. Code for checking the effect of mass on energy harvested.

```
% Checking for effect of Mass on Energy Harvested
M1=1;   % Mass
M2=1;
q=5.5;  % damping coefficient
c2=q; % damping coefficient
k1=0.12;
k2=0.12;
te =0:0.00057143:4;
F10=(k1.*z)+(q.*zdot);
N=4;
A=[zeros(N/4)   eye(N/4)   zeros(N/4)   zeros(N/4);-M1\(k1+k2)   -
M1\(2.*q)   M1\k2   M1\q;   zeros(N/4)   zeros(N/4)   zeros(N/4)
eye(N/4);M2\k2 M2\q -M2\k2 -M2\q];
B=[zeros(N/4);inv(M1);zeros(N/4);zeros(N/4)];
C=[zeros(N/4)    ones(N/4)    zeros(N/4)    zeros(N/4);zeros(N/4)
zeros(N/4) zeros(N/4) ones(N/4)];
D=0;
sys=ss(A,B,C,D);


z0=[0 0 0 0];
y1=lsim(sys,F10,t,z0);   % u,t define the input signal. y is the
mass relative displacement.
b1=abs(y1(:,1));
```

```
% plot(t,b6);
S1=q.*(y1(:,1).^2);  % Finding the energy harvested from formula.
E1=cumtrapz(S1,t);


% second
M3=0.5;   % Mass
M4=0.5;
F11=(k1.*z)+(q.*zdot);
N=4;
A=[zeros(N/4)  eye(N/4)  zeros(N/4)  zeros(N/4);-M3\(k1+k2)  -
M3\(2.*q)  M3\k2  M1\q;  zeros(N/4)  zeros(N/4)  zeros(N/4)
eye(N/4);M4\k2 M4\q -M4\k2 -M4\q];
B=[zeros(N/4);inv(M3);zeros(N/4);zeros(N/4)];
C=[zeros(N/4)  ones(N/4)  zeros(N/4)  zeros(N/4);zeros(N/4)
zeros(N/4) zeros(N/4) ones(N/4)];
D=0;
sys=ss(A,B,C,D);


z0=[0 0 0 0];
y2=lsim(sys,F11,t,z0);   % u,t define the input signal. y is the
mass relative displacement.
b2=abs(y2(:,1));
% plot(t,b6);
S2=q.*(y2(:,1).^2);  % Finding the energy harvested from formula.
```

```
E2=cumtrapz(S2,t);


% Third
M5=1.5;    % Mass
M6=1.5;
F12=(k1.*z)+(q.*zdot);
N=4;
A=[zeros(N/4)  eye(N/4)  zeros(N/4)  zeros(N/4);-M5\(k1+k2)  -
M5\(2.*q)  M5\k2  M5\q;  zeros(N/4)  zeros(N/4)  zeros(N/4)
eye(N/4);M6\k2 M6\q -M6\k2 -M6\q];
B=[zeros(N/4);inv(M1);zeros(N/4);zeros(N/4)];
C=[zeros(N/4)  ones(N/4)  zeros(N/4)  zeros(N/4);zeros(N/4)
zeros(N/4) zeros(N/4) ones(N/4)];
D=0;
sys=ss(A,B,C,D);


z0=[0 0 0 0];
y3=lsim(sys,F12,t,z0);   % u,t define the input signal. y is the
mass relative displacement.
b3=abs(y3(:,1));
% plot(t,b6);
S3=q.*(y3(:,1).^2);  % Finding the energy harvested from formula.
E3=cumtrapz(S3,t);
```

```
% Fourth
M7=2;    % Mass
M8=2;
F13=(k1.*z)+(q.*zdot);
N=4;
A=[zeros(N/4)   eye(N/4)   zeros(N/4)   zeros(N/4);-M7\(k1+k2)   -
M7\(2.*q)   M7\k2   M7\q;   zeros(N/4)   zeros(N/4)   zeros(N/4)
eye(N/4);M8\k2 M8\q -M8\k2 -M8\q];
B=[zeros(N/4);inv(M1);zeros(N/4);zeros(N/4)];
C=[zeros(N/4)    ones(N/4)    zeros(N/4)    zeros(N/4);zeros(N/4)
zeros(N/4) zeros(N/4) ones(N/4)];
D=0;
sys=ss(A,B,C,D);

z0=[0 0 0 0];
y4=lsim(sys,F13,t,z0);    % u,t define the input signal. y is the
mass relative displacement.
b4=abs(y4(:,1));
S4=q.*(y4(:,1).^2);  % Finding the energy harvested from formula.
E4=cumtrapz(S4,t);
wn=0:0.0035714286:25;
plot(wn,(abs(E1)),'DisplayName','M1',....
'color','b',...
'linestyle','-')
```

```
hold on
plot(wn,(abs(E2)),'DisplayName','M3',...
 'color','k',...
'linestyle','-')
plot(wn,(abs(E3)),'DisplayName','M5',...
 'color','g',...
'linestyle','--')
plot(wn,(abs(E4)),'DisplayName','M7',...
    'color','r',...
'linestyle','-.')
hold off
legend('M1=1','M3=0.5','M5=1.5','M7=2')
grid
xlabel('Frequency (Hz)')
ylabel('Energy Harvested(J)')
```

