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ELECTROPHORETIC DEPOSITION OF ADVANCED CERAMIC ACTUATOR

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Abstract

In recent years, remarkable developments have taken place in electromechanical system research. Among them, piezoelectric ceramics and their devices have drawn huge attention. Actuators utilizing piezoelectricity as driving elements have found a wide spectrum of applications. Piezoelectric bimorph, using two piezoelectric plates to produce bending displacement, is one of the most widely applied actuator designs. This type of actuator can provide large displacement, and can be applied in many areas such as valves, positioners and benders.

The recent advances in technology require the actuator to be applied in miniaturized and severe environments with high reliability. However, the currently available actuators have limitations in either low reliability or miniaturization. In the present work, the concept of functionally gradient material (FGM) monomorph actuator was proposed via a promising technique known as electrophoretic deposition (EPD). It is expected that this ceramic FGM monomorph actuator will find a wide range of applications due to its simple production process and superior properties.

The aim of this project is to establish the procedure to fabricate the miniaturized FGM monomorph actuator using EPD technique, and also characterize and model the electromechanical properties of the actuator. Several important aspects of the actuator will be introduced and studied. They are: (1) the synthesis and property characterization of the starting materials; (2) the fabrication and characterization of the monomorph; (3) the relationship between piezoelectric property distribution of the materials, structure of the monomorph and electromechanical output properties of actuator; (4) the stress distribution and its significance. Based on the above understanding, the optimized structure will also be proposed.

The project was carried out using the following procedure. Eleven PZT compositions were first prepared and characterized. Then three material systems were determined to fabricate monomorph actuators using electrophoretic deposition. The deposition procedure and conditions were investigated. After fabrication, the FGM monomorph was characterized both on its physical and electromechanical properties. To analyze the results, a theoretical model was proposed and compared with the experimental results. The stress distribution of the monomorph was also studied and discussed.

Important results and conclusions are summarized below.

- The designed FGM monomorph actuators fabricated exhibit gradient distribution in both microstructure and material properties (Young's modulus Y , piezoelectric constant d_{31} and dielectric constant ϵ_{33}^T), which results in a functional gradient and smooth stress distribution over the cross section.
- EPD is an efficient method to fabricate FGM monomorph actuator with uniform configurations. A gradient microstructure over the overall cross section was also observed.
- Depending on configurations of the actuator, the developed monomorph actuators generate displacement within the range from 2 μm to 40 μm at 100 V in static case. Compared with the monomorph reported, it has higher sensitivity, displacement and miniaturized dimensions.
- Constitutive modeling indicates that the bending displacement is a function of material properties, geometric properties, number of layers, electric field and frequency. In material properties, d_{31} is the most important parameter to produce displacement. In geometric properties, the bending displacement is found to increase with the ratio of length l to thickness h . The displacement is proportional to the electric field and decreases as the number of layers increases. In dynamic case, the bending displacement is frequency dependent and reaches maximum at resonant frequency.
- The maximum stress in the system decreases as the number of layers increases in both the static and dynamic case. The distribution of the stress was also found to become smoother. However, in the dynamic case, the improvement is not as significant as that in the static case.
- The 4-layer system is considered to be a good choice for most applications considering both larger bending displacement, smoother stress distribution and fabrication difficulties.

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Chapter 1 Introduction

1.1 Background

Since the discovery of the piezoelectricity one hundred years ago, many types of piezoelectric materials have been developed and widely used in applications such as actuators, sensors, and resonators. Among them, $\text{Pb}(\text{Zr}, \text{Ti})\text{O}_3$, or commonly known as PZT, based piezoelectric ceramics are one of the leading group of materials for displacement transducers and actuators. In these applications, large displacement from the actuator is required, which bulk piezoceramics generally cannot provide. In order to achieve such large displacement, the layer-structured device, bimorph actuator, which consists of two bonded piezoelectric plates, has been developed. However, problems such as low reliability and poor interfacial bonding conditions remain issues to be resolved in this device. In addition, in recent years, miniaturized actuators have been highly sought for applications in office equipments and surgical devices. As a result, the development of an effective miniaturized actuator is becoming an important task.

The method of “Functionally Gradient Material” (FGM) has been proposed to meet the requirements, such as the formation of a monolithic piezoelectric ceramic plate. A FGM monolithic actuator, the so-called monomorph, has the advantage of compositional, microstructural and/or piezoelectric gradient over macroscopic or microscopic scale. Due to the ability to achieve smooth transition of stress distribution over the cross section, the interfacial bonding problems could be minimized and the monomorph naturally becomes more reliable.

Tape casting, chemical vapor deposition, self-propagating and electrophoretic deposition (EPD) techniques are possible techniques to form FGM ceramics. Among them, EPD is a promising and useful preparation method for miniaturized functionally gradient and multilayer ceramic composites. The advantages of the EPD technique are (1) the process is simple and low cost, (2) it is possible to deposit various oxides on conductive substrates that have complex shapes and (3) it is a powerful method for the production of both bulk and miniaturized components with gradient properties.

1.2 Objective

The purpose of this work is to (1) develop an advanced functionally gradient monomorph actuator using EPD technique, (2) characterize its properties and establish constitutive relations to analyze and predict the electromechanical properties. The desired properties of the monomorph actuator developed are: (1) reasonable displacement; (2) smooth stress distribution; (3) reduced bonding problem and (4) miniaturized dimension.

1.3 Scope

To realize the above purposes, several studies were carried out in this work. The material systems of various compositions applied to fabricate the monomorph actuator were first synthesized and characterized. Then, electrophoretic deposition was studied and a procedure was established for the fabrication of the identified FGM monomorph systems. After that, the monomorph was characterized in terms of both physical and electromechanical properties. The constitutive modeling was also established to analyze electromechanical displacement and compared with the experimental results. Finally, stress distribution of the monomorph actuator was studied and discussed.

In Chapter 2, four areas, namely, piezoelectricity, piezoelectric actuators, FGM and EPD were reviewed. The fundamentals of piezoelectricity and piezoelectric materials were first introduced. Then, the designs, categories and applications of piezoelectric actuators were discussed. After that, the mechanism, historical development, fabrication techniques and applications of FGM were reviewed. Electrophoretic deposition was introduced in detail, including its mechanism, kinetics and applications. Finally, the development, structure, fabrication and principle of FGM monomorph actuator was also reviewed, discussed and summarized.

In Chapter 3, two PZT based starting materials were first synthesized using the conventional oxide mixing technique. The two materials were then mixed to form 11 compositions. Forming of the individual composition using EPD is described. The 11 compositions were characterized in their phases, microstructure, piezoelectric and ferroelectric properties. Based on the properties, particularly the piezoelectric constant, three material systems were determined to form the FGM monomorph actuators.

In Chapter 4, the fabrication of FGM monomorph actuators by electrophoretic deposition was studied. The piezoelectric FGM monomorph actuators of different configurations were formed. The deposits were sintered and characterized in physical properties, including phase and microstructure.

In Chapter 5, the electromechanical bending displacement of monomorph actuators was characterized both in static and dynamic states. The experimental procedure was introduced in detail. The results were compared and discussed.

In Chapter 6, the constitutive relationship between bending displacement and relevant properties, such as geometry, material properties and electric field, was established both in static and dynamic state based on the classic theories of piezoelectrics, strength of materials, and vibration at clamped-free boundary conditions. The modeling results were compared with the experimental results and discussed. The important parameters which affect the bending displacement were identified and discussed.

In Chapter 7, the stress distribution was analyzed based on the model derived in Chapter 6. As a reference, a bimorph actuator was also studied using finite element analysis. The results were analyzed and discussed. Considering the requirement of large bending displacement and small maximum stress, the three studied material system was compared and discussed.

In Chapter 8 and 9, the important conclusions were summarized and future work was also proposed.

Chapter 2 Literature Review

In this chapter, four areas, namely, (1) piezoelectricity and piezoelectric materials, (2) piezoelectric actuators, (3) functional gradient materials, and (4) electrophoretic deposition are introduced. The development, structure, fabrication methods and principle of piezoelectric FGM ceramic monomorph actuator, are also reviewed and discussed.

2.1 Piezoelectricity and piezoelectric materials

2.1.1 History of piezoelectrics [1-3]

The phenomenon that electricity could be produced in some crystals by subjecting them to mechanical pressures was proposed by Charles Coulomb in 1825. This was further verified by the research efforts of Jacques and Pierre Curie in 1880 at the University of Paris, where they studied this effect on crystals such as quartz, sodium potassium tartrate (Rochelle salt), and tourmaline. By placing weights on the faces of particular crystal cuts, they succeeded in detecting charges on the crystal surfaces and demonstrated that the magnitude of charge was proportional to the applied weight, thus confirmed the direct piezoelectric effect.

The inverse piezoelectric effect, that is the development of a mechanical strain when an electric field is applied to a crystal such as quartz, was predicted in 1881 by Lippmann, and was experimentally supported by the Curies in the same year. Shortly after, Hankel suggested the name “piezoelectricity” to describe this effect. The term “piezoelectricity” has been used since then.

Theoretical advances in understanding piezoelectricity in crystals were made during the late 1800’s and early 1900’s by the pioneering efforts of Lord Kelvin, Pierre Duhem, Friedrich Pockels, and Woldemar Voigt. Indeed, the classic work of Voigt has become the foundation of piezoelectricity research for the twentieth century.

Significant experimental contributions to the evolution and exploitation of the piezoelectric effect came from the contribution of crystallography, which received an enormous boost in 1912 with the discovery that crystals could act as the three-dimension X-ray diffraction gratings. This has led to a number of studies that linked the observed piezoelectric properties to material crystalline structures.

The first application of the piezoelectric effect was a force and charge measuring

apparatus patented by the Curies in 1887. They used the piezoelectric effect to measure voltages and forces by constructing bimorphs from two X cut quartz plates of opposite polarity. However, applications of the piezoelectric effect in crystals only appeared thirty years later.

Until 1940, only two types of ferroelectric materials were known, Rochelle salt and some closely related tartrates, and potassium dihydrogen phosphate, followed by quartz and its isomorphs. In 1941, the first introduction of unusual dielectric properties in refractory oxides amenable to ceramic preparation was reported by Thurnauer and Deaderick of American Lava Co. on a series of barium oxide-titanium oxide compositions. Test results have shown that these materials possessed much higher dielectric constant compared to the already known highest dielectric constant material, rutile. Wainer then carried out detailed exploration of dielectrics in the titania-alkaline earth oxide systems and his work was published in 1946. Meanwhile, the high dielectric constant of barium titanate has also been independently reported in Russia, England and Japan.

There were three basic discoveries that led to the understanding of piezoelectricity in ceramics. The first of these was the discovery of the high dielectric constant. The second was the realization that the cause of the high dielectric constant was ferroelectricity. The third significant discovery was poling process.

The first commercial piezoelectric barium titanate devices were phonograph pickups marketed by Sonotone Corporation in 1947. Rapid development of barium titanate piezoelectrics then followed. Compositional modifications were found desirable to improve the temperature stability or to gain moderate improvements in voltage output. Several other perovskite and oxide ceramic compositions investigated during the early 1950's have formed the basic constituents of modern piezoelectric ceramics. These compositions include lead titanate (PbTiO_3) (PT), lead zirconate (PbZrO_3), lead metaniobate (PbNb_2O_6), and lead zirconate titanate [$\text{Pb}(\text{Zr,Ti})\text{O}_3$] (PZT). Among them, the most significant discovery is the PZT, PT and PZT based binary or ternary series of solid solutions, which have become the dominant piezoelectric ceramics for electromechanical devices due to their superior ferroelectric natures today. From 1940's to 1960's, an intensive research of an understanding of the correspondence of the perovskite crystal structure to electromechanical activity was performed. Meanwhile, the rationale for doping these families with metallic impurities to achieve desired properties such as dielectric constant, stiffness,

piezoelectric coupling coefficients, ease of poling, etc, was also studied. These contributed to the development of devices including sonar, ceramic phono cartridge, microphone, piezo ignition system, etc. Other valuable piezoelectric products were then developed and commercialized in 1970's and 80's, such as audio buzzers, air ultrasonic transducers, and SAW filter devices. In recent years, persistent efforts in materials research have been made to develop new piezoceramic families and devices. The search for perfect piezo product opportunities is still in progress. Solid-state motion is presently the most important frontier. The technical goals are to obtain useful and reasonably priced actuators which are low in power consumption and high in reliability and environmental ruggedness.

2.1.2 Theories and constitutive relationships

The smallest repeating unit that builds up the structure or lattice of the crystal is the unit cell. The specific symmetry possessed by the unit cell determines whether it is possible for piezoelectricity to exist in the crystal. Based on the symmetry of the structure, all crystals can be divided into 32 different point groups. Among them, 20 point groups do not have a center of symmetry. When a stress is applied, the positive and negative charges will appear on crystal surfaces. These materials are known as piezoelectrics and possess the so-called piezoelectricity. Fig. 2.1 [4-8] explains the origin of piezoelectricity from both the intrinsic and extrinsic effects of the piezoelectrics. The intrinsic effect corresponds to the relative anion/cation shift that preserves the ferroelectric crystal structure. As shown in Fig. 2.1 (a), when an external electric field is applied, the cations are drawn in the direction of the electric field and

called ferroelectric. Piezoelectrics in general consists of many domains to reduce the electrostatic energy of the system [9]. In each domain, the spontaneous polarization has the same direction as shown in Fig. 2.1 (c). The domains may reorient under an applied electric field through domain wall motions and formation of new domains where the direction of spontaneous polarization is close to that of the electric field as shown in Fig. 2.1 (c). The contribution of the domain wall motions to the piezoelectric response is the extrinsic properties of the ceramics. From the previously published results, the extrinsic contributions to dielectric constant ϵ , piezoelectric constant d and compliance s of the soft PZT ceramics at room temperature and low field levels are significant and may account for 50-80% of the overall response [8]. From the viewpoint of lattice as shown in Fig. 2.1 (b), the extrinsic contribution is the rotation of lattice caused by the domain wall motions. The a- and c-axis is exchanged for a tetragonal structure ceramic. The rotation results in the contraction of the overall crystal in one direction and elongation in the perpendicular direction.

Fig. 2.1. Intrinsic and extrinsic effect of piezoelectricity [4-8]

The lively illustration of piezoelectric effect and inverse piezoelectric is shown in Fig. 2.2 [10]. A configuration of cylindrical body is chosen as example, and for the sake of clarity, only one dipole is shown. Fig. 2.2 (a) shows the cylinder under no-load conditions. If an external force produces compressive or tensile strain in the material, the resulting change in dipole moment causes a voltage to appear between the electrodes. If the cylinder is compressed, the voltage will have the same polarity as the poling voltage (Fig. 2.2 (b)). If it is stretched, the voltage across the electrodes will have opposite polarity to the poling voltage (Fig. 2.2 (c)). These are piezoelectric effect action, which can be found in cigarette and gas lighters, gramophone pick-ups, accelerometers, hydrophones and microphones.

If a voltage of opposite polarity to the poling voltage is applied to the electrodes, the cylinder will shorten (Fig. 2.2 (d)). If the applied voltage has the same polarity as the poling voltages, the cylinder will lengthen (Fig. 2.2 (e)). Finally, if an alternating voltage is applied to the electrodes, the cylinder will grow and shrink at the same frequency as that of the applied voltage (Fig. 2.2 (f)). It is known as inverse piezoelectric effect action, which can be found in transducers for ultrasonic cleaning equipment, ultrasonic atomizers, fuel injection systems and piezoelectric motors.

Fig. 2.2. The piezoelectric effect on a cylindrical body of piezoelectric ceramic [10]

The piezoelectric and ferroelectric responses of ceramics are dependent on the applied electric field. Fig. 2.3 [11] exhibits a hysteresis loop of the polarization

against electric field. Under a weak field, the motion of domain walls is reversible. The polarization thus linearly varies with the field. As the field is increased, the motion of domain walls becomes irreversible. The polarization in this case increases faster than it does according to the linear law. At a certain field strength corresponding to the point B , the crystal becomes a single-domain crystal, and the so-called saturation occurs. As the field is increased further, the total polarization of the crystal continues to increase because of the increase in induced polarization (the section BC). The curve $OABC$ is called the initial or fundamental branch of the hysteresis loop. If the field strength is decreased after reaching saturation, the polarization of the crystal will change in a manner corresponding to the curve CBD , rather than to the initial curve, and at zero field the crystal remains polarized. The magnitude of the polarization defined by the line segment OD is called the residual or remnant polarization P_r . By extrapolating the section CB on the P axis, we find the line segment OK , which is approximately equal to the spontaneous polarization P_s . If the direction of the field is reversed, the polarization will decrease, change sign and at a certain field will again reach saturation (the section DFG). The field strength defined by the line segment OF , at which the polarization is equal to zero, is called the coercive field E_c . Thus, the dependence of polarization on the electric field strength is nonlinear. The curve $CBDFGHBC$ is called the P-E hysteresis loop.

