Wireless drive of piezoelectric components

Satyanarayan Bhuyan

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WIRELESS DRIVE OF PIEZOELECTRIC COMPONENTS

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SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING

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SUMMARY

Piezoelectric devices are widely used due to their compact size, high power density, low power consumption, high output force, high precision positioning, etc. In most applications, electric energy is applied to the piezoelectric devices through lead wires soldered on the electrodes of piezoelectric components. Fundamental limitations of applying electric energy to the piezoelectric devices via lead wires necessitate the pursuit of wireless drive of piezoelectric components. To widen the application range of piezoelectric devices, new techniques of transmitting electric energy wirelessly to piezoelectric components have been proposed and investigated by the author.

In the work reported by the thesis, an A.C. electric field is used to drive piezoelectric components wirelessly. The piezoelectric components are made of lead zirconate titanate (PZT) ceramic material, and poled along the thickness direction. An equivalent circuit model is derived by using the fundamental constitutive piezoelectric equations, and then proposed by the author for a piezoelectric component operating in the thickness mode wirelessly driven by an A.C. electric field. The equivalent circuit of the wirelessly driven piezoelectric component has a current source, resulting from the external electric field. This is different from the equivalent circuit of conventional piezoelectric component driven by a voltage applied via lead wires. The concept of using a current source in the equivalent circuit may be applied to the wirelessly driven piezoelectric components operating in the other vibration modes.

Various new techniques including wireless drive of piezoelectric components by parallel plate capacitor structure, focused electric field, focused electric field structure in electric resonance with an inductor, dipole antenna-like structure and flat spiral coil antenna-like electric field generator in electric resonance with a capacitor are proposed and investigated by the author. Both theoretically and experimentally, it has been found that the real output power achieved wirelessly by the piezoelectric component depends on the operating frequency, vibration mode, electrical load, electrode pattern, position and size of the piezoelectric component, separation distance of electrodes, area of live and ground electrodes, and the electric field generated by the electric field generators. The theoretical results agree well with the experimental ones. The output power of the piezoelectric component reaches the maximum at resonance. If the piezoelectric component is detuned from the resonance, the output power of the piezoelectric component drops suddenly. The output power at resonance of the piezoelectric component, operating in the thickness vibration mode, is significantly higher than that of the component operating in the other modes like width and length extensional vibration modes. The output power at resonance reaches maximum at an optimum load resistance. At the resonant frequency and with an optimum electrical load, the output power of piezoelectric component increases with the decrease of the size of piezoelectric component, the increase of electrodes area, and the decrease of distance of piezoelectric component from the live and ground electrodes of electric field generators.

As a comparison, it has been found that the energy conversion efficiency of the piezoelectric component wirelessly driven by focused electric field structure in

electric resonance with an inductor is significantly higher than that wirelessly driven by the other proposed electric field generators. When the focused electric field generator and inductor are in electric resonance, a maximum output power of 206.04 mW, and an energy conversion efficiency of 1.02% have been achieved wirelessly by a small piezoelectric component with an area of 40 mm² operating in the thickness vibration mode at resonance frequency of 782 kHz, optimum electrical load resistance of 1365 Ω , input A.C. source power of 20.12 W (applied to the series of focused electric field generator and inductor), 1 cm live and ground electrodes separation, and a live electrode area of 900 cm² of the focused electric field structure. The technique of wireless drive of piezoelectric components by focused electric field structure in electric resonance with an inductor enables a relatively larger output power achieved wirelessly by the piezoelectric component than the other structures for a given input A.C. source voltage. Compared to the other proposed techniques, the technique of wireless drive of piezoelectric components by an antenna-like structure is robust for the free motion of piezoelectric components, and also may be effective to drive micro piezoelectric components in rotary machines.

The finite element method (COMSOL Multiphysics) simulation has been carried out in order to assess the electric field strength on the surface of the piezoelectric component wirelessly driven by an A.C. electric field produced from the electric field generator. It is seen that the value of the electric field on the surface of the wirelessly driven piezoelectric component depends on the structure of the electric field generator, size and position of the piezoelectric component for a given input A.C. source voltage.

The mechanical vibration characteristics of a piezoelectric component operating in the thickness mode wirelessly driven by focused electric field have been investigated theoretically. The effects of electric field, operating frequency, electrical load, position, and size of the piezoelectric component on the vibration displacement are studied. It is seen that the vibration displacement at resonance increases with the electrical load resistance, the area of the piezoelectric component, and decreases with the thickness of the wirelessly driven piezoelectric component.

Furthermore, a method to merge microdroplets by using a wirelessly driven piezoelectric stage is proposed and investigated, to simplify the device structure for microdroplets merging and extend the application range of this technology. The microdroplets to merge are dispensed onto the surface of a piezoelectric stage. The ultrasonic vibration of the piezoelectric stage is transmitted into the microdroplets and induces the merging of microdroplets. It has been observed that the time for merging of water microdroplets depends on the vibration displacement of the stage, separation distance and volume of microdroplets. At the resonant frequency of 776 kHz, two water microdroplets each of volume 0.8 μl separated by a distance of 0.6 mm are merged together 16 seconds after the mechanical vibration displacement of 0.112 μm is excited in the stage with an area of 40 mm^2 . Unlike the conventional method of merging, the proposed device offers a few key advantages: there is no need to use microchannels for the motion of droplets; the microdroplets can be dispensed on to the actuating surface simultaneously or at different time; two droplets with the same size and viscosity can be merged successfully; and the wireless drive provides the potential for miniaturization of the piezoelectric stage.

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CHAPTER 1 INTRODUCTION

The extensive research on piezoelectric properties, materials and devices has revealed interesting and promising devices for novel applications and that can be realized using various technologies [1-9]. The difficulties associated with the drive of piezoelectric components by using lead wires have resulted in an initiative to explore wireless drive to widen the application range of piezoelectric devices.

1.1 Motivation

Piezoelectric devices generate electric signals in response to mechanical vibrations and produce mechanical energy in response to electric signals [10]. The piezoelectric devices which include transducers [11-12], actuators and motors [13-17], transformers [18-21], oscillators [22-24], filters [25-27], generators [28-29], and sensors [30-32] are extensively used due to their compact size, high power density, low power consumption, high output force, high precision positioning, etc. As a result of their unique advantages, they have been employed in various areas such as miniature driving mechanisms [33-36], precision positioning [37-41], particle manipulations [42-45], communication systems [46-47], switching power supplies [48-49], vibration control [50-54], chemical engineering [55-56], biomedical engineering [57-59], and microfluidics [60-62].

In most applications, electric energy is applied to the piezoelectric devices via

lead wires soldered on the electrodes of piezoelectric components. However, this conventional method of applying electric energy to the piezoelectric devices via lead wires has some major disadvantages. At high input voltage, large vibration amplitudes or high temperature, the lead wires may fall off, causing the breakdown of the piezoelectric devices. The soldering of lead wires thus limits the miniaturization of the devices. As devices become increasingly smaller, challenges also faced in soldering of lead wires in micro and nano piezoelectric components. The soldering may affect the properties of micro and nano-scale devices. The lead wires also obstruct the applications of piezoelectric devices in rotary mechanisms and micro systems. Therefore, there is a need to introduce an alternative approach to apply electric energy to the piezoelectric devices, in response to the above stated challenges. The difficulties associated with the direct drive of piezoelectric components by using lead wires have resulted in an initiative to explore wireless methods to drive piezoelectric components.

To miniaturize and widen the application range of piezoelectric devices, wireless drive of piezoelectric components by an A.C. electric field have been proposed and investigated by the author. The lack of such a wireless drive is seen as a bottle neck for wide spread applications of micro and nano-systems. In this thesis, a fundamental theoretical model together with experimental investigations have been carried out in order to provide deep physical insights and help develop a better wireless drive of piezoelectric components.

1.2 Research Objectives

The need for wireless drive of piezoelectric components has motivated the

following major objectives of this research work to:

- (i) Explore new techniques of wirelessly driven piezoelectric components.
- (ii) Study the proposed structures and operating mechanism.
- (iii) Investigate the characteristics of wirelessly driven piezoelectric components.
- (iv) Outline the effects of parameters to optimize the wireless energy transmission.
- (v) Develop a fundamental theoretical equivalent circuit model for a piezoelectric component wirelessly driven by an A.C. electric field.
- (vi) Verify the effectiveness of the proposed model by comparing the theoretical and experimental characteristics.
- (vii) Investigate the mechanical vibration characteristics of wirelessly driven piezoelectric components.
- (viii) Explore the application of wirelessly driven piezoelectric components.

1.3 Major Contributions

The major contributions achieved in this study are summarized as follows:

1. An A.C. electric field is used to drive wirelessly piezoelectric components which are made of lead zirconate titanate (PZT) ceramic material, and poled vertically across its thickness. The thickness vibration direction and applied electric field are both parallel to the poling direction. So far, there has been no equivalent circuit model for a piezoelectric component wirelessly driven by electric field. A theoretical model is proposed by the author, and summarized into an equivalent circuit to investigate the structure, operating mechanism, and performance of a piezoelectric

component operating in the thickness vibration mode wirelessly driven by electric field. Different from the equivalent circuit of conventional piezoelectric components driven by a voltage applied through lead wires, the equivalent circuit of a wirelessly driven piezoelectric component has a current source, resulting from the external electric field. The concept of using a current source in the equivalent circuit may be applied to the wirelessly driven piezoelectric components operating in the other vibration modes.

2. Various new techniques of transmitting electric energy wirelessly to piezoelectric components have been proposed and explored by the author. These techniques include the wireless drive of piezoelectric components by using a parallel plate capacitor structure, focused electric field generator, focused electric field structure in electric resonance with an inductor, dipole antenna-like structure, and flat spiral coil antenna-like electric field generator in electric resonance with a capacitor.
3. The wireless electric energy transmission to piezoelectric components by using a parallel plate capacitor structure is explored. In the experimental design, for the generation of an A.C. electric field, an A.C. input voltage with tunable frequency is connected to the two brass plate-shaped live and ground electrodes mounted on a plastic table with a fixed separation which forms a parallel plate capacitor structure. The piezoelectric plate is inserted at the center of the gap between the two brass electrodes of the parallel plate capacitor structure. From the experiment, it has been seen that the output power achieved by the piezoelectric plate depends on various factors like the operating frequency, electrical load, vibration mode and electrode

pattern of the piezoelectric component, and the electric field. At the resonance frequency of 782 kHz, a maximum output power of 1.84 mW and an energy conversion efficiency of 0.12% have been achieved wirelessly by the piezoelectric plate operating in the thickness vibration mode with a 1 cm gap thickness, and an input A.C. source power of 1.52 W across the parallel plate capacitor structure. It is also observed that the output power at resonance of the piezoelectric plate operating in the thickness vibration mode is significantly higher than that of the piezoelectric plate operating in the other vibration modes like width and longitudinal vibrations.

4. A new method of wireless drive of piezoelectric components by employing a focused electric field is proposed and investigated. The A.C. electric field is focused, by using a stainless steel needle ground electrode and a brass plate-shaped live electrode to the piezoelectric plate placed in between them. The needle ground electrode enables better transmission of electric energy. The effects of electrode areas on the output power of the piezoelectric plate are investigated in order to optimize the wireless electric energy transmission to the piezoelectric plate. The output power of the piezoelectric plate depends on the operating frequency, electrical load, dimensions of the piezoelectric component, electric field, distance, and size of live and ground electrodes of the electric field generator. When the frequency of the A.C. electric field is close to the mechanical resonance frequency of the piezoelectric plate operating in the thickness vibration mode, the output power reaches the maximum. At the resonance frequency of 782 kHz, a maximum output power of 10.84 mW and an energy

conversion efficiency of 0.51% have been achieved wirelessly by the piezoelectric plate operating in the thickness mode with a needle ground electrode, an optimum electrical load of 1365 Ω , an input A.C. source power of 2.12 W across live and needle ground electrodes, a 1 cm electrodes separation, and a live electrode area of 900 cm² of the focused electric field structure. Theoretically, the electric field pattern is also studied by finite element method simulation (COMSOL Multiphysics) to elucidate the focusing of electric field by a needle ground electrode with a brass plate-shaped live electrode to the piezoelectric component placed in between them.

5. Nano-vibration characteristics of a piezoelectric component operating in the thickness mode, wirelessly driven by a focused electric field have been investigated. A mechanical resonance vibration is excited in the piezoelectric plate wirelessly driven by the A.C. electric field. Theoretically, it has been found that the vibration displacement depends on the electric field, operating frequency, electrical load, and dimensions of the wirelessly driven piezoelectric plate operating in the thickness vibration mode. The electric field pattern is theoretically calculated to assess the electric field produced on the surface by the focused electric field structure. It has been observed that the vibration displacement of the wirelessly driven piezoelectric plate reaches the maximum at resonance frequency, and the maximum vibration displacement is in the nanometer range. It is also found that the vibration displacement at resonance increases with the electrical load resistance, and the plate's lateral size, and decreases with the thickness of the wirelessly driven piezoelectric component.

6. In order to drive high power piezoelectric components wirelessly, an improved method of wireless drive of piezoelectric components is experimentally investigated by using the electric resonance of a focused electric field generator and an inductor in series. With an optimum area of a brass plate-shaped live electrode, a stainless steel needle ground electrode is used to form a focused electric field generator. In the focused electric field generator, the A.C. electric field is focused to the needle ground electrode from the plate-shaped live electrode through a piezoelectric plate placed in between them. When the focused electric field generator and inductor exhibit a series electric resonance, the wireless electric energy transmission to the piezoelectric component can be enhanced. This technique enables a relatively large output power achieved by the piezoelectric plate wirelessly. Experimentally, it has been found that the real output power of the wirelessly driven piezoelectric plate depends on the operating frequency, electrical load, vibration mode of the piezoelectric component, distance between the electrodes, and the electric field focused by the needle ground and live electrodes of the focused electric field generator. When the focused electric field generator and inductor are operating at electric resonance, a maximum output power of 206.04 mW, and an energy conversion efficiency of 1.02% have been achieved by the wirelessly driven piezoelectric plate operating in the thickness vibration mode at a resonance frequency of 782 kHz, an optimum electrical load resistance of 1365 Ω , an input A.C. source power of 20.12 W applied to the focused electric field structure cascaded in series with the inductor, a 1 cm live and ground electrodes separation, and a live electrode area of 900 cm²

of the focused electric field generator. The output power at resonance of the piezoelectric plate operating in the thickness vibration mode is significantly higher than that obtained when operating in the other modes, e.g. width and length extensional vibration modes.

7. Wireless drives of piezoelectric components by focused electric field and the electric field generated from parallel plate capacitor structure were proposed and investigated by the author. However, the structures of the proposed electric field generators constrain the free motion of the wirelessly driven piezoelectric components. To explore the possibility of solving this difficulty and widen the application range of piezoelectric devices, a wireless drive of piezoelectric components by using a dipole antenna-like electric field generator is proposed, and its characteristics are investigated. Two equal square size brass plate-shaped live and ground electrodes are used to form an electric dipole antenna-like structure to transmit A.C. electric fields wirelessly to the piezoelectric plate. The effects of the electrode areas of this dipole antenna-like structure, electric field, operating frequency, electric load, and position of the plate on the real output power of piezoelectric plate are investigated in order to optimize the wireless electric energy transmission. The electric field pattern is calculated by finite element method to assess the electric field on the surface of piezoelectric plate wirelessly driven by dipole antenna-like structure. A theoretical model is also developed for the wirelessly driven piezoelectric plate operating in the thickness vibration mode, which can explain the experimental results well. It is observed that at the resonance frequency and with an optimum electrical load, the output power achieved wirelessly by

the piezoelectric component increases with the electrodes area, the strength of electric field, and decreases with the distance of the piezoelectric component from the plane of electrodes of dipole antenna-like structure. In order to enhance the driving power, the electric dipole antenna-like structure is used in series with an inductor. When the electric dipole antenna-like structure and inductor are in electric resonance, a maximum output power of 1.92 mW and an energy conversion efficiency of 0.012% have been achieved wirelessly by the piezoelectric plate operating in the thickness vibration mode, placed at the centre 4 mm away from antenna plane with an optimum electrical load resistance of 350 Ω , a 1 cm electrodes separation, a 2500 cm² electrode area of electric dipole antenna-like structure, and an input A.C. source power of 15.58 W applied to the series of dipole antenna-like structure and inductor.

8. An improved compact electric field generator is also explored to transmit relatively large amounts of electric energy wirelessly to piezoelectric components by using the electric resonance of a flat spiral coil antenna-like structure and a capacitor in series. When the spiral coil antenna-like electric field generator and capacitor are in electric resonance, the wireless electric energy transmission to the piezoelectric component placed in a plane perpendicular to the plane of antenna can be enhanced. This technique enables a relatively large output power achieved wirelessly by the piezoelectric component. At the resonance frequency of 772 kHz and with an optimum electrical load resistance of 350 Ω , a maximum output power of 0.362 mW and an energy conversion efficiency of 0.027% have been achieved wirelessly by the piezoelectric plate operating in the thickness

vibration mode, placed 4 mm away from antenna plane with an input A.C. source power of 1.294 W applied to the series of flat spiral coil antenna-like structure and capacitor, and an inductance of 0.0413 mH of the flat spiral coil antenna-like structure.

9. A comparative study of all the proposed and investigated wireless energy transmission techniques has been conducted. It has been found that the energy conversion efficiency of the piezoelectric component wirelessly driven by the focused electric field structure in electric resonance with an inductor is significantly higher than that wirelessly driven by the other structures such as parallel plate capacitor structure, focused electric field generator, dipole antenna-like structure in resonance with inductor, and flat spiral coil antenna-like electric field generator in resonance with a capacitor. When the focused electric field generator and inductor are in electric resonance, an energy conversion efficiency of 1.02% has been achieved wirelessly by a small piezoelectric plate with an area of 40 mm^2 operating in the thickness vibration mode at the resonance frequency of 782 kHz, under an optimum electrical load resistance of 1365Ω , with an input A.C. source power of 20.12 W (applied to the series of focused electric field generator and inductor), a 1 cm electrodes separation, and a live electrode area of 900 cm^2 of the focused electric field generator. The technique of wireless drive of piezoelectric components by focused electric field structure in electric resonance with an inductor enables a relatively large output power achieved wirelessly by the piezoelectric component than the other structures for a given input A.C. source voltage. Compared to the other proposed techniques, the technique of wireless drive of

piezoelectric components by antenna-like structure is robust for the free motion of piezoelectric components, and also may be effective to drive micro piezoelectric components in rotary machines.

10. Furthermore, a method to merge microdroplets by using a wirelessly driven piezoelectric stage is proposed and investigated by the author. The separated microdroplets (with volumes varying from 0.5 μl to 2 μl) to be merged are dispensed onto the top surface of a piezoelectric stage wirelessly driven by a focused electric field. The ultrasonic vibration of the piezoelectric stage is transmitted into the microdroplets and induces their merging. Experimentally, it has been observed that the merging time of water microdroplets depends on the vibration displacement of piezoelectric stage, separation distance, and initial volume of the microdroplets. The merging time of two water microdroplets decreases with the separation distance between the microdroplets, and increases with their volume. At the resonance frequency of 776 kHz, two water microdroplets, each with a volume of 0.8 μl , separated by a distance of 0.6 mm are merged together 16 seconds after the mechanical vibration displacement of 0.112 μm is excited in the piezoelectric stage with an area of 40 mm^2 . The proposed device has simpler structure and the potential to be smaller than the conventional devices for microdroplet merging. It is also more flexible in the size and physical properties of microdroplets to merge.

The novelty of this research work is that we are the first to propose and explore the wireless drive of piezoelectric components by using a properly designed electric field. As a first author, a total number of fourteen research articles

related to this work have been published and communicated in international journals and conference proceedings. (See author's publications at page. 175).

1.4 Organization of the Thesis

This thesis includes eight chapters.

In Chapter 1, the motivation, objectives, main contributions, and organization of the thesis are presented.

Chapter 2 introduces the fundamental mechanism of piezoelectricity, practical piezoelectric materials, dynamic behavior, driving techniques and various applications of piezoelectric devices. The desirable characteristics of piezoelectric devices are outlined to justify the direction of the research pursuits of this work.

In Chapter 3, a theoretical model is proposed, and summarized into an equivalent circuit to investigate the structure, operating mechanism, and performance of a piezoelectric component wirelessly driven by an A.C. electric field.

In Chapter 4, a new technique of transmitting electric energy wirelessly to piezoelectric components is proposed. The characteristics of wireless energy transmission to piezoelectric components by parallel plate capacitor structure are investigated experimentally. The experimental result shows the feasibility to drive piezoelectric devices wirelessly by using a properly designed electric field.

In Chapter 5, the wireless drive of piezoelectric components by focused electric field is proposed and experimentally investigated. The electric field pattern is also theoretically analyzed by finite element method simulations to elucidate the focusing of the electric field by a stainless steel needle ground electrode with a brass plate-shaped live electrode to a piezoelectric component placed in between them. The nano-vibration characteristics of a piezoelectric component operating in the thickness mode wirelessly driven by focused electric field have been investigated. To explore the possibility of enhancing wireless electric energy transmission to the piezoelectric components and widen the application range of piezoelectric devices, wireless drive of piezoelectric components is experimentally investigated by using the electric resonance of a focused electric field generator and an inductor in series.

In Chapter 6, the theoretical and experimental characteristics of piezoelectric components wirelessly driven by an electric dipole antenna-like structure and a flat spiral coil antenna-like electric field generator have been investigated. The theoretical results are verified with the experimental ones. Also, a comparative study of all the proposed and investigated wireless energy transmission techniques has been conducted.

Chapter 7 presents a method to merge microdroplets by using a piezoelectric stage which is wirelessly driven by an A.C. electric field.

Finally, the conclusions and recommendations for future work are presented in Chapter 8.

CHAPTER 2 BACKGROUND AND BASIC THEORY

In piezoelectric device research, a meticulous understanding of the piezoelectric effect and of its theory provides deep insight into the aspects of device design, materials selection, and optimum driving conditions. This chapter introduces the theoretical background of piezoelectric devices, practical materials, dynamic behavior, driving techniques and typical applications. After a comprehensive review, the fundamental limitations of the conventional methods of applying electric energy to the piezoelectric components through lead wires soldered on the electrodes are outlined. This would subsequently enable us to explore the wireless methods of electric energy transmission to the piezoelectric components.

2.1. The fundamental mechanism of piezoelectricity

This section begins with a brief historical background of piezoelectricity and introduces some fundamental concepts related to the phenomenon.

2.1.1. Historical overview

The history of piezoelectricity dates back to 1880 when Pierre and Jacques Curie first discovered the piezoelectric effect in various substances including Rochelle salt, tourmaline, cane sugar and quartz [63-64]. They showed that the crystals generate electrical polarization from mechanical stress. The

phenomenon of electric polarization of crystals caused by deformation in certain directions was later given the name “piezoelectricity” by Hankel [64]. Converse piezoelectricity was mathematically deduced from fundamental thermodynamic principles by Lippmann in 1881, and the existence of the converse effect was immediately confirmed by the Curies [64]. Since then, piezoelectricity has been known as the interaction between the electrical and mechanical fields in solids. Shortly thereafter, Lord Kelvin described piezoelectric behavior using a precise thermodynamic theory [65] and later this work is carried out with more detailed formulation by Woldemar Voigt, which is the basis for the formulation of piezoelectric constitutive equations [66-68].

