Chapter 1

Introduction

Low power sensors are used in the tire pressure monitoring system (TPMS) configuration, realtime condition monitoring of turbine and propeller blades, so as for active vibration isolation of structures. The reliability of those sensor systems mainly depends on their power sources. The conventionally used electrochemical batteries have some severe disadvantages, including environmental and frequent maintenance problems. Therefore, developing a device that can harvest the remotely available abundant ambient energies and supply power to those sensors will be advantageous. The ambient energies can be in the form of solar power, wind energy, salinity gradient, and mechanical/kinetic energy. Various transduction methods like electrostatic, electromagnetic, piezoelectric, etc., are available to harvest the ambient kinetic energy. The piezoelectric transduction method always provides higher efficiencies while using compact structures. This thesis presents the design and development of parabolic and exponentially tapering width PVEH systems along with their experimental validations for both the transverse and rotational motion applications. This chapter concerns the reader with a brief background of piezoelectricity and general PVEH systems. The contributions to the existing knowledge this thesis intend to make are introduced, followed by a summary of the thesis structure.

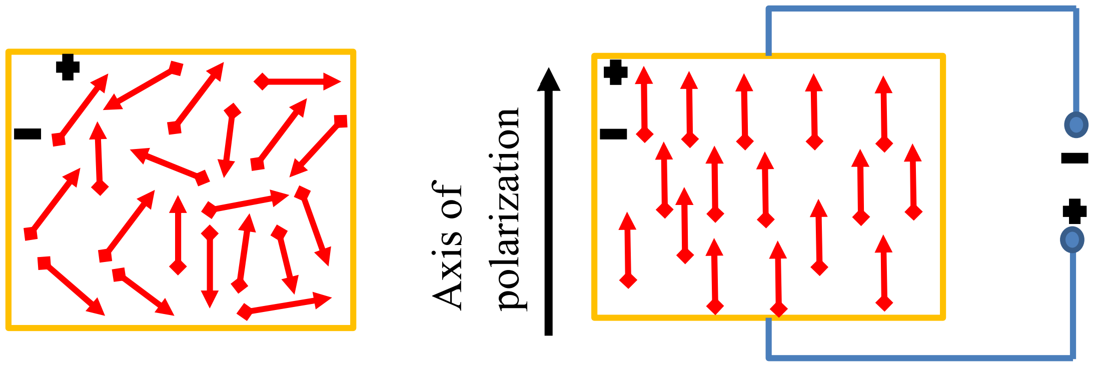
1.1 Background

French physicists Jacques and Pierre Curie discovered piezoelectricity in 1880. It is a property of certain materials to physically deform with the application of electricity or conversely to generate an electrical charge when mechanically distorted. This is attributed to charge separation occurring spontaneously in some crystal structures under ideal circumstances, i.e., a movement of the positive ions relative to the negative ions within their crystal structures. The characteristics of commonly used piezoelectric materials are listed in Table 1.1.

The Lead zinc niobate–lead titanate (PZN-PT) and Lead magnesium niobate–lead titanate (PMN-PT) have the best piezoelectric characteristics, but they are more sensitive to temperature, fatigue-prone, and challenging to fabricate than the Lead zirconate titanate (PZT). As a result, PZT continues to be the most widely used piezoelectric material in energy harvesting applications. The PZT is a perovskite ceramic that needs a precise method to fabricate. First, a proportionate quantity (x) of fine PZT powders of the constituent metal oxides ($Pb\ Zr_{1-x}\ Ti_x\ O_3$) is mixed. According to Yuhuan(1992), at $x \approx 0.5$, the piezoelectric effect is maximized. The crystalline PZT is around the phase boundary between the ferroelectric monoclinic and rhombohedral phases when $x = 0.5$. Also, a significant number of polar domains coexist for $x = 0.5$. A dry or isostatic press is used to heat the compound powder and form it into the desired shape. After that, the elements go through a sintering process to achieve a dense crystalline structure. Then for the polarization step, the crystalline components are ground to specifications and bo nded with electrodes on the surface. Figure 1.1 shows the polarization treatment of a piezoelectric element, accomplished by subjecting the PZT component to a high DC electric field just below the Curie temperature (Figure 1.1b). When the electric field is removed, the majority of the dipoles are locked into a near-aligned state, and the element becomes permanently polarized.