When a reverse electric field is applied to a piezoelectric ceramic, a strain variation, known as field-induced strain, is induced under electric field ranging from 0.32 kV/mm to 6.77 kV/mm as shown in Fig. 2.4 [12-15]. In a weak applied electric field, the field-induced strain curve appears nearly linear as that of “inverse piezoelectric effect”. However, with the increase in maximum field, the curve becomes distorted and exhibits large hysteresis. Finally, the curve transforms to a symmetric butterfly shape when the electric field exceeds the coercive field. The variation of strain for a polycrystalline material as a function of the electric field is the result of the domain reorientation under an external applied field [16-17].

Fig. 2.4. Field-induced strain as a function of electric field [15]

Piezoelectric response, as described above, is field dependent, at weak field, in general, is linear and can be mathematically described by a phenomenological model derived from thermodynamic potentials. The derivations are not unique and the set of equations describing the direct and inverse piezoelectric effects depend on the choice of potential and the independent variables used. For example, one such set of linear constitutive relations is [18]

$$\begin{cases} S_p = s_{pq}^E T_q + d_{pm} E_m \\ D_m = d_{pm} T_p + \varepsilon_{mn}^T E_n \end{cases} \quad (2.1)$$

where S is the strain, D is the electric displacement, T is the stress, E is the electric field, s is the elastic compliance, d is the piezoelectric constant and ϵ is the dielectric constant. The superscripts of the constants designate the independent variable that is held constant when defining the material coefficient and the subscripts define tensor directions when taking into account the anisotropic nature of the material. The elements of the tensor form a 9×9 matrix with 1, 2, 3 designating the orthonormal directions and 4, 5, 6 designating the shear directions. For the commonly used polycrystalline piezoelectric ceramic materials with C_∞ symmetry, such as PZT, there are 10 non-zero, independent matrix elements consisting of 5 independent elastic constants, 3 independent piezoelectric constants and 2 independent dielectric constants. For these materials, the reduced matrix form of the above constitutive relationships can be written as [18]

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \\ D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} s_{11}^E & s_{12}^E & s_{13}^E & 0 & 0 & 0 & 0 & 0 & 0 \\ s_{12}^E & s_{11}^E & s_{13}^E & 0 & 0 & 0 & 0 & 0 & 0 \\ s_{13}^E & s_{13}^E & s_{33}^E & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & s_{55}^E & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & s_{55}^E & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2(s_{11}^E - s_{12}^E) & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & d_{15} & 0 & \epsilon_{11}^T & 0 & 0 \\ 0 & 0 & 0 & d_{15} & 0 & 0 & 0 & \epsilon_{11}^T & 0 \\ d_{13} & d_{13} & d_{33} & 0 & 0 & 0 & 0 & 0 & \epsilon_{33}^T \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \\ E_1 \\ E_2 \\ E_3 \end{bmatrix} \quad (2.2)$$

In the above matrix, the piezoelectric constant d is a widely used parameter to measure the properties of field-induced-strain of the ceramics at weak and moderate fields. It is very useful for both sensing and actuating applications [19-21]. A high d constant is desirable since the large displacement is normally required.

Other important parameters to measure the piezoelectric properties of the ceramics include electromechanical coupling factor k , mechanical quality factor Q_m and dielectric loss factor $\tan \delta$. The coupling factor k is one of the best measurements to indicate the strength of piezoelectric effect [3]. It is defined as the square root of the fraction of the electric energy converted to mechanical energy in each input harmonic electric cycle (Eq. 2.3)), or vice versa (Eq. 2.4)). The actual relationship is in terms of k^2 :

$$k^2 = \frac{\text{electrical energy converted to mechanical energy}}{\text{input electrical energy}} \quad (2.3)$$

or

$$k'^2 = \frac{\text{mechanical energy converted to electrical energy}}{\text{input mechanical energy}} \quad (2.4)$$

The remaining energy is either stored elastically or dielectrically during each cycle, or is dissipated. Since the conversion of mechanical to electrical energy is always incomplete, k is always less than 1. Typical values for PZT based piezoelectric ceramics are $k_{33} = 0.5-0.8$ and $k_{31} = 0.2-0.4$ [22-29]. Electromechanical coupling factor k relates to the piezoelectric constant, dielectric constant and elastic compliance by the following form [15]

$$k^2 = d^2 / (\epsilon^T s^E) \quad (2.5)$$

Mechanical quality factor, Q_m , on the other hand, is defined as [3]

$$Q_m = 2\pi \frac{\text{stored energy per cycle}}{\text{dissipated energy per cycle}} \quad (2.6)$$

It reflects the damping properties of a vibrating piezoelectric body due to the mechanical loss caused by domain wall motion. A higher Q_m represents a lower mechanical loss. This is important to suppress heat generation in high power devices, such as ultrasonic motors [8,30-35]. Furthermore, the actual mechanical vibration amplitude at the resonance frequency is directly proportional to Q_m [36]. PZT based solid solutions usually have Q_m values ranging from 50 to 3000 [30-34].

The last important parameter to be mentioned is dielectric loss, $\tan \delta$, which is defined as

$$\begin{cases} \epsilon = \epsilon' - j\epsilon'' \\ \tan \delta = \frac{\epsilon''}{\epsilon'} \end{cases} \quad (2.7)$$

Considering the loss, the dielectric constant ϵ is usually expressed as a complex number with a real part ϵ' and an imaginary part ϵ'' as shown in the above equation.

The dielectric loss, $\tan \delta$, is the ratio of the imaginary part to the real part. It measures the electric losses of the materials under harmonic excitation due to electron polarization, ion vibration, migration and deformation [37]. Both electrical and mechanical losses will dissipate as heat. High power transducers and actuators in general need low dielectric loss materials to minimize heat generation [30-31, 38-39].

2.1.3 Categories of piezoelectric materials

Since the discovery of piezoelectricity, its existence has been proven in many different materials. However, only a few were found to be suitable for practical applications. The common piezoelectric materials can be generally divided into piezoelectric single crystalline materials, piezoelectric ceramics, piezoelectric polymers and piezoelectric composites [1, 40]. The polycrystalline piezoelectric ceramics have been found effective in a wide range of usage and can be further divided into perovskite and nonperovskite structured ceramics. The nonperovskite structured materials mainly include potassium tungsten bronze structured PbNb_2O_6 , pyrochlore structured $\text{Cd}_2\text{Nb}_2\text{O}_7$, and bismuth layer structured $\text{Bi}_4\text{Ti}_3\text{O}_{12}$ [41-43]. The perovskite structured materials that have been developed and investigated are mainly BaTiO_3 , PbTiO_3 , PbZrO_3 , $\text{Pb}(\text{Zr,Ti})\text{O}_3$ (PZT), $\text{Pb}[(\text{Sc,Nb})\text{Ti}]\text{O}_3$ (PSN-PT) [3, 40, 44-46]. Among so many types of piezoelectric ceramics, modified PZT based solid solutions are basically the dominant materials as they are ideal for most of electromechanical transducers such as in phonograph pickups, air transducers, instrument transducers, underwater sound and ultrasonic powers, delay line transducers, wave filters and high voltage sources, due to their ability to generate high force, large displacements, high conversion efficiency and design versatility [45-48].

$\text{Pb}(\text{Zr,Ti})\text{O}_3$ is perovskitic crystalline structured ceramic. The perovskite has a general formula of ABO_3 , in which A denotes a large divalent metal ion such as barium or lead, and B denotes a tetravalent metal ion such as titanium or zirconium [3, 49]. As shown in Fig. 2.5 [17], it can be described as a simple unit cell with a large cation A on the corners, a smaller cation B in the body center, and oxygens O in the centers of the faces. The structure is a network of corner-linked oxygen octahedral, with the smaller cation filling the octahedral holes and the large cation filling the dodecahedral holes.

Fig. 2.5. ABO_3 perovskite structure [17]

PZT is a binary solid solution of $PbTiO_3$ and $PbZrO_3$ as shown in the phase diagram (Fig. 2.6) [50]. Above Curie temperature, the solid solution exists in the form of a non-ferroelectric (paraelectric) cubic phase (Fig. 2.5). Reducing the temperature, the cubic cell elongates along the edge or body diagonal depending on Zr/Ti ratio. Then, ferroelectric rhombohedral or tetragonal phase forms (Fig. 2.7 [3]), whose noncentrosymmetric structure leads to the dipole existing in the unit cell. To minimize the electrostatic and elastic energies during the paraelectric-ferroelectric phase transition, the structure of domains forms [17, 51]. The domains are randomly oriented in the materials, thus, no overall polarization or piezoelectric effect is exhibited. A poling treatment, which involves exposing the material to a strong electric field at a temperature slightly below the Curie point, will align most domains to the poling direction and make the ceramic piezoelectric. After poling, the materials are ready for applications. One of the principal advantages of PZT materials is that their properties can be optimized to suit specific applications by appropriate adjustment of the Zr/Ti ratio. The frequently used PZT materials are usually modified by the small dopings and have Zr/Ti ratio near the morphotropic rhombohedral and tetragonal phase boundary (MPB) [52-58], which are considered to have good piezoelectric responses, including dielectric, piezoelectric constants and coupling factors.

Fig. 2.6. Phase diagram of PZT solid solution [50]

leading to a large remnant polarization, which helps to increase the piezoelectric coefficients at MPB [4,6,17,51].

Fig. 2.8. Piezoelectric constants of PZT ceramics as a function of composition in the vicinity of morphotropic phase boundary [17]

2.2 Piezoelectric ceramic actuators

2.2.1 Definition and introduction

An actuator can be loosely defined as a device that converts electrical energy into mechanical energy. There are mainly five microactuation types, i.e., piezoelectric, magnetic, thermal, surface tension and electrostatic. The goal of actuator research is an architecture that can generate high displacement and force throughout a broad frequency range while not consuming a significant amount of electrical power. However, all smart material actuators generally have at least one shortcoming involving either mechanical stroke, force, or frequency capability. Nevertheless, whenever speed is a consideration, piezoelectric actuation is commonly employed [59]. They have been applied in hundreds of applications, which span a wide range of products in the consumer, industrial, medical, aerospace and defense sectors [1]. These actuating applications are classified into three categories: positioners, motors, and vibration suppressors [60-61]. Ultrasonic motors whose efficiency is insensitive to size are superior to conventional electromagnetic motors in the mini-motor area. Vibration suppression in space structures and military vehicles using piezoelectric

actuators is also a promising technology. New solid-state displacement transducers controlled by temperature (shape memory alloy) or magnetic field (amorphous magnetostrictive alloy) have been proposed, but are generally inferior to the piezoelectric actuators because of the technological trends aimed at reduced driving power and miniaturization [60].

2.2.2 Actuator materials

The performance of actuator is largely determined by the material's behavior. Conventionally, piezoelectric ceramics have been used for electronic components such as buzzers, speakers and ultrasonic generators. However, for actuator applications, large electric fields are applied to generate large stresses or strains. Thus, electrical insulation strength and mechanical toughness are necessary material properties. Piezoelectric actuator materials are based primarily on PZT. They can be classified into either "hard" or "soft" materials [23-24,31,43,49,62]. The hard materials usually have a large coercive field (> 10 kV/cm) [62], higher mechanical quality factor Q_m and lower piezoelectric d constant compared to soft materials. The hard materials offer a wide linear drive region where strain is directly proportional to the applied electric field. However, the magnitude of field-induced strain is relatively small. Hence, the hard materials are suitable for resonant displacement actuators. These actuators are able to produce very rapid motion due to their high frequency operation. However, a lot of heats will be produced in the device because of the electrical and mechanical losses. That is the reason why this type of devices requires a very hard piezoelectric ceramic which provides a high mechanical quality factor Q_m and a low dielectric loss $\tan\delta$ in order to minimize heat generation [63]. On the other hand, the displacement of the device at the resonant frequency is proportional to Q_m [36, 63]. The soft piezoelectric material shows a large field-induced strain, but has a relatively large hysteresis. Soft PZT materials are hence suitable for devices which require a quick response, such as a pulse drive displacement actuator.

It should also be noted that there exists another important lead-based perovskite material $\text{Pb}(\text{B}'\text{B}'')\text{O}_3$, known as electrostrictive relaxor ferroelectrics, such as $\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3$ (PMN). This group of materials has exceptionally high permittivity values and therefore, is expected to be strongly electromechanically active, and thus it is especially suitable for particular transducer applications. Another attractive feature of these materials is the near absence of hysteresis compared to piezoelectric materials

as shown in Fig. 2.9 [50]. The feature makes electrostrictive materials best suited to serve as displacement actuator, which is controlled by a feedback system through a position detection signal [62].

Fig. 2.9. Dependence of strain on electric field for (a) a readily poled and depoled piezoelectric PLZT and (b) electrostrictive PMN [50]

2.2.3 Categories and applications

In advanced precision engineering there is a need for a variety of types of actuators. For example, in the fabrication of semiconductor chips, circuit components have to be precisely positioned for various processing steps. In optical equipment, lenses and mirrors require micropositioning, and even the shapes of mirrors are adjusted to correct image distortions arising from, for example, atmospheric effects. In autofocus cameras there are actuators capable of producing precise rotational displacements. Actuators are also required for ink-jet printers, positioning videotape-recording heads and micromachining metals. As a result, the certainty of market growth on these devices has stimulated intensive research on piezoelectric and electrostrictive materials.

Classified according to the shape and structure, the commonly used piezoelectric actuators include piezoelectric tubes, disks, multilayer actuators, bimorphs and flextentional composite actuators such as “Moonie” and “Cymbal” [1, 60]. These actuators have been applied in a broad spectrum of fields. Typical shapes and applications of the piezoelectric actuators have been listed in Table 2.1 [1]. In the following paragraphs, introduction to several widely used actuators will be presented.

Table 2.1. Actuators and respective applications [1]

Shape of actuators	Applications
Multilayer actuators (stacks)	Deformable mirrors, Active suspensions, Stabilizers, Optical fiber switches, Ultrasonic motors,
Bimorph, Unimorph and Multimorph	Benders, Printer heads, Video head, Positioners, Microphones, Transformer, Twister
Rainbow	Variable focus mirrors, Valves, Relays, Micropumps,
Moonie	Active hydrophone element, Micropositioners

(a) Multilayer actuator

The piezoelectric multilayer or stack actuator have long been focused on and investigated intensively. Fig. 2.10 shows the structure of a conventional multilayer actuator. It consists of a stack of alternate ferroelectric ceramics and internal electrode layers fabricated by cofiring. Several techniques including cut-and-bond, tape casting and screen printing are required to fabricate this actuator. Multilayer actuators have several advantages: quick response, low driving voltage, large generative force and high electromechanical coupling. However, higher displacement/voltage sensitivity can only be achieved for this type of actuator by greatly increasing the number of piezoelectric layers and decreasing the thickness of each layer. This in turn, has resulted in higher cost, lower reliability, and larger dimensions [64].

Fig. 2.10. Structure of a multilayer actuator with an interdigital electrode configuration [65]

(b) Bimorph, unimorph and multimorph

Bimorph, unimorph and multimorph are bending type actuators. They are generally applied to generate a large displacement. A bimorph actuator consists of two thin piezoelectric ceramic plates bonded together (Fig. 2.11) [66-67]. Two types of construction are available for bimorph fabrication. In the series type bimorph (Fig. 2.11 (a)), two piezoelectric sheets with opposite polarization direction are bonded together. The electric voltage is applied on the top and bottom electrodes of the device. The other is the parallel type bimorph (Fig. 2.11 (b)), in which the two piezoelectric layers have the same polarization directions. The electric voltage is applied between the intermediate electrode and the top/bottom electrodes. In both cases, when an electric field is applied, one plate extends while the other contracts, leading to a bending deflection. In a unimorph type (Fig. 2.11 (c)), one piezoelectric layer and one elastic layer are bonded together. The piezoelectric layer produces extension or contraction under an applied electric field. The elastic layer resists this dimension change, resulting in bending deformation. The application of the elastic layer can greatly increase the mechanical reliability of the actuator. The bending actuator can also be designed with a multi-layered structure as shown in Fig. 2.11 (d). This design provides a higher bending displacement and force factor of the actuator [67-68].