2.1.2. The piezoelectric effect

When a piezoelectric crystal is mechanically strained, or when it is deformed by the application of an external stress, electric charges appear on certain crystal surfaces. If the direction of the strain reverses, the polarity of the electric charge is also reversed. This is called the direct piezoelectric effect, and the crystals that exhibit it are classed as piezoelectric crystals. Conversely, when a piezoelectric crystal is placed in an electric field, or when charges are applied by external means to its faces, the crystal exhibits strain, i.e. the dimensions of the crystal change. When the direction of the applied electric field is reversed, the direction of the resulting strain is reversed. This is called converse piezoelectric effect [64, 65].

2.1.3. Piezoelectric materials

Quartz crystals are the first commercially exploited piezoelectric material [8, 66]. But scientists searched for higher-performance materials. After the

breakthrough invention of the high dielectric constant material barium titanate, scientists focused on piezoceramic materials directly derived from it. In the 20th century, very strong and stable piezoelectric effects were discovered on metal oxide-based piezoelectric ceramics which are physically strong, chemically inert and relatively inexpensive to manufacture. Ceramics manufactured from formulations of lead zirconate or lead titanate exhibit greater sensitivity and higher operating temperatures, relative to ceramics of other compositions. Lead Zirconate Titanate (PZT) ceramic is the most widely used piezoelectric ceramic, as it exhibits both the direct and inverse piezoelectric effects. PZT ceramics are available in many variations and are still the most widely used materials for actuator or sensor applications [8]. Many scientists have been working independently to improve the piezoelectric characteristics of ceramics, especially lead zirconate titanate. Production of the materials with desired characteristics such as good temperature stability, low hysteresis, high electromechanical coupling factor, and high linearity is the main challenge. PZT ceramics have crystal structures belonging to the perovskite family. A perovskite structure is any material with the same type of crystal structure as calcium titanium oxide (CaTiO₃), known as the perovskite structure or $A^{2+}B^{4+}X^{2-}_3$ with the oxygen in the face centers [67]. The general chemical formula for perovskite compounds is ABX₃, where 'A' and 'B' are two cations of very different sizes, and X is an anion that bonds to both. The chemical formula for PZT is Pb[Zr_xTi_{1-x}]O₃, 0<x<1. The perovskite type lead zirconate titanate crystal structure is shown in Fig.2.1. PZT crystallites are centrosymmetric cubic (isotropic) before poling, as shown in Fig.2.1 (a) and after poling exhibit tetragonal symmetry (anisotropic structure) below the Curie

temperature (T_c), as shown in Fig.2.1(b). The PZT-based compounds are composed of the chemical elements lead and zirconium and the chemical compound titanate which are combined under extremely high temperatures.

To prepare a piezoelectric ceramic, fine powders of the component metal oxides are mixed in specific proportions, then heated to form a uniform powder. The powder is mixed with an organic binder and is formed into structural elements having the desired shape (discs, rods, plates, etc.). The elements are fired according to a specific time and temperature program, during which the powder particles sinter and the material attains a dense crystalline structure. The elements are cooled, then shaped or trimmed to specifications, and electrodes are applied to the appropriate surfaces. Above a critical temperature, the Curie point, each perovskite crystal in the fired ceramic element exhibits a simple cubic symmetry with no dipole moment (Fig.2.1a). At temperatures below the Curie point, however, each crystal has tetragonal or rhombohedral symmetry and a dipole moment (Fig. 2.1b).

The crystal structure of the commercially available Fuji C-203 PZT is tetragonal perovskite structure. The piezoceramic elements are manufactured by “dry and press forming system.” The fabrication of C-203 PZT involves the following methods: (a) raw material blending (b) mixing, (c) Temporary firing, (d) grinding, (e) granulating, (f) forming, (g) main firing, (h) processing, (i) silver coating, (j) silver firing, (k) polarization, (l) inspection, packaging and shipment.

Fig.2.1: (a) Pervoskite-type PZT unit cell in the symmetric cubic state above T_c (before poling); (b) Tetragonally distorted PZT unit cell below T_c (after poling).

2.1.4. Dynamic behavior of piezoelectric components

The dynamic performance relates to the behavior of a material when subjected to alternating electric fields and stresses. The performance of each piezoelectric material is limited by some parameters like input frequency, electric field, mechanical stress and operating temperature. Operating a material outside of these limitations may cause partial or total depolarization of the material, and a diminishing or loss of piezoelectric properties.

Influence of input frequency- A piezoelectric ceramic element exposed to an alternating electric field changes dimensions cyclically, at the frequency of the field. The frequency at which the element vibrates most readily in response to the electrical input, and most efficiently converts the electrical energy input into mechanical energy, is the resonance frequency which is determined by the composition of the ceramic material and by the shape and volume of the element [1-3]. As the frequency of cycling is increased, the element's oscillation first approaches a frequency at which the impedance is minimum. This is the

resonance frequency. As the frequency is further increased, impedance increases to a maximum, which also is the anti-resonance frequency. The values of the minimum and maximum impedance frequencies can be used to calculate the electromechanical coupling factor (k), an indicator of the effectiveness with which a piezoelectric material converts electrical energy into mechanical energy or mechanical energy into electrical energy [1]. The electromechanical coupling factor depends on the mode of vibration and the shape of the ceramic element. Dielectric losses and mechanical losses also affect the efficiency of energy conversion.

Electrical limitations- A piezoelectric ceramic can be depolarized by a strong electric field with polarity opposite to the original poling voltage. The limit on the field strength is dependent on the type of material, the exposure time, and the operating temperature. An alternating current will have a depolarizing effect during each half cycle in which polarity is opposite that of the field [1, 3].

Mechanical stress- High mechanical stress can depolarize a piezoelectric ceramic. The limit on the applied stress is dependent on the type of ceramic material, and duration of the applied stress [1, 8].

Operating temperature- As the operating temperature increases, the piezoelectric performance of a material decreases, until complete and permanent depolarization occurs at the material's Curie temperature [1, 8]. The Curie point is the absolute maximum exposure temperature for any piezoelectric ceramic. Also, sudden temperature fluctuations can generate relatively high voltages, capable of depolarizing the ceramic element. The material's temperature limitation decreases with greater continuous operation or

exposure. At elevated temperatures, the ageing process accelerates, piezoelectric performance decreases and the maximum safe stress level is reduced. Mishandling the element by exceeding its electrical, mechanical, or thermal limitations can accelerate the stability of piezoelectric element [1, 3, 5].

2.1.5. Piezoelectric constitutive relations

The constitutive relations of piezoelectric crystals are originated from the appropriate thermodynamic functions [68-70]. The relevant thermodynamic functions depend on the choice of an independent variable set. For electrical variables, either polarization P or electric displacement (flux density) D can be selected as the extensive variable, although the intensive variable is always electric field E . The mechanical variables are generally strain S , and stress T . A common form of the constitutive equations derived from the thermodynamic functions based on the following convention is [68-70]:

$$T_{ij} = c_{ijkl}^D S_{kl} - h_{kij} D_k \quad (2.1)$$

$$E_i = -h_{kij} S_{kl} + \beta_{ik}^S D_k \quad (2.2)$$

Where

T_{ij} = Elements of the mechanical stress tensor

S_{kl} = Elements of the mechanical strain tensor

c_{ijkl} = Elements of the stiffness tensor

h_{kij} = Elements of the piezoelectric constant tensor

β_{ik}^S = Elements of the dielectric impermeability tensor

D_k = Elements of the dielectric displacement vector

E_i = Elements of the electric field vector

At this point it is appropriate to adopt a convention to denote the material's axial directions and polarization. The direction in which tension or compression develops polarization parallel to the strain is called piezoelectric axis. In quartz, this axis is known as the X-axis, and in poled ceramic materials such as PZT, the piezoelectric axis is referred to as the Z-axis. The new convention is shown in Fig. 2.2 [70-71]. The direction of polarization is conventionally taken as the third axis, with axes 1 and 2 perpendiculars to this. The terms 4, 5, and 6 refer to shear strains associated with the 1, 2, and 3 directions. The application of an electric field along the axis 3 can result in piezoelectric coupling along any of the six directions shown in Fig. 2.2. For a tetragonal structure, the crystal will only deform along the three principal directions, whereas rhombohedral and orthorhombic structures can also exhibit shear coupling. Such coupling is usually designated with two subscript numbers. For example, the coupling coefficient d_{31} shows that an electric field oriented along axis 3 results in a strain along axis 1 [70-71]. This idea is used throughout the constitutive equations for both the elastic and permittivity constants. The matrix equations (2.1) and (2.2) are often further simplified to scalar equations to represent the most commonly considered actuation scenarios such as the 31-mode and 33-mode, which gives [1, 68 and 69]:

$$T_1 = c_{11}^D S_1 - h_{31} D_3 \quad (2.3)$$

$$E_3 = -h_{31} S_1 + \beta_{33}^S D_3 \quad (2.4)$$

and

$$T_3 = c_{33}^D S_3 - h_{33} D_3 \quad (2.5)$$

$$E_3 = -h_{33} S_3 + \beta_{33}^S D_3 \quad (2.6)$$

Fig. 2.2: Axis designation

These constitutive equations are now well-suited for modeling the behavior of piezoelectric components in most practical piezoelectric device applications.

2.2. Piezoelectric Devices and Applications

The actions, designs, driving techniques and applications of the piezoelectric devices will be discussed in the following sections. The desirable characteristics of the piezoelectric devices are outlined to justify the direction of the research pursuits of this work. Additionally, the historical milestones in the development of piezoelectric devices are discussed to recognize important researcher's contribution to this field.

2.2.1. Piezoelectric Transducers

Piezoelectric transducers containing a piezoelectric element convert electrical pulses to mechanical vibration, often sound or ultrasound, and then convert the returned mechanical energy into electrical energy [1]. Piezoelectric transducers are shown in Fig.2.3 [72]. Piezoelectric transducers that generate audible

sounds afford significant advantages, relative to alternative electromagnetic devices. They are compact, simple, highly reliable, and minimal energy can produce a high level of sound. These characteristics are ideally matched to the needs of wireless-powered equipment. Micromanipulation can also be achieved with a piezoelectric actuator [73]. Piezoelectric microcantilever transducers based on PZT thin film have received considerable interest because of their wide potential applications in nanotechnology, biosensors and microelectromechanical systems [74]. Piezoelectric transducers are used for applications in bioengineering to disrupt cells, to affect the rate of bio-reactions and yields of metabolites, and for bio-separation [75]. Various solutions also have been developed in structural health monitoring systems employing piezoelectric transducers to alleviate some problems [76]. Ultrasonic transducers are used for ultrasonic imaging systems, ultrasonic treatment and treatment of wound [77].

Fig.2.3: Piezoelectric transducers

Fig.2.4: Piezoelectric actuators.

2.2.2. Piezoelectric Actuators

Piezoelectric actuators are devices that convert electrical signal into a mechanical motion. The piezoelectric actuators are forming a new field between electronic and structural ceramics [1]. Actuation making use of piezoelectric elements became widespread starting from the 1990s, and this is an important step forward for microsystems since it is very easy to integrate, it is relatively powerful and easy to use. Piezoelectric microactuators offer several advantages such as low power requirement (low voltage and current), ease of control, scaling to smaller dimensions, speed, microfabrication compatibility and simplicity of fabrication and packaging. Considerable research has been conducted on piezoelectric microactuators for nano positioning [78], micro manipulations [79-80], and miniature driving mechanisms [81-82]. Examples of piezoelectric actuators are shown in Fig.2.4 [72].

2.2.3. Piezoelectric Transformers

When input and output terminals are fabricated on a piezo-device and input/output voltage is changed through the vibration energy transfer, the device

is called a piezoelectric transformer [5]. Recent lap-top computers with a liquid crystal display require a very thin, no electromagnetic-noise transformer to start the glow of fluorescent back-lamp. This application recently accelerated the development of piezoelectric transformers. These devices can be used in D.C.-A.C. inverters to drive cold cathode fluorescent lamps, A.C./D.C. adaptors for low voltage applications such as the power supply for computers, D.C./D.C. adaptors and chargers. Since the original piezoelectric transformer was proposed by C. A. Rosen [83], there have been a variety of such transformers investigated. The Rosen transformer is shown in Fig.2.5.

Fig.2.5: Piezoelectric transformer, Source: C. A. Rosen

Fig.2.6: Piezoelectric sensor.

2.2.4. Piezoelectric Sensors

A sensor converts a physical parameter, such as acceleration or pressure, into an electrical signal [5]. In some sensors the physical parameters acts directly on the piezoelectric element; in other devices an acoustical signal establishes vibrations in the element and the vibrations are, in turn, converted into an electric signal. Often, the system provides a visual, audible, or physical response to the input from the sensor. Piezoelectric sensors are used for quality assurance, process control, and for research and development in many different industries. Detection of pressure variations in the form of sound is the most common sensor application, e.g. piezoelectric microphones [46]. Piezoelectric microbalances are used as very sensitive chemical and biological sensors [84]. A piezoelectric sensor is shown in Fig.2.6 [72].

2.3. Needs of Wireless Drive of Piezoelectric Components

There has been remarkably rising interest in the applications of piezoelectric devices due to their compact size, high power density, low power consumption, high output force, high precision positioning etc. In most of the applications of piezoelectric devices discussed above, electric energy is applied to the devices through lead wires soldered on the electrodes of piezoelectric components. But this conventional method of applying electric energy to the piezoelectric devices through lead wires has some major disadvantages. The lead wires soldered on the electrodes of piezoelectric components may fall off at large vibration, high input voltage or high temperature, and this causes the breakdown of piezoelectric devices. The soldering of lead wires also poses problems for the miniaturization of the piezoelectric devices, as it affects on the

properties of micro and nano piezoelectric devices. The lead wires also obstruct the applications of piezoelectric devices in rotary mechanisms. The fundamental limitation of applying electric energy to the piezoelectric devices necessitates the pursuit of this research work. Therefore, there is a need to introduce a wireless approach to apply electric energy to the piezoelectric components.

To explore the possibilities of solving the difficulties in the conventional way of applying electric energy via lead wires which is the bottleneck for further widespread applications of microsystems and widen the application range of piezoelectric devices, wireless energy transmission to piezoelectric components has been investigated. The potential reward for exploring wireless drive of piezoelectric components is significant, but it is a formidable challenge. In this research work, new techniques of transmitting electric energy wirelessly to piezoelectric components have been proposed and investigated. The technique of wireless drive of piezoelectric components has the potential for miniaturization of the piezoelectric devices. This technique may be effective to drive micro piezoelectric components wirelessly in rotary machines, while at the same time it may also enable a higher operating temperature.

CHAPTER 3 EQUIVALENT CIRCUIT MODEL OF A WIRELESSLY DRIVEN PIEZOELECTRIC COMPONENT

A theoretical model is essential to investigate the structure, operating mechanism and performance of a piezoelectric component wirelessly driven by electric field. Moreover, a good theoretical model can provide deep physical insight to develop a better method of wireless drive of piezoelectric components by electric field.

In the first section of this Chapter, the most important physical properties of the piezoelectric components are indexed. The concept of the thickness vibration mode of the piezoelectric has been discussed. The theoretical analyses of a piezoelectric component operating in the thickness vibration mode wirelessly driven by electric field will be presented in the second section of this chapter. The basic configuration and operating principle of the wirelessly driven piezoelectric component is also illustrated. So far, no equivalent circuit model of a piezoelectric component wirelessly driven by electric field has been reported. An equivalent circuit model is derived here by using the fundamental constitutive piezoelectric equations, and then proposed by the author for a piezoelectric component operating in the thickness mode wirelessly driven by an A.C. electric field. The equivalent circuit of the wirelessly driven piezoelectric component has a current source, resulting from the external

electric field. This is different from the equivalent circuit of a conventional piezoelectric component driven by a voltage applied via lead wires. The concept of using a current source in the equivalent circuit may be applied to the wirelessly driven piezoelectric components operating in the other vibration modes.

Furthermore, the impedance characteristics of the piezoelectric component operating in the thickness vibration mode are depicted in the last section of this chapter. The calculated and measured equivalent circuit parameters of the wirelessly driven piezoelectric plate are also compared. The calculated equivalent circuit parameters well agree with the measured ones.

3.1. Physical Properties of Piezoelectric Components

This section summarizes the physical properties of the piezoelectric materials [103]. Table 3.1 shows the material parameters of some important applied piezoelectric materials. It is seen that the single crystal lithium niobate (LiNbO_3) has a high mechanical quality factor and low piezoelectric loss, but its piezoelectric constants are low. The typical perovskite barium titanate (BaTiO_3) has relatively high piezoelectric constants, but its Q_m is low. Compared with the single crystal and perovskite piezoelectric materials, the lead zirconate titanate (PZT) also has the high piezoelectric constants and high mechanical quality factor. The PZT also has a larger electromechanical coupling factor (k_{33}) than that of the single crystal lithium niobate (LiNbO_3) and perovskite barium titanate (BaTiO_3). Thus, C-203 PZT (supplied by Fuji Ceramics Corporation, Japan) is chosen as the original material for the experiments and analyses.

Property		Units	BaTiO ₃	PZT	LiNbO ₃
Coupling factors	k_{31}	10^{-2}	46.8	35	2.3
	k_{33}	10^{-2}	60.8	71	47
	k_t	10^{-2}	38	47	51
Frequency constants	N_{31}	mm * kHz	1440	530	3615
	N_{33}	mm * kHz	1410	1470	3300
	N_t	mm * kHz	2130	920	2250
Piezoelectric charge constants	d_{31}	10^{-12} C/N	-78	-145	-0.85
	d_{33}	10^{-12} C/N	190	325	6
Relative dielectric constants	$\epsilon_{11}^T/\epsilon_0$	1	4400	470	85.2
	$\epsilon_{33}^T/\epsilon_0$	1	129	450	28.7
Dissipation factor	$\tan \delta$	%	1	0.3	1.5
Mechanical quality factor	Q_m	1	200	300	2000
Density	ρ	10^3 kg/m ³	5.7	7.7	4.64
Curie temperature	$T_c >$	°C	120	350	1133

Table 3.1: Physical properties of representative piezoelectric materials.

3.2. Concept of the Thickness Vibration Mode of Wirelessly Driven Piezoelectric Plate

Fig.3.1 (a) illustrates the thickness vibration mode of a piezoelectric plate wirelessly driven by an electric field. The piezoelectric plate is made of the Fuji C-203 PZT ceramic material, and is poled vertically across its thickness.

Fig.3.1 (a): The piezoelectric plate operating in the thickness vibration mode wirelessly driven by an electric field; (b) The thickness vibration of the piezoelectric plate shown by the dotted lines.

When an A.C. electric field penetrates the piezoelectric plate, a mechanical vibration is excited in the piezoelectric plate by the converse piezoelectric effect. The excitation of the piezoelectric plate takes place along its thickness direction at a resonance frequency of the thickness mode which is related with the thickness mode frequency constant and the thickness (t) of the piezoelectric plate. The thickness vibration direction and applied electric fields are both parallel to the poling direction. In the thickness vibration, the vibration is uniform on the surface of the piezoelectric plate which is shown by the dotted lines in Fig.3.1 (b).

The electromechanical coupling factor (k^2) of the thickness vibration mode is higher than that of the other vibration modes of the piezoelectric plate. The electromechanical coupling can be stronger as the applied electric field and mechanical vibrations of the piezoelectric plate are in the same direction. So, the output power and efficiency of the piezoelectric plate operating in the thickness vibration mode wirelessly driven by the A.C. electric field is significantly higher than that of the other vibration modes like width and length extensional vibration modes.

3.3. Theoretical Analyses of a Piezoelectric Component Operating in the Thickness Mode Wirelessly Driven by Electric Field

3.3.1. Configuration and operating mechanism

Fig.3.2 illustrates the basic configuration of a piezoelectric plate operating in the thickness vibration mode wirelessly driven by an electric field. The piezoelectric plate is made of the ceramic material Fuji C-203 PZT, and is poled vertically across its thickness. The top and bottom surfaces of the piezoelectric plate are fully covered by silver metal electrodes. The thickness vibration direction and applied electric field are both parallel to the poling direction. A load resistor R_L is connected across the two electrodes of the piezoelectric plate for measuring the real power which the piezoelectric plate delivers.

Fig.3.2: Basic configuration of a piezoelectric plate operating in the thickness vibration mode wirelessly driven by electric field.

When an A.C. electric field penetrates the piezoelectric plate, a mechanical vibration can be stimulated in the piezoelectric plate by the converse piezoelectric effect. When the frequency of the applied electric field is close to the mechanical resonance frequency of the piezoelectric plate, a mechanical resonance can be excited in the plate. This mechanical resonance can generate a relatively large voltage across the output electrodes due to the piezoelectric effect.

3.3.2. Derived equivalent circuit model

To explore the underlying physical phenomena, operating mechanism, resonant mechanical vibration and output power characteristics, an equivalent circuit model has been developed for the piezoelectric plate operating in the thickness mode wirelessly driven by electric field.

The one-dimensional thickness vibration along the z -direction of a piezoelectric plate with length l and constant cross sectional area A satisfies the following dynamical equation [1]:

$$\rho \frac{\partial^2 u_t}{\partial t^2} = c_{33}^D \frac{\partial^2 u_t}{\partial z^2} \quad (3.1)$$

where ρ , u , and c_{33}^D represent density, displacement and elastic stiffness constant of the piezoelectric plate respectively.