Table 1.1 Physical properties of commonly used piezoelectric materials (Caliò et al., 2014; Covaci and Gontean, 2020; Wu et al., 2021; Yang et al., 2018a)

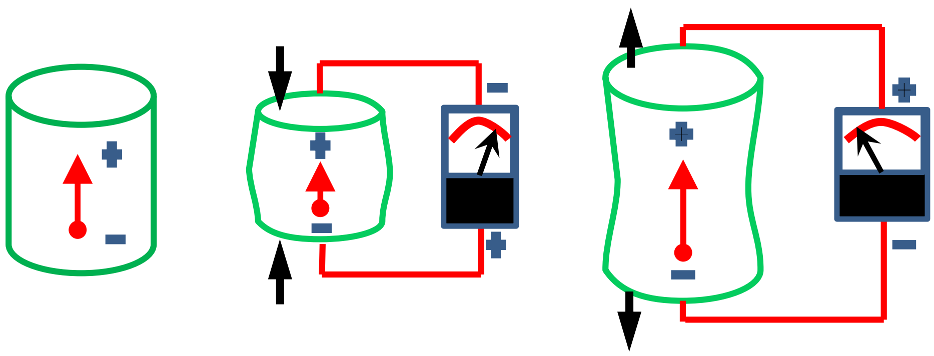
Property	Unit	PZT 4	PZT 8	PZT - 5A	PZT - 5H	PZT - 5J	$BaTiO_3$	PVDF	PMN -PT	PZN -PT
T_c	^{0}C	325	300	370	195	250	115	100	145	125
Y_{33}^E	GPa	15.5	13.5	58.1	54.3	56.7	59.2	2.5	38	-
Y_{11}^E	GPa	12.3	10.0	59.9	59.1	64.4	67	2.7	14	62.9
Dielectric loss	%	0.4	0.4	2.00	2.50	1.61	-	-	0.42	0.22
k_{33}	-	0.70	0.64	0.67	0.72	0.75	0.48	0.15	0.93	0.90
k_{31}	-	0.33	0.30	0.34	0.35	0.38	0.21	-	0.87	0.32
d_{33}	pC/N	295	225	409	620	554	149	33	2200	2400
d_{31}	pC/N	-122	-97	-176	-250	-234	-78	-23	-920	-1400
d_{15}	pC/N	500	330	584	741	670	270	-	-	-
g_{33} (10^{-3})	Vm/N	24.9	24.0	25.7	20.6	22.8	14.1	330	44	41.7
g_{31} (10^{-3})	Vm/N	-10.6	-10.9	-11	-8.3	-9.6	5.0	216	-17.1	24.3
g_{15} (10^{-3})	Vm/N	39.0	28.9	38.2	26.8	32.5	-	-	-	-
Q_m	-	400	1000	60	65	70	300	3-10	69	62



(a) (b)

Figure 1.1 Polarization of a piezoelectric element (a) randomly oriented polar domains before polarization (b) polarization in DC electric field

Figure 1.2 shows the generator actions of a piezoelectric element, i.e., conversion of mechanical energy into electrical energy. The compression parallel, or tension perpendicular to the polarization direction, produces a voltage with the same polarity as the poling voltage, as shown in Figure 1.2b. The tension parallel, or compression perpendicular to the polarization direction, produces a voltage with the polarity opposite that of the poling voltage, as shown in Figure 1.2c.



