SIMULATION OF CANTILEVERED PIEZOELECTRIC ENERGY HARVESTERS

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DECLARATION

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LIST OF ABBREVIATIONS

PEH	Piezoelectric Energy Harvester
IOT	Internet of Things
CAD	Computer Aided Design
ECM	Equivalent Circuit Models
SPICE	Simulation Program with Integrated Circuit Emphasis
PZT	Lead Zirconate Titranite
USM	Universiti Sains Malaysia

LIST OF APPENDICES

PEMODELAN DAN SIMULASI PENUAI TENAGA PIEZOELEKTRIK KANTILEVER UNTUK ANALISIS INTERAKSI ELEKTROMEKANIKAL

ABSTRAK

Penuaian tenaga berasaskan getaran telah disiasat secara meluas oleh beberapa penyelidik sepanjang dekad yang lalu. Penggunaan piezoelektrik terkenal dengan penukaran getaran kepada elektrik mekanikalnya. Kecekapan penuai tenaga piezoelektrik (PEHs) bergantung pada geomtry julur dan frekuensi sumber getaran. Dalam kertas ini, rasuk cantilever dengan lapisan piezoelektrik bahan PZT-5A digunakan sebagai penuai tenaga piezoelektrik. Tiga jenis rasuk julur PEH telah dibina iaitu unimorph, bimorph dan bimorph tanpa beban. Simulasi ketiga-tiga rasuk ini dibuat pada perisian ANSYS. Ini bertujuan untuk mengkaji prestasi bagi setiap rasuk julur PEH dan mereka telah membuktikan perbezaan di antara mereka. Analisis modal dan analisis Respons Harmonik telah disediakan dan dijalankan untuk tiga jenis rasuk dan hasilnya telah disahkan. Hasil analisis simulasi telah dijana dan ditafsirkan secara grafik yang menunjukkan ubah bentuk model, voltan dan tindak balas frekuensi untuk semua rasuk dengan berat beban dan dimensi yang sama.

MODELLING AND SIMULATION OF CANTILEVERED PIEZOELECTRIC ENERGY HARVESTERS FOR ELECTROMECHANICAL INTERACTION ANALYSE

ABSTRACT

Vibration-based energy harvesting had been extensively investigated by several researchers over the last decade. The use of piezoelectricity is known for its mechanical vibration-to-electricity conversion. The piezoelectric energy harvesters (PEHs) efficiency is dependent on the cantilever geomtry and the vibration source frequency. In this paper, cantilevered beams with piezoelectric layers of PZT-5A material are employed as piezoelectric energy harvesters. Three kinds of PEH cantilever beams were constructed which are the unimorph, bimorph and bimorph without load. The simulation of these three beams were made on ANSYS software. This was meant for the study of the performance for each of the PEH cantilever beams and they had proven distinctions among them. Modal analysis and Harmonic Response analysis were setup and run for the three types of beams and the results were validated. The outcome of the simulation analysis was generated and interpreted graphically which shows the model deformation, voltage and the frequency response for all the beams with same weight of load and dimensions.

CHAPTER 1

INTRODUCTION

1.1 Overview of Energy Harvesting Techniques

Microelectronics and wireless technologies have facilitated the creation of wearable gadgets in recent years, including garments and accessories that are powered by batteries or energy-harvesting technology [1]. The idea of the Internet of Things (IoT), where wireless sensor networks are frequently used, goes hand-in-hand with these strategies [2]. Smart equipment is now being installed in distant locations and other situations where it may be challenging or impossible to charge batteries as a result of IoT. (e.g., health care devices placed inside the human body, and smart buildings). Although low-power integrated circuit technology has advanced, chemical batteries still need to have their energy density increased in order to meet the difficult-to-meet power requirements for the aforementioned applications [3]. To maintain such self-powered devices, new energy harvesting techniques must be created. Energy harvesting is essential for maintaining self-powered systems since it provides an economically viable alternative to batteries while also lowering the risk of greenhouse gas emissions and preserving the environment [4].

An energy harvesting system typically consists of three components: the energy source, the harvesting device, and the load [5]. The energy source is an illustration of the energy that will be used to generate electrical power. This energy can be either ambient (found in the natural surroundings, such as sunlight, heat, or wind) or external (energy sources that are explicitly deployed, e.g., lightning, human heat, or vibrations) [6]. The structure that turns ambient energy into electrical energy makes up the harvesting mechanism. The load is made up of the sink, which uses or stores the energy produced by the electrical output. Sunlight, electromagnetic radiation, mechanical energy from the environment, body heat, and mechanical energy from the human body are the most prevalent small-scale energy sources. Human body energy harvesters can be incorporated into daily human activities to power a range of devices, unlike solar energy, electromagnetic radiation, and environmental mechanical energy, which are largely dependent on the environment [4].