The general solution of the equation (3.1) for thickness vibration mode is

$$u_t = (A \sin \beta z + B \cos \beta z) e^{j\omega t} = u e^{j\omega t} \quad (3.2)$$

where A and B are two constants, ω is the angular resonance frequency, and β is the wave number in the z -direction,

$$\beta = \sqrt{\omega^2 \rho / c_{33}^D} \quad (3.3)$$

and the displacement of the piezoelectric plate is

$$u = A \sin \beta z + B \cos \beta z. \quad (3.4)$$

When the piezoelectric plate works at its resonance frequency, the following displacement of the piezoelectric plate may be obtained by substituting (3.4) into the basic electromechanical equations of the ceramic plate.

$$u = \left(\frac{u_2 - u_1}{2 \sin \frac{\beta t}{2}} \right) \sin \beta z + \left(\frac{u_1 + u_2}{2 \cos \frac{\beta t}{2}} \right) \cos \beta z \quad (3.5)$$

where u_1 and u_2 are the displacement of the two surfaces at $z = -\frac{t}{2}$ and $z = \frac{t}{2}$, respectively, and t is the thickness of the piezoelectric plate. As the displacement at $z = -\frac{t}{2}$ and $z = \frac{t}{2}$ has the same amplitude but opposite direction, we have

$$u_2 = -u_1 = u_0. \quad (3.6)$$

Then, the displacement of the piezoelectric plate can be expressed as

$$u = \frac{u_0 \sin \beta z}{\sin \frac{\beta t}{2}} \quad (3.7)$$

The one dimensional constitutive equations of a piezoelectric plate operating in the thickness vibration mode are as follows [1],

$$T_3 = c_{33}^D S_3 - h_{33} D_3 \quad (3.8a)$$

$$E_3 = -h_{33} S_3 + \beta_{33}^S D_3 \quad (3.8b)$$

where T_3 is the stress, S_3 is the strain, E_3 is the electric field vector, D_3 is the

electric displacement vector, h_{33} is the piezoelectric coefficient, and β_{33}^S is the piezoelectric permittivity constant. From equation (3.8b), the electric displacement is

$$D_3 = \frac{E_3}{\beta_{33}^S} + \frac{h_{33}}{\beta_{33}^S} S_3 . \quad (3.9)$$

The mechanical and electrical conditions are given by

$$S_1 = S_2 = 0 , \quad (3.10)$$

$$\frac{\partial D_3}{\partial z} = 0 . \quad (3.11)$$

Also

$$S_3 = \frac{\partial u}{\partial z} \quad (3.12)$$

From (3.9), (3.-11) and (3.12), we get

$$\frac{\partial E_3}{\partial z} = -h_{33} \frac{\partial^2 u}{\partial z^2} \quad (3.13)$$

Thus

$$E_3 = -h_{33} \frac{\partial u}{\partial z} + a , \quad (3.14)$$

where a is an integral constant. There is a voltage V across the piezoelectric plate because of the external electric field on surface of the wirelessly driven piezoelectric plate operating in the thickness mode, and is given by

$$V = \int_{-t/2}^{t/2} E_3 dz . \quad (3.15)$$

From (3.6), (3.14) and (3.15), the integral constant a is

$$a = \frac{V}{t} + \frac{h_{33}}{t} (2u_0) , \quad (3.16)$$

From (3.14) and (3.16)

$$E_3 = -h_{33} \frac{\partial u}{\partial z} + \frac{V}{t} + \frac{h_{33}}{t} (2u_0) \quad (3.17)$$

Thus, from (3.9) and (3.17)

$$D_3 = \frac{V}{\beta_{33}^S t} + \frac{h_{33}}{\beta_{33}^S t} (2u_0) . \quad (3.18)$$

The current flowing through the piezoelectric plate is

$$i = j\omega \int_{-l/2}^{l/2} w \sigma(y) dy . \quad (3.19)$$

where $\sigma(y)$ is the surface charge density and w is the width of the piezoelectric plate. According to Gauss's law, the charge on the surface electrode of the piezoelectric plate is

$$\sigma(y) = D_3 - \varepsilon_0 E(y) . \quad (3.20)$$

where ε_0 is the permittivity of the free space. From equations (3.18) to (3.20), the current flowing through the piezoelectric plate can be obtained as

$$i = j\omega (VC_d + 2nu_0 - \varepsilon_0 \tilde{E}A) . \quad (3.21)$$

where the clamped capacitance is defined as $C_d = \frac{A}{\beta_{33}^S t}$, (3.22a)

the turn ratio $n = \frac{Ah_{33}}{\beta_{33}^S t}$, (3.22b)

and the average electric field on the surface of the wirelessly driven piezoelectric plate is

$$\tilde{E} = \frac{1}{l} \int_{-l/2}^{l/2} E(y) dy . \quad (3.22c)$$

From equation (3.21), the equivalent circuit of the wirelessly driven

piezoelectric plate operating in the thickness vibration mode shown in Fig.3.3 is derived.

Fig.3.3: Derived equivalent circuit of the piezoelectric plate operating in the thickness vibration mode wirelessly driven by electric field.

The impedance of the loop on the right hand side of the equivalent circuit is given by

$$Z'_m = \frac{nV}{j\omega(2u_0)} = \frac{1}{j\omega \left(\frac{2}{\omega A \sqrt{\rho C_{33}^D}} \right)} + j\omega \left(\frac{Ah_{33}^2}{\beta_{33}^S t \omega^2} \right). \quad (3.23)$$

From (3.23), the inductance of the loop is given by

$$L'_m = \frac{Ah_{33}^2}{\beta_{33}^S t \omega^2}, \quad (3.24)$$

and the capacitance of the loop at resonance is

$$C'_m = \frac{\beta_{33}^S t}{Ah_{33}^2}. \quad (3.25)$$

The resistance R'_m of the circuit can be calculated using the complex forms of the piezoelectric coefficient (h_{33}), impermittivity constant (β_{33}^S), and stiffness constant (c_{33}^D) in equation (3.23). However, in practice the resistance is calculated from

$$R'_m = \frac{\omega L'_m}{Q_m} . \quad (3.26)$$

where Q_m is the mechanical quality factor of the piezoelectric plate. The motional current shown in Fig.3.3 is

$$I_m = 2n\upsilon . \quad (3.27)$$

where υ is the vibration velocity of the wirelessly driven piezoelectric plate operating in the thickness mode. The source current resulting from external electric field shown in Fig.3.3 is

$$i_s = j\omega\epsilon_0\tilde{E}A . \quad (3.28)$$

From Fig.3.3 and eqn. (3.21), it is seen that there is a current source in the equivalent circuit of a wirelessly driven piezoelectric plate operating in the thickness mode. This is different from the equivalent circuit of conventional piezoelectric component which is driven by an input voltage applied via lead wires. The concept of using a current source in the equivalent circuit may also be applied to the wirelessly driven piezoelectric components operating in the other vibration modes.

After establishing the equivalent circuit model, the characteristics of the piezoelectric component wirelessly driven by electric field can be explored. When the piezoelectric plate operates near its mechanical resonance frequency, the real power delivered to the electrical load resistor connected across the output electrodes of the wirelessly driven piezoelectric plate can be

$$P_L = \frac{(\omega \varepsilon_0 \tilde{E} A)^2 R_L \left[R_m'^2 + \left(\omega L_m' - \frac{1}{\omega C_m'} \right)^2 \right]}{\left(R_m' + n^2 R_L - \omega^2 C_d R_L L_m' + \frac{C_d R_L}{C_m'} \right)^2 + \left(\omega L_m' - \frac{1}{\omega C_m'} + \omega C_d R_L R_m' \right)^2} \quad (3.29)$$

The above eqn. (3.29) shows that the output power of the piezoelectric component is a function of the operating frequency, electric load, size, and material properties of the piezoelectric plate, and electric field. The optimum load resistance can be explained by the equivalent circuit of piezoelectric plate operating in the thickness mode, shown in Fig.3.3. A maximum power can be delivered to the electric load resistor, when

$$\frac{dP_L}{dR_L} = 0 \quad (3.30)$$

From (3.29) and (3.30), we get the following relation of the optimum load resistance for which the piezoelectric component delivers maximum power to the electrical load resistance R_L connected across the two electrodes of the piezoelectric plate.

$$\left(n^4 + \omega^2 C_d^2 R_m'^2 + \omega^4 C_d^2 L_m'^2 - 2n^2 \omega^2 C_d L_m' + \frac{C_d^2}{C_m'^2} + \frac{2n^2 C_d}{C_m'} - \frac{2\omega^2 C_d^2 L_m'}{C_m'} \right) R_L^2 - \left(R_m'^2 + \omega^2 L_m'^2 + \frac{1}{\omega^2 C_m'^2} - \frac{2L_m'}{C_m'} \right) = 0 \quad (3.31)$$

The analytical solution of the optimum load resistance for the wirelessly driven piezoelectric plate is given by

$$R_L = \sqrt{\frac{R_m'^2 + \omega^2 L_m'^2 + \frac{1}{\omega^2 C_m'^2} - \frac{2L_m'}{C_m'}}{n^4 + \omega^2 C_d^2 R_m'^2 + \omega^4 C_d^2 L_m'^2 - 2n^2 \omega^2 C_d L_m' + \frac{C_d^2}{C_m'^2} + \frac{2n^2 C_d}{C_m'} - \frac{2\omega^2 C_d^2 L_m'}{C_m'}}} \quad (3.32)$$

Using the above solution and equivalent circuit parameters, the optimum load

resistance can be found for the wirelessly driven piezoelectric plate operating in the thickness vibration mode.

The vibration characteristics of a piezoelectric component operating in the thickness mode wirelessly driven by electric field can be analyzed by using the derived equivalent circuit as depicted in Fig.3.3. The vibration displacement at the electrode surface of the wirelessly driven piezoelectric plate operating in the thickness mode can be obtained from the equivalent circuit as

$$u_0 = \frac{(0.5\epsilon_0 \tilde{E} A n^2 R_L)}{\sqrt{\left(R'_m + n^2 R_L - \omega^2 C_d R_L L'_m + \frac{C_d R_L}{C'_m}\right)^2 + \left(\omega L'_m - \frac{1}{\omega C'_m} + \omega C_d R_L R'_m\right)^2}} \quad (3.33)$$

The vibration velocity of the wirelessly driven piezoelectric plate operating in the thickness vibration mode can be

$$v = \frac{(0.5\omega\epsilon_0 \tilde{E} A n^2 R_L)}{\sqrt{\left(R'_m + n^2 R_L - \omega^2 C_d R_L L'_m + \frac{C_d R_L}{C'_m}\right)^2 + \left(\omega L'_m - \frac{1}{\omega C'_m} + \omega C_d R_L R'_m\right)^2}} \quad (3.34)$$

The above equations (3.33) and (3.34) show that both the vibration displacement and vibration velocity of the piezoelectric plate wirelessly driven by electric field are function of the operating frequency, electric load, dimensions, and material properties of the piezoelectric plate, and electric field.

3.4. Impedance Analyses

3.4.1. Measured impedance characteristics

The impedance characteristic at the thickness vibration mode of the driven

piezoelectric plate with the dimensions of $3 \times 0.8 \times 0.2 \text{ cm}^3$ is shown in Fig.3.4. An impedance analyzer (HP 4194A) was used for the measurement. The impedance was measured without electric field from the port AA' of the equivalent circuit of the piezoelectric plate as shown in Fig.3.3. From the frequency constants of the piezoelectric material and impedance characteristic, it is found that the resonance frequency of the driven piezoelectric plate in the thickness vibration mode is 772 kHz.

3.4.2. Equivalent circuit parameters of the piezoelectric plate

The calculated and measured equivalent circuit parameters of the wirelessly driven piezoelectric plate operating in the thickness vibration mode are shown in Table 3.2. The equivalent circuit parameters of the piezoelectric plate are calculated by using equations (3.22a), (3.24), (3.25), (3.26) and the piezoelectric materials constants in Table 3.1. L_m , C_m and R_m are the equivalent inductance, capacitance and resistance of the piezoelectric plate looking from port BB' as shown in Fig.3.3. The equivalent circuit parameters are measured by an impedance analyzer (HP4194A) from the port AA' . It is seen that the calculated equivalent circuit parameters agree well with the measured ones. The small differences may result from the error in the material constants used for the theoretical calculation, and the error in our measurement.

Fig.3.4: Measured impedance characteristics of the piezoelectric plate at the thickness vibration mode.

Parameters	Calculated	Measured
L_m (mH)	2.82	2.39
R_m (Ω)	47	42
C_m (pF)	14.90	13.64
C_d (nF)	1.42	1.47

Table 3.2: A comparison of the calculated and measured equivalent circuit parameters of the driven piezoelectric plate operating in the thickness mode.

3.5. Summary

In summary, a theoretical model for a wirelessly driven piezoelectric component operating in the thickness mode is proposed and expressed by an equivalent circuit. In contrast with the equivalent circuit of conventional piezoelectric components driven by a voltage applied via lead wires, the equivalent circuit of a wirelessly driven piezoelectric component has a current source resulting from the external electric field. The concept of using a current source in the equivalent circuit may be applied to the wirelessly driven piezoelectric components operating in the other vibration modes. The impedance characteristics of the piezoelectric component operating in the thickness vibration mode are investigated. The calculated and measured equivalent circuit parameters of the wirelessly driven piezoelectric plate are also compared. The calculated equivalent circuit parameters agree well with the measured ones.

CHAPTER 4 WIRELESS ENERGY TRANSMISSION TO PIEZOELECTRIC COMPONENTS BY PARALLEL PLATE CAPACITOR STRUCTURE

A new technique of transmitting electric energy wirelessly to piezoelectric components has been proposed, and explored in this work. An A.C. electric field is used to drive a piezoelectric plate wirelessly, which is made of lead zirconate titanate (PZT) ceramic material. The piezoelectric plate is poled vertically across its thickness direction. When an electric field generated by an A.C. source penetrates the piezoelectric plate, an attenuated voltage is obtained across the output electrodes of the piezoelectric plate. When the frequency of the electric field is close to the mechanical resonance frequency of the piezoelectric plate the power received by the electrical load connected to the output electrodes of the piezoelectric plate reaches maximum. In the experimental design, for the generation of an A.C. electric field, an A.C. voltage source is connected to the two brass plate-shaped live and ground electrodes mounted on a plastic table with a tunable separation which forms a parallel plate capacitor structure. The piezoelectric plate is inserted at the center of the gap between; equidistant from; and parallel with the two brass electrodes of the parallel plate capacitor structure. The experiment has shown that the output

power achieved by the piezoelectric plate depends on various factors like the operating frequency, electrical load, vibration mode and electrode pattern of the piezoelectric component, and the electric field. At the resonance frequency 782 kHz, a maximum output power of 1.84 mW and an energy conversion efficiency of 0.12% have been achieved wirelessly by the piezoelectric plate operating in the thickness vibration mode with 1 cm gap thickness and an input power of 1.52 W across the parallel plate capacitor structure. From the experiment, it was also observed that the output power at resonance of the piezoelectric plate operating in the thickness vibration mode is significantly higher than that of the piezoelectric plate operating in the other vibration modes like width and longitudinal vibration modes.

4.1. Experimental Setup, Phenomenon and Operating Mechanism

To transmit electric energy to piezoelectric components, a parallel plate capacitor structure is used as shown in Fig.4.1 (a). The photograph of the experimental set up for the measurement is shown in figure 4-1(b). The brass plate shaped live and ground electrodes with dimensions of $5 \times 2 \times 0.1 \text{ cm}^3$, mounted on a fixed plastic table with a tunable separation are used to form a parallel plate capacitor structure. An A.C. voltage source (a function generator Tektronix AFG 320 and an amplifier HAS 4014) with tunable frequency is connected to the two brass electrodes of the parallel plate capacitor structure. The piezoelectric plate is inserted into the gap between the two brass electrodes, parallel to and equidistant from them, and the plate is aligned along the central

axis of the gap. There is no direct connection between the piezoelectric plate and the two brass electrodes. To measure the output power, two lead wires are soldered onto the output electrodes and a load resistor is connected across the output electrodes of the piezoelectric plate.

(a)

(b)

Fig.4.1: Experimental setup to drive a piezoelectric plate wirelessly by parallel plate capacitor structure. (a) Schematic diagram; (b) Photograph.

Fig.4.2 (a) shows the configuration of the piezoelectric plate used in the experiment. The photograph of the piezoelectric plate is shown in Fig.4.2 (b). The piezoelectric plate is made of PZT (supplied by Fuji Ceramics, Japan) with a size of $3 \times 0.8 \times 0.2 \text{ cm}^3$, poled along the thickness direction. The top and bottom surfaces of the piezoelectric plate are fully covered by silver electrodes.

(a)

(b)

Fig.4.2: Configuration of the piezoelectric plate. (a) Schematic diagram; (b) Photograph of PZT C-203.

When the electric field generated by the A.C. voltage penetrates the piezoelectric plate, a voltage was observed across the output electrodes. It was found that the output power reached the maximum at resonance frequency of the piezoelectric plate. When the frequency of the electric field in the gap between two brass electrodes is close to the mechanical resonance frequency of the piezoelectric plate, a mechanical resonance can be excited due to the converse piezoelectric effect. This mechanical resonance can generate a voltage across the output electrodes due to the piezoelectric effect.

4.2. Experimental Conditions

The experiments are performed under the following conditions. All the experimental piezoelectric plates are made of the same ceramic material PZT with a size of $3 \times 0.8 \times 0.2 \text{ cm}^3$, and are poled vertically across the thickness direction. The relevant properties of the PZT ceramic are shown in Table 3.1. In each case the piezoelectric plate is aligned along the central axis of the gap between the two brass electrodes. There is no direct connection between the piezoelectric plate and the two brass electrodes. The medium is air for the wireless electric field transmission to piezoelectric plates. Unless otherwise specified, the input A.C. voltage is $150 \text{ V}_{\text{rms}}$ across the live and ground electrodes of parallel plate capacitor structure, and 1 cm gap thickness between the two brass plate-shaped live and ground electrodes. From the frequency constants of the piezoelectric material shown in Table 3.1 (supplied by Fuji Techno System, Japan), and also from the measured impedance characteristics depicted in Fig.3.3, it is known that the measured resonance frequency of the piezoelectric plate operating in the thickness mode is 772 kHz.

4.3. Results and Discussion

4.3.1. Frequency characteristics of the output power of wirelessly driven piezoelectric plate

The frequency characteristics of the output power of piezoelectric plate operating in the thickness vibration mode are shown in Fig.4.3. It is observed that at the resonance frequency of 772 kHz, a maximum output power is achieved by the piezoelectric plate.

Fig.4.3: Frequency characteristics of the output power of the piezoelectric plate operating in the thickness vibration mode at different load resistances.

When the frequency of the electric field in the gap is close to the mechanical resonance frequency of the piezoelectric plate, a relatively large vibration can be excited in the piezoelectric plate by the converse piezoelectric effect. This mechanical resonance generates a relatively large voltage across the output electrodes of the piezoelectric plate by the piezoelectric effect. Due to the capacitance of the piezoelectric plates, there is also output power but that power does not reach the maximum at resonance. Hence the peaks of the output power are only due to the piezoelectric resonance.

4.3.2. Dependence of the output power on electrical load of PZT plate

Fig.4.4 shows the dependence of output power at resonance on the electrical load for the wirelessly driven piezoelectric plate, operating in the thickness vibration mode.

Fig.4.4: Dependence of the output power on the electrical load at resonant frequency of the piezoelectric plate operating in the thickness mode.

Fig.4.5: Equivalent circuit of the piezoelectric plate wirelessly driven by electric field. i_s is the current source resulting from electric field E and V is the output voltage across the load resistance R_L . L'_m , C'_m and R'_m are the inductance, capacitance and resistance. C_d is the clamped capacitance and n is the turn ratio.

It can be seen that the output power at resonance reaches the maximum at an optimum load resistance. The output power at resonance frequency of 772 kHz reaches the maximum at an optimum load resistance of 350 Ω , and the maximum output power is 0.46 mW where $V_{in}=150$ Vrms. The optimum load resistance can be explained by the equivalent circuit of wirelessly driven piezoelectric plate operating in the thickness mode, as shown in Fig.4.5. The real power (P_L) delivered to the electrical load resistor at resonance calculated from the equivalent circuit is

$$P_L = \frac{(\omega \epsilon_0 EA)^2 R_L \left[R_m'^2 + \left(\omega L_m' - \frac{1}{\omega C_m'} \right)^2 \right]}{\left(R_m' + n^2 R_L - \omega^2 C_d R_L L_m' + \frac{C_d R_L}{C_m'} \right)^2 + \left(\omega L_m' - \frac{1}{\omega C_m'} + \omega C_d R_L R_m' \right)^2}. \quad (4.1)$$

A maximum power can be delivered to the electric load resistor, when

$$\frac{dP_L}{dR_L} = 0. \quad (4.2)$$

From eqns. (4.1) and (4.2), we get the following analytical solution of the

optimum load resistance for which a maximum power is delivered to the electrical load.

$$R_L = \sqrt{\frac{R_m'^2 + \omega^2 L_m'^2 + \frac{1}{\omega^2 C_m'^2} - \frac{2L_m'}{C_m'}}{n^4 + \omega^2 C_d^2 R_m'^2 + \omega^4 C_d^2 L_m'^2 - 2n^2 \omega^2 C_d L_m' + \frac{C_d^2}{C_m'^2} + \frac{2n^2 C_d}{C_m'} - \frac{2\omega^2 C_d^2 L_m'}{C_m'}}} \quad (4.3)$$

Using the above solution and the equivalent circuit parameters in Table 3.2, it is found that the calculated optimum load resistance is 358 Ω , which well agrees with the measured value 350 Ω of the wirelessly driven piezoelectric plate operating in the thickness vibration mode.

4.3.3. Effects of the vibration modes on the output power of the PZT plate

The effects of the vibration modes on the output power of the wirelessly driven piezoelectric plate have also been investigated here.

Fig.4.6: Effects of the vibration modes on the output power of the piezoelectric plate.

Fig.4.6 shows the effects of vibration modes on the output power, at the optimum loads and resonance frequencies of the piezoelectric plate, wirelessly driven by the A.C. electric field generated from the parallel plate capacitor structure. It is seen that the output power of the piezoelectric plate operating in the thickness vibration mode is significantly higher than that obtained in the length and width extensional vibration modes. Thus, the vibration mode has an effect on the output power of the piezoelectric plate wirelessly driven by a parallel plate capacitor structure.

4.3.4. Effect of electric field on the output power of the piezoelectric plate

The effect of the electric field on the output power achieved wirelessly by the piezoelectric plate operating in the thickness vibration mode is investigated here.

Fig.4.7: Dependence of the maximum output power of the piezoelectric plate on the input voltage and gap thickness between the two parallel brass plate electrodes. The maximum power is for frequency and electric load.

The dependence of the maximum output power of the piezoelectric plate on the input voltage and gap thickness between the two brass plate-shaped live and ground electrodes of the parallel plate capacitor structure is shown in Fig.4.7. The maximum output power is for resonance frequency and optimum electric load resistance of the wirelessly driven piezoelectric plate operating in the thickness mode. It is seen that the maximum output power of the piezoelectric plate achieved wirelessly is inversely proportional with the gap thickness and directly proportional with the input voltage between the live and ground electrodes of the parallel plate capacitor structure. When the input voltage (V_{in}) increases and gap thickness (d) between the brass plate shaped live and ground electrodes decreases, the average electric field ($E = V_{in}/d$) of the parallel plate capacitor structure increases. Hence, the maximum output power of the piezoelectric plate achieved wirelessly increases. Therefore, the maximum output power of the piezoelectric plate can be increased wirelessly by increasing the input voltage (V_{in}) and by decreasing the gap thickness (d) between the two brass plate-shaped live and ground electrodes of the parallel plate capacitor structure. It is seen that an output power of 0.46 mW has been achieved with an optimum load resistance 350 Ω , resonance frequency of 772 kHz, input voltage of 150 V_{rms} and gap thickness of 1 cm across the live and ground electrodes of parallel plate capacitor structure.

4.3.5. Effect of electrode pattern on the output power of the PZT plate

To study the effect of the electrode pattern on the output power of the piezoelectric plate wirelessly driven by an A.C. electric field, the electrodes on the top and bottom surface of the piezoelectric plate are electrically separated

into two sections, P and Q. The electrodes of sections P and Q are isolated by a narrow insulating gap along the width direction of the PZT plate, and the lengths of two electrodes are changeable in this experiment. Fig.4.8 shows the configuration of the wirelessly driven piezoelectric plate operating in the thickness mode, which has two electrically separated sections P and Q. A resistance load is connected across the two electrodes of section P of the piezoelectric plate for measuring the real power which section P delivers.

The frequency characteristics of the output power at the optimum loads of the piezoelectric plates operating in the thickness vibration mode with different electrode length ratios are depicted in Fig.4.9. It is seen that the output power is maximum at the resonance frequencies of the piezoelectric plates having different electrode length ratios of Q to P, whose values depend on the Q to P electrode length ratio of the piezoelectric plate. When the frequency of the transmitted electric field generated by the parallel plate capacitor structure is close to the mechanical resonance frequencies of the piezoelectric plates with different electrode length ratios, a maximum mechanical vibration can be stimulated in the piezoelectric plates by the converse piezoelectric effect. This maximum mechanical vibration generates a maximum voltage across the piezoelectric plates by the piezoelectric effect.

Fig.4.8 Configuration of the piezoelectric plate having two separated electrodes.

Fig.4.9: Frequency characteristics of the output power of the piezoelectric plates with different electrode length ratios, operating in the thickness mode.

Fig.4.10: Dependence of the output power at resonance on the electrical loads and electrode length ratios for the wirelessly driven piezoelectric plates operating in the thickness vibration mode.