4. Code for Finding Maximum Relative Displacement

```
% Finding Maximum Relative Displacement for optimum
parameters
M1=1;   % Mass
M2=1;
c1=5.5;
c2=c1;
k1= 0.12;
k2=0.12;
fig = gcf;
axObjs = fig.Children;
dataObjs = axObjs.Children;
t= dataObjs(1).XData;
u= dataObjs(1).YData;


% velocity of the acceleration signal
velocity=cumtrapz(u,t);
zdot=velocity;

% Displacement of the acceleration signal
displacement=cumtrapz(velocity,t);
z=displacement;
```

```
F0=(k1.*z)+(c1.*zdot);
N=4;
A=[zeros(N/4)  eye(N/4)  zeros(N/4)  zeros(N/4);-M1\(k1+k2)  -
M1\(2.*c1)  M1\k2  M1\c1;  zeros(N/4)  zeros(N/4)  zeros(N/4)
eye(N/4);M2\k2 M2\c1 -M2\k2 -M2\c1];
B=[zeros(N/4);inv(M1);zeros(N/4);zeros(N/4)];
C=[ones(N/4)   zeros(N/4)   zeros(N/4)   zeros(N/4);zeros(N/4)
zeros(N/4) ones(N/4) zeros(N/4)];
D=0;
sys=ss(A,B,C,D);
z0=[0 0 0 0];
y=lsim(sys,F0,t,z0);    % u,t define the input signal. y is
the mass relative displacement.
plot (wn,(abs(y)))
xlabel('Natural Frequency(Hz)')
ylabel('Maximum Relative Displacement(m)')
```

5. Code for finding the optimum energy harvested

```
% Finding Energy Harvested

M1=1; % Mass

M2=1;

c1=5.5

c2=c1;

k1=0.12;

k2=0.12;

te =0:0.00057143:4;

fig = gcf; % Obtaining Acceleration signal data of vertical
displacement of a sleeper from data_figure

axObjs = fig.Children;

dataObjs = axObjs.Children;

t= dataObjs(1).XData;

u= dataObjs(1).YData;


% velocity of the acceleration signal

velocity=cumtrapz(u,t);

zdot=velocity;


% Displacement of the acceleration signal

displacement=cumtrapz(velocity,t);

z=displacement;

F0=(k1.*z)+(c1.*zdot);
```

```
N=4;
A=[zeros(N/4)   eye(N/4)   zeros(N/4)   zeros(N/4);-M1\(k1+k2)   -
M1\(2.*c1)   M1\k2   M1\c1;   zeros(N/4)   zeros(N/4)   zeros(N/4)
eye(N/4);M2\k2 M2\c1 -M2\k2 -M2\c1];
B=[zeros(N/4);inv(M1);zeros(N/4);zeros(N/4)];
C=[zeros(N/4)    ones(N/4)    zeros(N/4)    zeros(N/4);zeros(N/4)
zeros(N/4) zeros(N/4) ones(N/4)];
D=0;
sys=ss(A,B,C,D);
z0=[0 0 0 0];
y=lsim(sys,F0,t,z0); % F0,t define the input signal. y is the mass
relative displacement.
b1=abs(y(:,1));
S1=c1.*(y(:,1).^2); % Finding the energy harvested from formula.
E1=cumtrapz(S1,te);
wn=0:0.0035714286:25;
plot(wn,(abs(E1)))
xlabel('Natural Frequency(Hz)')
ylabel('Energy Harvested(J)')
sum (E1) % Finding the cumulative of the optimum energy harvested
```

