CONCEPTUAL DESIGN OF HARVESTING ENERGY SYSTEM FOR ROAD APPLICATION

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ABSTRACT

Energy harvesting becomes more and more important in our life. It refers to the practice of acquiring energy from the environment which would be otherwise wasted and converting it into usable electric energy. For this, every kind of energy can be exploited such as solar, wind or strain and kinetic energy. The idea is to propose a conceptual design that will carry out a suitable energy harvesting conversion to be applied for road application. Harvesting energy using piezoelectric generators has been chosen for this project. The project conduct a simulation analysis using a piezoelectric generator based on a model by S Roundy and P K Wright. The data used from a 15 mm x 3.2 mm x 0.14 mm single layer piezoelectric bending element which produce 0.95mW with a 1.727e6 Nm^{-2} of input stress. The simulation is done using MATLAB-Simulink-SimPowerSystems which also tested with others value by Luigi Pinna et al.. Piezoelectric generator can be one of the green solutions for sustainable development in energy generation.

ABSTRAK

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LIST OF SYMBOLS AND ABBREVIATIONS

CO_2	-	Carbon dioxide	1
RM	-	Ringgit Malaysia	4
USA	-	United State of America	10
Hz	-	Hertz	20
K	-	Stiffness	21
M	-	Mass	21
D	-	Damping	21
$\boldsymbol{\Theta}$	-	Piezoelectric coupling vector	21
ω	-	Angular frequency	24
α	-	Force factor	24
σ_{in}	-	Equivalent stress generator	26
η_s	-	Elastic constant ratio	28
SDOF	-	Single degree of freedom	30
Y_p	-	Young's Modulus	33

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CHAPTER 1

INTRODUCTION

1.1 Energy for Sustainable Development

Energy has always been a most important thing for the development of economy and social growth in country. There are two long-term energy challenges are being faced. One of them is undertaking climate change by mitigating Carbon Dioxide (CO2) emissions and the other one is ensuring a secure clean and affordable energy. Globally, the usage of fossil fuel for power generation grows each year. Thus, it will raise environmental issues whilst emitting the CO2 emissions. In Malaysia, CO2 emissions projection is carried out mainly from four important sectors such as electricity generation, industrial, transportation, residential for the period of 2000-2020 as shown in Figure 1 [1].

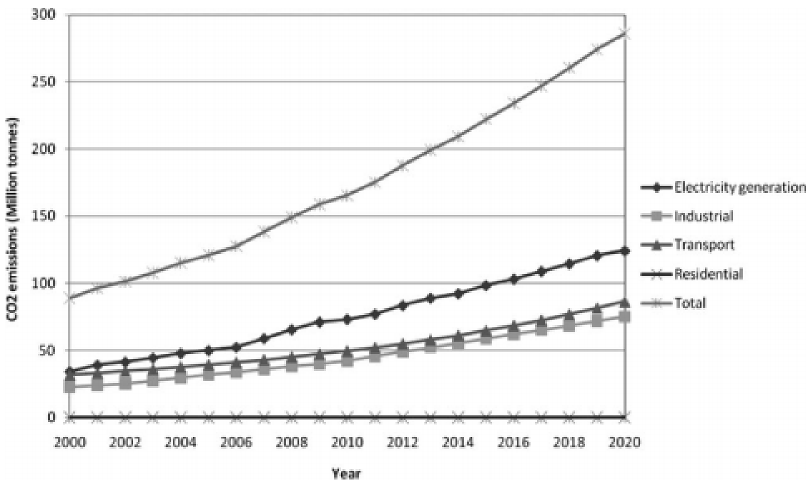


Figure 1.1: Projected Emissions for Four Sectors in Malaysia

This is where an alternative energy source is being introduced. Malaysia is actively looking for other sources of energy to meet the power demands. These alternative sources are defined as renewable energy. In Malaysia, renewable energy is familiar with solar panel or photovoltaic which convert the sun's energy into electrical energy by using a solar cell(s). Such energy are generate from natural resources. Recently, renewable energy also comes from non-natural resources which used another technique of energy harvesting. Energy harvesting or power harvesting refers to the practice of acquiring energy from the environment which would be otherwise wasted and converting it into usable electric energy [2].

1.2 Problem Statement

For power generation in Malaysia, diesel and fuel oil are considered as petroleum products. The consumption of diesel is nearly four times than the fuel oil in 2006. The tariff of electrical for surely increased. The electrical demand will keep growing globally. Foreign investors especially in manufacturing industries are one of the factors that will contribute into the increasing number especially in Malaysia. Converting wasted energy from the environment is introduced to be an alternative way to produce energy such as solid waste and biomass. This technology is hoped to be a viable solution for creating a new way in providing a green energy solution.

As mention before, energy can also harvested from ambient environment such as mechanical, thermal, light, electromagnetic and also human body to replace traditional sources. All this ambient energy could be a solution to harvest energy from the road surface or pavement. When referring to federal road or traffic, there is no doubt discussing about number of cars, trucks or even the motorbikes. It is understand that, according to *mStar online* (April 11, 2011 and August 16,2012) there is approximately 3 million vehicles entering Kuala Lumpur and 1.2 million vehicles using PLUS Highway every day respectively.

Taking advantage of this situation is to convert the energy waste by all the vehicles into electrical energy. There is a few possible source such as vibration cause by force (tyres) and also heat (engines, friction) which created by every single vehicle. There is a lot of waste energy can be captured and stored to power certain system or grid. There is some point to be considered for the project where the harvesting energy system is basically converting some ambient source that carried out from road pavement into electrical energy.