Fig. 2.11. Structure of bimorph and unimorph [66-67]

(c) Rainbow

Rainbow was invented by Haertling and has been investigated by many researchers [59, 69-71]. This actuator consists of an electromechanically active layer and a reduced passive layer as shown in Fig. 2.12 [59, 71]. The rainbow actuators can be fabricated by placing piezoelectric plates directly on carbon blocks, then heated to about 1000 °C for a period of time. The chemical oxidation reaction of carbon at the ceramic-carbon interface takes the oxygen atoms from the PZT oxide ceramics and resulted in part of the ceramic sample being reduced to a cermet layer without piezoelectric properties. During cooling to room temperature, a bending curvature (rainbow) is generated because of the thermal expansion mismatch between the reduced layer and the remaining piezoelectric layer. A 100 mm diameter electrostrictive rainbow wafer can produce a displacement as large as 3 mm [59].

Fig. 2.12. Piezoelectric rainbow actuator [59, 71]

(d) Moonie

A composite actuator structure called “Moonie” has also been developed to amplify the small displacements induced in a piezoelectric ceramic [59, 72]. The Moonie has intermediate characteristics between the conventional multilayer and bimorph actuators. This device sandwiches a piezoceramic stack between two end caps having shallow cavities (Fig. 2.13). Displacement of the stack flexes the end caps, producing an increased deflection. The displacement output of the actuator greatly increases with cavity diameter and depth. By modifying the end cap design (Cymbal type) as shown in Fig. 2.13 (b), twice the displacement can be obtained. The generative displacement is also rather uniform, independent of the position from the center of the end cap.

Fig. 2.13. Structure of a Moonie (a) and a modified Moonie (Cymbal) (b) [59]

2.3 Functionally gradient materials (FGMs)

Gradient materials are present in many natural materials. For example, bamboo, corn and barley culms have gradient structure of fibers in the cross section. The fiber distribution is dense in the outer region and sparse in the inner region. This unique hierarchical structure generates the marvelous flexibility and strength of these plants. Recognizing their advantages, researchers and engineers have been using it for structural and functional applications for years. The concept of functionally gradient materials (FGMs) was first proposed in 1984 by material scientists in Sendai, Japan as a means of preparing thermal barrier materials. Since then, much research was carried out on FGMs to improve conventional materials and to create new materials [73-77]. In the following part, the FGMs structure, application and its fabrication technique will be introduced in detail.

2.3.1 Concept of FGMs and applications

Functionally gradient materials (FGMs) display continuously or discontinuously varying compositions and/or microstructures over definable geometrical distances. The gradients can be continuous on a microscopic level, or they can be laminates comprised of gradients of metals, ceramics, polymers, or variations of porosity/density [77]. Fig. 2.14 shows a conceptual diagram of functionally gradient materials, taking into account the relaxation of thermal stress [78].

Fig. 2.14. Conceptual diagram of functionally gradient materials [78]

Generally speaking, gradient materials are not something new. For example, case-hardened steel which is still in common use today has been developed long ago. Nevertheless, what is new and exciting about FGMs is the realization that gradients can be designed at the microstructural level to tailor a material for the specific functional and performance requirements of an intended application. In addition, recent advances in processing are opening the possibility for the extension of the gradient materials concept to new material systems and engineering problems [75].

FGMs find applications in thermal shielding, joining metal to ceramics, optical and electronic functions, and biomaterial implants [79]. For example, efforts have been made to develop advanced heat-shielding structural materials using FGM technology for future space program. In general, the highest temperature on the surface of spaceplanes is estimated to reach 2100 K. Hence, materials at the surface must withstand temperatures as high as 2100 K and temperature differences of 1600 K. Currently, no industrial materials are found to meet such severe thermomechanical loadings. The idea of FGM was then proposed to prepare a new composite by using heat-resistant ceramics on the high-temperature side and tough metals with high thermal conductivity on the low-temperature side, with a gradual compositional variation from

ceramic to metal. Several FGMs developed for this purpose included: SiC/C FGM [80], PSZ/SUS 304 FGM [81], Ni-base alloy/ZrO₂ FGM [82-83], and TiB₂/Cu and TiC/Ni FGMs [84-86].

2.3.2 Fabrication of FGMs

Several processing methods have been used to fabricate gradient structures, such as thermal spraying [86], powder processing [87], chemical vapor deposition (CVD) [88], physical vapor deposition (PVD) [89], self-propagating high-temperature synthesis [90], diffusion treatments [91], and sedimentation [92]. More recently, electrophoretic deposition (EPD) has also been introduced to fabricate gradient structures [93].

Thermal spraying is a well-developed technique that introduces the feedstock materials into a combustion or plasma flame [86]. The particles melt in transit and impinge on the substrate where they flatten, undergo rapid solidification and form a deposit through successive impingement. Thermal spraying has been traditionally employed to produce a variety of thermal-barrier layered and graded coatings of ceramics, metals and polymers on a range of substrates.

Powder processing is a flexible method to fabricate metals/ceramics FGMs [87]. It starts from determination of the optimum composition of profile for certain purpose; then stepwise or continuous stacking of powder premixes; finally, compaction of the sacked powder heaps and sinters. This technique provides good microstructural control and product quality, and is capable of producing large structural parts.

Both thermal spraying and powder processing have complex processing steps and are energy consuming. They are more suitable for large structural products.

Sedimentation method can be applied to form FGMs with continuous distribution of composition [92]. It is based on the difference of sedimentation velocity of the two powders in a liquid medium, which is in turn determined by the particle size and density. When two kinds of powders sedimentate together, the particles with larger size or higher density will settle more quickly. Accordingly, a deposit layer with a continuous change in composition can be obtained by the co-sedimentation of two kinds of powders through conditioning the parameters of sedimentation and size distribution of the powers. However, this method is a slow process with poor gradient control because the sedimentation rates depend strongly on the particle size and morphology of the specific raw materials used.

2.4 Electrophoretic deposition (EPD)

2.4.1 Introduction [94-98]

Electrophoretic deposition (EPD) is a colloidal process wherein ceramic bodies are shaped directly from a stable colloid suspension by a dc electric field. It is essentially a combination of two processes: electrophoresis and deposition. Electrophoresis is the motion of charged particles in a suspension toward an electrode under an applied electric field. The phenomenon of electrophoresis has been known for nearly two centuries. It was first discovered in 1807 by the Russian physicist Reuss, who observed that when an electric current was passed through a suspension of clay in water, the clay particles migrated towards the anode. Deposition is the coagulation of particles to a dense mass. EPD was used first for ThO₂ and tungsten deposition on a platinum cathode in 1927 by Harsanyi. Since then, the technique has then been studied and used for a wide range of applications, including the deposition of metals, oxides, phosphors, inorganic and organic paints, rubber, dielectrics and glasses using both aqueous and non-aqueous media. A general historical development of electrophoretic forming is shown in Table 2.2 and the EPD process is schematically shown in Fig. 2.15. A dc field drives the charged particles to move towards, and deposit on, the oppositely charged electrode. The depositing electrode takes the shape of the ware required, and should be designed such that deposit release is facilitated.

Table 2.2. Historical development of electrophoretic forming [98]

Time	Contributor	Contributions
1808	Reuss	Discovery of electrophoresis

Fig. 2.15. Schematic drawing of electrophoretic deposition cell [94]

2.4.2 Suspension

In electrophoretic deposition, the first critical step towards obtaining a dense homogenous body is to achieve a stable colloidal suspension of particles. A colloidal suspension would naturally consist of very small particles where Van der Waals attractive forces, osmotic repulsive force and Brownian motion dominate over the gravitational and inertial forces of the particles. This system may be kinetically unstable because the collision between the particles of the dispersed phase will tend to enhance the Van der Waal attractive forces. This will cause the system to flocculate very fast, thus making the suspension very unstable.

Zeta potential can be used as a parameter on the stability of the suspension. It is noted that a stable suspension usually possesses high zeta-potential and low ionic conductivity. A necessary but not sufficient condition for a high zeta-potential is a high surface charge on the ceramic oxide particles suspended in the solvent [97]. The surface charge can be the result of dissociation or ionization of surface groups on the oxide particles, commonly observed with adsorbed carboxylic acid, amine on oxide surface. The degree of charge development and its sign under this system will depend

on the pH of the solution. Oxide surfaces can be considered to consist of a large number of amphoteric hydroxyl groups that can undergo reaction to produce either H^+ or OH^- [94]:

The surface charges induce the formation of a double layer and hence repulsion to overcome the Van der Waals attractive potential between the interactions of particles in the suspension [99]. While the particulate surfaces are charged, the surface charge in the system is compensated by the presence of counterions distributed evenly at the interface of the particulate surfaces [100]. The charges on the particle surface, together with the ionic atmosphere of counterions, then constitute an electrical double layer (Fig. 2.16 [101]), also known as lyosphere. The double layer can be divided into two sections as shown in Fig. 2.16. The first region, adjacent to the surface, is the Stern layer. In this layer, there exists a layer of counterions with its distance extending into the solution, depending on the size of the hydrated counterions adsorbed on the surface. Beyond the Stern layer, the diffuse layer of counterions extends into the solution and the boundary between the two layers is known as the shear plane. When the particle moves in the liquid, some ions in the lyosphere fluid-mechanically “shear off”, and the resultant potential between the surface and the shear layer plane is the zeta potential. The higher the zeta potential, the thicker the double layer, and the more stable against coagulation of the particles.

Interactions that occur between charges fixed at a particle surface and those free in the solution are important to the stability of a colloidal system. The surface charge on a particle is characterized by the charge density (σ) and surface potential (ψ_0). Debye-Huckel gives the potential ψ at distance r from the particle center as [94]

$$\psi = \psi_0 \frac{a}{r} \exp[-\kappa(r-a)] \quad (2.9)$$

where $1/\kappa$ is the characteristic double-layer thickness, a is the particle radius.

Particle surface
Stern plane

In the above Eqs. 2.10 and 2.11, c is ionic concentrations and ε is dielectric constant. The total force, $P = P_{es} + P_{osm}$, is independent of position and can be expressed as [94]

$$P = 2c\kappa T \left(\cosh \frac{ze\psi \frac{D}{2}}{\kappa T} - 1 \right) \quad (2.12)$$

where D is the distance between the two flat double layers, T is the temperature of the bulk. This equation applies to any geometry.

Using the Derjaguin approximation, the repulsive energy between two interacting spheres can be obtained as [94]

$$V_R = \pi a \int_0^\infty (G_{R,a}(D) - G_{R,a}(\infty)) dD \quad (2.13)$$

where $G_{R,a}$ is the Gibbs free energy per unit surface at distance D and infinite distance ∞ .

In addition, the dominant attractive energy, i.e., the London-van der Waals (LVDW) attractive energy is known as [102]

$$V_A = -\frac{A}{6D} \frac{r_1 r_2}{r_1 + r_2} \quad (2.14)$$

where A is the Hamaker constant, D the separation distance of the two particles, and r_1, r_2 the radii.

Derjaguin, Landau, Verwey and Overbeek developed a theory (DLVO) to describe the stability of a colloid suspension using the above repulsive energy and LVDW attractive energy concepts. The repulsive energy V_R , attractive energy V_A and the resultant total energy ($V_T = V_R + V_A$) as a function of distance D are schematically plotted in Fig. 2.17 [103]. At very low particle separations, the attractive forces dominate. A deep primary minimum results as the separation tends toward zero. As particle separation increases, double-layer repulsion dominates. Thus, the total-interaction-energy curve exhibits a peak of height E_B . This is the energy barrier to particle coagulation. Because the double-layer interaction is highly sensitive to pH and electrolyte concentration, these factors are used to modify the interaction energy curve so as to achieve a shallow secondary minimum. If particles approach closer than the primary energy barrier E_B , they adhere irreversibly [104]. The secondary

minimum also can result in coagulation, but adhesion is weak and reversible (soft agglomerates) which can be easily broken up using the ultrasonic bath [104].

Fig. 2.17. Schematic of the interaction energy as a function of separation between two particles in suspension [94]

There are generally two kinds of EPD suspension, aqueous (water) suspension and non-aqueous suspension. Water as a media for suspension has been studied very early and many materials including clays, oxide ceramic powders, paint or polymers were investigated to deposit from aqueous suspension. However, the use of water-based suspensions has been noted to cause a number of problems in electrophoretic forming. Electrolysis of water occurs at low voltages (~ 5 V), and therefore gas evolution at the electrode is inevitable at field strengths high enough to give reasonably short deposition times. This causes bubbles to be trapped within the deposit unless special procedures are adopted. In addition, current densities required for aqueous systems are high, leading to Joule heating of the suspension, and electrochemical attack of the metallic electrodes will also lead to contamination of the deposit. The use of

isopressed graphite/clay or graphite/cement electrodes has been suggested to solve some of these problems [98].

Non-aqueous suspensions, i.e., the suspension using organic liquids as media, generally have a lower dielectric constant, which is a disadvantage because it limits the charge on the particles. However, much higher field strengths (~100-1000 V/cm) can be used since the problems of electrolytic gas evolution, Joule heating and electrochemical attack of the electrodes are greatly reduced or non-existent. Therefore, organic liquids are generally preferred over water for electrophoretic deposition [97-98].

2.4.3 Mechanism of electrophoretic deposition

Sarkar and Nicholson [94] explained the deposition phenomenon using the mechanism of coagulation/deposition via lyosphere distortion and thinning as shown in Fig. 2.18. For an overall positively charged oxide, with the supply of dc current, particle/lyosphere system (e.g., $[(M-OH_2)^+-X^-]$) moves toward the cathode in an EPD cell. Fluid dynamics and the applied field distort the double-layer envelope, thinner ahead and wider behind of the particle, leading to the variation of zeta potential with position – greater for leading hemisphere of the particle and lesser for the trailing one. Cations in the liquid also move to the cathode with the positively charged particles. The counterions in the extended “tails” tend to react with these accompanying cations in high concentration around them.

The anion X^- in $[(M-OH_2)^+-X^-]$ comes from a dissociation reaction, such as $XY \rightleftharpoons Y^+ + X^-$ (where Y^+ can be H^+ or any other cation, and X^- can be OH^- or any other anion). In the bulk suspension, the equilibrium constant K for this dissociation at constant temperature is

$$K = \frac{[Y^+][X^-]}{[YX]} \quad (2.15)$$

where $[]$ indicates concentration. $[Y^+]$ is markedly adjacent to the cathode; therefore, to maintain K , $[YX]$ must increase and/or $[X^-]$ decrease. The latter constitutes the double-layer of the particles $(X^-)_{dl}$. X^- close to the particle surface is strongly bonded to it. Away from the surface, ions in the double layer are held less tightly. This

analysis assumes the latter react with the accompanying cations. Combination of X^- with Y^+ increases $[YX]$ and decreases $[X^-]$ and $[Y^+]$ simultaneously, i.e.,

The produced YX diffuses down its concentration gradient to the bulk suspension, i.e., away from the deposit, and, thus, K remains constant. As a result of this chemical “reaction”, the double layer around the tail of the particle thins so that the next incoming particle (which has a thin leading double layer) can approach close enough that LVDW attractive forces dominate and coagulation/deposition results.

Fig. 2.18. Schematic of the deposition mechanism by lyosphere distortion and thinning [94]

2.4.4 Kinetics of electrophoretic deposition

The rate at which a deposit forms during EPD is very important if the thickness of the deposited layer is to be controlled [105]. The rate is also important for controlling the compositional profile of functionally graded materials [93].

The first significant report on the kinetics of EPD was published in 1940. During a study of the phenomena of the EPD process, Hamaker observed that the deposited weight or yield of EPD varies linearly with the amount of charge passed. Based on this observation, Hamaker proposed that deposited weight is proportional to the concentration of the suspension, time of deposition, surface area of the deposit and electric field. This relationship has established the theoretical basis for the modern electrophoretic deposition. Sussman and Ward, on studying the EPD of glass particles, developed two kinetic equations: one for constant current that is identical to those of Hamaker and the other for constant voltage. In 1991, Hirata *et al.* also developed a kinetic equation based on Faraday's law for constant current. However, all the three equations ignored the change of solid concentration in the suspension during deposition [94].