6. Code for finding energy harvested for respective train speeds

```
% Finding Energy Harvested at different speeds
M1=1; % Mass
M2=1;
c1=5.5;
c2=c1;
k1=0.12;
k2=0.12;
te =0:0.00057143:4;

fig = gcf; % Obtaining Acceleration signal data of vertical
displacement of a sleeper from data_figure
axObjs = fig.Children;
dataObjs = axObjs.Children;
t= dataObjs(1).XData;
u= dataObjs(1).YData;
% R=u./195;
% velocity of the acceleration signal
v=cumtrapz(u,t);
zdot=v;

% Displacement of the acceleration signal
d=cumtrapz(v,t);
z=d;
```

```
F0=(k1.*z)+(c1.*zdot);
N=4;
A=[zeros(N/4)  eye(N/4)  zeros(N/4)  zeros(N/4);-M1\(k1+k2)  -
M1\(2.*c1)  M1\k2  M1\c1;  zeros(N/4)  zeros(N/4)  zeros(N/4)
eye(N/4);M2\k2 M2\c1 -M2\k2 -M2\c1];
B=[zeros(N/4);inv(M1);zeros(N/4);zeros(N/4)];
C=[zeros(N/4)   ones(N/4)   zeros(N/4)   zeros(N/4);zeros(N/4)
zeros(N/4) zeros(N/4) ones(N/4)];
D=0;
sys=ss(A,B,C,D);

z0=[0 0 0 0];
y=lsim(sys,F0,t,z0); % F0,t define the input signal. y is the mass
relative displacement.
b=abs(y(:,1));
S=c1.*(y(:,1).^2); % Finding the energy harvested from formula.
E=cumtrapz(S,te);

% speed 120km/h
% Obtaining the unit representation of acceleration signal of
vertical sleeper vibration
R=u./195;
s1=120.*R;
```

```
% velocity of the acceleration signal
v1=cumtrapz(s1,t);
zdot1=v1;

% Displacement of the acceleration signal
d1=cumtrapz(v1,t);
z1=d1;

F1=(k1.*z1)+(c1.*zdot1);
y1=lsim(sys,F1,t,z0); % F0,t define the input signal. y is the
mass relative displacement.
b1=abs(y1(:,1));
S1=c1.*(y1(:,1).^2); % Finding the energy harvested from formula.
E1=cumtrapz(S1,te);

% speed 80km/h
% Obtaining the unit representation of acceleration signal of
vertical sleeper vibration
R=u./195;
s2=80.*R;
% velocity of the acceleration signal
v2=cumtrapz(s2,t);
zdot2=v2;
```

```
% Displacement of the acceleration signal
d2=cumtrapz(v2,t);
z2=d2;
F2=(k1.*z2)+(c1.*zdot2);
y2=lsim(sys,F2,t,z0); % F0,t define the input signal. y is the mass relative displacement.
b2=abs(y2(:,1));
S2=c1.*(y2(:,1).^2); % Finding the energy harvested from formula.
E2=cumtrapz(S2,te);

% speed 70km/h
% Obtaining the unit representation of acceleration signal of vertical sleeper vibration
R=u./195;
s3=70.*R;
% velocity of the acceleration signal
v3=cumtrapz(s3,t);
zdot3=v3;

% Displacement of the acceleration signal
d3=cumtrapz(v3,t);
z3=d3;

F3=(k1.*z3)+(c1.*zdot3);
```

```
y3=lsim(sys,F3,t,z0); % F0,t define the input signal. y is the
mass relative displacement.
b3=abs(y3(:,1));
S3=c1.*(y3(:,1).^2); % Finding the energy harvested from formula.
E3=cumtrapz(S3,te);

% speed 60km/h
% Obtaining the unit representation of acceleration signal of
vertical sleeper vibration
R=u./195;
s4=60.*R;
% velocity of the acceleration signal
v4=cumtrapz(s4,t);
zdot4=v4;

% Displacement of the acceleration signal
d4=cumtrapz(v4,t);
z4=d4;

F4=(k1.*z4)+(c1.*zdot4);
y4=lsim(sys,F4,t,z0); % F0,t define the input signal. y is the
mass relative displacement.
b4=abs(y4(:,1));
S4=c1.*(y4(:,1).^2); % Finding the energy harvested from formula.