1.3 Energy Harvesting

Energy harvesting or energy scavenging technologies refer to applications that capture and exploit the unused and depleted energy so as to convert it to a more usable form. For this, every kind of energy can be exploited such as solar, wind or strain and kinetic energy. Moreover, thermal energy due to temperature gradients and ambient vibrations constitute some of the major sources of energy that has a lot of potential for being harvested. Harvesting energy stands alone as one of the most promising techniques for approaching the global energy problem without depleting natural resources. Generally, the first energy harvesting procedure is capturing the energy (resources), here by means the naturally wasted energy. Next would be the storage of energy that includes its condition by using batteries or other kind of system. Finally, all the energy stored will be used to power nearby grid or system as shown in Figure 1.2.

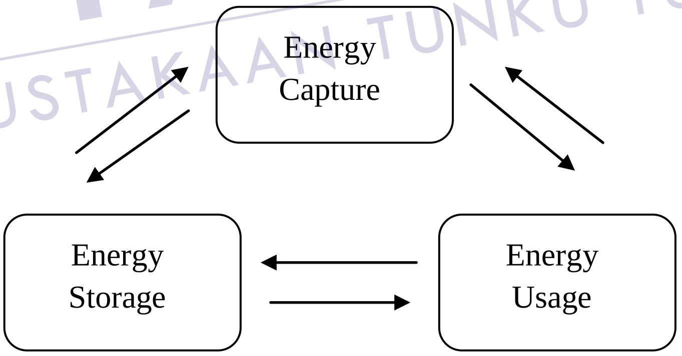


Figure 1.2: Energy Harvesting Principle

1.3.1 Energy Harvesting in Malaysia

Energy harvesting techniques are emerging as environmental friendly energy sources, even though it does not generate from natural resources such as the solar. The increase in coal consumption has contributed to the changes in CO_2 emissions pattern in Malaysia. Solar energy is not only renewable, it is also considered as clean energy sources that does not emit CO_2 in the process of electricity generation. The government also has announced the Malaysia Building Integrated Photovoltaic (MBIPV) in the 9th Malaysia Plan. The project which commenced under the Renewable Energy Policy was officially launched on July 2005 with the cost of RM 25 million. Harvesting energy also refers to the practice of converting energy from the environment which would be otherwise wasted into usable electrical energy Such waste in Malaysia is the biogas from Palm Oil Mill Effluents (POME), biomass power generation utilizing empty fruit brunches and Green House Gases (GHG) from municipal solid waste (MSW). All these type of waste are used to produce renewable energy (RE). Throughout the years, the government has formulated numerous energy related policies which include the Fifth Fuel Policy 2000, National Biofuel Policy 2006 and National Green Technology 2009 to combat the climate change and ensure the energy security. Harvesting energy as part of renewable Energy as a viable alternative source to address the growing energy needs of Malaysia. It will play an important role in meeting future energy demands. As such, many of private sectors in Malaysia have been actively seeking possible avenues to promote and develop green technology in efforts to be an environmentally responsible corporation. Therefore expert and technologist in harvesting the energy are needed to play their role in development of renewable energy in Malaysia. It is hope that, by research and exploring a new way to produce energy will enhance the sustainable development of energy.

1.4 Project Objectives

The major objective of this project is to study about the energy harvesting system that can be applied for road application. In other words, the project is mainly about a conceptual design of the energy conversion. Its measureable objectives are as follows:

i. To identify the source of energy harvesting system applied for road application
ii. To identify the analytical or equivalent model for converting the source into electrical energy
iii. To analyse the model using a simulation environment for energy conversion prediction.

1.5 Project Scopes

The projects are primarily concern on the energy conversion concept. In order to achieve the objective, we will be focusing on certain scopes. The scopes of the project are:

i. Research on the energy harvesting overview is expected to be the framework of the project. Previous works on energy harvesting technique will be a good guideline in order to study the source of energy, sensors and transducers, and also product that practically use in real usage.

ii. To propose a conceptual design for the system, we will define a suitable model for the energy harvesting system. The model will focus on energy conversion to apply with road application. For road application, there are a few ambient sources that can be taken into account. The model will represent the ambient sources, energy conversion as well as the load.

iii. The energy conversion study is the most critical part of the project. By using a simulation environment, the model chose will be analyse to shows the output products. The output products will show an overall understanding of the energy harvesting system for road application.

CHAPTER 2

LITERATURE REVIEW

2.1 Conceptual Design in Engineering

The conceptual design in engineering aims to identify the machinery, equipment, supplies and facilities necessary to operate a project. It is the generation of design alternatives or design concepts and the supporting analysis to determine the feasibility of each alternative [3]. A conceptual engineering study should logically consider the issues, concerns and goals that may be raised by an engineering request evaluate possible technical solutions and clearly report the findings and recommendations. It is intended to provide a comparative basis for decision making regarding further actions, without expenditure of exhaustive engineering efforts. Further preliminary engineering (e.g., equipment layouts, geological studies, testing and inspections) may then be suggested for the recommended conceptual solution prior to full project funding commitment and detailed engineering design.