In 1994, Zhang *et al.* [106] derived a kinetic equation incorporating the change of particle concentration in the suspension under constant current condition. The equation is

$$\begin{cases} w(t) = w_0(1 - e^{-kt}) \\ k = A\varepsilon\zeta(E - \Delta E) / 4V\pi\eta \end{cases} \quad (2.17)$$

where $w(t)$ is the yield of deposit (g); w_0 is the starting weight of the solid particles in the suspension (g); k is the kinetic parameter; ε is the dielectric constant of the liquid in the suspension (F/cm); η is the viscosity of the liquid media (Pas); ζ is the zeta potential of the particle in the suspension (mV); A is the deposition area (cm²); E is the applied electric field (V/cm); ΔE is the drop of the electric field across the deposited layer (V/cm); and V is the volume of the suspension.

In 1995, Zhang *et al.* [107] also derived a similar kinetic equation for constant-concentration and constant current condition. The equation is

$$w(t) = kw_0t \quad (2.18)$$

For constant-voltage EPD, the general equation is [108]

$$\int dw = f \iint dAu(t)C(t)dt = f \iint dA\mu_e E(t)C(t)dt = k' \int E(t)(w_0 - w(t))dt \quad (2.19)$$

where $E(t)$ is the voltage drop/unit length of suspension normal to the depositing electrode; $k' = Af\mu_e/V$, is a “universal” kinetic parameter, f is the efficiency factor (it is expected that a colloidally stable suspension, i.e., particles with high zeta potential, have $f \approx 1$), μ_e is the average velocity of the particles ($\mu\text{m/s}$), V is the applied voltage, A is the deposition area (cm^2). The total resistance of the deposit plus suspension can be replaced by a suspension of larger thickness (L_{equiv}) with equal resistance [108]

$$L_{\text{equiv}} = L + w(t)R' \quad (2.20)$$

where $R' = (R_r - 1)/\rho A$, L is the distance between the electrodes, R_r is the ratio of deposit resistivity to that of the suspension and ρ is the deposit density. Thus, the change of voltage per unit length of suspension with time, $E(t)$, can be calculated by [108]

$$E(t) = \frac{V}{L_{\text{equiv}}} = \frac{V}{L + w(t)R'} \quad (2.21)$$

Then the solution of the Eq. 2.19 is [108]

$$R'w(t) + (R'w_0 + L)\ln\left(\frac{w_0 - w(t)}{w_0}\right) + k'Vt = 0 \quad (2.22)$$

This equation can be used for the constant voltage but varying concentration condition.

Sarkar *et al.* also gave the kinetic equation under constant concentration/constant voltage condition from Eq. 2.19 as [94]

$$R'w^2 + Lw(t) - k'w_0Vt = 0 \quad (2.23)$$

Fig. 2.19 is a schematic plot of weight-fraction deposited as a function of time for the four different deposition conditions. Curve I was plotted using Eq. 2.18 for constant current and constant concentration EPD. The weight-fraction deposited varies linearly with time. Curve II was calculated from Eq. 2.17 for constant current and concentration varying with time. It deviates slightly from the curve I for ≤ 0.5 weight-fraction deposited but deviates considerably at higher weight fractions. This deviation is due to the decreased powder concentration in the suspension. Curve III

was calculated using Eq. 2.23 for constant voltage and constant concentration conditions. At >0.15 weight-fraction deposited, the deviation is considerable. This deviation is due to the higher resistivity of the deposit which causes the voltage drop/unit length of suspension to decrease with time during constant voltage deposition. As a result, the velocity of the particles decreases with time, and the deposition rate decreases. Thus, the amount of deviation can be controlled by R_r . If the deposit resistivity equals that of the suspension, curves I and III are identical, i.e., there is no difference between constant current and constant voltage deposition conditions. Curve IV was plotted using Eq. 2.22 for constant voltage and variable concentration conditions. This curve always deviates from curve I because of the decrease in suspension concentration and increase of deposit resistance. Curve IV deviates from curve III because of the concentration effect. Hamaker's observation on the formation of deposition by electrophoresis shows that the deposited weight is directly proportional to the amount of charges. Curves I and III show this behavior throughout the deposition and curves II and IV show this behavior in the initial stage of deposition.

Fig. 2.19. Schematic of deposited weight as a function of time for four different deposition conditions (I, constant current/constant concentration; II, constant current but variable concentration; III, constant voltage/constant concentration; and IV, constant voltage but variable concentration) [94]

2.4.5 Applications of electrophoretic deposition

With well-controlled quality of suspensions and deposition conditions, various materials and structures can be formed using EPD technique both in aqueous and nonaqueous solutions. In the early stage, EPD was mainly applied using aqueous suspensions. Choudary *et al.* [109] stabilized 5-10 μm Al_2O_3 particles in an aqueous suspension at constant voltage of 30 V using poly (acrylic acid) and tetramethylamine to adjust the pH. They also conducted a systematic study of mobility/zeta potential, conductivity, viscosity, deposited weight/thickness as functions of pH. They found that higher voltages, pH values, deposition times, and stabilizer content gave bubble containing deposits. Clark *et al.* [110] deposited sol-gel produced hydrate alumina on an aluminum-based alloy substrate using EPD. They obtained a 0.3 mm thick deposit taking 60 min at 2 V/cm. They also reported that an applied voltage >1 V/cm produced significant hydrogen and considerable density reduction. Hirata *et al.* [111] deposited Al_2O_3 at constant voltage of 50–300 V and observed that the deposition current was 5–200 mA. They produced ~ 1 mm thick Al_2O_3 deposits on a graphite cathode from an aqueous suspension of 1-20% (pH ~ 2.5).

Boncoeur and Carpenter [112] fabricated silica ingot mould with 80 mm in diameter and 150 mm high by deposition from an aqueous silica slip onto a metallic former. Clasen [113] electrophoretically deposited nanosized (10-100 nm) SiO_2 from an aqueous suspension using a semipermeable membrane that the ions of the suspension could pass but the particles couldn't. Oxygen evolution at the anode could still occur without causing porosity within the SiO_2 coatings. Nishimor *et al.* [114] produced 17 μm thick films of amorphous SiO_2 in 10 min at 93 V/cm and pH 11.7 on an aluminum substrate by combining sol-gel and EPD.

Nonaqueous suspensions are preferred for deposition of high-performance ceramics. Andrews *et al.* [115] used EPD of $\beta\text{-Al}_2\text{O}_3$ (<10 μm particle size) to form large (150 mm high) nose cones. They found that the ethanol media with dewaxed shellac and a small amount of water added gave the best results of the various organic mixtures that they investigated. They produced a 5 mm thick deposit in 15 min at 120 V and 0.3 mA/cm^2 . They covered the cathode with a silver-coated polymer to facilitate deposit release and drying. This work was extended by El-Jazairi *et al.* [116] who investigated the effects of addition of phosphoric acid to the ethanol/shellac suspending media. They found that the density of the deposit was dependent on pH.

Harbach *et al.* [117] used a fine colloidal suspension of alumina (0.45 μm) in ethanol with polyacrylic acid as a dispersant to produce homogeneous alumina components. Stainless steel was used as anodic deposition electrode.

Studies on EPD of ferroelectric materials have also been reported. Okamura *et al.* [118] deposited BaTiO_3 thick films on Pt-Si substrate. Fine hydrothermal-prepared powders (0.1 μm) in iodine and acetone suspensions were applied. Under condition 500 V/cm and for 2 minutes, dense and strong film with thickness nearly 40 μm was formed. The film shows tetragonal phase and good adhesion to the substrates. Ven Tassel *et al.* [119] have performed PZT powders deposition on Pt printed alumina substrates. After sintering at 900 $^{\circ}\text{C}$, a 10 μm dense continuous film was obtained. The film exhibited a polarization hysteresis equivalent to that of a bulk sample formed from the same starting powder, with a remnant polarization of 33 $\mu\text{C}/\text{cm}^2$.

EPD is flexible to deposit materials on conductive substrates with various shapes and dimensions. Harbach *et al.* [120-121] have used EPD to deposit zirconia tubes to fabricate homogeneous functional ceramic components. Using EPD, the drawback of agglomeration of the conventional powder processing and shaping methods was observed to be minimized. Smooth tubes with green dimensions of 110 mm length, 0.5 to 1.5 mm wall thickness, 34 mm outer diameter have been produced. The fired tubes had a characteristic strength of $\sigma_c = 420$ MPa and Weibull modulus $m = 15$. Zhitoirshky *et al.* [122] using this technique to deposit alumina and zirconia powders alternatively on carbon fibers. The thickness of individual layers was in the range of 1-10 μm and up to 20 layers of deposition. Also, Sarkar *et al.* [123] reported the use of EPD to fabricate yttria-stabilized zirconia (YSZ)/ Al_2O_3 multi-layered microcomposites. Totally 80 layers with each layer as thin as ~ 2 μm can be achieved by EPD. Van der Biest *et al.* [124-125] have also reported shaping different functionally graded ceramic and ceramic-metal composites successfully by EPD. Fully dense Y-TZP/Ce-TZP composites with a thickness of 2.1 mm were first produced by EPD. The obtained composites show a continuous gradient in composition, hardness and toughness. Later, they also fabricated continuously graded ceramic-ceramic $\text{ZrO}_2/\text{Al}_2\text{O}_3$ and ceramic-metal WC-Co composite plates. Boccaccini *et al.* [126-128] have established an EPD process to infiltrate fiber reinforced ceramic composites. The fibers (stainless steel or Ni-coated carbon fiber) were used as an electrode and put in the ceramic sols. Under a constant voltage (5~15 V), composites

with high green density were produced. These reports have suggested that EPD is flexible to deposit various sized and shaped structures using different materials.

2.5 Piezoelectric FGM monomorph ceramic actuators

A piezoelectric FGM monomorph actuator is a monolithic bending actuator made with gradient piezoelectric materials. The development of the actuator is aiming at solving the interface bonding problems of the conventional bimorph or unimorph actuators. A bimorph or unimorph is usually fabricated by bonding two PZT layers or one PZT layer and one elastic layer using polymeric epoxy binding agent. However, the physical bonding at the interface with a low bonding energy results in big problems on the performance and reliability of the bimorph and unimorph. These problems include [62, 69,129-138]

- (a) Increase of hysteresis and degradation of the displacement characteristics.
- (b) Driven by a periodic electric field, especially near resonance frequency and at high vibration amplitude, the interlayer is subject to relaxation, aging and delamination.
- (c) Fabrication processes involved, such as cutting, polishing, electroding and bonding, are rather laborious and costly.
- (d) The bonding agent may crack or peel off at low temperature, and creep occurs at high temperature.

The drawbacks have greatly limited the applications in the fields of measuring devices requiring high reliabilities. It is hence desirable to develop a monomorph with

three layers: a piezoelectric ceramic layer, a dielectric ceramic layer with a high dielectric constant and a transition layer whose dielectric and piezoelectric properties change gradually.

Fig. 2.20. Schematic structure of the FGM piezoelectric actuator, A: Dielectric layer, B: Piezoelectric layer, C: FGM middle layer, D: Electrode, E: Applied electric field, P: Polarization direction [131]

From Fig. 2.21, considering the difference in the sintering contraction, two layers with mixed compositions of A: $0.6\text{PNN}-0.4\text{Pb}(\text{Zr}_{0.3}\text{Ti}_{0.7})\text{O}_3$ and B: $0.5\text{PNN}-0.5\text{Pb}(\text{Zr}_{0.3}\text{Ti}_{0.7})\text{O}_3$ were pressed and sintered together to form the dielectric and piezoelectric layers, respectively. The gradient change of the compositional distribution can be observed from scanning electron microscope (SEM) photograph and electron probe microbeam analyses (EPMA) profile as shown in Fig. 2.21. The distribution of microstructure and composition induce the change of piezoelectric and dielectric constants, which resulted in the uneven strain along the cross section hence the bending displacement. The same bending principle was also applied by Kouvatov [136].

Fig. 2.21. SEM photograph and EPMA profile of A (0.6PNN-0.4Pb(Zr_{0.3}Ti_{0.7})O₃)-
B (0.5PNN-0.5Pb(Zr_{0.3}Ti_{0.7})O₃) diffusion couple monomorph [132]

Wu *et al.* [135] fabricated an asymmetric FGM actuator based on the change of the

Kouvatov [136] proposed a symmetric monomorph using materials $\text{BaTiO}_3 + \text{TiO}_2$. As shown in Fig. 2.23, where the piezoelectric constants mirror symmetrically align over the cross section according to the neutral surface. The advantage of this structure is that it induces a larger displacement compared with the asymmetric ones. However, the disadvantage is that it has an unreliable bonding interface. A similar symmetric structure was adopted by Shelley [137] who used materials of $\text{Pb}(\text{Zr}_{0.5}, \text{Ti}_{0.5})\text{O}_3$, $\text{Pb}(\text{Zr}_{0.475}, \text{Ti}_{0.525})\text{O}_3$, $\text{Pb}(\text{Zr}_{0.45}, \text{Ti}_{0.55})\text{O}_3$ to form a four-layer structure.

Fig. 2.23. Distribution of the piezoelectric constants [136]

The symmetric-asymmetric FGM actuator was proposed by Almajid [138]. As shown in Fig. 2.24, this actuator uses two FGM piezoelectric laminates (asymmetric) bonded together (symmetric). In each laminate, the piezoelectric and electroelastic properties varies smoothly from layer to layer. The reason to construct this configuration is to increase the out-of-plane displacement and also to decrease the stress concentration.

Two methods have been used to fabricate the FGM actuator up to now. One method is via diffusion bonding. In this method, two or more ceramic layers were first prepared with different compositions. The preparation of each layer can be made by powder metallurgy process or tape casting. Then, the layers were pressed and sintered together to form a single body. During sintering, the elements of each layer diffuse to their neighbors and finally form a monolithic ceramic. The monolithic plates were then cut and ground to the required dimension. After poling, the fabrication of the

FGM actuator is completed. Zhu and Wu [130, 135] have used this method to fabricate their actuators.

Fig. 2.24. Schematic of FGM symmetric-asymmetric actuator [138]

The other method to prepare the FGM actuator is through direct adhesion of poled plates. Such layers are usually glued to each other with epoxy [136]. To improve the bonding strength, Shelley has used centrifuge method to sequentially bind PZT layers with binders in between. This technique provides weak bond strength between the initial samples compared to that formed by diffusion method [137].

The above mentioned approaches to form the FGM actuators do provide a functional gradient, however, these techniques provide weak bond strength between the initial samples or lead to a discrete interface. Furthermore, the actuators fabricated by the above techniques have no improvement in miniaturization, especially in thickness (these actuators still having a thickness of 0.5-0.7 mm).

2.5.2 Performance characterization

The key parameter used to estimate the performance of the monomorph is the bending displacement. Zhu [131] has used a high magnification optical microscope equipped with a calibrated reticle to measure the displacement of an FGM actuator $20 \text{ mm} \times 8 \text{ mm} \times 0.7 \text{ mm}$ in dimension. A displacement of approximately $20 \text{ }\mu\text{m}$ was

measured under an applied voltage of 1000 V as shown in Fig. 2.25. The hysteresis is believed to be caused by the formation and movement of the domains.

Fig. 2.25. FGM monomorph actuator A (0.6PNN-0.4Pb(Zr_{0.3}Ti_{0.7})O₃)-B (0.5PNN-0.5Pb(Zr_{0.3}Ti_{0.7})O₃) bending displacement [131]

On the other hand, the displacement of the monomorph prepared by Wu [135] is determined by the resistivity gradients. Namely, the degree of bending depends on the difference in the ZB concentrations between the two sides of the composite. The larger the difference in doping concentrations is, the greater the bending deflection can be obtained. For example, a monomorph that is initially undoped on one side and that has 0.75 mol% ZB on the other side shows a 6 μm/cm deflection at a field of 500 V/mm. With the same field, a monomorph made from one side undoped and the other side 1 mol% ZB gives 18 μm/cm.