The harvested power density P_{res} for mechanical energy depends on the motion frequency and magnitude, as shown in the resonance power Formula (1) [7].

$$P_{res} = 4\pi^3 {f_{res}}^3 y Z_{max} \quad (1)$$

where m is the inertial mass, Z_{max} is the maximum displacement, f_{res} is the resonance frequency, and y is the amplitude of vibration of the housing

Energy harvesting efficiency can be defined as the ratio between the power consumed on the external load resistance and the total input mechanical power. Mechanical efficiency is the converted electrical power divided by the total input mechanical power, and the electrical efficiency can be defined as the ratio between the power consumed on the external load resistance and the converted electrical power [8]. Mechanical energy E_m (Equation (2)), electrical energy E_e (Equation (3)), and energy conversion efficiency $E\%$ (Equation (4)) are defined using the following equations [9].

$$E_m = \int_0^{\Delta t} F\, d(t) dt \quad (2)$$

$$E_e = P\Delta t = \frac{V^2}{R}\Delta t \quad (3)$$

$$E\% = \frac{E_e}{E_m}\ 100 \quad (4)$$

where F is the applied force, d is the movement distance while the force is applied, Δt is the generation time, P is the output power, V is the output voltage, and R is the resistive load applied to the harvester.

The energy produced by human walking can be captured using a mechanical energy harvester. Flywheels (which have high energy densities but also need a lot of areas and have complex constructions) and springs are two different forms of mechanical energy storage systems that can be used for this (which have a low energy density but are simple and reliable) [4]. These harvesters can be used to harvest mechanical energy, which can then be stored for use at a later time using a ratchet. Three common methods exist for transforming mechanical energy into electrical energy: electrostatic/triboelectric, electromagnetic, and piezoelectric [10]. Electromagnetic systems are best suited for high mechanical-to-electrical energy transfer efficiency because they typically contain coils and magnets, but this also entails large and complicated mechanics [11]. The application will determine which of the three approaches is best, but piezoelectricity has received the most attention [11].

1.2 Overview of Piezoelectricity And Its Structure

Briscoe and Dunn [12] defined piezoelectricity as an "electric charge that builds up in materials with non-centrosymmetric crystal structures in response to applied mechanical stress", while Ertuk and Inman [13] defined piezoelectricity as "a method of linking between the mechanical and electrical properties of specific kinds of ceramics and crystals". The Greek origin of the word "piezoelectricity" is "squeeze or press" [4], which refers to the property of the piezoelectric materials to generate an electric field when a mechanical force is applied, a phenomenon called the direct piezoelectric effect [4].

Two phenomena make up the piezoelectric effect: the direct piezoelectric effect and the inverse piezoelectric effect [13]. Pierre and Jacques Curie discovered the direct piezoelectric effect, or the ability of some materials to produce an electric field when a strain is applied, in 1880 [4]. A year later, Lippmann used mathematics to mathematically determine the opposite or inverse piezoelectric effect from the laws of thermodynamics [14], and it states that a piezoelectric material will deform if an electric field is applied to it [4]. These two effects coexist in a piezoelectric material, therefore disregarding one of them in a given application would be illogical from a thermodynamic standpoint [15].

With the benefits of flexibility and simple encapsulation, a piezoelectric cantilever beam is used for piezoelectric materials in infrastructure monitoring. Additionally, because of the low self-vibration frequency, it is highly ideal for low-frequency circumstances [16], such as on pavement and bridges. Although there has been great progress in the simulation of pavement materials and pavement structures [17], [18], reliable monitoring results can contribute significantly to direct maintenance. That mechanical strain can become an electrical charge thanks to the piezoelectric substance (voltage). There are many different kinds of piezoelectric materials, but the most widely used ones are Lead Zirconate Titanate PZT, PZT-5A, and PZT-5H because of their great efficiency [19]. The standard PEH configuration resembles a cantilevered beam made up of layers of various materials. The primary support structure is attached to one or more piezoelectric layers [20]. In order to categorize piezoelectric layers, it is typical to use the terms unimorph, bimorph, and bimorph without mass/load nomenclature, with the former denoting a single layer and the latter two [20].

1.3 Problem Statement

With the recent development and growth in power energy as well as the global interest in the green concept, green energy harvesting has been the center of attention from way back then. The demands for renewable energy requirements have elevated way higher with advancements made in energy harvesting systems. The use of batteries has been thoroughly worse these days. With the limited number of full discharge cycles and sudden thermal runaway due to improper charging, batteries are prone to less energy efficiency and environmental friendliness. Therefore, a piezoelectric energy harvesting cantilever beam is introduced with the aim of producing electrical energy from mechanical vibration. It also operates in the manner of harvesting green energy since mechanical vibration does not harm nature and the environment. In addition, it also acts as power storage by absorbing the vibration from the surrounding. In analyzing the electromechanical interaction and power output induced by the cantilevered piezoelectric energy harvesters, finite element method such as ANSYS software is utilized in this project. The reason for this is due to huge models are easier to be analyzed through ANSYS and it gives out more accurate results through full-wave analysis. Having to use ANSYS in conducting the study of electromechanical interaction proves more reliable.