2.1.1 Energy Conversion

Energy surrounds us and is available in many different forms, such as wind and solar energy or thermal and mechanical energy. Mankind's trends are characterized by an ascending energy consumption profile that has its detrimental consequences on energy security and the environment's viability. Energy harvesting from pavements is a new research territory and encompasses techniques that somehow use the same principals that could be used in general building engineering regarding the materials usage. Green building usually related with solar photovoltaic, thermal energy conversion and not to mention the technology use to construct the infrastructure itself. Some of these technologies are recently applied to be used to harvest energy from the road. The technology state where and how the energy harvested came from. Figure 2.1 shows the concept how energy can be harvested from road pavement.

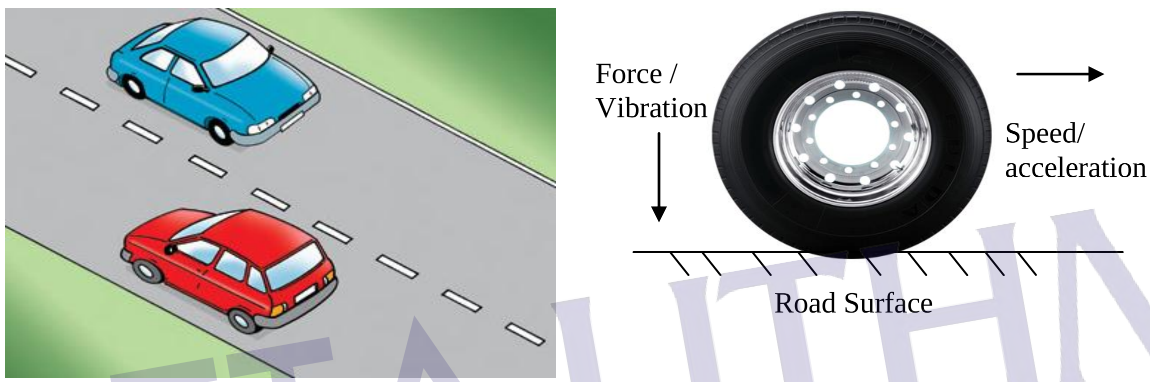


Figure 2.1: Energy Harvesting from Road Pavement

Vehicles such as cars, bus, trucks are the main 'user' on the road. Tires are the part of the vehicles contacting to the road. When every vehicles moving, it will release energy in the form of force or vibration direct to the road surface. An energy harvesting system will capture these energies and convert it into an electrical energy. Thus, energy conversion technique is very important to determine whether current technology for green building or others can be applied to road harvesting energy.

2.2 Energy harvesting from road pavement

Malaysia is targeting of 4000 MW of installed renewable energy capacity for 2030 as set in the Renewable Energy Policy and Action Plan. It is hope the success of the plan will raised the total capacity to 17 percent from less than 1 percent today (National Biomass Strategy). However, this policy does not include the idea that energy could be extracted from highways by fitting them with piezoelectric devices, solar panels, wind turbines and other energy generating tools. Researchers are also concentrating on biomass, biofuel, solid waste municipal and other kind of renewable energy. In future at a time when governments are finding it hard to make land available for new power plants, extracting energy while using the vast spread of highways all over the world seems no less lucrative proposition. The energy generating road designs could become a starting point for new sources of energy that can be implemented in the renewable energy policy.

2.2.1 Solar Power for Road

Solar energy is one of the most popular and well-known renewable energy due to its primary source of energy: The Sun. Solar energy can be harnessed either in passive or active methods. A solar roadway is a series of structurally engineered solar panels that are driven upon [4]. The idea is to replace current petroleum-based asphalt roads, parking lots, and driveways with solar road panels that collect energy to be used by homes and businesses, and ultimately to be able to store excess energy in or alongside the solar roadways. One kind of it was proposed in the United State by Solar Roadways starting with first prototype in 2009. It is expected to replace the need for the current fossil fuels used for the generation of electricity, which cuts greenhouse gases. Parking lots, driveways, and eventually highways are all targets for the panels. If the entire United States Interstate Highway system were surfaced with Solar Roadways panels, it would produce more than three times the amount of electricity currently used nationwide.

Figure 2.2: The USDOT solar road prototype

The United States Department of Transportation (USDOT) [4] solar road is the prototype of an energy generating road that has been fitted with 'structurally-engineered' solar panels. The designers have used light emitting diode (LED) for painting the road lines from beneath for lighting up the roads at night. Also, heating elements are used on the surface for preventing accumulation of ice on roads during winter. It will not only produce solar energy for homes and businesses, but also replace the currently popular petroleum-based asphalt roads.

2.2.2 Wind Power

We know that every passing car on the highway will lead to the emergence of significant wind movement. By using wind turbines, we could use the wind movement to generate renewable energy that we can use for street lighting, information panels and public phones. Designed by Pedro Gomes, the E Turbine (Figure 2.3) [5] is an idea a series of small circular turbines would be placed along the median of a highway that would use the wind created by passing cars to generate electricity from the wind energy. The electricity generated could then be used to power highway and street lights, information and warning signs, or even emergency phones set up along the road. Pedro Gomes is an industrial designer, who has submitted the idea to several design contests over the years.

He was invited as a speaker at the International Conference "Energy Harvesting and Storage" held at Boston, USA in 2011. It could be placed between the lanes as lane separators. The energy produced by the turbines can be stored in a main battery and used for different purposes.

Figure 2.3: E Turbine designed by Pedro Gomes

Currently, the E Turbine remains a concept without any immediate plans to begin implementing them despite getting attention by becoming a finalist in several competitions. However, the concept itself is still interesting and could have potential for a country looking to greatly expand their highway systems while catering to a renewable energy mindset.