2.5.3 Modeling of FGM actuators

The current theoretical study about FGM actuator focused on two areas. One is the calculation of bending displacement and the other is the stress field analysis. Based on the monomorph configuration shown in Fig. 2.20, Zhu [131] derived the displacement under assumptions that (1) the dielectric and piezoelectric constants distribute

linearly; (2) the dielectric layer, the piezoelectric layer and the sandwich layer are equal in thickness; (3) the difference of Young's modulus along the across section are negligible and the static energy density is invariable. Using the energy method, the equation is derived to be [131]:

$$\zeta = \frac{2V}{1 + \frac{\varepsilon_1}{\varepsilon_2} + \frac{\varepsilon_1}{\varepsilon_3}} \left(d_{31}^B \frac{\varepsilon_1}{\varepsilon_3} - d_{31}^A + \frac{1}{12} (d_{31}^B - d_{31}^A) \frac{\varepsilon_1}{\varepsilon_2} \right) \frac{l^2}{t^2} \quad (2.24)$$

where d_{31}^A and d_{31}^B are the piezoelectric constants, ε_1 , ε_2 and ε_3 are dielectric constants, V is applied voltage, l and t are length and thickness respectively. Using this equation, the calculated displacement is larger than the experimental value. Therefore, this equation obtained on the above assumptions may deviate from the actual case, i.e., the equation cannot precisely predict the bending displacement of this type of FGM actuators.

Kouvatov [136], on the other hand, studied the relations between bending displacement and number of layers using the finite element method (FEM). The result is shown in Fig. 2.26. It was found that the displacement reduced with the increasing number of layers.

Fig. 2.26. Dependence of deflection on number of layers [136]

An important approach to analyze the stress distribution is FEM. The normal stress along the longitudinal direction σ_{xx} has been studied by Kouvatov [136]. The result is

shown in Fig. 2.27. The maximum stress is found at the interfaces and both the mechanical stress near the interfaces between the layers and the stresses at the surfaces of the sample are minimized when the number of layers is increased.

The Classical Lamination Theory (CLT) developed for composite materials was also proposed by Almajid *et al.* [138] to model the FGM actuator. Using this method, both the stress field and displacement of the actuator can be predicted. The results were in agreement with the FEM analyzed by the author himself.

Fig. 2.27. Dependence of the mechanical normal stress on the symmetric 2-layer and 4-layer monomorph [138]

2.5.4 Summary and future development

Several types of FGM actuators have been fabricated aiming at optimizing the stress distribution and improve the bending displacement. The materials used are piezoelectric or electrostrictive materials such as PZT, PNN and BaTiO₂. Diffusion and bonding techniques are applied for construction. The FGM actuators are characterized in the aspect of displacement. Theoretical works on predicting the displacement and stress field have also been carried out. The drawbacks of the reported work in the literatures are: (1) the bonding technique using epoxy cannot produce a high bonding strength interface; (2) the calculation of displacement and stress field distribution is not elaborated; and (3) the effect of the functional material properties and geometrical properties is not discussed. As a result, there exist a number of tasks to develop a FGM monomorph actuator with better performance, particularly in the following aspects:

- (a) Fabrication technique which can facilitate the production of desired continuous compositional and functional gradient.
- (b) Microstructure and materials improvement.
- (c) Complete study of displacement and stress distribution both in static and dynamic conditions with or without external loading.
- (d) More accurate and complete model on the monomorph behavior both in static and dynamic conditions.
- (e) Miniaturization of the actuator.

Chapter 3 Preparation and Characterization of Piezoelectric Ceramic Materials

In this chapter, the synthesis and characterization of the materials used for the fabrication of FGM monomorph actuators were described. The samples were first prepared, and then examined by XRD and SEM to study the physical properties of the materials. The piezoelectric properties were also measured. Based on the property analysis, the material systems of the optimum monomorph for later study were determined.

3.1 Synthesis of materials

In this section, the synthesis of the initial materials was introduced. The compositions of the initial materials, PZT0 and PZT1, are listed in Table 3.1. These two materials were selected due to the following reasons [139-146]

- (a) A large difference in piezoelectric properties, which induces the bending motion of the monomorph, exists between PZT1 and PZT0.
- (b) PZT1 is a hard material with small field-induced hysteresis.
- (c) PZT1 contains sintering additives $0.03\text{BiFeO}_3\text{-}0.02\text{Ba}(\text{Cu}_{0.5}\text{W}_{0.5})\text{O}_3$ which aid the sintering behavior and reduce its sintering temperature.
- (d) PZT1 and PZT0 have similar shrinkage behavior (PZT0, 14.36%; PZT1, 14.19%) after sintering at 1100 °C. This is propitious to reduce the warp of the monomorph during sintering due to different shrinkage.

in a programmable furnace for PZT1 and PZT0, respectively. The temperature profile is shown in Fig. 3.1. Then, the calcined powders were smashed and ground by planetary ball milling under the speed of 150 rpm in ethanol for 20 hours. The ratio of powder/ball/ethanol is approximately 2/4/1. After planetary ball milling and drying, the powders were passed through a 100-mesh sieve to remove those big agglomerated particles.

Table 3.1. Composition and preparation condition of the selected PZT systems

System	Composition	Raw powders	Calcination condition
PZT0	$\text{Pb}(\text{Zr}_{0.52}\text{Ti}_{0.48})\text{O}_3$	PbO>99.9% ZrO ₂ >99.9% TiO ₂ >99.9% +3%PbO	850 °C ×2 hrs
PZT1	0.95Pb(Zr _{0.52} Ti _{0.48})O ₃ · 0.03BiFeO ₃ · 0.02Ba(Cu _{0.5} W _{0.5})O ₃ +0.5wt%MnO ₂	PbO>99.9% ZrO ₂ >99.9% TiO ₂ >99.9% BiO ₃ >99.99% Fe ₂ O ₃ >99% BaO >99% CuO>99.99% WO ₂ >99% MnO ₂ >99.99% +3% PbO	750 °C ×2 hrs

* All powders were from Aldrich Chemical Company, Inc., USA, except for Fe₂O₃ from Merek KgaA, Germany.

Fig. 3.1. Temperature profile for calcinations

3.2 Sample preparation

3.2.1 Suspension characterization

The properties of the final deposited products are largely dependent on the quality of the suspensions. In this section, the suspension properties for EPD were studied. The essential parameters include particle size, zeta potential and pH value.

In this thesis, the ceramic powders in absolute ethanol were applied as suspensions. In electrophoresis, the suspension medium is of great importance. The preferred properties of the suspension medium are low viscosity, high dielectric constant and moderate conductivity [93, 122, 143-155]. In this work, the medium selected was ethanol due to its better chemical stability than water. It is also less hazardous to health than other non-aqueous media [93, 152-153].

For electrophoretic deposition, a stable and dispersed suspension is essential. Suspension stability can be studied by measuring the zeta potential of the suspension. The zeta potential provides information on the double layer interactions and gives a qualitative idea about the dispersing conditions [154].

The zeta potential is sensitive to pH. It can be determined as a function of pH value to identify the stability of the suspensions. In general, a high absolute zeta potential value represents a well dispersed suspension. In this work, the PZT0 and PZT1 suspensions were prepared in ethanol with concentration of 0.20 mg/ml. 10% HNO₃ acid (HNO₃ in ethanol) was added to the suspension to adjust pH value. The suspensions were dispersed using ultrasonic agitation for 10 minutes. The zeta potential measurement was then carried out using ZetaPlus (Brookhaven Instruments, USA) on suspensions of various pH values.

Fig. 3.2 shows the zeta potential of PZT0 and PZT1 suspensions as a function of pH. The measurement range is pH < 7. Ceramic powders are positively charged with H⁺. This can be indicated from the positive zeta potentials in all the measurement range in Fig. 3.2 and it also implies that under an applied electric field, the powders move towards and deposit on the cathode graphite substrate. The PZT0 suspension has shown larger zeta potential than PZT1, indicating that PZT0 suspension is more stable. To be noted, PZT0 and PZT1 suspensions showed the similar profile with a maximum zeta potential around pH = 4.6, implying the presence of a stable suspension near this pH value. As a result, pH value of the suspensions was adjusted to 4.6 for subsequent deposition. The variation of the zeta potential with pH is due to

the effect of ionic concentration in the suspension [94, 156-158]. When HNO_3 acid is added into the suspension, the surface charge density of H^+ increases on the particles, leading to the formation of thicker double layers. This, in turn, repulses the particle from attraction and sedimentation. Thus, a stable suspension with high zeta potential was observed. However, as more acid is added, there is a presence of excess free H^+ ions, which may not be able to adsorb onto the surface of the oxide particles so that the total number of ions available in the suspension would increase. The increase in the ionic concentration increases the reaction between free ions and counter-ions. As a result, the thickness of the double layer reduces and Van der Waal attractive forces became dominant, which may narrow the distance between two particles and induce coagulation [103,159]. So a decrease in the measured zeta potential with further increasing content of acid can be observed.

Fig. 3.2. Zeta potential vs. pH value of PZT0 and PZT1 suspensions

The particle sizes of the fine PZT0 and PZT1 powders after ball milling used for subsequent electrophoretic deposition were measured and analyzed. The suspension with 1.2 g powder in 120 ml ethanol was prepared for characterization. The pH value was controlled to be approximately 4.6 at room temperature for maximum dispersion. The suspension was subject to ultrasonic agitation for 10 minutes to break any agglomerations. The particle size of PZT0 and PZT1 powders were then measured using an Acoustic Spectrometer DT-1200 (Dispersion Technology, Inc.) and confirmed by scanning electron microscopic observation.

The particle size distributions of PZT0 and PZT1 powders are shown in Fig. 3.3. The particles size distributes in a range from 0.83 to 1.51 μm for PZT0 powders. The mean particle size was 1.12 μm . Over 70 wt% of PZT1 powders have a diameter above 1 μm . The particle size range for PZT1 powders was 0.80 to 1.37 μm and the

Table 3.2. The designed compositions in the PZT0-PZT1 system for EPD

Specimen No.	1	2	3	4	5	6
Composition (wt%)	PZT1 100%	PZT1 90% PZT0 10%	PZT1 80% PZT0 20%	PZT1 70% PZT0 30%	PZT1 60% PZT0 50%	PZT1 50% PZT0 50%
Specimen No.	7	8	9	10	11	/
Composition (wt%)	PZT1 40% PZT0 60%	PZT1 30% PZT0 70%	PZT1 20% PZT0 80%	PZT1 10% PZT0 90%	PZT0 100%	/

Fig. 3.4 shows the schematic drawing of the electrophoretic deposition system. The electrophoretic cell includes a cathodic graphite substrate placed in the center of a cylindrical-shaped stainless-steel counter anodic electrode. The cathode and anode were separated with a constant distance. The suspension was stirred using a magnetic stirrer to avoid sedimentation of the powders during the process. A dc power supply is used to generate electric field between the anode and cathode. During deposition, the particles move towards and deposit on the graphite cathodic electrode.

Fig. 3.4. Setup for electrophoretic deposition system

A graphite rod with a dimension of 3 mm in diameter and 60 mm in length was applied as the deposition substrate in this deposition. Suspensions were prepared by adding the prepared powders as listed in Table 3.2 in ethanol and then subjected to

ultrasonic agitation for 10 minutes. The powder concentration in the suspension was 50 g/l and the suspension pH was controlled to be 4.6 by adding HNO_3 . The suspension was stirred for 3 to 6 hours to make sure the complete dissolution and dispersion of the powders in the media. The deposition was performed at a constant voltage of 70 V for 3 minutes. The deposits were then dried for 12 hours in a dry keeper at room temperature before sintering.

Fig. 3.5 shows the SEM observation of the PZT0 and PZT1 powders after deposition. The images have shown consistent result with the Acoustic Spectrometer measurement. It can also be seen that a distribution of the particle size exists. It is believed that it improves the deposition density [104]. This is because the smaller particles could insert into the pores formed between the bigger particles during deposition. This can hence minimize the porosity of the deposit and finally result in a dense and uniform sintered product.

Fig. 3.5. SEM images of the PZT powders after deposition

The deposits were then put in an alumina crucible containing PbZrO_3 tablets to minimize PbO evaporation during sintering in air. The sintering process was divided into two steps as shown in Fig. 3.6. First, the deposits were fired at 600 °C for 30 minutes. The graphite substrate was burnt out in this process. Then, the deposits were heated to 1100 °C and sintered for 1 hr. To prevent warp and cracking of the sintered body, a low heating rate (2 °C/min) was applied as shown in the figure. The final wall thickness of the sample obtained was approximately 0.3 mm.

The green density and sintering density of the 11 compositions with their percentage to the theoretical value were measured and shown in Fig. 3.7. The green

density was estimated by measuring the volume and weight of the deposits. The green density of the six materials distributed from 48% to 52% of the theoretical value (7.9 g/cm³). After sintering, the density of the eleven materials was measured using Densimeter MD-200S. The sintering density exceeds 93% of the theoretical density. From PZT0 to PZT1, the density increases. This may be the effect of the doping elements which promote the densification of the materials [161].

Fig. 3.6. Sintering temperature profile of the deposits

Fig. 3.7. Density of the 11 compositions

The samples of the 11 compositions after sintering are shown in Fig. 3.8. They exhibit uniform shapes. After sintering, the samples exhibited a linear shrinkage of about 15%. The samples were then cut and ground to the desired dimensions for materials characterization.

Fig. 3.8. Samples for materials characterization (from left to right, specimen No. 1 to 11)

3.3 Physical characterization

3.3.1 Crystallographic characterization

The planetary ball-milled powders (PZT0 and PZT1) and the sintered deposited samples were analyzed using X-ray diffraction technique to determine the composition of the ferroelectric phase structure and the variation in crystal lattice with the increasing doping elements. The sintered samples were crushed into powders in order to obtain sufficient number of crystalline particles for observation and measurement in all directions. The measurements were performed using Shimadzu XRD-6000 Diffractometer with Cu target under 50.0 kV, 20.0 mA and 2.0 deg/min scan speed for 20° ~ 70° analysis and 0.2 deg/min scan speed for 43° ~ 46° analysis.

Figs. 3.9 and 3.10 illustrate the X-ray diffraction patterns of ball-milled (planetary ball-milling) PZT0 and PZT1 powders, respectively. During calcination, the starting oxide powders react with each other and form the PZT solid solutions. From the XRD pattern, both materials showed perovskite structures. No peaks corresponding to the starting powders of PbO, ZrO₂, TiO₂ or additive oxides were observed. This indicated a complete chemical reaction of all the starting powders under the employed calcination condition. Also, no peaks at position 29° corresponding to pyrochlore phase were observed. The pyrochlore structure will degrade the piezoelectricity of the materials if it is formed due to its non-ferroelectric properties [3].

Fig. 3.9. X-ray diffraction pattern for ball-milled PZT0 ceramic

Fig. 3.10. X-ray diffraction pattern for ball-milled PZT1 ceramic

Based on the composition, there are two phases near the morphotropic phase boundary (MPB) for PZT materials as introduced in the literature review. They are tetragonal and rhombohedral phases. The main peaks for tetragonal phase are

$$\begin{array}{cccccc} (001) & (100) & (101) & (110) & (111) & (002) & (200) \\ (102) & (201) & (112) & (211) & (022) & (220) \end{array}$$

And the main peaks for rhombohedral phase are

$$\begin{array}{cccccc} (100) & (110) & (1\bar{1}0) & (111) & (11\bar{1}) & (200) & (210) \\ (2\bar{1}0) & (211) & (21\bar{1}) & (\bar{2}11) & (220) & (2\bar{2}0) \end{array}$$

Because the composition near MPB and also due to composition fluctuation, both phases may exist. Since these two phases have close lattice parameters, they may stack together or overlap each other. To distinguish them, the peaks near 45° can be analyzed as shown in Fig. 3.11 [162], where the relations between phase structure and diffraction peaks are clearly illustrated. The shape of the peaks gradually changes from two sharp peaks (002) and (200) of the tetragonal phase (Fig. 3.11 (a)), passing through three stacking peaks representing the coexistence of the two phases (Fig. 3.11 (b, c, d)), to one single peak (200) of rhombohedral phase (Fig. 3.11 (e)). Based on this relation and comparing the diffraction peaks in the inserts in Figs. 3.9 and 3.10 with Fig. 3.11 (b), the similar shape and position of the diffraction peaks can be found indicating the coexistence of tetragonal and rhombohedral phases for the calcined materials. The overall peak was then split by fit. The split peaks were considered to have a Gaussian distribution. The exact peak position is determined by the lattice parameters of corresponding phase. During fit, the highest point was regarded as the peak position. Three peaks, $(002)_T$ and $(200)_T$ representing the tetragonal phase and $(200)_R$ representing the rhombohedral phase, were identified as shown in the Figs. 3.9 and 3.10, respectively. The ratio of rhombohedral and tetragonal phases can be roughly estimated using the areas of the peaks. The coexistence of the two phases near morphotropic phase boundary (MPB, Zr/Ti~52/48) provides many advantages. The piezoelectric coefficients, electromechanical coupling coefficients, dielectric permittivity and remnant polarization measured on the piezoelectric ceramic samples reach a peak in this region of MPB, due to the ease of domain reorientation at compositions close to MPB [4, 6, 17, 51]. These coexisting phases were indexed in Figs. 3.9 and 3.10.