Fig.4.10 shows the dependence of the output power at resonance on the electrical loads and electrode length ratios of the wirelessly driven piezoelectric plates, operating in the thickness mode. It can be seen that the output power at resonance reaches the maximum at an optimum load resistance whose value resistance depends on the electrode length ratio of Q to P. For the piezoelectric plate whose electrode length ratio of Q to P is 5:1, the output power at resonance frequency 782 kHz reaches the maximum at an optimum load resistance of 1365 Ω , and the maximum output power is 1.84 mW. The equivalent circuit of the wirelessly driven piezoelectric plate shown in Fig.4.5 can be used to explain these results. When the electrical load resistance R_L is not much larger than $1/(\omega C_d)$, the output voltage V increases with R_L for a given A.C. electric field. When R_L is much larger than $1/(\omega C_d)$, the load branch can be regarded as an open circuit. In such a case, V is constant and the output power (V^2/R_L) decreases as the electrical load resistance R_L increases.

The dependence of maximum output power at resonance and the optimum electrical load on the electrode length ratio of the wirelessly driven piezoelectric plates operating in the thickness vibration mode is depicted in Fig.4.11. It is seen that both the maximum output power at resonance and the optimum electrical load resistance increase as the electrode length ratio of Q to P increases. A high output power of 1.84 mW has been achieved for a large electrode length ratio of 5:1. When the electrode length ratio of Q to P increases, the clamped capacitance (C_d) of section P decreases. Then, $1/(\omega C_d)$ increases with the decrease of C_d for a given frequency. This increases the output voltage V . When the change of R_L is not very large, the output power increases as the

output voltage V increases. Hence the maximum output power at resonance of the wirelessly driven piezoelectric plate with large electrode length ratio is significantly higher than that obtained in other conditions (outside resonance).

Furthermore, it has been experimentally found that the energy conversion efficiency (the ratio of real power delivered to the electrical load resistor connected across the piezoelectric plate to the real power applied to the parallel plate capacitor structure) depends on the operating frequency, electric load and electric field. An energy conversion efficiency of 0.12% has been achieved by the wirelessly driven piezoelectric plate (electrode length ratio of Q to P is 5:1) operating in the thickness vibration mode at resonance frequency 782 kHz, optimum electrical load resistance of 1365 Ω , real input A.C. source power of 1.52 W across the live and ground electrodes of parallel plate capacitor structure, and a 1 cm gap thickness between two brass electrodes of the parallel plate capacitor structure.

Fig.4.11: Dependence of the output power and electrical load on the electrode length ratio at resonance frequency of the piezoelectric plate.

4.4. Summary

In summary, a method of wireless electric energy transmission to piezoelectric components is proposed here and the output power characteristics of the piezoelectric components are investigated experimentally. The output power of the piezoelectric plate depends on the operating frequency, electrical load, vibration mode and electrode pattern of the piezoelectric component, and the electric field generated by parallel plate capacitor structure. The output power attains the maximum at resonance frequency and an optimum load resistance of the piezoelectric plate. The piezoelectric plate with properly divided electrode has a large output power than the one with whole electrode. The output power at resonance of the piezoelectric plate operating in the thickness vibration mode is significantly higher than that of the plate operating in the other modes, like width and longitudinal vibrations. At the resonance frequency 782 kHz, a maximum output power of 1.84 mW and an energy conversion efficiency of 0.12% have been achieved wirelessly by the piezoelectric plate operating in the thickness mode, with an optimum load 1365 Ω , 1 cm gap thickness of the two brass electrodes, and input A.C. source power of 1.52 W across the live and ground electrodes of the parallel plate capacitor structure.

CHAPTER 5 WIRELESS DRIVE OF PIEZOELECTRIC COMPONENTS BY FOCUSED ELECTRIC FIELD

To explore the possibility of enhancing wireless electric energy transmission to the piezoelectric components and widen the application range of piezoelectric devices, the wireless drive of piezoelectric components by focused electric field has been investigated.

In the first section of this chapter, a new method of wireless drive of piezoelectric components by focused electric field is proposed and explored. A bottom stainless- steel needle ground electrode is used to focus the A.C. electric field from a top square brass plate live electrode through a piezoelectric plate placed in between them. The needle ground electrode enables better transmission of electric energy. The effects of electrode areas on the output power of the piezoelectric plate are investigated in order to optimize the wireless electric energy transmission to the piezoelectric plate. The output power of the piezoelectric plate depends on the operating frequency, electrical load, dimensions of the piezoelectric component, electric field, distance, and size of the live and ground electrodes of the electric field generator. When the frequency of the A.C. electric field is close to mechanical resonance frequency of the piezoelectric plate operating in the thickness vibration mode, the output power reaches the maximum. At the resonant frequency 782 kHz, a maximum

output power of 10.84 mW and an energy conversion efficiency of 0.51% have been achieved wirelessly by the piezoelectric plate operating in the thickness mode with a needle ground electrode, optimum electrical load of 1365 Ω , input average power of 2.12 W from A.C. source across the live and needle ground electrodes, 1 cm electrodes separation, and a live electrode area of 900 cm² of the focused electric field structure. Theoretically, the electric field pattern is also studied by finite element method simulation (COMSOL Multiphysics) to elucidate the focusing of electric field by a needle ground electrode with a brass plate live electrode to the piezoelectric component placed in between them.

Nano-vibration characteristics of a piezoelectric component operating in the thickness mode wirelessly driven by focused electric field have been investigated in this work, reported in the thesis in section 5.2 of this chapter. A mechanical resonance vibration is excited in the piezoelectric plate wirelessly driven by an A.C. electric field. Theoretically, it has been found that the vibration displacement depends on the electric field, operating frequency, electrical load, and dimensions of the wirelessly driven piezoelectric plate operating in the thickness vibration mode. The electric field pattern is theoretically calculated to assess it on the surface of the piezoelectric plate wirelessly driven by the focused A.C. electric field produced with the needle structure. It has been observed that the vibration displacement of the wirelessly driven piezoelectric plate reaches the maximum at resonance frequency, and its magnitude is in the nanometer range. It is also found that the vibration displacement in resonance increases with the electrical load resistance, the area of piezoelectric component, but is inversely proportional with the thickness of

the piezoelectric plate operating in the thickness vibration mode wirelessly driven by the focused electric field.

In section three, an improved method of wireless drive of piezoelectric components is experimentally investigated by using the electric resonance of a focused electric field generator and an inductor in series, in order to drive high power piezoelectric components wirelessly. When the focused electric field generator and the inductor are in series electric resonance, the wireless electric energy transmission to the piezoelectric component can be enhanced and a relatively large output power can be achieved by the piezoelectric plate wirelessly. Experimentally, it has been found that the real output power of the wirelessly driven piezoelectric plate depends on the operating frequency, electrical load, vibration mode of the piezoelectric component, distance between the electrodes, and the electric field focused by the needle ground and live electrodes of the focused electric field generator. When the focused electric field generator and inductor are in electric resonance, a maximum output power of 206.04 mW and an energy conversion efficiency of 1.02% have been achieved by the wirelessly driven piezoelectric plate operating in the thickness vibration mode at the resonance frequency of 782 kHz, optimum electrical load resistance of 1365 Ω , input source power of 20.12 W (applied to the series of focused electric field structure and inductor), 1 cm live and ground electrodes separation, and a live electrode area of 900 cm² of the focused electric field generator. The output power at resonance of the piezoelectric plate, operating in the thickness vibration mode, is significantly higher than that of the piezoelectric plate operating in the other modes like width and length extensional vibration modes.

5.1. Wireless Drive of Piezoelectric Components by Focused Electric Field Generator

Wireless electric energy transmission to a piezoelectric plate using a focused A.C. electric field is explored in this work. The A.C. electric field is focused by using a bottom stainless-steel needle ground electrode and a top brass square plate live electrode connected to the piezoelectric plate placed in between them. The needle ground electrode enables better transmission of the electric energy. The effects of the bottom electrode surface area on the output power achieved by the piezoelectric plate are investigated in order to optimize the wireless electric energy transmission to the piezoelectric plate.

5.1.1. Experimental Setup, Operating Conditions and Mechanism

To transmit a relatively large electric energy to the piezoelectric plate, a focused A.C. electric field generator is used, as shown in Fig.5.1 (a). With a square brass plate live electrode, a stainless steel needle ground electrode is used to focus the A.C. electric field to enhance the electric energy transmission to the piezoelectric plate. The needle ground electrode is placed below perpendicular to the live electrode which is suspended above the piezoelectric plate. The piezoelectric plate is placed in between the live and needle ground electrodes. Fig.5.1 (b) shows the configuration of piezoelectric component used in the experiments. The piezoelectric component is made of PZT ceramic material, and poled vertically across its thickness. The top and bottom surfaces of the PZT plate are fully covered by silver electrodes. In order to measure the output power, a load R_L is connected across the output electrodes of the PZT plate.

Fig.5.1: (a) Experimental setup to drive a piezoelectric plate wirelessly by focused ac electric field; (b) Configuration of the piezoelectric plate wirelessly driven by electric field.

The experiments are performed under the following conditions. The piezoelectric plate operates in the thickness vibration mode; the square size

brass plate-shaped live electrode area (A) is 900 cm^2 ; the ground electrode is a metal needle whose tip is assumed to have zero area; the medium between the live and ground electrodes is air. Unless otherwise specified, the input A.C. voltage applied to the focused electric field structure is 150 Vrms; the dimension of the piezoelectric plate is $3 \times 0.8 \times 0.2 \text{ cm}^3$; the piezoelectric plate is placed equidistantly in between the live and needle ground electrodes; the distance (d) between the live and ground electrodes is 1 cm.

When an A.C. electric field penetrates the piezoelectric plate, a mechanical vibration can be excited in the piezoelectric plate by the converse piezoelectric effect. When the frequency of electric field is close to mechanical resonance frequency of the piezoelectric plate, a mechanical resonance can be excited in the plate. This mechanical resonance can generate a relatively large voltage across the output electrodes due to the piezoelectric effect.

5.1.2. Frequency characteristics of the output power of piezoelectric plate

Fig. 5.2 (a) shows the frequency characteristics of the output power of the wirelessly driven piezoelectric plate operating in the thickness vibration mode placed at the middle in between the live and needle ground electrodes of focused electric field structure at a distance of 4 mm from each electrode. Fig.5.2 (b) shows the frequency characteristics of the output power of the driven piezoelectric plate, just 2 mm to the needle ground electrode from the lower surface of piezoelectric plate. It is observed that at the resonance frequency 772 kHz of the wirelessly driven piezoelectric plate operating in the thickness mode, a maximum output power is achieved.

Fig.5.2: Frequency characteristics of the output power of the wirelessly driven piezoelectric plate operating in the thickness mode. (a) Piezoelectric plate placed equidistantly in between live and needle ground electrodes at a distance of 4 mm from each electrode; (b) placed 2 mm to the needle ground electrode.

When the A.C. electric field produced from focused electric field structure penetrates the piezoelectric plate, a mechanical vibration can be excited in the piezoelectric plate by the converse piezoelectric effect. When the frequency of the transmitted electric field is close to mechanical resonance frequency of the piezoelectric plate, a mechanical resonance can be excited in the plate. This mechanical resonance generates a voltage across the output electrodes of piezoelectric plate by the piezoelectric effect. Hence the peaks of the output power are only due to the piezoelectric resonance. If the piezoelectric plate is detuned from the resonance, the output power of the wirelessly driven piezoelectric plate drops suddenly. It is also found that the maximum output power achieved wirelessly by the piezoelectric plate placed at the middle at a distance of 4 mm from each electrode and 2 mm to the needle ground electrode is 2.82 mW and 3.46 mW, respectively. This is because larger electric field is focused from the live electrode to the piezoelectric plate placed very near to the needle ground electrode, and enhances the output power of piezoelectric plate.

5.1.3. Effect of live electrode area on the output power of PZT plate

The effect of the live electrode surface area on the output power at resonance of the driven piezoelectric plate operating in the thickness mode is shown in Fig.5.3. It is seen that the output power of the wirelessly driven piezoelectric plate increases with the increase of live electrode area (A), when the electrode area is less than 900 cm^2 . At larger live electrode area, the output power becomes more saturated. For larger live electrode area, the electric field near the edge of the live electrode cannot be focused to the needle ground electrode, and the output power becomes saturated.

Fig.5.3: Effect of live electrode area on the output power at resonance of the piezoelectric plate operating in the thickness vibration mode.

5.1.4. Effect of the ground electrode surface area on the output power of piezoelectric plate

The effect of ground electrode surface area on the output power at resonance of the wirelessly driven piezoelectric plate operating in the thickness vibration mode is depicted in Fig.5.4. It is observed that the output power of the wirelessly driven piezoelectric plate decreases with the increase of ground electrode area (B). Thus, the needle ground electrode is responsible for focusing the A.C. electric field, and enhancing the electric energy transmission wirelessly to the piezoelectric plate operating in the thickness vibration mode placed in between the live and ground electrodes of the focused electric field structure.

Fig.5.4: Effect of ground electrode surface area on the output power at resonance of the piezoelectric plate operating in the thickness mode.

5.1.5. Effect of the distance between the lower surface of the piezoelectric plate and needle ground electrode on the maximum output power

Fig.5.5 shows the dependence of maximum output power on the distance between the lower surface of wirelessly driven piezoelectric plate and needle ground electrode of focused electric field structure. The maximum output power occurs at the resonance frequency and optimum load of the piezoelectric plate, operating in the thickness mode. It is seen that the maximum output power achieved wirelessly by the PZT plate increases with the decrease in the distance between the lower surface of the piezoelectric plate and needle ground for a given input ac voltage. This is because the electric field at the piezoelectric plate increases as the piezoelectric plate is moved towards the needle ground electrode, for a given input A.C. source voltage.

Fig.5.5: Dependence of the maximum output power on the distance between the lower surface of piezoelectric plate and needle ground electrode. The maximum output power is for frequency and electrical load.

5.1.6. Effect of the electrical load on the output power of PZT plate

The dependence of the output power at resonance on the electrical load for the wirelessly driven piezoelectric plate operating in the thickness vibration mode was experimentally investigated and the result are shown in Fig.5.6. It is found that the output power at the resonance reaches maximum at an optimum load resistance. The output power at resonance frequency of 772 kHz of the wirelessly driven piezoelectric plate operating in the thickness vibration mode, reaches the maximum at an optimum load of 350Ω for a needle ground electrode and live electrode area of 900 cm^2 .

Fig.5.6: Dependence of the output power at resonance on the electrical load for a wirelessly driven piezoelectric plate operated with a focused electric field.

Fig.5.7: Equivalent circuit of the piezoelectric plate wirelessly driven by electric field. i_s is the current source resulting from electric field E and V is the output voltage across the load resistance R_L . L'_m , C'_m and R'_m are the inductance, capacitance and resistance. C_d is the clamped capacitance and n is the turn ratio.

The equivalent circuit of the wirelessly driven piezoelectric plate operating in the thickness vibration mode which is shown in Fig.5.7 can be used to explain this result. When the load resistance R_L is not much larger than $1/(\omega C_d)$, the output voltage V increases with the load resistance R_L for a given input source current i_s , resulting from the external electric field. When R_L is much larger than $1/(\omega C_d)$, the load branch can be regarded as open circuit. In this latter case, V is constant and the output power (V^2/R_L) decreases as the electrical load R_L increases. Hence, there will be an optimum load for which a maximum power can be delivered to the electrical load connected across the output electrodes of the piezoelectric plate wirelessly driven by the focused e- field.

When the piezoelectric operates near its resonance, the real power (P_L) delivered to the electrical load resistor calculated from the equivalent circuit is

$$P_L = \frac{(\omega \varepsilon_0 EA)^2 R_L \left[R_m'^2 + \left(\omega L_m' - \frac{1}{\omega C_m'} \right)^2 \right]}{\left(R_m' + n^2 R_L - \omega^2 C_d R_L L_m' + \frac{C_d R_L}{C_m'} \right)^2 + \left(\omega L_m' - \frac{1}{\omega C_m'} + \omega C_d R_L R_m' \right)^2}. \quad (5.1)$$

A maximum power can be delivered to the electric load, when

$$\frac{dP_L}{dR_L} = 0. \quad (5.2)$$

From equations (5.1) and (5.2), we get the following solution of the optimum load resistance for which a maximum power is delivered to the electrical load resistance connected across the output electrodes of the wirelessly driven piezoelectric plate operating in the thickness vibration mode.

$$R_L = \sqrt{\frac{R_m'^2 + \omega^2 L_m'^2 + \frac{1}{\omega^2 C_m'^2} - \frac{2L_m'}{C_m'}}{n^4 + \omega^2 C_d^2 R_m'^2 + \omega^4 C_d^2 L_m'^2 - 2n^2 \omega^2 C_d L_m' + \frac{C_d^2}{C_m'^2} + \frac{2n^2 C_d}{C_m'} - \frac{2\omega^2 C_d^2 L_m'}{C_m'}}} \quad (5.3)$$

From the above solution and the calculated equivalent circuit parameters listed in Table 3.2, it is found that the calculated optimum load resistance is 358 Ω , which agrees well with the measured value of 350 Ω of the wirelessly driven piezoelectric plate operating in the thickness vibration mode.

5.1.7. Analyses of the focused e- field pattern by finite element method

In order to study the electric field pattern around the piezoelectric plate wirelessly driven by focused electric field structure, finite element method simulation (COMSOL Multiphysics) has been carried out. Here the finite element analyses are performed using the 2-D in-plane electrostatics application mode of COMSOL Multiphysics. The following steps are taken into consideration to obtain the distribution of the electric field on the surface of the piezoelectric plate wirelessly driven by the focused electric field structure.

The first step is to define the overall model and draw its geometry. The finite element model presented in this work is based on the geometry as shown in Fig.5.8. The 2-D finite element model geometry consists of an air box ($0.4 \times 0.02 \text{ m}^2$) that contains the piezoelectric plate ($0.03 \times 0.002 \text{ m}^2$) wirelessly driven by the focused electric field structure formed by a brass plate live electrode ($0.3 \times 0.001 \text{ m}^2$) and a stainless steel needle ground electrode whose tip is assumed to have zero area. The piezoelectric plate is placed at the middle of live and needle ground electrodes separated by 1 cm.

After defining the model geometry, the next task is to define the material properties of the calculation domains and the boundaries. The boundaries of the live electrode are defined with an electric potential of 150 Vrms and the needle electrode boundary is defined as ground. The finite element calculations are solved using non-uniform mesh sizes. The results presented in this work are found to be independent of the mesh refinement when the mesh consists of at least 68517 elements. After solving the problem, COMSOL Multiphysics shifts to its post processing mode and plots simulated 2-D electric field pattern around the piezoelectric plate wirelessly driven by the focused electric field structure, as shown in Fig.5.9. It has been observed that the A.C. electric field is focused, by using a needle ground electrode and a plate-shaped live electrode between which the piezoelectric plate is located. The needle ground electrode enables better transmission of electric energy wirelessly.

Fig.5.8: Geometry used for 2-D finite element method (COMSOL Multiphysics) simulation of electric field pattern around a piezoelectric plate wirelessly driven by focused electric field structure.

Fig.5.9: Simulated 2-D electric field pattern around the piezoelectric plate wirelessly driven by the focused electric field.

5.1.8. Dependence of the output power on the size of piezoelectric plate

The size effect in wireless drive of piezoelectric components by focused electric field has also been investigated here in order to drive a high power piezoelectric component wirelessly. Fig.5.10 (a) shows the dependence of the measured output power at resonance on the electrical load and area of the wirelessly driven piezoelectric plates, operating in the thickness vibration mode. The effect is studied for the wirelessly driven piezoelectric plates of constant thickness 2 mm. It can be seen from Fig.5.10 (a) that the output power at resonance reaches the maximum at an optimum load resistance, and the optimum load resistance depends on the size of the piezoelectric plate. It is also observed that the measured output power at resonance becomes large when the size of piezoelectric plate is reduced.

Fig.5.10: (a) Dependence of the output power at resonance on the area of PZT plate and electrical load; (b) Effect of calculated average electric field and measured equivalent resistance on the area of PZT plate.

A maximum output power of 10.84 mW has been achieved wirelessly by a small piezoelectric plate with an area of 40 mm^2 operating in the thickness vibration mode at the resonant frequency of 782 kHz, optimum load of 1365Ω , input voltage of 150 Vrms across the live and needle ground electrodes, 1 cm electrodes separation, and a live electrode area of 900 cm^2 of focused electric field structure. The change of output power at resonance with the area of piezoelectric plate is caused by the change of calculated average electric field on the measured area of the piezoelectric plate, and the change of measured equivalent resistance of the piezoelectric plate as shown in Fig.5.10 (b).

5.1.9. Energy conversion efficiency characteristics

Fig.5.11 shows the frequency dependence energy conversion efficiency characteristics at the optimum electrical load resistance of a small piezoelectric plate with an area of 40 mm^2 , operating in the thickness vibration mode. The energy conversion efficiency is the ratio of the real power delivered to the electrical load resistor connected across the output electrodes of the piezoelectric plate and the real power applied to the live and needle ground electrodes of focused electric field structure. Experimentally, it is found that the energy conversion efficiency depends on the operating frequency, electrical load, electrode size, and distance between the electrodes. An energy conversion efficiency of 0.51% has been achieved wirelessly by a small piezoelectric plate with an area of 40 mm^2 operating in the thickness mode at resonance frequency of 782 kHz, optimum electrical load resistance of 1365Ω , real input power of 2.12 W across the live and needle ground electrodes, 1 cm electrodes separation, and a live electrode area of 900 cm^2 of the focused e-field structure.

Fig.5.11: Frequency dependence energy conversion efficiency characteristics at the optimum load of the piezoelectric plate operating in the thickness vibration mode, wirelessly driven by focused electric field.

5.1.10. Summary

In summary, a method of wireless drive of piezoelectric plate by focused electric energy transmission is proposed and explored in this work reported by the thesis. A needle ground electrode is used to focus the A.C. electric field and enhances the wireless energy transmission. The output power achieved wirelessly by the piezoelectric plate operating in the thickness vibration mode depends on the operating frequency, electrical load resistance, distance between the piezoelectric plate and needle ground electrode, size of the piezoelectric component, electric field, and areas of the live and ground electrodes of the

focused electric field structure. The electric field pattern is also theoretically studied by finite element method simulation (COMSOL Multiphysics) to illustrate the electric field focusing by using a needle ground electrode with a brass plate-shaped live electrode to the piezoelectric component placed in between them. When frequency of the A.C. electric field is close to the mechanical resonance frequency of the piezoelectric plate operating in the thickness vibration mode the output power reaches the maximum. The output power and energy conversion efficiency of the wirelessly driven piezoelectric plate with smaller size are significantly higher than that of the driven piezoelectric plate with larger size. A maximum output power of 10.84 mW and an energy conversion efficiency of 0.51% have been achieved wirelessly by a small piezoelectric plate with an area of 40 mm^2 operating in the thickness vibration mode at the resonance frequency of 782 kHz, optimum electrical load resistance of 1365Ω , real input A.C. source power of 2.12 W across the live and needle ground electrodes, 1 cm electrodes separation, and a live electrode area of 900 cm^2 of the focused electric field generator.

5.2. Theoretical Analyses of Nano-vibration Characteristics of a Piezoelectric Component Wirelessly Driven by Focused Electric Field

To widen the application range of piezoelectric devices, several types of wireless drives of piezoelectric components have been investigated by the author using a properly designed electric field. It has been observed that the energy in an A.C. electric field can be transmitted to a piezoelectric plate. However, the mechanical vibration characteristic of the driven piezoelectric component has not been studied yet. Therefore, the vibration displacement characteristic of the wirelessly driven piezoelectric component needs to be investigated further.