(a) (b) (c)

Figure 1.2 Generator actions of a polarized piezoelectric element, (a) after polarization (b) compressed (c) stretched

A piezoelectric energy harvester, in general, is a cantilevered structure containing one or more piezoelectric layers that are surface bonded to a non-piezoelectric host beam. When the piezoelectric material is subjected to mechanical motion, the dynamic strain induces an alternating voltage. Figure 1.3 shows the equivalent circuit diagram for a piezoelectric voltage generator. The two output terminals are the only things accessible to the outside world. The voltage output V is the open-circuit voltage and proportional to the applied stress, and C_p is the laboratory-measured capacitance of the piezoelectric patch. Moreover, PVEHs have certain intriguing features, such as increased power densities and ease of implementation, and they can be easily manufactured at both the macro and micro scales. It's also worth noting that a PVEH's life span can be unlimited under optimal operating conditions. Furthermore, a wide variety of piezoelectric materials readily exists to use in piezoelectric harvesters.

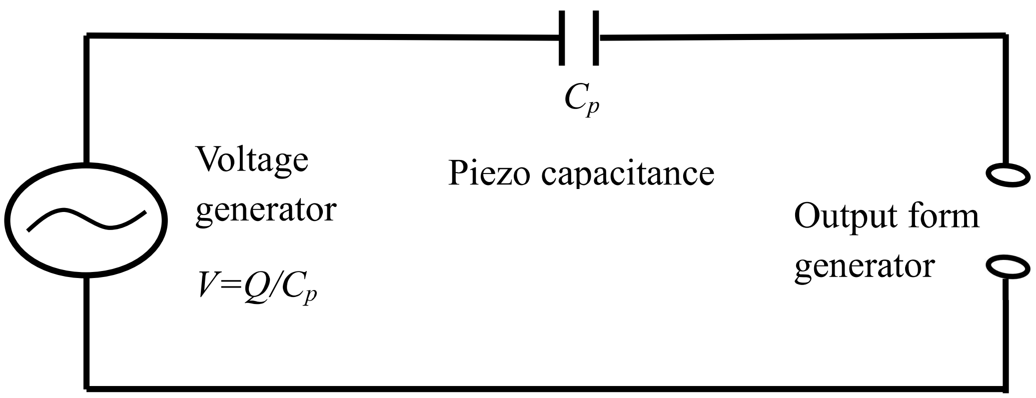


Figure 1.3 Piezoelectric transducer modelled as an electric unit (voltage generator)

The design and development of any PVEH involve understanding mechanical behaviour, electrical circuitry, material sciences, and nonlinearity. For these reasons, research communities from various areas have been continuously working together to create effective modeling techniques for PVEH systems. Weak mathematical assumptions like lumped mass consideration in the formulations lead to severe modeling problems and predict incorrect responses. Moreover, the piezoelectric materials behave nonlinearly, and the geometric nonlinearities appear at higher excitation levels. Furthermore, the existing research in PVEH lacks the necessary understanding to investigate the harvester's host beam morphologies in the case of rotational motion applications, which can significantly influence the efficiency/ voltage-per-total mass (VPM) as discovered in this thesis. The prime objective of this study is to address the limitations and inadequacies in existing PVEH modeling approaches.

1.2 Contributions to Knowledge

The research presented in this thesis aims to provide the reader with a deeper insight into the electromechanical modeling of PVEH systems and its potential use in transverse and rotational motion applications. The following is a list of the thesis's novel contributions to the existing knowledge:

1. The earlier presented mathematical models predict incorrect responses of a PVEH system, specifically at higher base acceleration levels, because of the linear consideration of the strain-displacement relation, piezoelectric constitutive relation, and electric displacement relation. Again, a mathematical model of a rotational piezoelectric vibration energy harvester (RVEH) should consider all the characteristic parameters associated with rotational motion and vibration energy harvesting. Therefore, to provide a deeper insight into the mathematical modeling of PVEH systems, this research presents a model that considers the system's material and geometric nonlinearities. This thesis also illustrates the

application of method of multiple scales (MMS) and chain rule with detuning parameters to solve the nonlinear coupled electromechanical motion equations. The proposed nonlinear mathematical model predicted PVEH's responses accurately at a sufficiently higher level of acceleration amplitude. For the RVEH, this thesis presents multimodal electromechanical coupled motion equations considering all the characteristic parameters associated with vibration energy harvesting and rotational motion to conduct the frequency and voltage response analysis.