Fig. 3.11. Relations between phase structure and diffraction peaks [162], T: tetragonal; R: rhombohedral

Fig. 3.12 shows the diffraction patterns of deposited powders from specimen No. 1 to 11 after sintering at 1100 °C for 1 hour. The scan ranges from 43° to 46°. It is apparent that the compositions mainly consist of tetragonal phase implied from the two sharp peaks at 45°. It can also be seen that the 2θ position of (002) and (200) peaks changes gradually, indicating the continuous change of the lattice parameters as composition changes.

Fig. 3.12. X-ray diffraction patterns around 45° for different composition deposited powders

In the tetragonal phase, the following relations exist

$$\begin{cases} a \sin \theta_{200} = b \sin \theta_{200} = 2d_{200} \sin \theta_{200} = \lambda_{Cuka} \\ c \sin \theta_{002} = 2d_{002} \sin \theta_{002} = \lambda_{Cuka} \\ c/a = \sin \theta_{200} / \sin \theta_{002} = kP_s \end{cases} \quad (3.1)$$

in which, a, b, c are the lattice parameters, d_{200} and d_{002} are the inter-planar spacings

of the (200) and (002) planes, respectively, θ is diffraction angle, P_s is the spontaneous polarization and k is a constant. It is also noted that in the tetragonal phase, the spontaneous polarization is proportional to the c/a ratio. As the spontaneous polarization affects the piezoelectric properties of the material such as dielectric constant and piezoelectric constant, the calculation of the c/a ratio is important. This ratio can be calculated using Eq. 3.1 and has been shown in Fig. 3.13. It can be seen that the c/a ratio increases as PZT1 content reduces. This indicates that the c/a ratio or spontaneous polarization decreases with the increase of doping elements. The significance of the change in c/a ratio to the piezoelectric properties will be discussed in more detail in the following sections.

Fig. 3.13. The c/a ratio of different composition deposited powders

3.3.2 Microstructural study

Fig. 3.14 displays the microstructure of the 11 compositions. The grain size distribution and average grain size were calculated and presented in Fig. 3.15. The grain size distribution was obtained by measuring the average size of individual grain and calculating the weight ratio of different-size grains over all the studied grains. The average grain size calculation is based on the following equation [163]

$$Z = \frac{\sum_{i=1}^4 \text{Length of Line } i}{\text{Number of grains}} \times 1.5 \quad (3.2)$$

where the four lines ($i = 1-4$) selected for the estimation is shown in Fig. 3.16. It can be seen that the average grains size falls in the range from 4.5 to 7.5 μm with maximum value in the middle composition. The variation of the grain size is mainly due to the doping content in the composition. The increase of the grain size in the initial compositions (near PZT1 side) as shown in Fig. 3.15 is attributed to the decrease of the grain growth inhibitor content, $\text{Ba}(\text{Cu}_{0.5}\text{W}_{0.5})\text{O}_3$ [146]. After reaching the maximum value, the grain size begins to decrease due to the influence of the PZT0. There are no dopings in PZT0 content and PZT0 doesn't grow significantly under the current sintering conditions. As the PZT0 content increases, the grain size becomes smaller. Large grain size is usually advantageous to obtain good piezoelectric properties [4, 44].

Fig. 3.14. Surface microstructure of the 11 samples

(a) Grain size distribution

(b) Average grain size

Fig. 3.15. Grain size distribution and average grain size of the 11 compositions

Fig. 3.16. Estimation of grain size

3.4 Electromechanical property characterization

For the materials designed for the monomorph actuator, the most important consideration is the electromechanical property of the materials. In the following sections, the electromechanical properties of the 11 compositions used were investigated. Young's modulus Y , piezoelectric constant d_{31} , dielectric constant ϵ_{33}^T and other related parameters were measured and analyzed.

3.4.1 Experimental process

(a) Poling of the sample

The samples were cut and ground to the desired dimension of about 12 mm in length. Then the samples were coated with silver electrode on both outer and inner surfaces. After that, poling was carried out in silicone oil at 100 °C by applying a DC field of 2 kV/mm in the thickness direction for 30 minutes. After 24 hrs of aging at room temperature, the electromechanical properties were measured.

(b) Measurement of P-E hysteresis loop

RT6000HVA ferroelectric tester (Radiant Technologies. Inc.) was used to conduct the measurement. Eleven samples were coated with silver electrode and used to carry out the P-E hysteresis loop measurement. They were immersed into the silicon oil in order to prevent arcing during measurement. The electric field was controlled at 2 kV/mm.

(c) Measurement of Young's modulus

The dielectric constant and Young's modulus of the materials were measured using the conventional resonance method with HP 4194A Impedance/Gain-Phase Analyzer. The variation of impedance against frequency of the sample was measured. A typical profile of impedance was shown in Fig. 3.17. The profile is characteristic by two peaks, the low impedance peak corresponding to the resonant frequency f_r and the high impedance peak corresponding to the antiresonant frequency f_a . By measuring the resonant frequency f_r , Young's modulus Y can be determined using

$$Y = 4l^2 f_r^2 \rho \quad (3.3)$$

where l is the length and ρ is the density of the samples.

Fig. 3.17. Impedance profile of a sample

(d) Measurement of dielectric constant

The measurement of dielectric constant ϵ_{33}^T is based on the following equation [164]

$$\epsilon_{33}^T = \frac{C^T \cdot \ln(r_{ou}/r_{in})}{2\pi l} \quad (3.4)$$

where C^T is the capacitance at low frequency, normally 1 kHz; l is the length; and r_{ou} and r_{in} are the outer and inner radius of the samples respectively. By measuring the capacitance, the dielectric constant can be obtained.

(3) Measurement of piezoelectric constant d_{31}

To determine the piezoelectric constant d_{31} of the sample, the static measurement method was applied based on the following standard piezoelectric relationship

$$S_1 = d_{31} E_3 \quad (3.5)$$

where S_1 is the strain in the longitudinal direction of the sample and can also be expressed as

$$S_1 = \frac{\Delta l}{l} \quad (3.6)$$

in which Δl and l are the displacement in the longitudinal direction and length of the sample, respectively. E_3 is the average electric field and can be expressed as [10]

$$E_3 = \frac{2V}{(r_{ou} + r_{in}) \ln \frac{r_{ou}}{r_{in}}} \quad (3.7)$$

where V is the voltage applied in the wall thickness direction. By measuring the electric field E_3 and mechanical strain S_1 , d_{31} can be determined using Eq. 3.5.

The setup for displacement measurement consists of a RT6000HVS ferroelectric test system (Radiant Technologies, Inc.), a Vibraplane (RS Kinetic Systems, Inc.), a MTI-2000 fonic sensor (probe: MTI2032RX, MTI Instruments) and the sample assembled together as shown in Fig. 3.18. The fonic sensor is a fiber optical displacement sensor which utilizes adjacent pairs of light-transmitting and light-receiving fibers. The basis for the operating mechanism is the interaction between the field of illumination of transmitting fibers and the field of view of the receiving fibers. In the measurement, the light from the source transmitting fibers of the MTI 2000 probe will be reflected by the target surface to be measured and captured by the receiving fibers. The amount of captured light is the function of the probe-to-target displacement. Fonic sensor thus can detect the variation of the captured light and indicates the probe-to-target displacement. The resolution limit of fonic sensor using 2032RX probe is 2.5 Å over a frequency range from DC to 130 kHz and the accuracy is within 1.0% [165-166]. The sample was coated with silver paste at both inner and outer surfaces as conductive electrodes. One end of the sample was fixed to the vibraplane to avoid any vibration-induced errors. The other end was attached with a reflection mark. The fonic sensor probe was targeted at the center of the mark and placed parallel to the longitudinal direction. During the measurement, a bipolar step voltage as shown in Fig. 3.19 [167] was applied in the wall thickness direction of the sample. The step voltage was increased from zero to maximum set voltage V_{set} , then decreased to the negative maximum set voltage $-V_{set}$, and finally returned to zero. The fonic sensor measured the displacement Δl of the sample in response to the step voltage. The measured data were transferred to the RT6000HVS ferroelectric tester and recorded.

The piezoelectric constant can be determined from Fig. 3.20. The figure shows the strain S_1 as a function of Electric field E_3 . According to Eq. 3.5, the piezoelectric constant d_{31} of the sample can be obtained from the slope of the fit line in the figure.

Fig. 3.18. Setup for displacement measurement

Fig. 3.19. Voltage profile for hysteresis measurement

Fig. 3.20. Determination of piezoelectric constant d_{31}

3.4.2 Results and discussion

The polarization against electric field hysteresis loop and remnant polarization are plotted in Fig. 3.21. The remnant polarization was obtained from the polarization at the zero electric field in the P-E curve. It can be seen that as PZT1 composition reduces, the remnant polarization increases gradually, reaches a maximum and then drops. This variation is attributed to the result of domain reorientation in the ceramics [5, 9]. In piezoelectric ceramics, the domains rearrange when subjected to the external electric field. The remnant polarization is mainly determined by two factors: the number of reoriented domains and the magnitude of spontaneous polarization, which is proportional to the c/a ratio in tetragonal phase. It is noted from Fig. 3.13 that as PZT1 content decreases, the c/a ratio increases linearly. As a result, the remnant polarization may first increase due to the increase of the magnitude of spontaneous polarization. However, as the c/a ratio further increases, the restriction from the stress will also increase. Thus, upon reaching a certain value, the number of reoriented domains decreases due to the restriction of the stress, and the remnant polarization decreases after that point.

(a) P-E hysteresis loop

(b) Remnant polarization

Fig. 3.21. P-E hysteresis loop and remnant polarization of specimen No. 1 to 11

The density ρ and electromechanical properties, Young's modulus Y , piezoelectric constant d_{31} and dielectric constant ϵ_{33}^T , were determined and listed in Table 3.3. They will be applied to the calculation of the displacement and the analysis of the stress field of the monomorph actuator. High density is an important basic requirement on the piezoelectric ceramic. Density affects both the electric and mechanical properties of the actuator. First of all, the high-density material with lower porosity will increase dielectric constant ϵ_{33}^T of the materials. This is because piezoelectric materials have much larger dielectric constant than air. A large porosity will obviously reduce the average value of the dielectric constant due to air in the pores. The porosity will also produce non-uniform electric field in the ceramics. The electric field in pores is much larger than that in the ceramics. Thus the pores are more likely to discharge due to lower breakdown voltage than ceramics if high electric field is applied. Once discharge happens, much heat generates and burns the ceramics. This hence reduces the breakdown voltage or dielectric strength of the ceramics. Large porosity also allows the ingress of moisture into the ceramics, leading to degradation of the insulation resistance. This will increase the leakage current and dielectric loss of the

material. The piezoelectric constant d_{31} is also affected by the density. This is because that the piezoelectricity is largely contributed by the extrinsic effect – motion of domain walls – of the ceramics. However, pores as defects pin and restrict the domain wall motion and domain switch, hence, reduces the piezoelectric properties of the materials. In mechanical properties, pores obviously decrease the cross-sectional area on which the load is applied and also act as stress concentrators. The strength of ceramics and Young's modulus Y are thus decreased with the increase of the porosity.

Table 3.3. Properties of the characterized PZT compositions

Specimen No.	ρ (10^3 kg/m^3)	Y (10^{10} Pa)	d_{31} (10^{-10} m/V)	ϵ_{33}^T (10^{-8} F/m)
1	7.641	8.72	-9.95	6.09
2	7.617	8.59	-10.72	6.38
3	7.583	8.29	-10.91	6.54
4	7.545	8.03	-11.33	6.86
5	7.548	7.77	-12.20	7.00
6	7.542	7.41	-12.36	7.22
7	7.523	7.32	-10.41	6.90
8	7.511	6.86	-9.69	6.82
9	7.442	6.49	-9.08	6.65
10	7.415	5.67	-7.98	6.60
11	7.400	5.47	-6.25	6.36

Piezoelectric constant, d_{31} , is another important parameter, because it is directly proportional to the displacement. The deflection amplitude of the monomorph is largely determined by this factor. Dielectric constant ϵ_{33}^T , on the other hand, affects the distribution of electric field and also influences the amplitude of deflection. Young's modulus, Y , describes the stress T and strain S relation by $T = YS$. A sample with a higher Young's modulus will produce a larger force at the same deflection and dimensions. Young's modulus is a function of frequency constant ($f_r \cdot l$) and density (ρ) as indicated in Eq. 3.3. It does not significantly contribute to the displacement. The effects of these three parameters will be discussed further in Chapter 5.

The ϵ_{33}^T values of the 11 compositions measured are shown in Fig. 3.22. As the PZT1 content decreases in the composition, the dielectric constant increases initially,

and reaches a peak value, then drops. This variation can be explained from the aspect of domains reorientation and changes of the c/a ratio. There exists both 90° domain and 180° domain in the ceramics, which have different effects on the dielectric constant. The reorientation of 180° domain will increase the dielectric constant; whereas the 90° domain will decrease the constant [168]. However, the reorientation of 90° domain will induce stress in contradiction to the 180° domains. As analyzed earlier, the c/a ratio increases as PZT1 content decreases, hence, the number of reoriented 90° domains may reduce due to the stress restrictions. This will result in the increase of dielectric constant. On the other hand, it is also noted that the increase of the c/a ratio will reduce the dielectric constant [17]. The 180° domain can be assumed to be constant because it is not stress related. Therefore, the combination of the three effects, 90° domain, 180° domain and c/a ratio, gives rise to the final profile of the distribution of the dielectric constant. From the viewpoint of the microstructure, the later drop of the dielectric constant may also due to the decrease of the density because pores reduce the dielectric constant as introduced earlier.

Fig. 3.22. Variation of dielectric constant ϵ_{33}^T as a function of composition

The variation of Young's modulus Y with the composition is shown in Fig. 3.23. It can be found that Young's modulus Y basically decreases monotonously with the increase of PZT0 content in the mixed materials. This variation is consistent with that

of the density. This indicates that Young's modulus is largely affected by the porosity of the samples. Because from PZT1 to PZT0, the porosity monotonously increases, Young's modulus Y decreases.

Fig. 3.23. Variation of Young's modulus Y as a function of composition

The piezoelectric constant d_{31} of the 11 compositions is plotted in Fig. 3.24. The variation is similar as that of the dielectric constant and remnant polarization. There is a peak value near specimen No. 6. The variation of piezoelectric constant can be verified as follows:

It is noted that d_{31} is a function of electrostrictive factor Q_{12} , remnant polarization P_r and dielectric constant ϵ_{33}^T [16, 51, 167-168] as shown in the following relation

$$d_{31} = 2Q_{12}P_r\epsilon_{33}^T \quad (3.8)$$

where Q_{12} is electrostrictive factor and can be estimated using

$$x_1 = Q_{12}P_s^2 \quad (3.9)$$

In this equation, x_1 is the strain of lattice parameter a from cubic to tetragonal phase; P_s is the spontaneous polarization. x_1 can be estimated by

$$x_1 = \frac{a_T - a_c}{a_c} \quad (3.10)$$

where a_T and a_c are the lattice parameters in tetragonal and cubic phases, respectively. The spontaneous polarization P_s can be estimated by using c/a as indicated in Eq. 3.1. The lattice parameters can be estimated from Fig. 3.12.

Fig. 3.24. Variation of piezoelectric constant d_{31} as a function of composition

The variation of Q_{12} , ϵ_{33}^T and P_r has been shown in Fig. 3.25. The parameters have been normalized by dividing their maximum. The product of the three parameters determines the variation of d_{31} . However, from these results, it can be seen that Q_{12} and ϵ_{33}^T does not vary significantly. So, the profile of d_{31} is mainly determined by the remnant polarization.