2.2.3 Piezoelectric Generator for Road

The piezoelectric energy-generating roads have been proposed in the car capitol of the world – California. This design is based on the concept of piezoelectricity that is produced in response to the mechanical stress applied on some solid materials like crystals and some ceramics. The design proposes the placement of piezoelectric sensors beneath the road surface which would produce electricity from the vibrations caused by the movement of vehicles on the road. The technology works in this way: When a car or truck passes over pavement, the pavement vibrates slightly. By placing relatively inexpensive piezoelectric sensors underneath a road, the vibrations produced by vehicles can be converted into electricity, which can be used to power roadside lights, call boxes, and neighbouring communities. Identical technology has already been placed underneath highways in Israel.

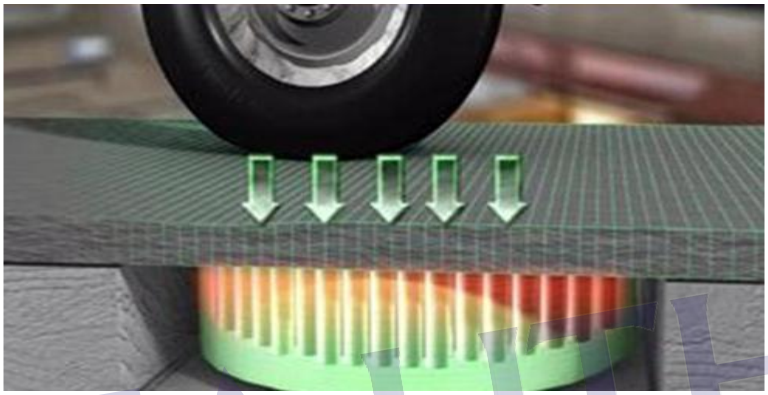


Figure 2.4: IPEG by Innowattech

Innowattech [6] has conducted trials to demonstrate this energy at the Technion Institute of Technology in Haifa where a vehicle travelled over a road under which IPEG (Innowattech Piezoelectric Electric Generators) had been planted 6cm under the road level and at a distance of 30cm apart. The IPEGs are piezoelectric crystals that can harvest mechanical energy created by changes in weight, motion, vibration and temperature, and convert it to electrical current. The energy harvested was stored in the electronic capacitors of the storage system. According to Innowattech, IPEGs are easy and inexpensive to install. Embedded between a road's layers, they are mounted with electronic cards to store traffic-generated energy. The system is usually covered with a layer of asphalt, but concrete or composite concrete and asphalt can also be used. Because systems can be installed when new roads are laid or when regular maintenance work is performed on existing surfaces, installation costs are substantially less than those incurred with either wind or solar systems.

Innowattech's claims of producing significant amounts of electricity, about 400 kWh from a 1 km stretch of generators along the dual carriageway (assuming 600 vehicles go through the road segment in an hour), enough energy to power 600-800 homes.

2.3 Energy Conversion

Energy surrounds us and is available in many different forms, such as wind and solar energy or thermal and mechanical energy. Energy conversion is the process of changing one form of energy to another. Energy in a system may be transformed so that it resides in a different state, or a different type of energy. Energy in many states may be used to do many varieties of physical work or task. Energy may be used in natural processes or machines. For example, an internal combustion engine converts the potential chemical energy in gasoline and oxygen into heat, which is then transformed into the propulsive energy to move a vehicle. The same way as a solar cell converts solar radiation into electrical energy that can then be used to light a bulb or power a computer. The generic name for a device which converts energy from one form to another is a transducer. For energy harvesting, transducer may came in a bulk form such as the solar panel (photovoltaic).

2.3.1 Solar Photovoltaic

Solar Energy is one of the most popular and well-known renewable energy due to its primary source of energy. Solar energy is not only renewable; it is also considered as clean energy sources that does not emit CO_2 in the process of electricity generation. In direct sunlight at midday, the power density of solar radiation on the earth’s surface is roughly 100 mW/cm^3. Silicon solar cells are a mature technology with efficiencies of single crystal silicon cells ranging from 12% to 25%. Thin film polycrystalline, and amorphous silicon solar cells are also commercially available and cost less than single crystal silicon, but also have lower efficiency [7].

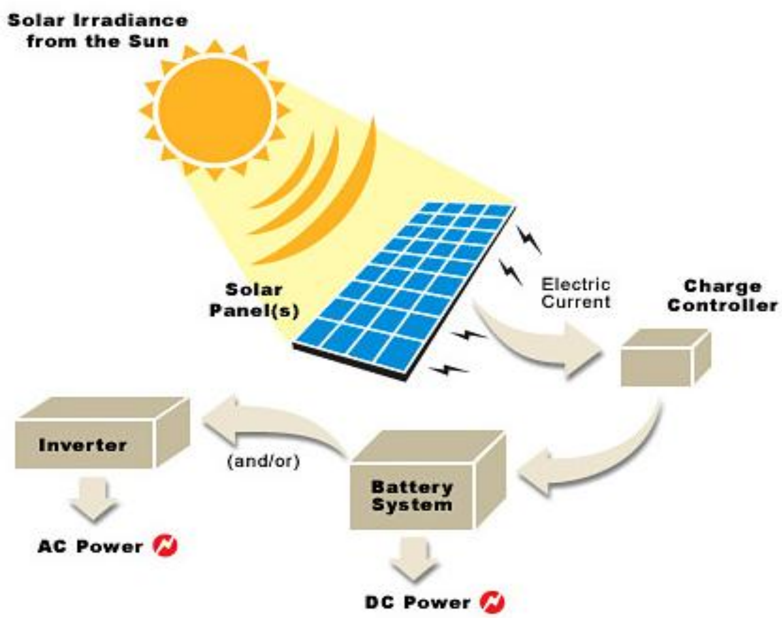


Figure 2.5: Solar Panel (Photovoltaic) generating electric from the Sun

Researchers at the Korea Institute also investigated several approaches to harvest solar energy from asphalt pavements. In addition to the heat generated inside the pavement itself, they also intended to identify if it is feasible to utilize current solar cell or photovoltaic technologies by embedding those into the pavement infrastructure. It should be noted, however, that current thin film solar cells are difficult to use in surfaces that receive vast mechanical load cycles and environmental conditioning could cause premature corrosion and wear [8].