The vibration characteristics of a piezoelectric plate operating in the thickness vibration mode wirelessly driven by focused electric field have been investigated here. A mechanical resonance vibration is excited in the piezoelectric plate wirelessly driven by the A.C. electric field produced from focused electric field structure. The effects of the electric field, operating frequency, electrical load, and dimensions of the piezoelectric component on the vibration displacement of the wirelessly driven piezoelectric plate operating in the thickness vibration mode are studied theoretically. The electric field pattern is theoretically calculated to assess the electric field on the surface of the piezoelectric plate. It was noticed that the vibration displacement reaches the maximum at resonance frequency, and the maximum vibration displacement of the driven piezoelectric plate is in the nanometer range. It has also been observed that the vibration displacement at resonance increases with the

electrical load resistance, the area of piezoelectric plate, and is inversely proportional to the thickness of piezoelectric plate.

5.2.1. Structure and principle

To investigate the mechanical vibration characteristics of a wirelessly driven piezoelectric component operating in the thickness mode, a focused electric field structure was used as shown in Fig.5.12 (a). With a square size brass plate-shaped live electrode, a stainless steel needle ground electrode is used to focus the ac electric field, and enhance the electric energy transmission to the piezoelectric plate wirelessly. The needle ground electrode is placed below perpendicular to the live electrode which is suspended above the piezoelectric plate. The piezoelectric plate is placed equidistantly in between the live and needle ground electrodes of the focused electric field structure at a distance of 4 mm from each electrode. The optimum live electrode area is $30 \times 30 \text{ cm}^2$. Fig.5.12 (b) shows the configuration of the wirelessly driven piezoelectric plate operating in the thickness vibration mode. The piezoelectric plate is made of PZT (supplied by Fuji Ceramic Corporation, Japan) with the dimensions of $3 \times 0.8 \times 0.2 \text{ cm}^3$. It is poled vertically across the thickness direction. The PZT plate is fully covered by silver electrode on its top and bottom surfaces. The vibration direction and applied electric field are both parallel to the poling direction. A load resistor R_L is connected across the two electrodes of the piezoelectric plate to study the effect of the electrical load on the vibration displacement.

When an A.C. electric field penetrates the piezoelectric plate, a mechanical vibration can be stimulated in the plate by the converse piezoelectric effect.

When the frequency of the A.C. electric field generated by the focused electric field structure is close to mechanical resonance frequency of the piezoelectric plate, a mechanical resonance vibration can be excited in the plate.

(a)

(b)

Fig.5.12: (a) Focused electric field structure to drive piezoelectric plate wirelessly; (b) Configuration of a wirelessly driven piezoelectric plate operating in the thickness vibration mode.

The theoretical calculations are performed under the following conditions. The wirelessly driven piezoelectric plate operates in the thickness vibration mode; the live electrode area is 900 cm^2 ; the ground electrode is a metal needle whose tip is assumed to be have zero area; the A.C. input source voltage across the focused electric field structure is 150 Vrms; the live and needle ground electrodes separation is 1 cm. Unless otherwise specified, the piezoelectric plate is placed equidistantly in between the live and needle ground electrodes.

5.2.2. Theoretical analyses of electric field by finite element method

The finite element method (COMSOL Multiphysics) simulation has been carried out for the wirelessly driven piezoelectric plate in order to assess the electric field on the surface of the piezoelectric plate.

Fig.5.13: Calculated 2-D electric field pattern around the piezoelectric plate wirelessly driven by focused electric field structure.

Fig.5.13 shows the calculated 2-D electric field pattern around the piezoelectric plate wirelessly driven by focused electric field structure. The distribution of electric field on the surface of the piezoelectric plate along the x -direction is shown in Fig.5.14. It is seen that the electric field on the surface of the piezoelectric plate wirelessly driven by focused electric field structure is non-uniform. For a piezoelectric plate with the dimensions of $3 \times 0.8 \times 0.2 \text{ cm}^3$, optimum live electrode area of 900 cm^2 , 1 cm live and needle ground electrodes separation, and an input source voltage of 150 Vrms across the live and needle ground electrodes of focused electric field structure, the average value of the electric field on the surface of the piezoelectric plate is $4.53 \times 10^4 \text{ V/m}$, which is used in our calculation.

Fig.5.14: Distribution of the electric field on the surface of wirelessly driven piezoelectric plate along the x -direction, $x=-0.015 \text{ m}$ to $x=0.015 \text{ m}$.

5.2.3. Theoretical analyses of vibration displacement characteristics

The one-dimensional thickness vibration of a piezoelectric plate with length l and constant cross sectional area A is analyzed here to study the vibration displacement characteristics of the wirelessly driven piezoelectric component operating in the thickness mode. The thickness vibration in the z -direction satisfies the following dynamical equation (Ikeda, 1984):

$$\rho \frac{\partial^2 u_t}{\partial t^2} = c_{33}^D \frac{\partial^2 u_t}{\partial z^2} \quad (5.4)$$

where ρ , u , and c_{33}^D represent density, displacement and elastic stiffness constant, respectively.

The general solution of the equation (5.4) for thickness vibration mode is

$$u_t = (A \sin \beta z + B \cos \beta z) e^{j\omega t} = u e^{j\omega t} \quad (5.5)$$

where A and B are two constants, ω is the angular resonance frequency, and β is the wave number in the z -direction,

$$\beta = \sqrt{\omega^2 \rho / c_{33}^D} \quad (5.6)$$

and the displacement of the piezoelectric plate is

$$u = A \sin \beta z + B \cos \beta z. \quad (5.7)$$

When the piezoelectric plate works at its resonance frequency, the following displacement of the piezoelectric plate may be obtained by substituting (5.7) into the basic electromechanical equations of the ceramic plate.

$$u = \left(\frac{u_2 - u_1}{2 \sin \frac{\beta t}{2}} \right) \sin \beta z + \left(\frac{u_1 + u_2}{2 \cos \frac{\beta t}{2}} \right) \cos \beta z \quad (5.8)$$

where u_1 and u_2 are the displacement of the two surfaces at $z = -\frac{t}{2}$ and $z = \frac{t}{2}$,

respectively, and t is the thickness of the piezoelectric plate. As the displacement at $z = -\frac{t}{2}$ and $z = \frac{t}{2}$ has the same amplitude but opposite direction, we have

$$u_2 = -u_1 = u_0. \quad (5.9)$$

Then, the displacement of the piezoelectric plate can be expressed as

$$u = \frac{u_0 \sin \beta z}{\sin \frac{\beta t}{2}} \quad (5.10)$$

The vibration displacement of the piezoelectric plate operating in the thickness vibration mode can be obtained from the derived equivalent circuit of the wirelessly driven piezoelectric plate as shown in Fig.5.15, in which L'_m , C'_m and R'_m are the inductance, capacitance, and resistance, respectively. n is the turn ratio and C_d is the clamped capacitance of the wirelessly driven piezoelectric plate. They are given by

$$L'_m = \frac{Ah_{33}^2}{\beta_{33}^S t \omega^2}, \quad (5.11a)$$

$$C'_m = \frac{\beta_{33}^S t}{Ah_{33}^2}, \quad (5.11b)$$

$$R'_m = \frac{\omega L'_m}{Q_m} \quad (5.11c)$$

$$C_d = \frac{A}{\beta_{33}^S t}, \quad (5.11d)$$

$$n = \frac{Ah_{33}}{\beta_{33}^S t}. \quad (5.11e)$$

where Q_m is the mechanical quality factor. h_{33} and β_{33}^S are the piezoelectric

coefficient and imperitivity constant, respectively.

The calculated vibration displacement of the wirelessly driven piezoelectric plate operating in the thickness vibration mode is

$$u_0 = \frac{(0.5\varepsilon_0 \tilde{E} A n^2 R_L)}{\sqrt{\left(R'_m + n^2 R_L - \omega^2 C_d R_L L'_m + \frac{C_d R_L}{C'_m}\right)^2 + \left(\omega L'_m - \frac{1}{\omega C'_m} + \omega C_d R_L R'_m\right)^2}}. \quad (5.12)$$

where ε_0 is the permittivity of the free space. The average electric field on the surface of the wirelessly driven piezoelectric plate is given by

$$\tilde{E} = \frac{1}{l} \int_{-l/2}^{l/2} E(y) dy. \quad (5.13)$$

where $E(y)$ is the external non-uniform electric field on surface of piezoelectric plate. The current source resulting from the external electric field shown in Fig.5.15 is

$$i_s = j\omega\varepsilon_0 \tilde{E} A. \quad (5.14)$$

The motional current also shown in Fig.5.15 is

$$I_m = 2nv. \quad (5.15)$$

where v is the vibration velocity of the wirelessly driven piezoelectric plate.

Fig.5.15: Equivalent circuit of the wirelessly driven piezoelectric plate operating in the thickness vibration mode.

The relevant material properties of the piezoelectric plate (PZT C-203, commercially available from Fuji Techno system, Japan) used in the calculations are listed in Table 5.1. The equivalent circuit parameters inductance (L_m), resistance (R_m) and capacitance (C_m) of the piezoelectric plate looking from port BB' are listed in Table 5.2. Their experimental values are measured by an impedance analyzer (HP4194A) from port AA' without external electric field.

Properties		Value
Electromechanical coupling factor	k_{33}	0.71
Frequency constant (mm*kHz)	N_{33}	1470
Relative dielectric constant	$\epsilon_{33}^T / \epsilon_0$	1450
Piezoelectric coefficient (10^{-12} C/N)	d_{33}	325
Density (10^3 kg/m ³)	ρ	7.7
Dimensions (mm ³)	$t \times w \times l$	2×8×30

Table 5.1: Relevant material properties of the piezoelectric plate.

Parameters	Measured	Calculated
L_m (mH)	2.39	2.82
C_m (pF)	13.64	14.90
R_m (Ω)	42	47
C_d (nF)	1.47	1.42

Table 5.2: Equivalent circuit parameters of the piezoelectric plate.

5.2.4. Results and Discussion

Fig.5.16 shows the calculated frequency characteristics of vibration displacement of the wirelessly driven piezoelectric plate operating in the thickness vibration mode when the electrical load resistances are $R_L = \infty$ (open circuit), $R_L = 0$ (short circuit), and $R_L = 350 \Omega$ (output power is maximum across the piezoelectric plate). It is found that a relatively large vibration displacement of 8.40 nm has been achieved when the load branch is open circuited. The reason for this phenomenon can be explained by the equivalent circuit of the wirelessly driven piezoelectric plate operating in the thickness mode, as depicted in Fig.5.15.

Fig.5.16: Theoretical frequency characteristics of the vibration displacement of wirelessly driven piezoelectric plate operating in the thickness mode.

When the load branch is open circuited, the current i through the load resistance R_L is zero, resulting a large motional current $I_m = 2n\psi$. However, when the load branch is short circuited, all i_s passes through the load branch, and thus the motional current I_m is zero. Hence the vibration displacement is relatively large when the load branch is open circuited, and the vibration displacement is zero when the load branch is short circuited.

The theoretical electrical load characteristic of the vibration displacement at resonance of the piezoelectric plate, operating in the thickness vibration mode wirelessly driven by focused electric field is shown in Fig.5.17.

Fig.5.17: Theoretical electric load characteristics of the vibration displacement at the resonance of the piezoelectric plate wirelessly driven by focused electric field.

It is observed that the vibration displacement at resonance increases with the electrical load resistance, and reaches a stable value when R_L is very large. For a given operating frequency when the electrical load resistance R_L increases, the current i through the load resistance R_L decreases, and thus the motional current I_m increases. Hence the vibration displacement at resonance increases with the electrical load resistance R_L .

Fig.5.18 shows the effect of the area of the piezoelectric plate on the vibration displacement at resonance with the constant thickness and electric load resistance of the piezoelectric plate operating in thickness mode wirelessly driven by the focused electric field structure. The effect is studied for a piezoelectric plate 2 mm thick and with an electrical load resistance $R_L = \infty$.

Fig.5.18: Effect of the area on vibration displacement at resonance of the wirelessly driven piezoelectric plate operating in the thickness mode.

Fig.5.19: Effect of the calculated average electric field and measured equivalent resistance on the area of the wirelessly driven piezoelectric plate.

It is found that the vibration displacement at resonance increases with the area of the piezoelectric plate. The theoretical calculation is based on the calculated average electric field and measured equivalent resistance R_m of the piezoelectric plate as depicted in Fig.5.19. The change of vibration displacement at resonance with the area of the wirelessly driven piezoelectric plate is caused by the change of calculated average electric field on the measured area of the piezoelectric plate, and the change of measured equivalent resistance R_m of the piezoelectric plate.

The effect of the thickness on the vibration displacement at resonance has been

investigated theoretically for a wirelessly driven piezoelectric plate, operating in the thickness vibration mode with constant length, width and electrical load resistance. The effect is studied for a piezoelectric plate of length 30 mm, width 8 mm, and the electrical load resistance R_L is ∞ . The effect of thickness on the vibration displacement at resonance is depicted in Fig.5.20, for a wirelessly driven piezoelectric plate of constant area operating in the thickness vibration mode. Theoretically, it is found that the vibration displacement at resonance decreases with the thickness of piezoelectric plate. This is because the electric field strength at the piezoelectric plate decreases with the thickness of the piezoelectric plate operated in the thickness vibration mode wirelessly driven by focused electric field structure.

Fig.5.20: Effect of the thickness on the vibration displacement at resonance of the piezoelectric plate operating in the thickness mode wirelessly driven by focused electric field.

5.2.5. Summary

The vibration displacement characteristics of a piezoelectric plate operating in the thickness vibration mode wirelessly driven by an A.C. electric field produced from a focused electric field structure have been investigated here theoretically. The electric field pattern is theoretically calculated by finite element method (COMSOL Multiphysics) to assess the electric field on the surface of the wirelessly driven piezoelectric plate, placed at the middle in-between the live and needle ground electrodes of the focused electric field structure. It has been observed that when the electric field produced from focused electric field structure penetrates the piezoelectric plate, a mechanical resonance vibration is excited in the piezoelectric plate. Theoretically, it has been found that the vibration displacement depends on the electric field, operating frequency, electrical load, and dimensions of the driven piezoelectric plate. The vibration displacement reached a maximum at the resonance frequency, and the maximum vibration displacement is in the nanometer range. Theoretically, it is found that at the resonance frequency of 773.8 kHz and electrical load resistance $R_L = \infty$, a maximum vibration displacement of 8.40 nm has been achieved wirelessly by the piezoelectric plate operating in the thickness vibration mode with an input voltage of 150 Vrms across the live and needle ground electrodes, 1 cm electrodes separation, and a live electrode area of 900 cm² of the focused electric field structure. It has been seen that the vibration displacement at resonance increases with the electrical load resistance, the area of the piezoelectric component, and is inversely proportional to the thickness of piezoelectric plate operating in the thickness vibration mode, wirelessly driven by the focused electric field structure.

5.3. Wireless Drive of Piezoelectric Components by Focused Electric Field Structure in Electric Resonance with an Inductor

In the earlier proposed wireless energy transmission techniques, the output power of wirelessly driven piezoelectric component is not high enough. In order to drive a high-power piezoelectric device wirelessly by an electric field and widen the application range of piezoelectric devices, the wireless drive of piezoelectric components needs to be investigated further.

The wireless drive of piezoelectric components is experimentally investigated by using the electric resonance of a focused electric field generator and an inductor in series. In this design, an A.C. electric field is focused to a piezoelectric plate placed in between a plate-shaped live and needle ground electrodes which form a focused electric field generator in series with an inductor. The transmission of electric energy is enhanced when the focused electric field generator and inductor are in electric resonance. The technique enables a relatively large output power achieved by the piezoelectric plate. The effects of operating frequency, electric load, vibration mode, position and dimensions of the piezoelectric plate, on the real output power of the wirelessly driven piezoelectric plate are investigated in order to optimize the wireless electric energy transmission to piezoelectric components.

5.3.1. Experimental Setup, conditions and operating mechanism

To transmit a relatively large electric energy to piezoelectric components, a

focused electric field generator in series with an inductor is used as shown in Fig.5.21 (a). With an optimum square brass plate-shaped live electrode, a stainless steel needle ground electrode is used to form the focused electric field generator. In the electric field generator, the A.C. electric field is focused to a needle ground electrode from a plate-shaped live electrode through a piezoelectric plate placed in between them. When the electric field generator and inductor are in electric resonance, the transmitted power is increased because of the large voltage across the focused electric field structure. Two piezoelectric plates of different dimensions are used in this experiment. The upper and lower surfaces of the piezoelectric plates are covered with silver metal electrodes. Both piezoelectric plates are made of PZT (Fuju C203), and poled vertically across the thickness direction. Piezoelectric charge constant d_{33} , mechanical Q , dissipation factor $\tan\delta$, and relative dielectric constant $\epsilon_{33}^T/\epsilon_0$ are 325×10^{-12} m/V, 2000, 0.3 and 1450, respectively. Fig.5.21 (b) shows the configuration of plate A (having the dimensions of $30 \times 8 \times 2$ mm³) and Fig.5.21 (c) shows the configuration of plate B (size of $8 \times 5 \times 2$ mm³), used in these experiments. A resistance load is connected across the two electrodes for measuring the real power which the piezoelectric plate delivers.

The experiments are performed under the following conditions. The live electrode area is 30×30 cm²; the ground electrode is a metal needle whose tip is assumed to have zero area; the inductances (L) have equal values of 1.48 mH with piezoelectric plates A and B, respectively, and thus, the electric field generator and inductor are in resonance. Unless otherwise specified, the piezoelectric plate is placed equidistantly at distance of 4 mm in-between the live and needle ground electrodes positioned perpendicular to each other. The

A.C. input voltage applied to the series of electric field generator and inductor is 150 Vrms, the distance between the live and needle ground electrode is 1 cm, and the piezoelectric plates operate in the thickness vibration mode. Table 5.3 shows the measured resonance frequencies, and equivalent circuit parameters of piezoelectric plates A and B by an impedance analyzer (HP4194A).

(a)

(b)

(c)

Fig.5.21 (a) Experimental setup to drive piezoelectric component wirelessly by focused electric field generator in series with an inductor; (b) Configuration of piezoelectric plate-A; (c) Configuration of PZT plate-B.

Piezoelectric plates	Resonance frequency f_r (kHz)	Equivalent Resistance R_m (k Ω)	Equivalent Inductance L_m (mH)	Equivalent Capacitance C_m (pF)	Clamped Capacitance C_d (nF)
Plate A	772	0.042	2.39	13.64	1.47
Plate B	782	2.182	19.74	2.12	0.122

Table 5.3: Measured equivalent circuit parameters of the PZT plates.

When the focused electric field electric field generator and inductor are in electric resonance, the current flowing through the electric field generator is very large. Thus, at resonance, a relatively large A.C. electric field can be focused to a needle ground electrode from the plate-shaped live electrode through a piezoelectric plate placed in between them. When an A.C. electric field penetrates the piezoelectric plate, a mechanical vibration can be stimulated in the piezoelectric plate by the converse piezoelectric effect. When the frequency of the A.C. electric field is close to the mechanical resonance frequency of the piezoelectric plate, a mechanical resonance can be excited in the plate. This mechanical resonance can generate a relatively large voltage across the output electrodes due to the piezoelectric effect.

5.3.2. Frequency characteristics of the output power of piezoelectric plates

Fig.5.22 (a) and 5.22 (b) show the frequency characteristics of the output power of both piezoelectric plates A and B operating in the thickness vibration mode, placed inside the focused electric field generator. Fig.5.22 (a) represents the result when the electric field generator is electrically resonant with the inductor.

Fig.5.22 (b) represents the result without the inductor.

Fig.5.22: Frequency characteristics of the output power of the piezoelectric plates A and B at optimum load resistance for: (a) electric field generator with inductor and (b) electric field generator without an inductor.

It is observed that at the resonance frequencies of 772 kHz and 782 kHz of plates *A* and *B* respectively, a maximum output power is achieved. When the frequency of the A.C. electric field is close to the mechanical resonance frequency of the plate, a relatively large vibration can be excited in the plate by the converse piezoelectric effect. This mechanical resonance generates a relatively large voltage at the output electrodes by the piezoelectric effect. It is also seen that when the electric field generator and inductor are in electrical resonance, the output power of the piezoelectric plate is significantly higher than that of the electric field generator without an inductor. When the electric field generator is in series electric resonance with an inductor, the voltage across the focused electric field structure is five times greater than the A.C. source voltage. Thus at resonance, a relatively large amount of A.C. electric field can be focused to the needle ground electrode and hence a relatively large electric energy can be transmitted to the piezoelectric plate placed in between the live and needle ground electrodes. Therefore, for a given input A.C. voltage, the output power is larger for an electric field generator which is in electric resonance with an inductor.

5.3.3. Electrical load characteristics of the output power of PZT plates

The dependence of the output power at resonance on the electrical load for the piezoelectric plates, operating in the thickness vibration mode is shown in Fig.5.23. It is seen that the output power at resonance reaches the maximum at an optimum load resistance. For plate- *B*, the output power reaches the maximum at an optimum load resistance of 1365 Ω , and the maximum output power is 206.04 mW. The equivalent circuit of the piezoelectric plate is shown

in Fig.5.15, which can be used to explain the optimum load. When the load resistance R_L is not much larger than $1/(\omega C_d)$, the output voltage V increases with R_L for a given i_s . When R_L is much larger than $1/(\omega C_d)$, the load branch can be regarded as open circuit. Consequently, V is constant and the output power (V^2/R_L) decreases as the electrical load R_L increases. From the equivalent circuit of the wirelessly driven piezoelectric plate, the following solution of the optimum load resistance for which a maximum power is delivered to the electrical load resistance can be obtained.

$$R_L = \sqrt{\frac{R_m'^2 + \omega^2 L_m'^2 + \frac{1}{\omega^2 C_m'^2} - \frac{2L_m'}{C_m'}}{n^4 + \omega^2 C_d^2 R_m'^2 + \omega^4 C_d^2 L_m'^2 - 2n^2 \omega^2 C_d L_m' + \frac{C_d^2}{C_m'^2} + \frac{2n^2 C_d}{C_m'} - \frac{2\omega^2 C_d^2 L_m'}{C_m'}}} \quad (5.16)$$

From the above solution and the equivalent circuit parameters listed in Table 5.3, we found an optimum load resistance of 1358Ω which agrees well with the measured value of 1365Ω .

Fig.5.23: Dependence of the output power at resonance on the electric load.

5.3.4. Effect of vibration modes on the output power of piezoelectric plate

The effect of vibration modes on the output power at the optimum load resistance and resonance frequency of the wirelessly driven piezoelectric plate was investigated experimentally and the results are shown in Fig.5.24. The output power is measured for the wirelessly driven piezoelectric plate-*B* when the electric field generator is in electric resonance with an inductor. It is seen that the output power of the wirelessly driven piezoelectric plate operating in the thickness vibration mode is significantly higher than that of the plate operating in the width and length extensional vibration modes. Thus, the vibration mode has an effect on the output power of the piezoelectric plate wirelessly driven by the focused e- field structure in resonance with an inductor.

Fig.5.24: Effect of vibration modes on the output power of wirelessly driven piezoelectric plate *B* when the electric field generator is in electric resonance with the inductor.