```

```
E4=cumtrapz(S4,te);

% speed 50km/h
% Obtaining the unit representation of acceleration signal of
vertical sleeper vibration
R=u./195;
s5=50.*R;
% velocity of the acceleration signal
v5=cumtrapz(s5,t);
zdot5=v5;

% Displacement of the acceleration signal
d5=cumtrapz(v5,t);
z5=d5;

F5=(k1.*z5)+(c1.*zdot5);
y5=lsim(sys,F5,t,z0); % F0,t define the input signal. y is the
mass relative displacement.
b5=abs(y5(:,1));
S5=c1.*(y5(:,1).^2); % Finding the energy harvested from formula.
E5=cumtrapz(S5,te);
```

```
%  speed 30km/h
% Obtaining the unit representation of acceleration signal of
vertical sleeper vibration
R=u./195;
s6=30.*R;
% velocity of the acceleration signal
v6=cumtrapz(s6,t);
zdot6=v6;


% Displacement of the acceleration signal
d6=cumtrapz(v6,t);
z6=d6;
F6=(k1.*z6)+(c1.*zdot6);
y6=lsim(sys,F6,t,z0); % F0,t define the input signal. y is the
mass relative displacement.
b6=abs(y6(:,1));
S6=c1.*(y6(:,1).^2); % Finding the energy harvested from formula.
E6=cumtrapz(S6,te);
wn=0:0.0035714286:25;
plot(wn,(abs(E)),'DisplayName','195km/h',....
'color','m',...
'linestyle','-')
hold on
plot(wn,(abs(E1)),'DisplayName','120km/h',...
```

```
 'color','k',...
'linestyle','-')
plot(wn,(abs(E2)),'DisplayName','80km/h',...
 'color','c',...
'linestyle','-')
plot(wn,(abs(E3)),'DisplayName','70km/h',...
    'color','g',...
'linestyle','-')
plot(wn,(abs(E4)),'DisplayName','60km/h',...
    'color','b',...
'linestyle','-')
plot(wn,(abs(E5)),'DisplayName','50km/h',...
    'color','r',...
'linestyle','-')
plot(wn,(abs(E6)),'DisplayName','30km/h',...
    'color','y',...
'linestyle','-')
hold off
legend('E=195km/h','E1=120km/h','E2=80km/h','E3=70km/h','E4=60km
/h','E5=50km/h','E6=30km/h')
xlabel('Natural Frequency(Hz)')
ylabel('Energy Harvested(J)')
% Finding the cumulative energy harvested for the respective speeds
sum(E)
```

```
sum(E1)

sum(E2)

sum(E3)

sum(E4)

sum(E5)

sum(E6)
```

APPENDIX B: DATA COLLECTED FROM FIELD

1. Power rating of way side equipment

Signaling Department					
Power rating of way side equipments					
Types of equipment	**Volatage rating**	**Current rating**	**Wat rating**	**Frequency**	**Ambient temprature**
Axle counter	24V ± 5% DC		20W	2Hz to 9Hz	(-40°C) ~+ 85°C
Signaling machine	220V AC				
TRE equipment	220V AC				
Level crossing	220V AC	0.5A			
Switch machine	380V AC			50/60 Hz	
Beacon					

2. Current readings of signaling and communication equipment at the depot and substation


Power supply of signal interlocking at control center (for service)
11.20
11.10
11.40
Power supply of central signal at control center (for service)


Power supply of central signal at control center (for service)
34.21
0.000
0.000
Power supply of communication at comprehensive maintenance center(for service)


Power supply of
communication equipment
room in substation
(for service)
通信
2.968
0.000
0.000


Power supply of
signal in substation
(for service)
7.860
7.960
8.040
污水

3. The data_figure from which the input vertical vibration acceleration data was got.