Fig. 3.25. Factors influencing the distribution of piezoelectric constant d_{31}

3.4.3 Determination of material system

From above material property analysis, it is found that both piezoelectric constant d_{31} and dielectric constant ϵ_{33}^T have a complicated relationship with the composition of the samples. On the other hand, the Young’s modulus basically decreases with the increase of PZT0 content in the mixed materials. As piezoelectric constant d_{31} is the key parameter to generate the bending displacement of the monomorph, the compositions to form the FGM structure over the cross section of the monomorph is determined according to the variation of d_{31} . Based on this, three systems have been selected and are shown in Fig. 3.26. They are: (a), 2-layer system; (b), 4-layer system; and (c), 6-layer system. These systems form a compositional and functional gradient over the cross section and will be briefly discussed below.

(a) 2-layer system

This system is chosen for the first improvement on the traditional bimorph. It is different from the bimorph on its binding. Bimorph basically consists of two piezoelectric ceramic sheets which are bonded over their entire long faces using bonding agent (usually epoxy resin) and suitably covered with electrodes. The current 2-layer system monomorph is fabricated using EPD technique and then fired together under high temperature. Thus, it has a stronger binding interface than bimorph type actuator.

(b) 4-layer system

This system is studied on the multi-layer approach. A monomorph with 5 layers has been developed in the earlier stage of this work, however, it is noted that the piezoelectric constant d_{31} , as shown in Fig. 3.27, does not vary monotonically over the cross section. This will result in the uneven stress distribution on the monomorph. Hence, the 4-layer system is selected. This is because this material distribution will result in both microstructural and function gradient. In addition, largest piezoelectric constant difference exists between the first layer and last layer, which will result in larger bending displacement of the monomorph.

Fig. 3.27. Distribution of piezoelectric constant d_{31} for the monomorph developed earlier

(c) 6-layer system

We also want to know if more layers are adopted, the property of the monomorph will get better or worse. So 6-layer system is chosen to check the effect of the number of layers on the bending displacement and stress distribution of the monomorph.

These systems will be studied in detail in the following chapters.

3.5 Concluding remarks

In this chapter, we performed the preparation and characterization of the 11 material compositions, namely, 100% PZT1, 90% PZT1 + 10% PZT0, 80% PZT1 + 20% PZT0, 70% PZT1 + 30% PZT0, 60% PZT1 + 40% PZT0, 50% PZT1 + 50% PZT0, 40% PZT1 + 60% PZT0, 30% PZT1 + 70% PZT0, 20% PZT1 + 80% PZT0, 10% PZT1 + 90% PZT0, and 100% PZT0. Their crystallographic structure, microstructure and piezoelectric properties were studied. The gradient variations in composition, microstructure and piezoelectric parameters such as Y , d_{31} , ϵ_{33}^T were also discussed. Several conclusions are drawn as follows:

1. The particle size of PZT0 and PZT1 distributes in a wide range with a mean value of 1.12 and 1.01 μm , respectively. The size variation exists to help deposition by filling in cavities with small particles.
2. Both PZT0 and PZT1 prepared suspensions have maximum zeta potential around $\text{pH} = 4.6$, indicating the similar deposition properties. The pH value can be adjusted by adding acid into the suspension.
3. The conventional powder metallurgy technique to prepare PZT0 and PZT1 powders were confirmed to be effective to provide perovskite structure after calcination. This structure contains rhombohedral and tetragonal phases with different ratio in the mixture.
4. After sintering, the 11 mixtures of PZT0 and PZT1 were proven to be tetragonal phase perovskite structure. Also, the c/a ratio linearly increases with the increase of the content of PZT0 in the mixture.
5. The microstructure of the sintered materials varies with composition. The maximum grain size was found when equal amount of PZT0 and PZT1 were mixed.

6. The electromechanical properties are determined. Both piezoelectric constant d_{31} and dielectric constant ε_{33}^T increase first, and then reach a maximum before dropping with increasing PZT0 content. The Young's modulus Y decreases monotonously with more PZT0 content.
7. Three material systems, 2-layer system, 4-layer system and 6-layer system, were identified to be studied further on their functional properties.

Chapter 4 Fabrication of FGM Monomorph

The fabrication of the FGM monomorph actuators on the material systems identified in Chapter 3 is discussed in this chapter. Fabrication technique is an important part of the monomorph actuator. It determines the distribution of the compositions and properties, which will lead to the final performance of the device. The normally used methods such as bonding, tape casting or diffusion-couple result in either weak interface or little control of the compositional gradient. Applying EPD to fabricate the FGM monomorph actuator minimizes these problems and also allows the miniaturization of the actuator.

4.1 Introduction of experimental procedure

The fabrication process of FGM monomorph actuator can be generalized in a flow chart as shown in Fig. 4.1. The process starts from the initial powders, and then EPD is used to form the deposits. Next, the deposits are sintered and cut into the final desired dimensions. After poling, a monomorph is formed.

Fig. 4.1. Flow chart of fabricating FGM monomorph actuators

The powders were prepared by mixing different compositional ball-milled PZT0 and PZT1 powders according to the material systems described in Chapter 3. Then, these powders were prepared into suspensions for the EPD process. The details of suspension preparation have been discussed in Chapter 3.

Instead of the round cylindrical cathode used in Chapter 3, a flat cylindrical cathode as shown in Fig. 4.2 was employed to deposit the FGM monomorphs. The tube wall

between AC and BD can be cut to form two plates for monomorph actuator. The application of the flat cylindrical cathode substrate has two advantages. First, two plates can be obtained in one process. Second, the distortion of the deposits will be minimized due to more homogeneous shrinkage of the symmetrical tubular structure.

Fig. 4.2. Schematic drawing of the cross section of graphic substrate and deposits

After deposition, the plate-tubes were sintered under the sintering profile (Fig. 3.6) and then cut into two plates (Fig. 4.2(b)). The plates were then ground into the rectangular shape with desired dimensions.

The rectangular-shaped piezoelectric plate was coated with silver electrode and poled in silicone oil at 100 °C for 30 mins under 2 kV/mm. After poling, the fabrication of the FGM piezoelectric monomorph actuator was completed.

4.2 Fabrication of FGM monomorph actuators using EPD

4.2.1 Deposition parameters and procedure

In this section, multilayer deposition technique was used to form the FGM structure of the monomorph (Fig. 4.3). The procedure for the fabrication of the monomorph of 6-layer system is illustrated. The other two systems, i.e., 2-layer and 4-layer systems, follow similar procedure.

Fig. 4.3. Schematic drawing of the deposition procedure

Six suspensions with required composition were first prepared. The powder concentration in the suspension was 50 g/l and the suspension pH was controlled to be 4.6. The suspension was stirred for 3 to 6 hours to make sure the complete dissolution and dispersion of the powders in the medium. Then Suspension 1 was first utilized to deposited n ($n = 3 \sim 6$) times depending on the desired thickness. The same procedure was followed by suspension 2 to 6. For each individual deposition, 1 minute was applied. The interval between each deposition was controlled to be 10 minutes. The duration of each deposition and interval between depositions are critical for the procedure. If the deposition was too long (i.e., too thick deposit at one go), the deposits will peel off from the electrode. On the other hand, very little powders can be deposited if the time is too short. If the interval between depositions was too short, the deposit cannot be dried and tends to peel off during the next deposition. If the interval time is too long, a sharp interface between layers may appear. In this work, the cathode with 5 mm in width, 1 mm in thickness and 50 mm in length were applied as substrate. The surface roughness is 1.44 μm . As the resistance will increase with the thickness of the deposits, the voltage profile as shown in Fig. 4.4 was applied. The voltage was increased by 20V for each additional deposit of materials. After deposition, the deposits were dried in a dry keeper for 12 hours.

Fig. 4.4. Voltage profile used for monomorph deposition

The deposited mass varies with time as shown in Fig. 4.5 for a 4-layer system. It can be seen that the deposited weight increases almost linearly with deposition time. This indicates that the composition and thickness of the layers can be well controlled by adjusting the deposition time and voltage of the suspension.

Fig. 4.5. Deposited mass as a function of deposition time for a 4-layer deposition

After deposition, the deposits were sintered using the profile shown in Fig. 3.6. The heating rate was controlled to as low as 2 °C/min. This is because the thermal expansion mismatch caused by the gradient change in composition will result in distortion of the sintered body. The slow heating rate and the symmetric structure of

the sintered body balance the shrinkage of the sintered body and hence minimized the distortion.

4.2.2 Geometrical configuration

The deposits were first fired at 600 °C to burn out the graphite substrate as introduced earlier. Fig 4.6 shows the deposits after this step. After sintering, the deposit is shown in Fig. 4.7. Uniform structure was observed. The deposits exhibit about 15% linear shrinkage after sintering. The deposits were then cut and ground to the desired dimensions and poled for subsequent characterization.

Fig. 4.8. Photograph of the cross section of the FGM sample after sintering

4.2.3 XRD analysis

In this section, the phase of the sintered deposits was analyzed. Figs. 4.9, 4.10 and 4.11 show the XRD patterns of the 2-, 4- and 6-layer systems, respectively. Perovskite structures were confirmed to be present in all the three systems. It is also noted that from the inserts of figures the main phase is tetragonal phase in all three systems. Thus, it can be confirmed that the expected perovskite structure has been obtained for the monomorphs with different layers.

Fig. 4.9. XRD patterns of 2-layer system monomorph showing tetragonal phase perovskite structure

Fig. 4.10. XRD patterns of 4-layer system monomorph showing tetragonal phase perovskite structure

Fig. 4.11. XRD patterns of 6-layer system monomorph showing tetragonal phase perovskite structure

4.2.4 Microstructural study

In this section, the microstructure of the deposits after deposition and sintering was examined using SEM. Fig. 4.12 (a) shows the wall cross-section of the deposits after

deposition. This sample was prepared by deposition of each composition five times. The thickness of the wall was 0.35 mm. It can be observed that the cross section is smooth and uniform. No discrete interface or defects were observed, implying the good adhesion between each layer. Fig. 4.12 (b) is an observation with higher magnification. The powders were observed to be homogeneously distributed.

(a) 100% PZT0

(b) 60% PZT1 + 40% PZT0

Fig. 4.14. Microstructure of two side surfaces of 4-layer system after sintering

(a) 10% PZT1 + 90% PZT0

(b) 60% PZT1 + 40% PZT0

Fig. 4.15. Microstructure of two side surfaces of 6-layer system after sintering

Figs. 4.16, 4.17 and 4.18 show the cross sections of the FGM plates for the 2-, 4- and 6-layer systems after sintering at 1100 °C, respectively. The cross sections have a thickness of approximately 0.26 mm, 0.33 mm and 0.35 mm, respectively. For all the three systems, the gradient change in microstructure can be observed over the cross sections. From more PZT0 content side (right) to more PZT1 side (left), the grain size gradually increases as the percent of PZT1 increases. The compositional and microstructural gradient induced variation in piezoelectric properties over the cross section is the driving source to actuate the monomorph. The observed image in microstructure gradient confirms the microstructural effectiveness of our procedure to fabricate FGM monomorph actuator.

Fig. 4.16. Gradient variation of microstructure of 2-layer system FGM monomorph over cross section

4.3 Concluding remarks

In this chapter, detailed procedure of electrophoretic deposition of multi-layer PZT system was described. First, the deposition system was introduced. Then, the monomorph using individual composition was deposited sequentially. Finally, the physical properties of the monomorph were characterized. Some conclusions are drawn below:

1. The FGM monomorph can be obtained using multilayer deposition technique. The duration of deposition and interval between depositions are critical for good quality products.
2. The configuration of substrate and sintering temperature are important. The symmetric structured electrode and slow sintering temperature will balance the thermal induced stress and reduce distortion, warp and cracking of the deposits.
3. The FGM monomorph has a tetragonal-phase perovskite structure.
4. The powders homogeneously distributed over the cross section during the deposition of FGM monomorph. No significant defects and discrete interfaces were observed.
5. The monomorph fabricated using EPD demonstrate the uniform structure. The thickness of the present plate tube indicates that EPD technique is superior to fabricate miniaturized FGM monomorph actuator.
6. The microstructure of both cross section and surface morphology shows gradual change in grain size due to the gradient composition. The gradient variation in both microstructure and composition will result in the difference in piezoelectric properties, leading to the deflection of the monomorph actuator.

Chapter 5 Electromechanical Characterization of the FGM Monomorph Actuator

In this chapter, the monomorphs fabricated in Chapter 4 with different dimensions were characterized on their electromechanical property. The characterized parameter is the bending displacement, which varies with the composition, dimension and electric excitations. The characterization was performed under both static (frequency near zero) and dynamic conditions (frequency dependence of the displacement).

5.1 Static characterization

5.1.1 Experimental procedure

The configuration of the FGM monomorph actuator is shown in Fig. 5.1. It consists of the FGM piezoelectric plate fabricated earlier and coated with silver electrodes on both top and bottom surfaces. Poling was carried out at 2 kV/mm at 100 °C for 30 minutes as described earlier. After poling, the monomorph was aging for 24 hrs. In practical applications, the monomorph actuator is usually clamped at one end and free at the other end. When an electric field is applied, the layers extend or contract. Due to the difference in piezoelectric properties, the extensions or contractions are different, which then leads to the deflection of the monomorph. The bending direction and amplitude can be achieved by controlling the poling and electric field directions.

Fig. 5.1. Schematic drawing of a FGM monomorph actuator

The bending displacement of the prepared FGM monomorph actuator was characterized using the setup as shown in Fig. 5.2. This setup is similar as that for material characterization in Chapter 3, except that the piezoelectric tube was replaced with a monomorph and the characterized parameter is the bending displacement.

effect on the displacement according to the conventional theory of strength of materials and piezoelectrics, as the case when w/l ratio is much small.

Table 5.1. Dimensions of the studied FGM monomorphs

Number	Efficient length (mm)	Width (mm)	Thickness (mm)	Sample type
A1	10.5	2.84	0.21	2-layer system
A2	14.5	2.94	0.23	
A3	19.5	3.30	0.22	
B1	10.0	2.66	0.25	4-layer system
B2	15.0	2.62	0.26	
B3	19.0	2.90	0.26	
C1	11.0	2.94	0.35	6-layer system
C2	15.0	2.55	0.34	
C3	20.0	3.06	0.33	

5.1.2 Results and discussion

Figs. 5.3, 5.4 and 5.5 show the bending displacement of the FGM monomorph actuators of the three systems in response to the applied step voltage. Displacements of approximately 11.09, 19.39, 38.05, 5.56, 12.13, 17.31, 2.60, 5.29, and 10.06 μm were measured at a voltage of 100 V for FGM monomorph actuators A1, A2, A3, B1, B2, B3, C1, C2 and C3, respectively. Also as seen from the figures, when the monomorphs have similar dimensions, such as A1, B1 and C1, 2-layer system (A1) generates much larger displacement than 4-layer system (B1), and 4-layer system generates larger displacement than 6-layer system (C1). Thus, the bending displacement decreases with the increase of the layers when the dimension is fixed. While in the same system as shown in the figures, for example, 2-layer system, the longer the length, the larger the bending displacement obtained. The effect of the geometry and composition on the displacement of the monomorph will be further discussed in Chapter 6.

The measured data of displacement under the applied step voltage composes of the hysteresis loop. The hysteresis present is due to the internal damping of the materials. For piezoelectric ceramics, it normally results from the time dependant properties of domain wall motions and domain switching [8]. The loop of hysteresis confirms the loss of energy during the cycle. The area within the field-strain curve is proportional to the energy loss [164].

Comparing the hysteresis loops shown in Figs. 5.3, 5.4 and 5.5, the monomorph actuators with more layers show better linearity and smaller hysteresis than those with fewer layers. The linearity is an important factor in the control ability of the monomorph for precision applications.

Fig. 5.3. Bending displacement of the 2-layer system FGM monomorph actuators in response to the applied step voltage

Fig. 5.4. Bending displacement of the 4-layer system FGM monomorph actuators in response to the applied step voltage

Fig. 5.5. Bending displacement of the 6-layer system FGM monomorph actuators in response to the applied step voltage

It is also of great interest that the performance of the FGM monomorph developed in the present work is compared to a monomorph reported in the literature [126]. It is noted that the bending displacement can be expressed as [130, 165]:

$$\delta_l = k \frac{l}{h} E \quad (5.1)$$

where δ_l is the bending displacement per unit monomorph length (δ/l); E is the electric field applied to the monomorph in the thickness direction (V/h); k is a constant, representing the influence of the material properties and monomorph configurations; the product of k and the ratio of length to thickness (l/h) is the sensitivity of the monomorph, representing the device unit output (δ/l) in response to the unit input (E) [130, 165]. In Table 5.2, the displacements for various actuators and their sensitivity are listed. In which, monomorph A, B and C were actuators prepared in the present work; monomorph R is the actuator reported in literature [126].