5.3.5. Dependence of the distance on the output power at resonance between the live and needle ground electrodes

The dependence of the output power at resonance on the distance between the live and needle ground electrodes of the focused electric field generator is shown in Fig.5.25. The output power is measured for piezoelectric plates *A* and *B* operating in the thickness vibration mode, when the electric field generator and inductor are in electric resonance. The piezoelectric plate is placed equidistantly in between the live and needle ground electrodes of the focused electric field structure at a distance of 4 mm from each electrode. It is seen that the maximum output power increases with the decrease in the distance between the live and needle ground for a given input A.C. voltage.

Fig.5.25: Dependence of the maximum output power on the distance between the live and needle ground electrodes. The maximum output power is for resonant frequency and optimum load of the piezoelectric plate placed equidistantly from the live and needle ground electrodes.

When the distance between the live and needle ground electrodes of the focused electric field generator is larger than 100 cm, the output power of piezoelectric plate is less than 0.004% of that when the distance is 1 cm. This is because the electric field at the piezoelectric plate increases as the distance between the live and needle ground electrodes decreases. Hence the output power is inversely proportional to the distance between the live and needle ground for a given input ac voltage for the wirelessly driven piezoelectric plates placed at the middle of electrodes.

5.3.6. Energy conversion efficiency characteristics

Fig.5.26 shows the frequency dependence energy conversion efficiency (the ratio of the real power delivered to the electrical load resistor connected across the output electrodes of the piezoelectric plate and the real power applied to the series of focused electric field structure and inductor) characteristics at the optimum electrical load resistances of piezoelectric plates *A* and *B*, operating in the thickness vibration mode. It is seen that when the electric field generator and inductor are in electric resonance, an energy conversion efficiency of 1.02% has been achieved for the wirelessly driven piezoelectric plate *B* at the resonance frequency of 782 kHz and electrical load resistance of 1365 Ω , which is higher than that of the energy conversion efficiency of 0.27% achieved wirelessly by the piezoelectric plate *A* at the resonance frequency of 772 kHz and electrical load resistance of 350 Ω for a real input power of 20.12 W applied to the series of focused electric field structure and inductor, 1 cm live and ground electrodes separation, and a live electrode area of 900 cm² of the capacitor like electric field generator.

Fig.5.26: Frequency dependence energy conversion efficiency characteristics at the optimum load of PZT plates A and B, operating in the thickness vibration mode, when the electric field generator is in electric resonance with the inductor.

The dependence of energy conversion efficiency on the electrical load resistance at resonance frequency of the plate B operating in the thickness vibration mode is depicted in Fig.5.27. This result is obtained when the electric field generator and inductor are in electric resonance for piezoelectric plate B operating in the thickness vibration mode. It is seen that the energy conversion efficiency depends on the electrical load and a maximum efficiency of 1.12% is achieved for piezoelectric plate B at the resonance frequency of 782 kHz, electric load resistance of 1450 Ω , real input power of 20.12 W applied to the series of focused electric field structure and inductor, 1 cm live and ground

electrodes separation, and a live electrode area of 900 cm^2 of the capacitor like electric field generator.

Fig.5.27: Dependence of energy conversion efficiency on the electrical load resistance at resonance of the piezoelectric plate *B* operating in the thickness vibration mode.

5.3.7. Summary

In summary, an improved method of wireless drive of piezoelectric components is explored by using the electric resonance of a focused electric field generator and an inductor in series. In the focused electric field generator, the A.C. electric field is focused to a needle ground electrode from the plate-shaped live electrode through a piezoelectric plate placed equidistantly from the live and

needle ground electrodes. When the focused electric field generator and inductor are in electric resonance, the wireless electric energy transmission is enhanced. The technique enables a relatively large output power delivered to the piezoelectric plate wirelessly. The output power attains the maximum at resonance frequency of piezoelectric plate, and the plate with small area has a larger output power than the one with large area. The output power at resonance of the piezoelectric plate, operating in the thickness vibration mode, is significantly higher than that of the plate operating in the other modes like width and length extensional vibration modes. Experimentally, it has been found that the real output power of piezoelectric plate depends on the operating frequency, electrical load, vibration mode, dimensions of the piezoelectric component, distance between the electrodes, and the electric field. When the focused electric field generator and inductor are in electric resonance, a maximum output power of 206.04 mW and energy conversion efficiency of 1.02% have been achieved by the wirelessly driven piezoelectric plate operating in the thickness vibration mode at the resonance frequency of 782 kHz, optimum electrical load resistance of 1365 Ω , real input power of 20.12 W (applied to the series of focused electric field structure and inductor), 1 cm live and ground electrodes separation, and a live electrode area of 900 cm² of the focused electric field generator. Methods of increasing the transmission power and efficiency will be investigated further both theoretically and experimentally.

CHAPTER 6 CHARACTERISTICS OF PIEZOELECTRIC COMPONENTS WIRELESSLY DRIVEN BY ANTENNA-LIKE ELECTRIC FIELD GENERATORS

Earlier, new techniques of wireless energy transmission to piezoelectric components by focused electric field and the electric field generated from parallel plate capacitor structure were proposed and investigated by the author. It has been observed that the energy in an A.C. electric field can be transmitted to a piezoelectric component, placed in between the live and ground electrodes of the electric field generator structures. But the structures of the proposed electric field generators constrain the free motion of the wirelessly driven piezoelectric components. To solve the above stated problem, new techniques of wireless drives of piezoelectric components by antenna-like structures are proposed.

In first section of this chapter, wireless drive of piezoelectric components by dipole antenna-like electric field generator structure has been proposed, and its characteristics are investigated. Two equal size square brass plate-shaped live and ground electrodes are used to form an electric dipole antenna-like structure

to transmit the A.C. electric field wirelessly to the piezoelectric plate. The effects of electrode areas of dipole antenna-like structure, electric field, operating frequency, electric load, and position of the piezoelectric plate on the real output power of the piezoelectric plate are investigated in order to optimize the wireless electric energy transmission to the piezoelectric plates. The electric field pattern is calculated by finite element method to assess the electric field on the surface of the piezoelectric plate wirelessly driven by dipole antenna-like structure. A theoretical model is also developed for the wirelessly driven piezoelectric plate operating in the thickness vibration mode, which can explain the experimental results well. It has been observed that at resonance frequency and optimum electrical load, the output power achieved wirelessly by the piezoelectric component increases with the electrodes area, the electric field, and decreases with the distance of piezoelectric component from the plane of the electrodes of the dipole antenna-like structure. In order to enhance the driving power, the electric dipole antenna-like structure is used in series with an inductor. When the electric dipole antenna-like structure and inductor are in electric resonance, a maximum output power of 1.92 mW and energy conversion efficiency of 0.012% have been achieved wirelessly by the piezoelectric plate operating in the thickness vibration mode, placed at the centre 4 mm away from antenna plane with an optimum electrical load resistance of 350 Ω , 1 cm electrodes separation, 2500 cm² electrode area of electric dipole antenna-like structure, and input source power of 15.58 W applied to the series of dipole antenna-like structure and inductor.

In the second section of this chapter, an improved compact electric field generator is explored to transmit relatively large electric energy wirelessly to a

piezoelectric component by using the electric resonance of a flat spiral coil antenna-like structure and a capacitor in series. In the flat spiral coil antenna-like electric field generator, the A.C. electric field is transmitted wirelessly to the piezoelectric plate placed perpendicular to the plane of antenna. When the spiral coil antenna-like electric field generator and capacitor are in electric resonance, the wireless electric energy transmission to the piezoelectric component can be enhanced. This technique enables a relatively large output power achieved wirelessly by the piezoelectric component. At resonance frequency of 772 kHz and optimum electrical load resistance of 350 Ω , a maximum output power of 0.362 mW and energy conversion efficiency of 0.027% have been achieved wirelessly by the piezoelectric plate operating in the thickness vibration mode, placed 4 mm away from antenna plane with an input ac source power of 1.294 W applied to the series of flat spiral coil antenna-like structure and capacitor, and an inductance of 0.0413 mH of the flat spiral coil antenna-like electric field generator.

6.1. Characteristics of Piezoelectric Components Wirelessly Driven by an Electric Dipole Antenna-like Structure

Wireless electric energy transmission to a piezoelectric component operating in the thickness vibration mode, by using an electric dipole antenna-like structure is investigated here both theoretically and experimentally. The electric field pattern around the wirelessly driven piezoelectric plate is analyzed by finite element method (COMSOL Multiphysics). The effects of the electrode areas of the dipole antenna-like structure, as well as of the electric field, operating

frequency, electric load, and position of the piezoelectric plate on the real output power of the wirelessly driven piezoelectric plate are investigated in order to optimize the wireless electric energy transmission to the piezoelectric plate by using dipole antenna-like structure.

6.1.1. Structure and principle

To transmit electric energy to a piezoelectric plate wirelessly, an electric dipole antenna-like electric field generator is used as shown in Fig.6.1. The square size brass plate-shaped live and ground electrodes are used to form a dipole antenna-like structure to transmit ac electric field to the piezoelectric plate. An A.C. input source voltage is connected to the live and ground electrodes of the electric dipole antenna-like structure. The piezoelectric plate is placed in a plane perpendicular to the electrodes and equidistant from the live and ground electrodes of the dipole antenna-like structure.

Fig.6.1: Experimental setup to drive piezoelectric plate wirelessly by an electric dipole antenna-like structure.

Fig.6.2 illustrates the configuration of piezoelectric plate operating in the thickness mode wirelessly driven by an electric dipole antenna-like structure. The piezoelectric plate is made of PZT material, and poled vertically across the thickness direction. The vibration direction and electric field generated by the electric dipole antenna-like structure, both are parallel to the poling direction of the PZT plate. A load resistor R_L is connected across the output electrodes of piezoelectric plate for measuring the real output power which the piezoelectric plate delivers.

When an A.C. electric field generated by the electric dipole antenna-like structure penetrates the piezoelectric plate placed at the center away from antenna plane, a mechanical vibration can be stimulated in the piezoelectric plate by the converse piezoelectric effect. When the operating frequency of the A.C. electric field is close to the mechanical resonance frequency of the piezoelectric plate, a mechanical resonance can be excited in the piezoelectric plate. This mechanical resonance can generate a voltage across the output electrodes due to the piezoelectric effect.

Fig.6.2: Configuration of the piezoelectric plate wirelessly driven by an electric dipole antenna-like electric field generator.

The theoretical and experimental studies are performed under the following conditions. The wirelessly driven piezoelectric plate operates in the thickness vibration mode; the square size brass plate-shaped live and ground electrodes of the dipole antenna-like structure have the same area 2500 cm^2 ; the distance between the live and ground electrodes of the antenna-like structure is 1 cm; the input A.C. source voltage is 150 Vrms. Unless otherwise specified, the dimensions of the piezoelectric plate is $3 \times 0.8 \times 0.2 \text{ cm}^3$, the piezoelectric plate is placed at the center, 4 mm away from the antenna plane, and the area of each electrode of the dipole antenna-like electric field generator is 2500 cm^2 .

6.1.2. Theoretical analyses of electric field by FEM

In order to assess the electric field on the surface of the piezoelectric plate wirelessly driven by dipole antenna-like structure, finite element method (COMSOL Multiphysics) 2D in-plane electrostatic simulations have been carried out. The following steps were taken into consideration to obtain the distribution of electric field on the surface of the piezoelectric plate wirelessly driven by the dipole antenna-like structure.

The first step is to define the overall model and draw its geometry. The finite element model presented in this work is based on the geometry shown in Fig.6.3. The 2D finite element model geometry consists of an air box ($1.2 \times 0.02 \text{ m}^2$) that contains the piezoelectric plate ($0.008 \times 0.002 \text{ m}^2$) wirelessly driven by dipole antenna-like structure formed by brass plate-shaped live and ground electrodes of the same area ($0.5 \times 0.001 \text{ m}^2$). The piezoelectric plate is placed at the center 0.004 m away from the electrode plane of dipole antenna-like structure. After defining the model geometry, the next task is to define the

material properties of the calculation domains and the boundaries. The boundaries of the live electrode are defined with an electric potential of 150 Vrms and the other electrode boundary is defined as ground. The finite element calculations are solved using non-uniform mesh sizes. The results presented in this work are found to be independent of the mesh refinement when the mesh consists of at least 66336 elements. After solving the problem, COMSOL Multiphysics shifts to its post processing mode and shows the plot of the streamline electric field. Fig.6.4 shows the calculated 2D electric field pattern around the wirelessly driven piezoelectric plate by an electric dipole antenna-like structure.

Fig.6.3: Geometry used for 2D finite element model of electric field analysis of the piezoelectric plate wirelessly driven by the dipole antenna-like structure.

Fig.6.4: Simulated 2D electric field pattern around the piezoelectric plate wirelessly driven by dipole antenna-like structure.

Fig.6.5: Distribution of the electric field on the surface of wirelessly driven piezoelectric plate along the x -direction, $x = -0.004$ m to $x = 0.004$ m.

The electric field distribution on the surface of the piezoelectric plate along the x -direction is shown in Fig.6.5. It is seen that the electric field on the surface of the wirelessly driven piezoelectric plate is non-uniform. For a 2500 cm^2 electrode area of the dipole antenna-like structure and input source voltage of 150 Vrms , the average value of the electric field on the surface of the piezoelectric plate is $5.72 \times 10^3 \text{ V/m}$, which is used in our calculation.

6.1.3. Equivalent circuit model

To understand the operating mechanism and investigate the characteristics, an equivalent circuit model is developed for the piezoelectric plate operating in the thickness vibration mode, wirelessly driven by an A.C. electric field generated from the electric dipole antenna-like structure.

From the basic piezoelectric constitutive equations (Ikeda, 1984), the electric displacement of the piezoelectric plate operating in the thickness vibration mode is

$$D = \frac{V}{\beta_{33}^S t} + \frac{h_{33}}{\beta_{33}^S t} (2u_0). \quad (6.1)$$

where h_{33} and β_{33}^S are the piezoelectric coefficient and impermittivity constant, respectively, t is the thickness and u_0 is the displacement at the electrode surface of the piezoelectric plate. A voltage V appears across the piezoelectric plate because of the external electric field. FEM analysis results show that the electric field on the surface of the piezoelectric plate is non-uniform, as depicted in Fig.6.5. Hence, the current flowing through the piezoelectric plate

can be obtained as:

$$i = j\omega \int_{-w/2}^{w/2} l\sigma(x)dx \quad (6.2)$$

where $\sigma(x)$ is surface charge density, l is length and w is the width of the driven piezoelectric plate.

According to Gauss's law, the charge on the surface electrode of the piezoelectric plate is

$$\sigma(x) = D - \varepsilon_0 E(x) \quad (6.3)$$

where ε_0 is the permittivity of free space and $E(x)$ is the external non-uniform electric field on the surface of driven piezoelectric plate. From Eqs. (6.1) to (6.3), the current flowing to the piezoelectric plate with an electrode area A can be obtained as:

$$i = j\omega(VC_d + 2nu_0 - \varepsilon_0 \tilde{E}A) \quad (6.4)$$

$$\text{where } \tilde{E} = \frac{1}{w} \int_{-w/2}^{w/2} E(x)dx; \quad (6.4a)$$

$$\text{clamped capacitance } C_d = \frac{A}{\beta_{33}^s t}; \quad (6.4b)$$

$$\text{turn ratio } n = \frac{Ah_{33}}{\beta_{33}^s t}. \quad (6.4c)$$

The derived equivalent circuit of the piezoelectric plate operating in the thickness vibration mode wirelessly driven by an A.C. electric field generated from dipole antenna-like structure is shown in Fig.6.6. The inductance, capacitance and resistance of the loop on the right hand side of the equivalent circuit are given by:

$$L'_m = \frac{Ah_{33}^2}{\beta_{33}^S t \omega^2}, \quad (6.5)$$

$$C'_m = \frac{\beta_{33}^S t}{Ah_{33}^2}, \quad (6.6)$$

$$R'_m = \frac{\omega L'_m}{Q_m} \quad (6.7)$$

where Q_m is the mechanical quality factor of the piezoelectric plate.

Fig.6.6: Equivalent circuit of the piezoelectric plate wirelessly driven by an A.C. electric field generated from dipole antenna-like structure.

When the piezoelectric plate operates near its resonance, the real power delivered to the electrical load resistor can be obtained from the equivalent circuit

$$P_L = \frac{(\omega \varepsilon_0 \tilde{E} A)^2 R_L \left[R_m'^2 + \left(\omega L_m' - \frac{1}{\omega C_m'} \right)^2 \right]}{\left(R_m' + n^2 R_L - \omega^2 C_d R_L L_m' + \frac{C_d R_L}{C_m'} \right)^2 + \left(\omega L_m' - \frac{1}{\omega C_m'} + \omega C_d R_L R_m' \right)^2}. \quad (6.8)$$

Eq. (6.8) shows that the output power of the piezoelectric plate is a function of the electric field, operating frequency, electric load, size, and material properties of the piezoelectric plate. The material properties of the piezoelectric plate used in our calculation and experiments are listed in Table 6.1. The circuit

parameters of the piezoelectric plate are calculated by Eqs. (6.4b), (6.5), (6.6), (6.7), and the material constants listed in Table 6.1.

Properties		Value
Electromechanical coupling factor	k_{33}	0.71
	k_t	0.47
Frequency constants (mm*kHz)	N_{33}	1470
	N_t	1620
Relative dielectric constants	$\epsilon_{33}^T / \epsilon_0$	1450
Piezoelectric coefficients (10^{-12} C/N)	d_{33}	325
Density (10^3 kg/m ³)	ρ	7.7
Dimensions (mm ³)	$t \times w \times l$	2×8×30

Table 6.1 Relevant material properties of the used PZT plate.

The calculated and measured equivalent circuit parameters are shown in Table 6.2. L_m , C_m and R_m are the equivalent inductance, capacitance and resistance of the piezoelectric plate looking from port BB' as shown in Fig.6.6. The equivalent circuit parameters of the piezoelectric plate were measured by an impedance analyzer (HP4194A) from port AA' .

Parameters	Measured	Calculated
L_m (mH)	2.39	2.82
C_m (pF)	13.64	14.90
R_m (Ω)	42	47
C_d (nF)	1.47	1.42

Table 6.2: Equivalent circuit parameters of the used PZT plate

6.1.4. Results and discussion

6.1.4.1. Electrical load characteristics of the driven piezoelectric plate

Fig.6.7 shows the theoretical and experimental dependence of the output power on the electrical load at the resonance frequency of the piezoelectric plate. It can be seen that, after a short and rapid increase to the peak power, the output power rapidly decreases with the load resistance. It is seen that the theoretical result agrees well with the experimental one, and the output power at resonance reaches the maximum at an optimum load resistance of 350 Ω . Additionally, the resonance frequency decreases slightly as the load resistance increases, but remains around 772 kHz.

Fig.6.7: Theoretical and experimental dependence of the output power on the load resistance at the resonance frequency of the piezoelectric plate.

The optimum load resistance can be explained by the equivalent circuit of piezoelectric plate operating in the thickness mode, as shown in Fig.6.6. A maximum power can be delivered to the electric load resistor, when

$$\frac{dP_L}{dR_L} = 0. \quad (6.9)$$

Using eqs. (6-8) and (6-9), we get the following solution of the optimum load resistance for which a maximum power is delivered to the load resistor connected across the output electrodes of the wirelessly driven piezoelectric plate operating in the thickness vibration mode.

$$R_L = \sqrt{\frac{R_m'^2 + \omega^2 L_m'^2 + \frac{1}{\omega^2 C_m'^2} - \frac{2L_m'}{C_m'}}{n^4 + \omega^2 C_d^2 R_m'^2 + \omega^4 C_d^2 L_m'^2 - 2n^2 \omega^2 C_d L_m' + \frac{C_d^2}{C_m'^2} + \frac{2n^2 C_d}{C_m'} - \frac{2\omega^2 C_d^2 L_m'}{C_m'}}} \quad (6.10)$$

Using the above solution and the equivalent circuit parameters in Table 6.2, we found an optimum load resistance of 358 Ω for the wirelessly driven piezoelectric plate operating in the thickness mode, which agrees well with the measured value of 350 Ω .

6.1.4.2. Frequency characteristics of the output power of PZT plate

The theoretical and experimental frequency characteristics of the output power of the driven piezoelectric plate operating in the thickness mode are depicted in Fig.6.8.

Fig.6.8: Theoretical and experimental frequency characteristics of the output power of the wirelessly driven piezoelectric plate.

It can be seen that the theoretical results agree quite well with the experimental results, and the output power of the piezoelectric plate reaches the maximum at its resonance frequency. When the frequency of the transmitted electric field generated by the dipole antenna-like structure is equal to the mechanical resonance frequency of the piezoelectric plate, a maximum mechanical vibration can be stimulated in the piezoelectric plate by the converse piezoelectric effect. This maximum mechanical vibration generates a maximum voltage across the piezoelectric plate by the piezoelectric effect. Hence the output power peaks only due to the piezoelectric resonance. The error in the calculated maximum output power and the frequency at which the maximum output power occurs may be due to the errors of the material constants used in the theoretical calculation.

6.1.4.3. Effect of electrode area of dipole antenna-like structure

The effect of the electrode area of the dipole antenna-like electric field generator on the output power at the optimum load and resonance frequency of the driven piezoelectric plate has been investigated, and is shown in Fig.6.9. It can be seen that the theoretical result agrees well with the experimental one. It was observed that the output power at resonance frequency and optimum load resistance of the piezoelectric plate increases with the increase of electrode area of the dipole antenna-like structure for a given input source voltage. Finite element method simulations showed that the electric field at the piezoelectric plate, and hence, the output power at the resonance frequency, increase with the electrode area of the dipole antenna-like structure for a given input voltage, as depicted in Fig.6.9.

Fig.6.9: Effect of the electrode area of the dipole antenna-like structure on the output power at resonance frequency and optimum load resistance of the piezoelectric plate.

6.1.4.4. Dependence of the output power on the distance of piezoelectric plate from electrode plane of the dipole antenna-like structure

The theoretical and experimental dependence of the output power at resonance on the distance of the piezoelectric plate from the electrode plane of the dipole antenna-like structure is shown in Fig.6.10. It is found that the output power at resonance decreases with the increase of the distance of the piezoelectric plate from the electrode plane of the dipole antenna-like structure for a given input A.C. voltage of $150 V_{rms}$ across the electrodes. When the distance between the piezoelectric plate and the electrode plane of the dipole antenna like structure is larger than 60 cm, the output power of piezoelectric plate is less than 0.006% of

that when the distance is 4 mm. This is because the electric field at the piezoelectric plate decreases as the plate is moved away from the electrode plane of the dipole antenna-like structure. Both the nonlinear and linear curve fitting approach has been carried out to investigate the characteristics of the measured output power at resonance and distance of the piezoelectric plate from the electrode plane of dipole antenna-like structure, as depicted in Fig. 6.11(a). The output power is considered as quadratic polynomial that describes the nonlinear output power-distance characteristics of the piezoelectric plate.

Fig.6.10: Theoretical and experimental dependence of the output power at resonance on the distance of piezoelectric plate from the electrode plane of the dipole antenna-like structure.

(a)

(b)

Fig.6-11: (a) Curve fitting with the experimental dependence of the output power on the distance of piezoelectric plate from the electrode plane of the dipole antenna-like structure; (b) Residuals of linear and non-linear curve fit.