2.3.2 Wind Turbine

Wind power is the conversion of wind energy into a useful form of energy, such as using: wind turbines to make electrical power, windmills for mechanical power, windpumps for water pumping or drainage, or sails to propel ships. Wind power, as an alternative to fossil fuels, is plentiful, renewable, widely distributed, clean, produces no greenhouse gas emissions during operation and uses little land. Any effects on the environment are generally less problematic than those from other power sources. Small onshore wind facilities are used to provide electricity to isolated locations and utility companies increasingly buy surplus electricity produced by small domestic wind turbines.

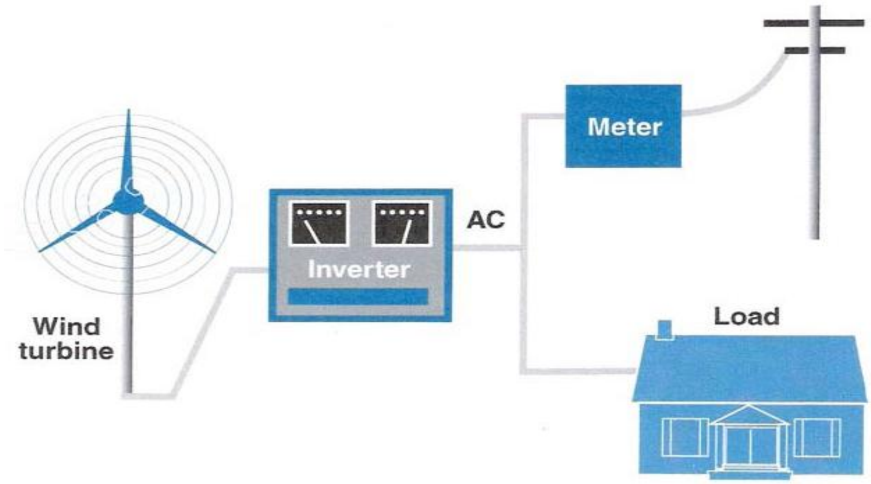


Figure 2.6: General Wind Turbine System

Wind turbines are classified into two general types: horizontal axis and vertical axis. A horizontal axis machine has its blades rotating on an axis parallel to the ground. A vertical axis machine has its blades rotating on an axis perpendicular to the ground. There are a number of available designs for both and each type has certain advantages and disadvantages.

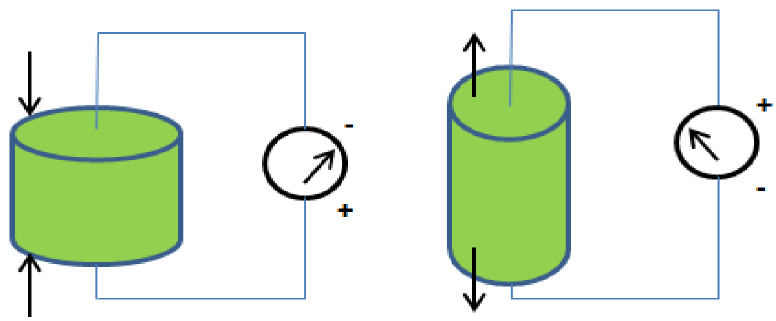
Figure 2.7: Vertical-axis Wind Turbine type

Vertical-axis wind turbines (or VAWTs) have the main rotor shaft arranged vertically. Key advantages of this arrangement are that the turbine does not need to be pointed into the wind to be effective. This is an advantage on sites where the wind direction is highly variable, for example when integrated into buildings. The key disadvantages include the low rotational speed with the consequential higher torque and hence higher cost of the drive train, the inherently lower power coefficient, and the difficulty of modelling the wind flow accurately and hence the challenges of analysing and designing the rotor prior to fabricating a prototype [9].

2.3.3 Piezoelectric Generator

This method alters mechanical energy into electrical energy by straining a piezoelectric material. Piezoelectric effect was discovered by J and P Curie in 1880. They found that strain or deformation of a piezoelectric material causes charge separation across the device, producing an electric field. This strain comes from many different sources. For example, the sources could be from human motion, low frequency seismic vibrations and acoustic noise. Moreover, piezoelectricity has the ability of some elements such as crystals and some types of ceramics, to generate an electric potential from a mechanical stress [10].

Mechanical compression or tension on a poled piezoelectric ceramic element changes the dipole moment, creating a voltage. Compression along the direction of polarization, or tension perpendicular to the direction of polarization, generates voltage of the same polarity as the poling voltage (Figure 2.8(a)). Tension along the direction of polarization, or compression perpendicular to the direction of polarization, generates a voltage with polarity opposite that of the poling voltage (Figure 2.8 (b)). These actions are generator actions where the ceramic element converts the mechanical energy of compression or tension into electrical energy.