1.4 Objectives

1.4.1 Objectives 1

To create a model of the Piezoelectric Energy Harvester (PEH) cantilever beam for unimorph, bimorph, and bimorph without mass/load types using the finite element method which is the ANSYS software.

1.4.2 Objectives 2

To simulate the model of the PEH cantilever beam using Modal analysis and Harmonic Response analysis.

1.5 Scope of Project

In the project, the piezoelectric energy harvesting (PEH) cantilever beam will be categorized into 3 types which are unimorph, bimorph, and bimorph without mass/load. Those types of PEH will be investigated through the use of the finite element method which emphasizes the modeling of the PEH systems and simulation for the modeled systems to achieve appropriate results through the observation in the time and frequency domain which can be represented in the graphical analysis. Each model of PEHs is simulated separately as they are different in their structures and respond with dissimilar output variables through Modal analysis and Harmonic Response analysis. The modeling and simulation will be done via ANSYS Software which consists of both CAD modeling and the simulation for the CAD drawings. Therefore, it is a suitable yet effective all-in-one finite element method for conducting this project.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview of Piezoelectric Energy Harvester

The goal of piezoelectric energy harvesting research over the past 20 years has been to create a long-lasting power source for wireless electronics by transforming environmental vibrations into useful electricity. It is well known that a piezoelectric energy harvester's (PEH) power output is highly dependent on the impedance of the load. Although complicated power management circuits are required to transfer the power efficiently from the PEHs to energy storage [21], a load resistor is usually connected to characterize the generated power during the transducer design and optimization stage. The load resistance that results in the highest power consumption on the load resistor is the ideal load resistance. A piezoelectric energy harvester can be conceptualized as two separate mechanical and electrical systems in their most basic form. The free capacitor of the piezoelectric material is typically modelled as an analogous circuit model with a current source connected in parallel or a voltage source linked in series [11].

2.2 Model of Piezoelectric Energy Harvesters

Analytical models have been developed to acquire the full expression of power output, which is then investigated to determine the ideal load resistance and peak power, in order to more correctly predict the electric power output of PEHs [22]. Through analytical models, Renno et al. [23] and Goldschmidtboeing et al. [24] found that two power peaks and two optimal load resistance values may exist near the resonance of a PEH when the electromechanical coupling coefficient K is high enough or the mechanical damping is low enough. Liao and Sodano [24] noticed this behavior in both experiment and analytical modelling. Optimal resistance and maximum power generation can be predicted with excellent precision by analytical models. When it comes to PEH design optimization, they can be very useful. However, they do not provide a physical or logical explanation for the power characteristics of closely coupled PEHs.

In simulation tools like SPICE, PEH equivalent circuit models (ECMs) with lumped parameters have been developed. The lumped parameters can be computed using analytical modelling or finite element analysis [24]. Kong et al. [25] derived the internal impedance network of PEHs based on the analogy between electrical and mechanical domains. They emphasized that resistive impedance matching allowed for the greatest power transmission at frequencies with entirely resistive internal impedances, or when the impedance phase is zero. To achieve a less-than-ideal matching when the zero-phase is unavailable, the load resistance should nevertheless match the internal impedance magnitude [25]. There were two power peaks accessible when the internal impedance of the PEH had two zero-phase frequencies approaching resonance and the coupling efficiency figure of merit K QM 2 (QM being the mechanical quality factor) was greater than 2. Strongly linked PEHs' double power peaks have a logical explanation thanks to the connection between power peaks and the zero-impedance phase. When constructing power management circuits, which is often done after the design of a PEH is complete and the lumped parameters are determined, ECMs with lumped parameters are beneficial. However, because the design factors, such as geometry and material qualities, are not immediately reflected in the lumped parameters, it is not practical for the design and optimization of energy harvesters [26].

2.3 Optimization of PEHs' Structure and Design

For energy harvester design and optimization, commercial software packages such as ANSYS and COMSOL provide a powerful tool because of their ability to simulate complicated transducer structures [24] and more importantly to couple the fields of mechanical structures, piezoelectricity, and electrical circuits. This makes it possible to create piezoelectric circuit coupled finite element models (FEMs), in which electrical circuits are connected to piezoelectric energy harvesters. This establishes a clear connection between the electrical power output and the physical design characteristics. Even though the internal impedance network of strong coupled PEHs is significantly more complex than the free capacitor of the piezoelectric material, most FEMs still employ the crude RC matching technique, which may produce erroneous findings when operating close to resonance. There have not yet been any documented FEMs for tightly coupled PEHs [24]. For strongly coupled PEHs connected to a load circuit, a novel and effective finite element modelling approach are proposed in this work. In order to determine the value of the ideal load resistance at a given frequency and to simulate power generation, the FEM first analyses the internal impedance of the

PEH across the frequency range of interest. Regardless of the level of electromechanical coupling, the full performance of the PEH, including the ideal load resistance and the maximum power output across the entire frequency range, may be properly recreated using the suggested method. Any harmonically actuated linear PEHs or nonlinear PEHs that can be linearized around the operating point can be subject to the procedure [24].