It is seen from Fig.6-11(b) that the residual of the nonlinear curve fitting is 0.55% and linear curve fitting is 2.07%. It is found that the quadratic curve fit more accurately with experimental results and the output power- distance characteristic is nonlinear. But for smaller distance of the piezoelectric plate from the antenna plane, the output power-distance characteristic is almost linear. Also, the residual of the linear curve fitting is only 2%, which is normally acceptable. Thus it can be assumed that the experimental results agree with the theoretical ones. The small discrepancy between the non-linear dependence of the measured data and the linear dependence of theoretical results may be due to the measurement error and power loss across the load resistor connected to the output electrodes of the piezoelectric plate.

6.1.5. Enhancement in the driving power of piezoelectric plate

In order to increase the driving power, the electric dipole antenna-like structure in series with an inductor is used as shown in Fig.6.12. When the electric dipole antenna-like structure and inductor are in electric resonance, the voltage across the dipole antenna-like structure is nearly five times greater than the A.C. source voltage. For an input source voltage of 150 Vrms, the voltage across the live and ground electrodes of dipole antenna-like structure is around 720 Vrms. Thus, at series resonance of the electric dipole antenna-like structure with an inductor, a relatively large electric energy can be transmitted to the piezoelectric plate. When large electric field is transmitted, the voltage across the piezoelectric plate becomes large. If the frequency of the electric field is close to mechanical resonance frequency of the piezoelectric plate, a mechanical resonance can be excited due to the converse piezoelectric effect. This

mechanical resonance can generate a large voltage across the output electrodes due to direct piezoelectric effect. With the increase of the voltage, the current across the piezoelectric plate at resonance increases. Hence larger output power resulted with an increased voltage applied across the piezoelectric plate only due to piezoelectric resonance. Fig.6.13 shows the frequency characteristics of the output power of the piezoelectric plate when the electric dipole antenna-like structure is electrically resonant with an inductor of 1.21 mH, and without inductor. It is observed that at resonance frequency 772 kHz, optimum load resistance 350 Ω of the piezoelectric plate, and an input A.C. source power of 15.58 W, a maximum output power of 1.92 mW has been achieved for the electric resonance of dipole antenna-like structure and inductor in series. Also, the output power for the dipole antenna-like structure which is in electric resonance with an inductor is larger than that of without inductor.

Fig.6.12: Experimental setup to increase the driving power of the wirelessly driven piezoelectric plate by cascading an inductor in series with the dipole antenna-like structure.

Fig.6.13: Frequency characteristics of the output power of PZT plate when the dipole antenna-like structure is in electric resonance with an inductor.

Furthermore, experimentally it has been found that the energy conversion efficiency (the ratio of real power delivered to electrical load resistor connected to the PZT plate and real power applied to the series of dipole antenna-like structure and inductor) depends on the operating frequency, electric load, electrode area, and distance of the piezoelectric plate from the electrode plane of dipole antenna-like structure. A maximum energy conversion efficiency of 0.012% has been achieved wirelessly by the piezoelectric plate operating at resonance in the thickness vibration mode, placed 4 mm away from the electrode plane of the dipole antenna-like structure with an optimum electrical load resistance of 350 Ω , 1 cm antenna electrodes separation, 2500 cm² electrode area of electric dipole antenna-like structure, and an input A.C. source power of 15.58 W applied to the dipole antenna-like structure connected in series with an inductor ($L=1.21$ mH).

6.1.6. Summary

Wireless drive of piezoelectric components by a dipole antenna-like structure is proposed here, and its characteristics are investigated both theoretically and experimentally. The real output power of the piezoelectric plate depends on the operating frequency, electrical load, electrode area of the antenna, and position of the piezoelectric plate. The electric field pattern is studied by finite element method to assess the electric field on the surface of the piezoelectric plate. A theoretical model is also developed to investigate the characteristics of wirelessly driven piezoelectric plate operating in the thickness mode. The theoretical results agree well with the experimental results. At resonance frequency and optimum electrical load, the output power achieved wirelessly by the piezoelectric component increases with the electrode area of dipole antenna, and decreases with the distance of piezoelectric component from the antenna plane. In order to enhance the driving power, the electric dipole antenna-like structure was used in series with an inductor. When the electric dipole antenna-like structure and the inductor are in electric resonance, a maximum output power of 1.92 mW and energy conversion efficiency of 0.012% have been achieved wirelessly by the piezoelectric plate operating in the thickness vibration mode, placed at the centre 4 mm away from antenna plane with an optimum electrical load resistance of 350 Ω , at a resonance frequency of 772 kHz, 1 cm electrodes separation, 2500 cm² electrode area of electric dipole antenna-like structure, and input A.C. source power of 15.58 W applied to the series of dipole antenna-like structure and inductor. This technique provides a method of driving wirelessly micro piezoelectric devices in rotary machine such as piezoelectric microactuators and micromotors.

6.2. Wireless Energy Transmission to Piezoelectric Components by Flat Spiral Coil Antenna-like Structure in Electric Resonance with a Capacitor

An improved compact electric field generator is proposed to transmit relatively large electric energy wirelessly to piezoelectric components by using the electric resonance of a flat spiral coil antenna-like structure and a capacitor in series. In the flat spiral coil antenna-like electric field generator, the A.C. electric field is transmitted wirelessly to the piezoelectric plate placed in a plane perpendicular to the plane of antenna. When the spiral coil antenna-like electric field generator and capacitor are in electric resonance, the wireless electric energy transmission to the piezoelectric component can be enhanced. This technique enables a relatively large output power achieved wirelessly by the piezoelectric component.

6.2.1. Structure and principle

To transmit a relatively large electric energy to a piezoelectric plate wirelessly, a flat spiral coil antenna-like electric field generator in series with a capacitor is used as shown in Fig.6.14 (a). An A.C. input source with tunable frequency is connected to the series of flat spiral coil antenna-like electric field generator and capacitor. In the flat spiral coil antenna-like electric field generator, the coil windings are wound to form a circle of radius 5 cm. The piezoelectric plate is placed perpendicular to the plane of spiral coil antenna-like electric field generator, at a distance away from the centre of the spiral coil. When the spiral coil antenna-like electric field generator and capacitor are in electric resonance,

the wireless electric energy transmission to the piezoelectric component is enhanced because of the large current across the antenna.

Fig.6.14: (a) Experimental setup to drive piezoelectric plate wirelessly by using a flat spiral coil antenna-like electric field generator in electric resonance with a capacitor. (b) Configuration of the wirelessly driven PZT plate.

Fig.6.14 (b) illustrates the configuration of the wirelessly driven piezoelectric plate operating in the thickness vibration mode. The piezoelectric plate is made of PZT ceramic material (supplied by Fuji Ceramic Corporation, Japan). It is poled vertically across the thickness direction. The Piezoelectric charge constant d_{33} , mechanical Q , dissipation factor $\tan\delta$, and relative dielectric constant $\epsilon_{33}^T/\epsilon_0$ are 325×10^{-12} m/V, 2000, 0.3 and 1450, respectively. The vibration direction and applied electric field both are parallel to the poling direction. A load resistor R_L is connected across the two electrodes for measuring the real power which the piezoelectric plate delivers.

When the flat spiral coil antenna-like electric field generator and capacitor are in electric resonance, the current flowing through the electric field generator is very large. Thus at resonance, a relatively large A.C. electric field can be transmitted to the piezoelectric plate placed in a plane perpendicular to the plane of antenna. When an A.C. electric field penetrates the piezoelectric plate, a mechanical vibration can be stimulated in the piezoelectric plate by the converse piezoelectric effect. When the frequency of the A.C. electric field is close to the mechanical resonance frequency of the piezoelectric plate, a mechanical resonance can be excited in the plate. This mechanical resonance can generate a relatively large voltage across the output electrodes due to the piezoelectric effect.

The experiments were performed under the following conditions. The dimension of piezoelectric plate used in the experiment is $3 \times 0.8 \times 0.2$ cm³, and it operated in the thickness vibration mode. In the flat spiral coil antenna-

like electric field generator, the coil windings are wound to form a circle of radius 5 cm, and the measured inductance of the spiral coil is 0.0413 mH. Thus, the spiral coil antenna-like electric field generator is in electric resonance with a capacitor of 1.029 nF for the wirelessly driven piezoelectric plate operating in the thickness vibration mode. Unless otherwise specified, the piezoelectric plate is placed at the centre 4 mm away from the plane of spiral coil antenna-like electric field generator and input ac source voltage is 10 Vrms.

6.2.2. Experimental results and discussion

Fig.6.15 shows the frequency characteristics of the output power of piezoelectric plate operating in the thickness vibration mode, placed in a plane perpendicular to the spiral coil antenna-like electric field generator. It represents the result when the electric field generator is electrically resonant with, and without the capacitor. It is observed that at the resonance frequency of 772 kHz, the output power of the piezoelectric plate attains the maximum. If the piezoelectric plate is detuned from the resonance, the output power of the plate drops suddenly. When the frequency of the A.C. electric field is close to mechanical resonance frequency of the plate, a relatively large vibration can be excited in the plate by the converse piezoelectric effect. This mechanical resonance generates a relatively large voltage at the output electrodes by the piezoelectric effect. It is also seen that when the electric field generator and capacitor are in electrical resonance, the output power of the piezoelectric plate is significantly higher than that of the electric field generator without a capacitor in series. When the electric field generator is in series electric resonance with a capacitor, the current across the spiral coil antenna-like

structure is eight times greater than that without a capacitor in series. Thus at resonance, a relatively large amount of A.C. electric field can be transmitted to the piezoelectric plate placed away from the centre of spiral coil electric field generator. Therefore, for a given input A.C. voltage, the output power is larger for an electric field generator which is in electric resonance with a capacitor.

Fig.6.15: Frequency characteristics of the output power of the piezoelectric plate at the optimum load resistance for spiral coil antenna-like electric field generator in electric resonance with, and without capacitor.

The dependence of the output power at resonance on the electrical load for the wirelessly driven piezoelectric plate, operating in the thickness vibration mode is shown in Fig.6.16. It can be seen that the output power at resonance reaches the maximum at an optimum load resistance. The output power at resonance frequency of 772 kHz reaches the maximum at an optimum load resistance of 350 Ω , and the maximum output power is 0.362 mW. The optimum load

resistance can be explained by the equivalent circuit of piezoelectric plate operating in the thickness mode, as shown in Fig.6.6. It was found that the calculated optimum load resistance is 358Ω for the wirelessly driven piezoelectric plate operating in the thickness mode, which agrees well with the measured value of 350Ω .

Fig.6.16: Dependence of the output power on the electrical load at the resonance frequency of the piezoelectric plate for a spiral coil antenna-like electric field generator in resonance with, and without capacitor.

The experimental dependence of the output power at resonance on the distance of the piezoelectric plate from the plane along the central axis of spiral coil antenna-like structure is shown in Fig.6.17. The output power is measured for the piezoelectric plate operating in the thickness vibration mode, when the spiral coil antenna-like electric field generator and capacitor are in series electric resonance. It is found that the output power at resonance frequency and optimum load resistance of the piezoelectric plate decreases with the distance of

the piezoelectric plate from the plane along the central axis of spiral coil antenna-like electric field generator for a given input A.C. power. When the distance between the piezoelectric plate and spiral coil antenna is larger than 20 cm, the output power of the piezoelectric plate is less than 0.09% of that when the distance is 4 mm. This is because the electric field at the piezoelectric plate decreases as the plate is moved away from the plane of antenna.

Fig.6.17: Dependence of the output power at the resonance frequency on the distance of the piezoelectric plate from the plane of spiral coil antenna-like electric field generator along the central axis.

Furthermore, it has been experimentally found that the energy conversion efficiency (the ratio of real power delivered to electrical load resistor, and the real power applied to the series of spiral coil antenna-like electric field generator and capacitor) depends on the operating frequency, electric load, and

distance of the piezoelectric plate from the plane of spiral coil antenna-like electric field generator. A maximum energy conversion efficiency of 0.027% has been achieved by the piezoelectric plate operating in the thickness vibration mode at the resonance frequency of 772 kHz, optimum electrical load resistance of 350 Ω , 4 mm distance of piezoelectric from the antenna plane along the central axis of spiral coil, an input ac source power of 1.294 W, and an inductance of 0.0413 mH of the flat spiral coil antenna-like generator.

6.2.3. Summary

An improved compact electric field generator is explored to transmit wirelessly relatively large electric energy to a piezoelectric component by using the electric resonance of a flat spiral coil antenna-like structure in series with a capacitor. In the flat spiral coil antenna-like electric field generator, the A.C. electric field is transmitted wirelessly to the piezoelectric plate placed in a plane perpendicular to the plane of antenna along the central axis of spiral coil. When the spiral coil antenna-like electric field generator and capacitor are in electric resonance, the wireless electric energy transmission to the piezoelectric component is enhanced. This technique enables a relatively large output power achieved wirelessly by the piezoelectric component. At resonance frequency of 772 kHz and optimum electrical load resistance of 350 Ω , a maximum output power of 0.362 mW and an energy conversion efficiency of 0.027% have been achieved wirelessly by the piezoelectric plate operating in the thickness vibration mode, placed 4 mm away from antenna plane, with an input A.C. source power of 1.294 W applied to the series of flat spiral coil antenna-like structure and capacitor, and an inductance of 0.0413 mH of the flat spiral coil

antenna-like electric field generator. At the resonance frequency and optimum electrical load, the output power achieved wirelessly by the piezoelectric component decrease with the distance of the piezoelectric component from the plane of spiral coil antenna-like electric field generator. This technique provides a compact and flexible method of driving wirelessly micro piezoelectric devices in rotary machine and in human body.

6.3. Comparative Study of All Proposed Wireless Techniques

Fig.6.18: Proposed E-field generators to drive piezoelectric component wirelessly.

A comparative study of all the proposed and investigated wireless energy transmission techniques has been conducted. The investigated techniques include wireless drive of piezoelectric components by parallel plate capacitor structure, focused electric field generator, focused electric field structure in electric resonance with an inductor, dipole antenna-like structure in resonance with inductor, and a flat spiral coil antenna-like electric field generator in resonance with a capacitor, as shown in Fig.6.18.

For comparison, the experiments of all the proposed wireless drive techniques are performed under the following conditions. The piezoelectric component is made of the Fuji C-203 PZT ceramic material, and is poled vertically across its thickness. The thickness vibration direction and applied electric field are both parallel to the poling direction. The dimension of the PZT plate is $8 \times 5 \times 2$ mm³; the piezoelectric plate operates in the thickness vibration mode; the resonant frequency is 782 kHz; the optimum load resistance is 1365 Ω ; the distance of the piezoelectric plate from both the live and ground electrode is 4 mm; the input A.C. source voltage is 150 Vrms. The proposed wireless drive techniques are compared and summarized in Table 6.3.

The energy conversion efficiency of the piezoelectric plate wirelessly driven by parallel plate capacitor structure, focused electric field generator, focused electric field structure in electric resonance with an inductor, dipole antenna-like structure in electric resonance with an inductor, and flat spiral coil antenna-like electric field generator in electric resonance with a capacitor is shown in Fig.6.19. It has been found that the energy conversion efficiency of the

piezoelectric component wirelessly driven by focused electric field structure in electric resonance with an inductor is significantly higher than that of any other methods.

Fig.6.19: The energy conversion efficiency of the various wireless drive methods.

Wireless drive techniques	Input A.C. source power (W)	Output power of PZT plate (mW)	Efficiency (%)	Remarks (Advantages/unique features)
Parallel plate capacitor structure	1.44	2.28	0.15	Feasible to drive low power piezoelectric actuators.
Focused electric field structure	2.12	10.84	0.51	Effective to drive relatively large power micro and nano piezoelectric devices.
Focused electric field structure in resonance with an inductor	20.12	206.04	1.02	Higher output power and efficiency than the other proposed wireless drive techniques.
Dipole antenna-like structure in resonance with an inductor	6.18	2.84	0.046	Enable free motion of PZT component and effective to drive micro actuators in rotary machine.
Spiral coil antenna in resonant with a capacitor	1.45	1.46	0.10	This solution is more compact, light weight, and robust for free motion of the PZT components.

Table 6.3: Comparison of all the proposed wireless drive techniques.

CHAPTER 7 MERGING OF MICRO-DROPLETS BY A WIRELESSLY DRIVEN PIEZOELECTRIC STAGE

Microdroplet merging has potential applications in microreactors [85-89], nanoparticle synthesis [90-91], cell encapsulation [92-93], and protein crystallization [94]. Conventionally, two microdroplets are merged by the difference in speed of microdroplets moving along the channels in a microfluidic device. They utilize droplet size and viscosity difference [95], pillar structure [96], fusion chamber [97], and surface properties [98] to induce the difference in speed of microdroplets. Microdroplets are also merged in an electric field by utilizing charges of opposite sign on two different microdroplets, thus overcoming the stabilized forces caused by surface tension and lubrication [99-102].

So far, there has been no report on microdroplets merging by ultrasonic actuation. To simplify the device structure for microdroplets merging and widen the application range of this technology, a method to merge microdroplets by using a piezoelectric stage which is wirelessly driven by an A.C. electric field is proposed and investigated by the author. The microdroplets to merge are dispensed onto the surface of a piezoelectric stage. The piezoelectric stage is wirelessly driven by a focused electric field. The ultrasonic vibration of the piezoelectric stage is transmitted into the microdroplets and induces the

merging of microdroplets. The vibration displacement of the stage is determined by the strength of the applied electric field and its operating frequency. The electric field pattern was theoretically calculated by finite element method (COMSOL Multiphysics) to assess the electric field on the surface of the wirelessly driven piezoelectric stage. Experimentally, it has been observed that the time for merging of water microdroplets depends on the vibration displacement of piezoelectric stage, separation distance, and volume of microdroplets. The time for merging two water microdroplets is proportional to the separation distance between two microdroplets, and the increase in volume of microdroplets. It was also noticed that the merging speed of larger volume of microdroplets is significantly higher than that of smaller volume microdroplets. At the resonance frequency of 776 kHz, two water microdroplets each of volume 0.8 μl separated by a distance of 0.6 mm were merged together 16 seconds after the mechanical vibration displacement of 0.112 μm was excited in the piezoelectric stage with an area of 40 mm^2 . In contrast with the conventional method of merging, the proposed device has the following unique features.

- The proposed device does not need to use microchannels for the motion of the droplets.
- Furthermore, the microdroplets can be dispensed onto the actuating surface simultaneously or at different moments.
- Two droplets with the same size and viscosity can be merged successfully
- The wireless drive provides the potential for miniaturization of the piezoelectric stage.

7.1. Experimental Setup and Operating Mechanism

Fig.7.1 (a) shows the experimental setup for the merging of microdroplets by a piezoelectric stage wirelessly driven by focused electric field. With a square size brass stage-shaped live electrode, a stainless steel needle ground electrode is used to focus the A.C. electric field to enhance the electric energy transmission to the piezoelectric stage. The needle ground electrode is placed below, and perpendicular to the live electrode which is suspended above the piezoelectric stage. The piezoelectric stage is placed equidistantly in between the live and needle ground electrodes of the focused electric field structure. The optimum live electrode area is $30 \times 30 \text{ cm}^2$. Fig.7.1 (b) shows the configuration of the wirelessly driven piezoelectric stage operating in the thickness mode.

The piezoelectric stage is made of PZT ceramic material (Fuji C-203) and is poled vertically across the thickness direction. The Piezoelectric charge constant d_{33} , mechanical Q , dissipation factor $\tan\delta$, and relative dielectric constant $\epsilon_{33}^T/\epsilon_0$ are $325 \times 10^{-12} \text{ m/V}$, 2000, 0.3 and 1450, respectively. The plate has silver electrodes on its top and bottom surfaces. The dimension of the piezoelectric plate used in the experiments is $8 \times 5 \times 2 \text{ mm}^3$. The vibration direction and applied electric field both are parallel to the poling direction. Droplets of volume varying from $0.5 \text{ }\mu\text{l}$ to $2 \text{ }\mu\text{l}$ are dispensed on to the top surface of the wirelessly driven piezoelectric plate by using a micropipette (Brand CAPP, C1 9291).

When an A.C. electric field produced from the focused electric field generator penetrates the piezoelectric plate, a mechanical vibration can be stimulated in

the plate by the converse piezoelectric effect. When the frequency of the A.C. electric field is close to the mechanical resonance frequency of the piezoelectric plate, a strong enough mechanical resonance vibration can be excited in the plate. This mechanical vibration of the piezoelectric plate transmitted to the microdroplets placed on its surface, reduces the intermolecular forces of attraction or Van der Waal's force between the microdroplets. The microdroplets can move closer to each other due to the vibration of the piezoelectric plate and ultimately merge after some time.

Fig.7.1: (a) Experimental setup for the merging of droplets by a piezoelectric stage wirelessly driven by focused electric field; (b) Configuration of wirelessly driven piezoelectric stage operating in the thickness vibration mode.

7.2. Results and Discussion

The theoretical and experimental studies are performed under the following conditions. The piezoelectric plate operates in the thickness vibration mode; its dimensions were $8 \times 5 \times 2 \text{ mm}^3$; the live electrode area is 900 cm^2 ; the ground electrode is a metal needle whose tip is assumed to be have zero area; voltage across the live and ground electrodes of focused electric field structure is 6000 Vrms; live and needle ground electrodes separation distance of 4 cm.

7.2.1. Theoretical calculation of electric field by finite element method

The finite element method (COMSOL Multiphysics) simulation has been carried out in order to assess the electric field on the surface of the piezoelectric plate without droplets on its top surface.

Fig.7.2: Calculated 2-D electric field pattern around the piezoelectric plate wirelessly driven by focused electric field structure.

Fig.7.3: Distribution of the electric field on the surface of wirelessly driven piezoelectric plate along the x -direction, $x=0.145$ m to $x=0.153$ m.

Fig.7.2 shows the calculated 2-D electric field pattern around the piezoelectric plate wirelessly driven by a focused electric field. The electric field distribution on the surface of the piezoelectric plate along the x -direction is shown in Fig.7.3. It is found that the calculated average value of the electric field on the surface of the piezoelectric stage is 9.02×10^6 V/m.

7.2.2. Measurement of vibration displacement

The vibration displacement of the wirelessly driven piezoelectric stage was measured with a microscope (BX51, Olympus, Japan), as shown in Fig.7.4. In the measurement, a marked point on the edge of piezoelectric stage is chosen to

be the measured point, and its picture is taken by the microscope without vibration of the piezoelectric stage as shown in Fig. 7.5 (a). When the A.C. electric field penetrates the piezoelectric stage, a mechanical vibration is stimulated in the stage by the converse piezoelectric effect. Consequently, the width of the marked point increases. The image of the measured point is also viewed by the microscope when the piezoelectric stage is in vibration, as depicted in Fig. 7.5 (b). The exposure time of BX51 has an order of ms or larger; while the time period of the ultrasonic vibration is in microsecond order ($f_r = 782 \text{ kHz}$). Therefore, during the exposure time, there are several thousands of vibration periods. This gives us a quite clear image of the measured point. The image of the measured point in vibration is larger than that of without vibration. Taking difference in the width of measured point between the two images, the peak to peak vibration displacement can be experimentally measured. Based on this principle, a root mean square vibration displacement of the piezoelectric stage of $0.112 \text{ }\mu\text{m}$ was measured.

Fig.7.4: Experimental setup for measuring the vibration displacement of the piezoelectric stage wirelessly driven by a focused electric field.

(a)

(b)

Fig.7.5: The pictures of the measured point are taken by the microscope when the piezoelectric stage is (a) without vibration, and (b) in vibration.