(a) (b)

Figure 2.8: a) Disk compressed: generated voltage has same polarity as poling voltage b) Disk stretched: generating voltage has polarity opposite that of poling voltage

A piezoelectric generator design by S Roundy and P K Wright based on two layer bender mounted as a cantilever has been tested. Two designs have been optimized within an overall space constraint of 1 cm^3. These designs have been built and tested with both resistive and capacitive loads. Experimental results have demonstrated power transfer to a resistive load of 375 µW cm^{-3} from driving vibrations of 2.5 m s^{-2} at 120 Hz.

2.3.4 Thermoelectric (TE)

In 1821, Thomas Johann Seebeck discovered that a thermal gradient formed between two dissimilar conductors produces a voltage. Temperature changes between opposite segments of a conducting material result in heat flow and consequently charge flow since mobile, high energy carries diffuse from high to low regions. Ideal thermoelectric materials have a high Seebeck coefficient, high electrical conductivity and low thermal conductivity. The most important advantage is that no moving parts allow continuous operation for many years, as they contain no materials that must be replenished. One downside to the energy conversion is low efficiency (currently less than 10%) [11].
The simplest TE generator consists of a thermocouple consisting of n-type (materials with excess electrons) and p-type (materials with deficit of electrons) elements connected electrically in series and thermally in parallel. Heat is input on one side and

rejected from the other side, generating a voltage across the TE couple (Figure 2.9) [11]. The magnitude of the voltage produced is proportional to the temperature gradient.

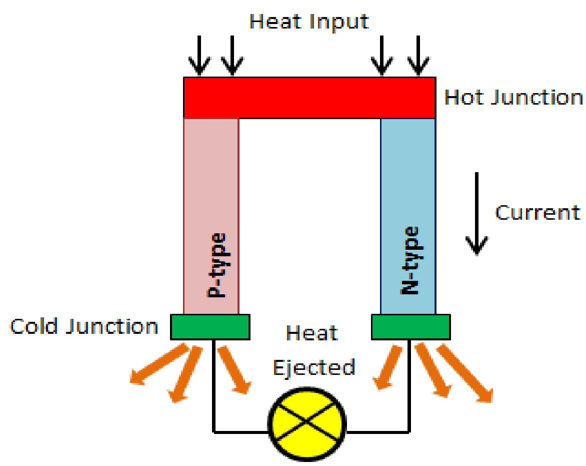


Figure 2.9: Thermoelectric Power Generator (TEG)

One of the latest designs of thermoelectric energy harvester is the TEG designed and introduced by Pacific Northwest National Laboratory (2007). This new TEG is used to convert environmental (ambient) thermal energy into electric power for a variety of applications that necessitates low power use.

2.4 Green Road Concept

Nowadays the green energy concept is discussed globally. It is focusing in most of the science and engineering aspect in order the reach a sustainable energy development. Throughout the years, the government has formulated numerous energy related policies which include the Fifth Fuel Policy 2000, National Biofuel Policy 2006 and National Green Technology 2009 to combat the climate change and ensure the energy security. In the 9th Malaysia Plan, RE is targeted in the country's energy mix was just 5%. Under the Green Technology Financing Scheme (GTFS), the government has announced a RM1.5 billion to support the development of Green Technology in Malaysia. Andriopoulou Symeoni said that the "Green Road Concept" should serve a dual purpose; mining the energy that is otherwise wasted by vehicles, incident solar radiation and pedestrians and;

secure the service life of the pavement by improving their thermal and mechanical properties. This configuration is a sustainable road that uses limited natural resources for its use, reduces energy consumption and greenhouse gases emissions, prohibits the pollution of the air, water and noise and ensures traffic safety and health. For example, Solar Roadways and Innowattech technology use sources of energy at pavements surfaces i.e the solar radiation and mechanical energy from the stresses caused by traffic. Harvesting energy from pavements by piezoelectricity is a new research field of pavement engineering as by now it has been used for harvesting small scale energy. The application of piezoelectric at the pedestrians or bikes supplies the electrical energy for road lighting and as well as storing it in batteries. The idea of mining the energy occurred from heavy traffic loads by using only small piezoelectric devices/sensors applied at particular layouts across the pavement infrastructure has open a new bridge of energy development . The storage of the harvested energy is desirable to occur at the inner structure of the pavement minimizing with that way the use of batteries and the transition of the new form of energy.

CHAPTER 3

METHODOLOGY

3.1 Project Methodology

This project is mainlyadopting research study on harvesting energy technique. There are few papers which lead the study on how to convert vibration into electrical energy, to implement on road ambient. The project is conducting in phase's basis as follow:

Phase 1: Literature Review on Harvesting Energy on Road Application

- To access the information on harvesting energy technology
- To study the current invention for harvesting energy for road application
- To discover the related topics rather than electrical or electronic such as road and vehicles

Phase 2: To Identify the suitable technology to implement in the project

- To make a comparison on existing technology mainly on energy conversion
- To identify the suitable model for energy conversion
- To synchronize between the energy conversion technique with road application

Phase 3: To analyze and conclude the results

- To simulate the model chosen using software (e.gMatlab, PSCadetc)
- To analyze the output data

- To conclude whether the model is suitable and can be strengthen for the application

3.2 Piezoelectric or Energy Harvester

Piezoelectric materials can be used as a means of transforming ambient vibrations into electrical energy that can be stored and used to power other devices. The energy produced by these materials is, in many cases, far too small to directly power an electrical device. However, if the material is use in a large scale and in a collective power (storage), it is shown that the small energy is just a turning point to harvest slightly large electrical energy (Innowattech). An experimental study shows that a Micro Fibre Composite (MFC) type was installed on a bicycle handlebar harvested 3.5 mW at 5 ms^{-2} of input vibration and 12.5 Hz of frequency for an optimal resistive load of 100 kΩ [12].