2. The mathematical models presented in this thesis incorporate the proposed parabolic and exponentially tapering width of the host beam as well as the piezoelectric patches. The variable cross-section areas and the area moment of inertia (MOI) of the systems are modified accordingly.
3. This thesis presents the effects of taper parameter, piezoelectric patch thickness, and tip load mass on the PVEH's performances and nonlinearity in the case of transverse excitation. In the case of rotational motion, the influences of the characteristic parameters like taper parameter, piezoelectric patch to host beam thickness ratio, piezoelectric coupled beam length, and overall radius of rotation on the voltage and frequency responses are presented.
4. The model validation part of this research demonstrates the FE modeling and simulation procedures of the parabolic and exponentially tapered RVEHs in ANSYS Mechanical APDL. The modeling presents the voltage coupling method to simulate the electrodes over the piezoelectric patch surfaces. The simulations are conducted to acquire the OC voltage responses and the power generating potential of the RVEHs.

5. The prototype fabrication and the experimental setup development for the RVEH systems are significant concerns for researchers. This thesis presents the complete fabrication procedure of the parabolic and exponentially tapering harvesters, including cutting the host beam and surface bonding the piezoelectric patch. This thesis also presents the design and development of the experimental setup to test the harvester's performances under rotational motion applications. Furthermore, the experimental procedures to test the harvester's performances under transverse excitations are also presented in this thesis.
6. This thesis presents a detailed parametric analysis of the harvesters to identify the influences of the characteristic parameters for self-frequency-tuning applications. The parametric analysis includes the study of taper parameters, piezoelectric coupled beam's length, the overall radius of rotation, and the piezoelectric patch to host beam thickness ratio on the OC voltage responses and the frequency characteristics of the harvesters.

1.3 Thesis Structure

Chapter 1 - Introduction: This chapter deliberates the thesis' motivation, background, research framework, and contributions to knowledge. A summary of the thesis structure concludes the chapter.

Chapter 2 - Literature review: The first part of this chapter presents a comprehensive literature review summarizing the earlier published work in the major areas relevant to this thesis. These areas include transduction methods of vibration energy harvesters, PVEH for transverse and rotational motion applications, tapering cross-section PVEH, and parametric analysis and its applications. After the critical literature review, research gaps are identified and discussed. Finally, the chapter concludes with the research objectives of the thesis.

Chapter 3 - Design and analysis of parabolic tapering width PVEH under transverse excitation: This chapter deliberates the nonlinear electromechanical modeling of the proposed parabolic tapering width PVEH under transverse excitation and its experimental validations. Finally, the effects of the tapering and piezoelectric patch thickness on the harvester's performance and nonlinearity are discussed to compare the linear and nonlinear formulations.

Chapter 4 - Design and analysis of the PVEHs for rotational motion application: The mathematical formulations for the parabolic and exponentially tapering RVEHs are presented in the first part of this chapter. Then the FE simulations conducted to validate the proposed models are presented. Finally, the experimental methods followed to test the harvester's performance are presented.

Chapter 5 - Parametric analysis of the RVEHs: This chapter presents the parametric analysis of the proposed parabolic and exponentially tapered RVEHs. The parametric study is conducted to identify the influences of the characteristic parameters on the voltage generation performances and frequency characteristics. The chapter concludes with a comprehensive performance comparison of the proposed RVEHs with previously reported models.

Chapter 6 - Conclusions and future scopes for the research: The thesis's findings are summarized in this chapter. The proposals for future research are also suggested.

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