7.2.3. The effect of ultrasonic vibrations on a single microdroplet

The effect of ultrasonic vibrations on a single microdroplet placed on the top surface of wirelessly driven piezoelectric plate operating in the thickness vibration mode is shown in Fig.7.6. Fig.7.6 (a) shows the water microdroplet without vibration, and Fig.7.6 (b) shows the water microdroplet flows down due to vibration of the piezoelectric plate.

(a)

(b)

Fig.7.6: (a) Water microdroplet on the top surface of the wirelessly driven piezoelectric plate without vibration; (b) Water microdroplet flows down due to the vibration of the piezoelectric plate.

The volume of the water droplet is 2 μl , and the calculated value of the electric field on the surface of piezoelectric plate is $9.02 \times 10^6 \text{ V/m}$. It is observed that at resonant frequency of 776 kHz, the water droplet flows down from top surface of the piezoelectric stage as the vibration of the stage attains the maximum. The water droplet starts to flow down after 24 seconds of excitation of PZT plate.

Fig.7.7: Illustration of a water microdroplet on plastic substrate placed inside a focused electric field generator. (a) Without electric field, and (b) with E-field.

If the wirelessly driven piezoelectric stage operating in the thickness vibration mode is detuned from resonance, there is no flow down of the water droplet. In order to illustrate the influence of electric field on the water droplet, the same experiment was carried out on the surface of a plastic stage, which has no vibration. Fig.7.7 illustrates the water microdroplet on a plastic substrate (a) without electric field, and (b) with electric field. It is observed that there is no change in shape of water droplet after 24 seconds, and also even after 15 minutes of experimentation. From this experiment, it is confirmed that the water droplets cannot merge without the ultrasonic vibration.

7.2.4. Frequency characteristics of the contact angle of microdroplets

The frequency characteristics of the contact angle of water microdroplet placed on the surface of the wirelessly driven piezoelectric stage operating in the thickness vibration mode is shown in Fig.7.8. It is seen that the contact angle θ

made by the tangent line to the water droplet at the edge and the surface horizontal line of the piezoelectric stage decreases sharply at resonance frequency of 776 kHz, from 76.45° to 38.12°. This is because at resonance the vibration of the piezoelectric stage is maximum. When the vibration of the piezoelectric stage goes higher, the intermolecular force of attraction between the water molecules is reduced, and the water droplet tends to flatten. Thus, the contact angle measured is minimum at the maximum vibration.

The contact angle of the microdroplets of water, sunflower oil, and olive oil at resonance has also been investigated, and the results are shown in Fig.7.9. At resonance, it is seen that the contact angle of water droplet reduces more than that of other liquids like sunflower oil and olive oil. This is because the viscosity of the oils (~ 80 mPa.S at room temperature) is much larger than that of the water droplet (0.894 mPa.S at room temperature), and the ultrasonic vibration in the water droplet is much larger than that in the oils.

Fig.7.8: The frequency characteristics of the contact angle of water droplet placed on the surface of piezoelectric stage operating in the thickness mode.

Fig.7.9: The contact angle of liquid microdroplets on the horizontal surface of the wirelessly driven piezoelectric stage without vibration and in vibration.

7.2.5. Merging of microdroplets

The above experimental results show the feasibility of microdroplets merging on the surface of a piezoelectric stage wirelessly driven by electric field. Figure 7-10 shows the merging of two water microdroplets placed with a fixed separation distance on the surface of a wirelessly driven piezoelectric stage operating in the thickness mode.

Experimentally it has been observed that the merging speed of the microdroplets depends on the vibration displacement at resonance of the piezoelectric plate, and the droplets initial separation distance and volume. The dependence of the measured time for merging of water microdroplets on the separation distance and volume of the water droplets is shown in Fig.7.11.

Fig.7.10: Merging of two water microdroplets placed with a fixed separation distance on the surface of a wirelessly driven piezoelectric plate operating in the thickness vibration mode. (a) without vibration; (b) after 10 seconds of sonication ; (c) after 16 seconds of sonication.

Fig.7.11: Dependence of the time for merging of water microdroplets on the distance and volume of water droplets.

It has been found that the time necessary to merge of two water microdroplets is proportional to the separation distance between two microdroplets, and the volume of each droplet. From Fig.7.11 it can be noticed that the former dependence is non-linear, may be due to the surface properties of the piezoelectric plate, dielectric loss, air, and increased inertia of the microdroplets. Also, a nonlinear curve fitting has been carried out to investigate the characteristics of the merging time and distance between the two water microdroplets each of volume 0.8 μl , as depicted in Fig.7.12. The merging time is considered as quadratic polynomial that describes the nonlinear merging time-distance characteristics of the water microdroplets. At the resonance

frequency of 776 kHz, two water droplets each of volume $0.8 \mu\text{l}$ separated by a distance of 0.2 mm merge in 8 seconds after the vibration of $0.112 \mu\text{m}$ (rms) is excited in a wirelessly driven piezoelectric plate. It is also seen that the merging speed of larger volume of microdroplets is significantly higher than that of smaller volume microdroplets. Once the microdroplets start to move, the microdroplet with larger volume flows faster because of its larger inertia. It was also observed that the measured temperature of the water droplets before the vibration of the piezoelectric plate was 25.6°C whereas during the merging it was 25.8°C . Thus, the temperature rise of the microdroplets is very small, and its effect on the merging may be ignored.

Fig.7-12: Curve fitting with the experimental dependence of the merging time on the distance of water microdroplets.

7.3. Summary

A method to merge microdroplets by using a wirelessly driven piezoelectric stage is proposed and investigated. Separate microdroplets (volume varying from 0.5 μl to 2 μl) are dispensed onto the top surface of a piezoelectric plate which is wirelessly driven by a focused electric field. The ultrasonic vibration of the piezoelectric stage is transmitted into the microdroplets and induces the merging of microdroplets. The vibration displacement of the stage is determined by the strength of the applied electric field and its operating frequency. The electric field pattern was theoretically calculated by finite element method to assess the electric field on the surface of the wirelessly driven piezoelectric plate. Experimentally, it has been observed that the time for merging of water microdroplets depends on the vibration displacement of piezoelectric stage, separation distance, and volume of microdroplets. The time for merging of two water microdroplets depends nonlinearly on the separation distance between two microdroplets, and is directly proportional with the initial volume of the microdroplets. The merging speed of larger volume of microdroplets is significantly higher than that of smaller volume microdroplets due to their increased inertia, which dictates the above mentioned nonlinear dependence. At the resonance frequency of 776 kHz, two water microdroplets each of volume 0.8 μl separated by a distance of 0.6 mm merged together 16 seconds after the mechanical vibration displacement of 0.112 μm was excited in the piezoelectric plate with an area of 40 mm^2 . The proposed device has simpler structure and is smaller than the conventional devices for microdroplet merging. It is also more flexible as it can be used easily for a wide range of sizes and physical properties (i.e different liquids) of microdroplets to merge.

CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS

8.1. Conclusions

This thesis has aimed at:

- Wirelessly driving a relatively large power in piezoelectric components by using a properly designed electric field.
- Developing a theoretical model for better understanding of the structure, operating mechanism and performance of a piezoelectric component wirelessly driven by an A.C. electric field.
- Analyzing the mechanical vibration characteristics of the wirelessly driven piezoelectric components.
- Exploring the possible applications of the wirelessly driven piezoelectric components.

The thesis has accomplished the followings:

- (1) Proposed and developed a fundamental theoretical equivalent circuit model for a piezoelectric component wirelessly driven by an A.C. electric field.
- (2) Explored various new techniques of wireless drive of piezoelectric components: by parallel plate capacitor structure, focused electric field, focused electric field structure in electric resonance with an inductor,

dipole antenna-like structure in resonance with an inductor and flat spiral coil antenna-like electric field generator in electric resonance with a capacitor.

- (3) Investigated the characteristics of piezoelectric components wirelessly driven by proposed electric field generators to outline the effects of parameters in optimizing wireless energy transmission to piezoelectric components.
- (4) Verified the theoretical results with the experimental ones.
- (5) Analyzed the electric field patterns by the finite element method (COMSOL Multiphysics) simulation in order to assess the electric field on the surface of the piezoelectric component.
- (6) Investigated the mechanical vibration characteristics of the piezoelectric component operating in the thickness mode wirelessly driven by electric field.
- (7) Proposed and experimentally investigated a method to merge microdroplets by using a wirelessly driven piezoelectric plate.

The details are as followings:

8.1.1. Equivalent circuit model

A theoretical model for a piezoelectric component operating in the thickness vibration mode, wirelessly driven by an A.C. electric field was proposed and expressed by an equivalent circuit. The equivalent circuit of the wirelessly driven piezoelectric component has a current source, resulting from the external electric field. This is different from the equivalent circuit of conventional

piezoelectric component driven by a voltage applied via lead wires. The concept of using a current source in the equivalent circuit may be applied to the wirelessly driven piezoelectric components operating in the other vibration modes. The calculated and measured equivalent circuit parameters of the wirelessly driven piezoelectric plate were also compared. The calculated equivalent circuit parameters agree well with the measured ones.

8.1.2. Parallel plate capacitor structure

Wireless electric energy transmission to piezoelectric components by parallel plate capacitor structure was proposed, and its characteristics were investigated experimentally. The output power of the piezoelectric plate depends on the frequency, electrical load, vibration mode and electrode pattern of the piezoelectric component, and the electric field generated by the parallel plate capacitor structure. The output power attains the maximum at the resonance frequency and an optimum load resistance of the piezoelectric plate. The piezoelectric plate with properly divided electrode has a larger output power than the one with whole electrode (i.e. undivided). The output power at resonance of the piezoelectric plate operating in the thickness vibration mode is significantly higher than that of the plate operating in the other modes like width and longitudinal vibrations. At the resonance frequency of 782 kHz, a maximum output power of 1.84 mW, and an energy conversion efficiency of 0.12% have been achieved wirelessly by the piezoelectric plate operating in the thickness mode, with an optimum load 1365 Ω , 1 cm gap thickness of electrodes, and input A.C. source power of 1.52 W across the live and ground electrodes of parallel plate capacitor structure.

8.1.3. Focused electric field

A new method of wireless drive of piezoelectric components by focused electric field was proposed and explored. A needle ground electrode was used to focus the ac electric field from a square size brass plate-shaped live electrode through a piezoelectric plate placed in between them. The needle ground electrode enables better transmission of electric energy. The effects of the electrode surface areas on the output power of the piezoelectric plate were investigated in order to optimize the wireless electric energy transmission to the piezoelectric plate. The output power achieved wirelessly by the piezoelectric plate operating in the thickness vibration mode depends on the operating frequency, electrical load resistance, distance between the piezoelectric plate and needle ground electrode, size of the piezoelectric component, electric field, and areas of the live and ground electrodes of the focused electric field structure. The electric field pattern was also theoretically studied by finite element method simulation (COMSOL Multiphysics) to elucidate the electric field focusing by using a needle ground electrode with a brass plate-shaped live electrode to the piezoelectric component placed equidistantly in-between them. When the frequency of the A.C. electric field is close to the mechanical resonance frequency of the piezoelectric plate operating in the thickness vibration mode the output power reaches the maximum. The output power and energy conversion efficiency of the wirelessly driven piezoelectric plate with smaller size are significantly higher than those of the driven piezoelectric plate with larger size. A maximum output power of 10.84 mW, and an energy conversion efficiency of 0.51% have been achieved wirelessly by a small piezoelectric plate with an area of 40 mm² operating in the thickness vibration mode at the

resonance frequency of 782 kHz, optimum electrical load resistance of 1365 Ω , input A.C. source power of 2.12 W across the live and needle ground electrodes, 1 cm electrodes separation, and a live electrode area of 900 cm² of the focused electric field structure.

An improved method of wireless drive of piezoelectric components was also experimentally investigated by using the electric resonance of a focused electric field generator and an inductor in series, in order to drive high power piezoelectric components wirelessly. With an optimum area of brass plate-shaped live electrode, a stainless steel needle ground electrode is used to form a focused electric field generator. When the focused electric field generator and inductor are in electric resonance, the wireless electric energy transmission is enhanced. The technique enables a relatively large output power delivered to the piezoelectric plate wirelessly. The output power attains the maximum at the resonance frequency of piezoelectric plate, and the plate with a small area has a larger output power than that with large area. When the focused electric field generator and inductor were in electric resonance, a maximum output power of 206.04 mW, and an energy conversion efficiency of 1.02% have been achieved by the wirelessly driven piezoelectric plate operating in the thickness vibration mode at the resonance frequency of 782 kHz, optimum electrical load resistance of 1365 Ω , real input A.C. source power of 20.12 W (applied to the series of focused electric field structure and inductor), 1 cm live and ground electrodes separation, and a live electrode area of 900 cm² of the focused electric field generator.

8.1.4. Antenna-like electric field generators

Wireless drives of piezoelectric components by focused electric field and the electric field generated from parallel plate capacitor structure were proposed and investigated by the author. It has been observed that the energy in an A.C. electric field can be transmitted to a piezoelectric component, placed in between the live and ground electrodes of the electric field generator structures. But the structures of the proposed electric field generators constraint the free motion of the wirelessly driven piezoelectric components. To explore the possibility of solving this difficulty and widen the application range of piezoelectric devices, wireless drives of piezoelectric components by antenna-like electric field generators have been proposed, and their characteristics are investigated.

Wireless drive of piezoelectric components by an electric dipole antenna-like structure was proposed, and its characteristics were investigated both theoretically and experimentally. The real output power of the piezoelectric plate depends on the operating frequency, electrical load, electrode area of the dipole antenna-like structure, and position of the piezoelectric plate. The electric field pattern was studied by finite element method (COMSOL Multiphysics) to assess the electric field strength on the surface of the piezoelectric plate wirelessly driven by dipole antenna-like structure. A theoretical model was also developed to investigate the characteristics of wirelessly driven piezoelectric plate operating in the thickness vibration mode. The theoretical results agree well with the experimental results. At the resonance frequency and optimum electrical load, the output power achieved wirelessly by the piezoelectric component decreases with the distance of the

piezoelectric component from the plane of electrode, and is proportional to the electrode area of dipole antenna-like electric field generator. In order to enhance the driving power, an electric dipole antenna-like structure in series with an inductor was used. When the electric dipole antenna-like structure and inductor are in electric resonance, a maximum output power of 1.92 mW and energy conversion efficiency of 0.012% have been achieved wirelessly by the piezoelectric plate operating in the thickness vibration mode, placed at the centre 4 mm away from antenna plane with an optimum electrical load resistance of $350\ \Omega$, resonance frequency of 772 kHz, 1 cm electrodes separation, 2500 cm^2 electrode area of the electric dipole antenna-like structure, and an input source power of 15.58 W applied to the dipole antenna-like structure cascaded in series with the inductor.

An improved compact electric field generator was also explored to transmit a relatively large electric energy wirelessly to piezoelectric components by using the electric resonance of a flat spiral coil antenna-like structure and capacitor in series. In the flat spiral coil antenna-like electric field generator, the A.C. electric field is transmitted wirelessly to the piezoelectric plate placed in a plane perpendicular to the plane of antenna along the central axis of spiral coil. When the spiral coil antenna-like electric field generator and capacitor are in electric resonance, the wireless electric energy transmission to the piezoelectric component is enhanced. This technique enables a relatively large output power achieved wirelessly by the piezoelectric component. At the resonance frequency of 772 kHz and optimum electrical load resistance of $350\ \Omega$, a maximum output power of 0.362 mW and energy conversion efficiency of 0.027% have been

achieved wirelessly by the piezoelectric plate operating in the thickness vibration mode, placed 4 mm away from antenna plane, with an input A.C. source power of 1.294 W applied to the flat spiral coil antenna-like structure in series with a capacitor, and an inductance of 0.0413 mH of the flat spiral coil antenna-like electric field generator. At resonance frequency and optimum electrical load, the output power achieved wirelessly by the piezoelectric component decreases with the distance of the piezoelectric component from the plane of spiral coil antenna-like electric field generator. This technique provides a compact and flexible method of driving wirelessly micro piezoelectric devices in rotary machine and in human body.

8.1.5. Comparative study

A comparative study of all the proposed and investigated wireless energy transmission techniques has been conducted. As a comparison, it has been found that the energy conversion efficiency of the piezoelectric component wirelessly driven by a focused electric field structure in electric resonance with an inductor is significantly higher than that wirelessly driven by the other structures such as parallel plate capacitor structure, focused electric field generator, dipole antenna-like structure in resonance with inductor, and flat spiral coil antenna-like electric field generator in resonance with a capacitor. When the focused electric field generator and inductor are in electric resonance, an energy conversion efficiency of 1.02% has been achieved wirelessly by a small piezoelectric plate with an area of 40 mm² operating in the thickness vibration mode at the resonance frequency of 782 kHz, optimum electrical load resistance of 1365 Ω , input A.C. source power of 20.12 W (applied to the

focused electric field generator cascaded in series with the inductor), 1 cm live and ground electrodes separation, and a live electrode area of 900 cm^2 of the focused electric field generator. The wireless drive of piezoelectric components by a focused electric field structure in electric resonance with an inductor enables a relatively large output power for the piezoelectric component than that obtained using the other structures for a given input A.C. source voltage. Compared to the other proposed techniques, the technique of wireless drive of piezoelectric components by the antenna-like structure is robust for the free motion of piezoelectric components, and may also be effective to drive micro piezoelectric components in rotary machines.

8.1.6. Mechanical vibration characteristics

The vibration displacement characteristics of a piezoelectric plate operating in the thickness vibration mode wirelessly driven by an A.C. electric field were investigated theoretically. The electric field pattern was also theoretically calculated by finite element simulations (COMSOL Multiphysics) to assess the electric field strength and distribution on the surface of the wirelessly driven piezoelectric plate, equidistantly placed at the middle in-between the live and needle ground electrodes of the focused electric field structure. It has been observed that a mechanical resonance vibration is excited in the piezoelectric plate when the electric field produced by the focused electric field structure penetrated the piezoelectric plate. It has been found that the vibration displacement depends on the electric field, operating frequency, electrical load, and dimensions of the driven piezoelectric plate, reaching its maximum value (in the nanometer range) at the resonance frequency. It was determined that at

resonance frequency of 773.8 kHz and electrical load resistance R_L is ∞ , a maximum vibration displacement of 8.40 nm has been achieved wirelessly by the piezoelectric plate operating in the thickness vibration mode with an input voltage of 150 Vrms across the live and needle ground electrodes, 1 cm electrodes separation, and a live electrode area of 900 cm² of the focused electric field structure. It has been seen that the vibration displacement at resonance increased with the electrical load resistance, and the area of the piezoelectric component, but decreased with the thickness of the piezoelectric plate operating in the thickness vibration mode, wirelessly driven by an A.C. electric field produced from the focused electric field structure.

8.1.7. Microdroplets merging

A method to merge microdroplets by using a wirelessly driven piezoelectric stage was proposed and investigated. Separate microdroplets (with volume varying from 0.5 μ l to 2 μ l) were initially dispensed onto the top surface of a piezoelectric plate that was wirelessly driven by a focused electric field. The ultrasonic vibration of the piezoelectric plate was transmitted to the microdroplets and induced their merging. The vibration displacement of the stage was determined by the strength of the electric field and its operating frequency. Simulations using finite element analysis software (COMSOL Multiphysics) were also carried out in order to assess the electric field strength and distribution on the surface of the wirelessly driven piezoelectric plate. Experimentally, it has been observed that the time for merging of water microdroplets depended on the vibration displacement of piezoelectric stage, separation distance, and volume of microdroplets. The time for merging of two

water microdroplets was proportional to the initial separation distance between two microdroplets, and the volume of the microdroplets. It was observed that the merging speed of microdroplets of larger volume was significantly higher than that of smaller volume microdroplets. At the resonance frequency of 776 kHz, two water microdroplets each of volume 0.8 μl separated by a distance of 0.6 mm merged together 16 seconds after switching on the mechanical vibration displacement of 0.112 μm excited in the piezoelectric plate with an area of 40 mm^2 . The proposed device has simpler structure and the potential to be smaller than conventional devices for microdroplet merging. It is also more flexible in usage in terms of size and liquid type of the microdroplets.

8.2. Recommendations for Further Research

The wireless drive of piezoelectric components by a focused electric field generator has the potential to drive high power micro and nano piezoelectric devices for various applications. The method of wireless drive of piezoelectric component by antenna-like structure enables the free motion of the piezoelectric components, and may also be effective to drive micro piezoelectric components in rotary machines.

The proposed wireless drive techniques are quite useful and essential for real-life applications where the direct wire connection is not possible and also not convenient to drive directly the piezoelectric devices used for miniature driving mechanisms, precision positioning, chemical engineering, biomedical applications and microfluidics etc. The wireless drive provides the potential for

miniaturization of the piezoelectric devices, simplify the device structure, flexible, highly reliable, and also be convenient for different applications such as fluid manipulation in a microsystem, driving of microactuators in rotary machines, driving of micropump in human body for drug delivery, controlled vibration and nano-positioning.

Some recommendations for future work are proposed as follows:

(1) Enhancement of the output power and efficiency

From both the experimental and theoretical investigations, the wireless electric energy transmission techniques resulted to be effective ways to drive piezoelectric components wirelessly. In this study, various wireless techniques were employed to drive the piezoelectric components wirelessly. However, the output power provided by the wirelessly driven piezoelectric plate is relatively small (in mW range), and the energy conversion efficiency is also very small. Therefore, further study is necessary to increase both the output power and energy conversion efficiency by wireless electric energy transmission to the piezoelectric components towards the strategy of various potential applications. To improve the efficiency and output power, further study is essential to reduce the large amount of power loss due to the dielectric loss and enhancement of the large amount of the electric field focusing.

(2) Larger distance

It has been seen that the output power of the piezoelectric components

decreased with the distance of the piezoelectric plate as the electric field decreased. It was observed that for a relatively large distance around 1 m between the live and ground electrodes of the electric field generator, the output power of the wirelessly driven piezoelectric component becomes very small. Therefore, future work should aim to develop a method to transmit large electric energy to the piezoelectric components placed at larger distances.

(3) Compact electric field generator

The wireless drive of piezoelectric components by an A.C. electric field produced by various electric field generators have been investigated in the work reported in this thesis. Based on the proposed electric field generators, the future research should develop a compact, flexible, highly reliable and efficient electric field generator to drive piezoelectric components wirelessly. The proposed wireless drive technique of flat spiral coil antenna-like structure is compact and flexible. However, the output power and efficiency is quite low. Further analyses and experimental study is necessary to redesign the structure for minimization of scattered electric field and power loss.

(4) Fluid manipulation in a microsystem

Further experiments and analyses on the novel method of wireless drive for microdroplets merging are essential to extend the application of wireless drive techniques. The method of wireless drive for microdroplets merging can be combined with the the traditional devices or structures, e.g. microfluidics realized in polymers or in glass, and/or with other elements in a microsystem

for fluid manipulation by using the piezoelectric thin film. It will have more advantage by using the piezoelectric channels for fluid manipulation in a microsystem. The future research should aim to fabricate and test some microfluidic chip which could combine classical channels.

(5) Modeling and experiments of different vibration modes of the PZT plate

In this work, the modeling and experiments of the thickness vibration mode of the piezoelectric plate have been discussed. The concept of using a current source in the equivalent circuit of the piezoelectric plate operating in the thickness vibration mode may also be applied to the wirelessly driven piezoelectric components operating in the other vibration modes such as width and longitudinal vibration modes. The piezo-effect on the 3-3 direction is only considered for the modeling and experiments reported in this work. Further modeling and experiments are also necessary to study the piezo-effect on the 3-1 direction of the wirelessly driven piezoelectric component.

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