3.2.1 A General Unimorph Model

The proposed use of electrical harvestershas included the monitoring of both machines andstructures, and is of wide interest in the electrical,mechanical, and civil engineering communities.Piezoelectric energy generation has been extensivelystudied as one of the relatively inexpensive andhigh-power density alternative in vibrational energyscavenging [13]. In reality, most circuits that are attached to thepiezoelectric harvester are more complex than a singleresistor (as has been modeled extensively in the past),and might include nonlinear elements. The accuratemodeling of these circuits would require electroniccircuit simulators such as SPICE.The results from a derived equivalentmodel are compared with the analytical solution ofErturk and Inman (2008) for the first three vibrationalmodes of cantilever unimorph generator.The model which developed by Niell G. Elvin and Alex A. Elvin where based on Figure 3.1 [13].

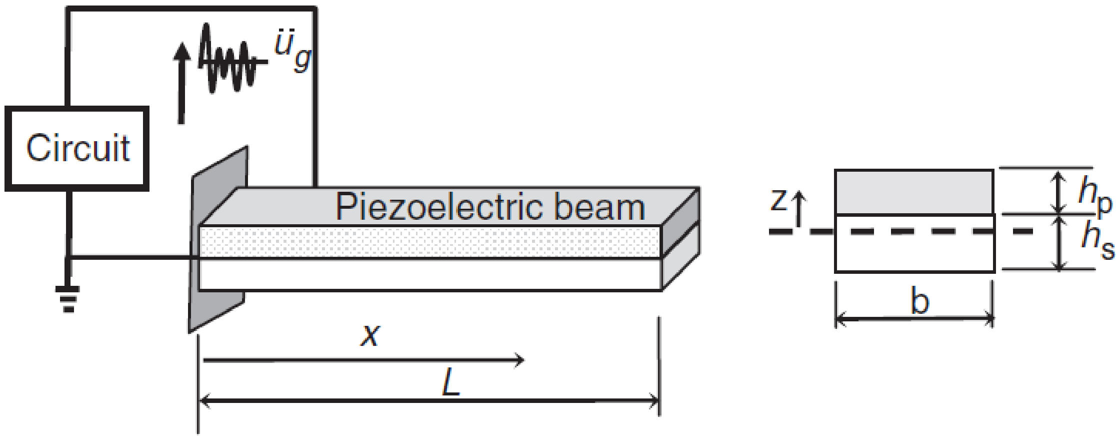


Figure 3.1: Schematic depiction of a cantilever beam, unimorph piezoelectric vibration scavenger.

The derivation of the single degree of freedom (SDOF) equivalent piezoelectriccircuit has been presented by Roundy and Wright(2004).In this model, the single equivalent mass, stiffness,and damping is represented by an inductor, capacitor,and resistor. The electromechanical coupling is representedby an ideal transformer as shown in Figure 3.2.

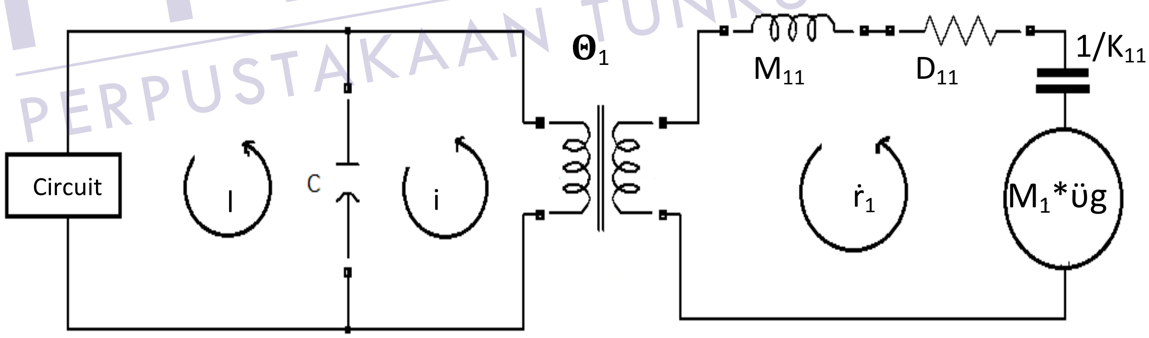


Figure 3.2: The equivalent circuit for a single degree of freedom piezo-generator.