2.4 Simulation of PEHs

In 1995, William and Yates made the discovery of energy harvesting using vibration. They developed a basic excitation model that produces electricity through energy harvesting. Piezoelectricity is a method for combining a material's electrical and mechanical capabilities. Currently, there are many simulation evaluations of piezoelectric energy systems, and research into piezoelectric energy harvesting technologies is fairly advanced. Some studies have made corresponding improvements to the traditional cantilever piezoelectric energy flotation device [27], which improves the energy harvesting efficiency of the harvester but ignores the energy harvester's electromechanical coupling effect; there are also studies using MATLAB software to improve the energy harvesting efficiency of the harvester. The piezoelectric energy trap system was simulated [28], which confirmed the stability of the system's output voltage and intuitively reflected the piezoelectric trap system's output characteristics. However, this method has a high computational cost and a difficult solution procedure; there have been studies that use COMSOL simulation to evaluate the piezoelectric energy trap system [29], and the influence of piezoelectric materials on the energy trap has been obtained. This study uses a piezoelectric vibration energy harvester to enhance the energy collecting rate and proposes an electromechanical coupling model to simplify the potential energy analysis, based on previous relevant research and overcome the inadequacies of existing technology [30]. The Runge-Kutta numerical differential equation approach is used to simulate the model while simultaneously developing a mathematical model based on the dynamics of the piezoelectric cantilever system and simulating the impact of precipitation on the potential energy and dynamic parameters. The relationship between the diameter of a raindrop and the system output voltage is shown more clearly by the corresponding system output response law curve, which is created.

The cantilever shape must be optimized and its natural frequency must be matched with the vibration source frequency for the piezoelectric energy harvester to function well. Additionally, the resonance frequency must be tuned according to how harvester factors affect natural frequency. In order to compute the resonance frequencies and examine the impact of the harvester parameters, a COMSOL Multi-physics finite element analysis, Eigen frequency research, and an analytical analysis using MATLAB were built [19]. The evolutionary algorithm was used to optimize five harvesters with various shapes, including T-shaped, rectangular, L-shaped, variable width, and triangular cantilevers. Utilizing COMSOL, the simulation of the five forms was carried out. The findings showed that the T-shaped cantilever generated the most power [19]. The T-shaped cantilever with changeable width was optimized with the COMSOL optimization tool due to its high power and inclusive shape (BOBYQA). The output power has significantly increased thanks to the integration of genetic algorithms and the COMSOL optimization module. Utilizing an experimental set-up of piezoelectric cantilevers, the COMSOL results were confirmed. The base excited harvester's voltage was calculated using the experimental setup with very low excitation frequencies ranging from 0.5 to 10 Hz. Additionally, the experimental design looked at how the output voltage was affected by the tip mass, cantilever length, and volume of the piezoelectric material [19].

2.5 Post-Modelled PEHs

Due to the direct piezoelectric effect, mechanical vibrations can be used as a source of electrical energy by piezoelectric power generators. In-depth research has been done on these generators as a low-cost, high-efficiency choice for harvesting low-level energy. Researchers have proposed a variety of models to represent the electromechanical behavior of piezoelectric energy harvesters, ranging from lumped parameter models [31] to Rayleigh-Ritz type approximate distributed parameter models [31], [32] as well as analytical distributed parameter solution attempts [32]. Certain difficulties in several of these lumped and distributed parameter piezoelectric energy harvester models have recently been clarified in the literature [33]. Analytical distributed parameter solutions with closed-form formulas for unimorph [33], [34] and bimorph [32] piezoelectric energy harvester setups have recently been reported. When enough acceptable functions were utilized, Elvin and Elvin discovered convergence of the Rayleigh-Ritz type electromechanical solution [31] to the analytical solution proposed by Erturk and Inman [33]. The lumped parameter solution [31] has been shown to be effective in gaining a basic grasp of the problem and investigating system parameter optimization for improved electrical outputs [32]. However, applying distributed parameter solutions to accurately anticipate the electromechanical behavior of piezoelectric energy harvesters is required. For the approximate [32] and analytical

[33] distributed parameter electromechanical solutions, experimental verifications and validations were also provided.