Depending on the assumed mode shape the **K, M, D,M*,** and **Θ** matrices can be fully populated where **K** is the stiffness matrices, **M** is the mass, **D** is damping, **M*** is effective forcing vector and **Θ** is piezoelectric coupling vector.Neill G. Elvin et al. wrote that by assuming a unimorph piezoelectric geometrywith no tip mass, and the first three modes given by Rayleigh-Ritz approximation equation, the circuit element determination become:

$$M = \bar{m}L\begin{bmatrix} \frac{3}{2}-\frac{4}{\pi} & 1-\frac{4}{3\pi} & 1-\frac{12}{5\pi} \\ 1-\frac{4}{3\pi} & \frac{3}{2}+\frac{4}{3\pi} & 1+\frac{4}{15\pi} \\ 1-\frac{12}{5\pi} & 1+\frac{4}{15\pi} & \frac{3}{2}-\frac{4}{5\pi} \end{bmatrix} \quad (3.1)$$

$$K = \frac{1}{32}\frac{\pi^4 Y I_{xx}}{L^3}\begin{bmatrix} 1 & 0 & 0 \\ 0 & 81 & 0 \\ 0 & 0 & 625 \end{bmatrix} \quad (3.2)$$

$$D = \propto_0 M + \propto_1 K \quad (3.3)$$

$$\Theta^T = \frac{b\pi e_{31}}{4L}\left(2h_{pa} - h_p\right)\begin{bmatrix} 1 & -3 & 5 \end{bmatrix} \quad (3.4)$$

$$C = \frac{bL\varepsilon}{h_p} \quad (3.5)$$

$$M^{*T} = \bar{m}L\begin{bmatrix} 1-\frac{2}{\pi} & 1+\frac{2}{5\pi} & 1-\frac{2}{5\pi} \end{bmatrix} \quad (3.6)$$

3.2.2 Piezoelectric Generator Applied on A bicycle

Usually, a dynamo or batteries are used to feed electrical energy either front or rear lamp for bicycle. E. Minazara et al. (Figure 3.3) have developed a piezoelectric generator, which employ active materials that generate a charge when mechanically activated. A bicycle in movement is vibrating permanently, these vibrations then converted into electrical energy to power devices. The electrical behavior were modelledby a mass+piezo+spring+damper considering the generator is excited around its resonance frequency and in the case of a little displacement for which the movement remains linear.

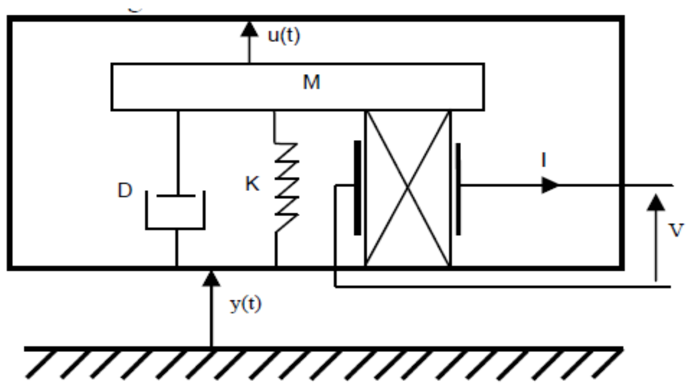


Figure 3.3: Equivalent model of a vibrating piezoelectric structure.

The considered structure is a rigid mass, M bonded on a spring, K corresponding to the stiffness of the mechanical structure. A damper, D is corresponding to the mechanical losses of the structure and on a piezoelectric disk corresponding to the bonded piezoelectric elements. D is the direct electric displacement vector. Figure 3.4 shows a general diagram for energy conversion using piezoelectric with a load.

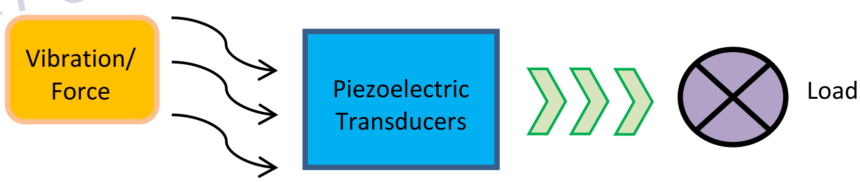


Figure 3.4: Energy conversion using piezoelectric transducers.

The modelled by E. Minarza et al. were also developed using experimental test by installing a beam type piezoelectric generator which consists of a metal flexible beam called Micro Fibre Composite (MFC) type with a good flexibility (Figure 3.5).

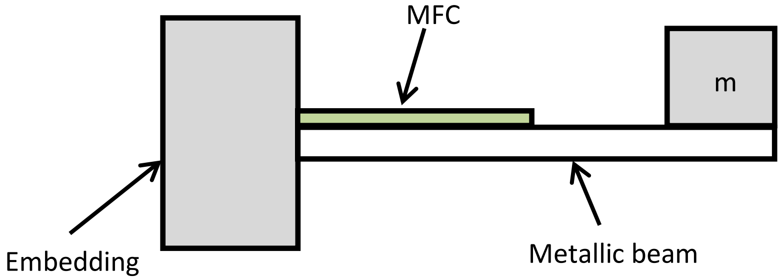


Figure 3.5: Metallic beam with piezoelectric element.

It considers a purely resistive load directly connected to the piezoelectric element. The voltage on the piezoelectric element can be expressed in the frequency domain as a function of the displacement,

$$V = \frac{\propto R}{1 + jRC\omega} j\omega u \qquad (3.7)$$

where ω is the angular frequency, C is its clamped capacitance, α is a force factor, R is load resistance and u is mass displacement. At the resonance of the structures with low viscous losses, the expression linking voltage V and displacement y(t) can be simplified as:

$$\frac{V}{y} = \frac{M \propto R\omega^2}{\alpha^2 R + D + jRCD\omega} \qquad (3.8)$$

For weakly electromechanically coupled structure, the variable α is close to zero. In this case the harvested power reaches a maximum P_{max} for an optimal load, R_{opt} :

$$P = \frac{y^2}{2} \frac{M^2 \alpha^2 R\omega^4}{(1 + (RC\omega)^2)D^2} \qquad (3.9)$$

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