Comparing monomorph A1, A2, A3, B1, B2, B3, C1, C2, C3 with R, it can be seen that our prepared monomorph possess advantages of larger sensitivities, smaller dimension, lower applied voltage and larger maximum displacement. The sensitivity of monomorph A3 was noted to have more than six times that of the monomorph R. From Eq. 5.1, it can be seen that the sensitivity is highly related to the l/h ratio. Thus, to achieve higher sensitivity, high l/h ratio is required. The advantage of EPD

technique is that the thickness of the monomorph can be controlled to be very thin. For example, monomorph C3 has six layers with a total thickness only of 0.33 mm. Using other traditional methods, it is difficult to achieve this thickness coat effectively with so many layers. For example, one of the smallest FGM monomorphs prepared by Kouvatov [131] with 5 layers had to have a total thickness of 0.5 mm, which is almost double in size of the monomorphs in the present work. In other words, for the same l/h ratio, EPD technique could miniaturize the monomorph (for example, via thinning the thickness), whereas the other traditional methods enlarge the monomorph (for example, via extending the length). The miniaturized dimension of the monomorph brings many advantages such as

- (a) Miniaturization of the total device
- (b) High sensitivity
- (c) Low consumption of the electric power which is highly sought in advanced technology

Monomorph R in Table 5.2 given by Zhu [126] has a displacement of 18 μm under 1000 V. The monomorph has two layers bonded using diffusion method. With the same number of layers, the present monomorph (A3) could generate 38.05 μm under 100 V. Despite having a smaller piezoelectric constant, A3 monomorph can generate a larger displacement. This is attributed to the superior EPD fabrication technique, which provides higher mechanical integrity, compared to that by diffusion-couple process.

Table 5.2. Available data for FGM monomorph actuators

Monomorph	d_{31} (10^{-10}m/V)	Dimension (mm)	Voltage (V)	Displacement (μm)	Sensitivity ($10^{-3}\mu\text{m/v}$)
A1	-1.220 -1.236 -1.041 -0.969 -0.908 -0.798 -0.625	10.50×2.84×0.21	100	11.09	2.22
A2		14.50×2.94×0.23		19.39	3.08
A3		19.50×3.30×0.22		38.05	4.30
B1		10.00×2.66×0.25		5.56	1.39
B2		15.00×2.62×0.26		12.13	2.10
B3		19.00×2.90×0.26		17.31	2.37
C1		11.00×2.94×0.35		2.60	0.83
C2		15.00×2.55×0.34		5.29	1.20
C3		20.00×3.06×0.33		10.06	1.66
R[126]	-2.60 -0.50	20.00×8.00×0.70	1000	18	0.63

5.2 Dynamic characterization

5.2.1 Experimental procedure

The dynamic displacement was measured using the setup as shown in Fig. 5.6. It consists of a function generator (FG3000, Yokagawa), MTI2000 fotonic sensor and an oscilloscope (DL1640L, Yokagawa). The measurement was performed at 1 Vp-p and frequency ranging from 100 Hz to 700 Hz. During the measurement, a sinusoidal voltage was generated by the function generator and applied on the monomorph to be measured. The voltage amplitude and frequency were also controlled by the function generator. The monomorph vibrates under the sinusoidal excitation. The vibration amplitude varies with the excitation frequency. The variation of the bending displacement is detected by the fotonic sensor and recorded by the digital oscilloscope.

Fig. 5.6. Experimental setup for dynamic displacement measurement

5.2.2 Results and discussion

Three samples A2, B2 and C2 listed in Table 5.1 were measured. The result is shown in Fig. 5.7. Similar profiles were found in all the three samples. The bending displacement does not vary significantly at low frequencies. When the frequency increases to a certain value, the displacement begins to increase, reach maximum and then decreases, as the frequency continues to increase. The frequency, where the maximum displacement appears, is also known as the resonant frequency of the monomorph. The magnitude of resonant displacement follows the same trend in the

static measurement, i.e., the 2-layer system has the largest dynamic displacement, the 4-layer system has the second largest displacement, and the 6-layer system gives the smallest displacement. It is found that the resonant frequencies of the three systems are also different. This is due to the effect of geometry and material property difference and will be discussed in Chapter 6.

Fig. 5.7. Frequency dependence of the bending displacement

5.3 Concluding remarks

In this chapter, the FGM monomorph actuators were characterized both in static and dynamic states. The characterization was performed using an integrated system mainly consists of ferroelectric tester, fotonic sensor, function generator and oscilloscope. Comparison between the FGM monomorph and the literature reported monomorph was also performed. The main conclusions are:

1. Various FGM piezoelectric monomorph actuators with different compositions and dimensions were characterized. The displacement of the monomorph falls in the range from 2 μm to 40 μm under an applied voltage of 100 V.

2. The displacement of FGM monomorph actuator is shown to be a function of geometrical parameters and compositions. As the number of layers (varying composition) increases, the overall displacement decreases. The displacement is found to increase when the actuator length increases or thickness decreases.
3. FGM monomorph prepared by EPD technique have shown advantages of miniaturized dimension, larger sensitivities, lower applied voltage and larger maximum displacement, when compared to a traditional diffusion-coupled monomorph actuator.
4. The dynamic displacement is found to be frequency dependant. At low frequency, it does not vary much. At resonant frequency, the bending displacement reaches a peak value. All three systems have different resonant

frequencies. The 2-layer system generates the largest displacement and the 6-

layer system gives the smallest displacement under their resonant frequency.

Chapter 6 Theoretical Analysis of Electromechanical Properties

The theoretical study of the monomorph actuator in this work includes two parts. They are: the calculation of bending displacement and the analysis of stress distribution. In this chapter, the constitutive relationship between the bending displacement and related geometry, material properties and electrical conditions was established in static state, which is essential in most applications. The dynamic relationship is also established. The models are based on conventional mechanical, piezoelectric and vibration theories. The results were compared with the experiments and discussed.

6.1 Static modeling

First, some classical theories on strength of materials were applied [172]. Fig. 6.1 shows a piezoelectric beam with length l which is clamped at one end. The beam is loaded at the other end with shear force Q , bending moment M and axial force N at the free tip. To keep equilibrium, at any cross section x , the following holds:

$$\begin{cases} Q_x - Q = 0 \\ M_x - M + Q(l - x) = 0 \\ N_x = N \end{cases} \quad (6.1)$$

Fig. 6.1. A piezoelectric beam loaded with a shear force Q , moment M and axial force N at the free end

Under the Clamped-Free boundary conditions for the monomorph, all the external loads, including shear force Q , moment M and axial force N , are zero. The plane moment M_x and plane force N_x at cross section x are hence also zero. M_x and N_x can also be expressed as

$$M_x = \iint_A Tz dA \quad (6.2)$$

$$N_x = \iint_A T dA \quad (6.3)$$

where T is the normal stress at a distance z from the neutral plane (a plane whose length doesn't change under deflection); A is the area of cross section. Thus, under the present condition, the moment and plane force become:

$$\begin{cases} M_x = \iint_A Tz dA = 0 \\ N_x = \iint_A T dA = 0 \end{cases} \quad (6.4)$$

which provide the basis for subsequent derivation on FGM systems.

The structure of the FGM monomorph is assumed to consist of n layers as shown in Fig. 6.2. The dimension of this actuator is l in length, w in width and h in thickness. For simplicity, each layer is assumed to have the same thickness. The origin of the coordinate is positioned at the bottom surface of the actuator. The x - and z -axis are along the length and thickness direction, respectively.

Fig. 6.2. Schematic structure of FGM monomorph actuator

In this work, it is assumed that the total thickness h and the width w are negligibly small compared with the length l , thus the deflections in thickness and width are neglected. In addition, the plane cross section of the beam remains plane after deflection and the radius of curvature of the bend beam is large compared with the beam's thickness [173].

Following the assumption, the tensile stress and strain in the monomorph along the x-axis are denoted as T_1 and S_1 , respectively, and the dielectric field along the z-axis in the monomorph is denoted as E_3 , the piezoelectric constant is denoted as d_{31} . Because of the asymmetric structure of the monomorph, the neutral plane is no longer in the middle plane of the monomorph. Thus, the longitudinal strain S_1 at a distance z from the origin plane in the direction of x-axis should be modified as [173]

$$S_1 = -\frac{z - d_0}{\rho} \quad (6.5)$$

where d_0 is the position of the neutral plane.

According to the classical piezoelectric equations [2], the stress in the i th layer can be expressed as

$$T_{1(i)} = Y_{(i)}S_{1(i)} - Y_{(i)}d_{31(i)}E_{3(i)} \quad (6.6)$$

Taking Eqs. 6.5 and 6.6 into the plane force expression in Eq. 6.4, we have

$$\begin{aligned} N_x &= \int_A T_1 dA \\ &= w \int_0^h T_1 dz \\ &= w \sum_{i=1}^n \int_{\frac{(i-1)h}{n}}^{\frac{ih}{n}} \left(-\frac{z - d_0}{\rho} Y_{(i)} - Y_{(i)}d_{31(i)}E_{3(i)} \right) dz = 0 \end{aligned} \quad (6.7)$$

Thus it can be obtained that the neutral plane is positioned at

$$d_0 = \frac{\rho \sum_{i=1}^n Y_{(i)}d_{31(i)}E_{3(i)} + \frac{h}{2n} \sum_{i=1}^n Y_{(i)}(2i-1)}{\sum_{i=1}^n Y_{(i)}} \quad (6.8)$$

The plane torque of the FGM monomorph actuator can be expressed by substituting Eqs. 6.5 and 6.6 into the moment expression in Eq. 6.4. We obtain

$$\begin{aligned} M_x &= \int_A T_1 z dA \\ &= w \int_0^h T_1 z dz \\ &= w \sum_{i=1}^n \int_{\frac{(i-1)h}{n}}^{\frac{ih}{n}} \left(-\frac{z - d_0}{\rho} Y_{(i)} - Y_{(i)}d_{31(i)}E_{3(i)} \right) z dz = 0 \end{aligned} \quad (6.9)$$

As a result, we arrive at

$$-\frac{h^3}{3n^3\rho} \sum_{i=1}^n (3i^2 - 3i + 1)Y_{(i)} + \frac{d_0 h^2}{2n^2\rho} \sum_{i=1}^n (2i - 1)Y_{(i)} - \frac{h^2}{2n^2} \sum_{i=1}^n Y_{(i)} d_{31(i)} E_{3(i)} (2i - 1) = 0 \quad (6.10)$$

Substituting the neutral plane position Eq. 6.8 into Eq. 6.10, the radius of curvature is

$$\frac{1}{\rho} = \frac{6 \left[\sum_{i=1}^n d_{31(i)} E_{3(i)} Y_{(i)} \sum_{i=1}^n (2i - 1)Y_{(i)} - \sum_{i=1}^n d_{31(i)} E_{3(i)} Y_{(i)} (2i - 1) \sum_{i=1}^n Y_{(i)} \right]}{\frac{4h}{n} \sum_{i=1}^n (3i^2 - 3i + 1)Y_{(i)} \sum_{i=1}^n Y_{(i)} - \frac{3h}{n} \left[\sum_{i=1}^n (2i - 1)Y_{(i)} \right]^2} \quad (6.11)$$

In the above expression, $E_{3(i)}$ which is the electric field in the i th layer is dependant on dielectric constant ϵ_{33}^T and can be derived as shown in the following.

Fig. 6.3 shows the distribution of electric displacement $D_{3(i)}$ ($i = 1$ to n) in the FGM actuator. Applying Gauss's law to the relations in any arbitrary i th layer and $(i+1)$ th layer [164],

$$\oint \vec{D}_3 d\vec{s} = -D_{3(i)}s + D_{3(i+1)}s = 0 \quad (6.12)$$

where s is the arbitrary selected closed area at the interface. Hence

$$D_{3(i)} = D_{3(i+1)} \quad (6.13)$$

Following the same process, it can be found that

$$D_{3(1)} = D_{3(2)} = \dots = D_{3(i)} = \dots = D_{3(n)} \quad (6.14)$$

As

$$D_3 = \epsilon_{33}^T E_3 \quad (6.15)$$

we could then obtain

$$\epsilon_{33(1)}^T E_{3(1)} = \epsilon_{33(2)}^T E_{3(2)} = \dots = \epsilon_{33(i)}^T E_{3(i)} = \dots = \epsilon_{33(n)}^T E_{3(n)} \quad (6.16)$$

Thus the electric field in any layer can be expressed as

$$E_{3(i)} = \frac{\epsilon_{33(1)}^T}{\epsilon_{33(i)}^T} E_{3(1)} \quad (6.17)$$

If a voltage of V is applied over the cross section, the following relation exists

$$\sum_1^n E_{3(i)} \frac{h}{n} = V \quad (6.18)$$

Taking Eq. 6.17 into 6.18 and simplify the result, it is obtained that

$$E_{3(1)} = \frac{nV}{h\epsilon_{33(1)}^T \sum_1^n \frac{1}{\epsilon_{33(i)}^T}} \quad (6.19)$$

So, taking Eq. 6.19 back to 6.17, we have

$$E_{3(i)} = \frac{nV}{h\epsilon_{33(i)}^T \sum_1^n \frac{1}{\epsilon_{33(i)}^T}} \quad (6.20)$$

Fig. 6.3. Distribution of electric displacement in FGM monomorph

Combining Eqs. 6.20 and 6.11 (the expression of radius of curvature), the radius of curvature ρ can be obtained. Meanwhile, from the classical theory of strength of materials [172], the radius of curvature ρ relates the bending displacement δ by

$$\frac{1}{\rho} = \frac{d\delta^2}{dx^2} \quad (6.21)$$

Solving Eq. 6.21 gives

$$\frac{d\delta}{dx} = \frac{1}{\rho}x + C \quad (6.22)$$

$$\delta = \frac{1}{2} \frac{1}{\rho} x^2 + Cx + D \quad (6.23)$$

where C and D are constants. Considering the Clamped-Free boundary conditions:

$$\begin{cases} \frac{d\delta}{dx} = 0 \\ \delta = 0 \end{cases} \bigg|_{x=0} \quad (6.24)$$

C and D are forced to be zero. Hence, the deflection at the free tip of the beam can be obtained as

$$\delta = \frac{1}{2} \frac{l^2}{\rho} \quad (6.25)$$

Finally, we combine the radius of curvature Eq. 6.11, the electric field in i th layer Eq. 6.20 and the deflection expression Eq. 6.25 to arrive at the bending displacement of the monomorph actuator in terms of material property and geometry variables as

$$\delta = \frac{3l^2 n^2 V}{h^2} \frac{\sum_{i=1}^n \frac{d_{31(i)} Y_{(i)}}{\epsilon_{33(i)}^T \sum_1^n 1/\epsilon_{33(i)}^T} \sum_{i=1}^n (2i-1) Y_{(i)} - \sum_{i=1}^n \frac{(2i-1) d_{31(i)} Y_{(i)}}{\epsilon_{33(i)}^T \sum_1^n 1/\epsilon_{33(i)}^T} \sum_{i=1}^n Y_{(i)}}{4 \sum_{i=1}^n (3i^2 - 3i + 1) Y_{(i)} \sum_{i=1}^n Y_{(i)} - 3 \left[\sum_{i=1}^n (2i-1) Y_{(i)} \right]^2} \quad (6.26)$$

This complicated expression of displacement is a function of material properties, including piezoelectric constant d_{31} , dielectric constant ϵ_{33}^T and Young's modulus Y , geometric properties such as length l , thickness h and number of layers n , and the applied voltage V . Different from the deflection expression Eq. 2.24 proposed by Zhu [131], the present Eq. 6.26 is based on properties of each layer, i.e., by direct measuring the properties of the materials, the distribution of properties is naturally obtained. The advantage is that one doesn't need to assume the distribution of the properties. This equation has also incorporated the effect of the Young's modulus Y , which is not commonly considered as a variable in the literature [131]. It can be seen that the present derived equation can be applied to any layered-structure or quasi layered-structure FGM monomorph actuators. Compared with the FEM analysis [136-138], present analytical equation reveals the relations of each parameter.

In the latter section, the derived constitutive relationship will be discussed in relation to material and geometrical properties. Piezoelectric constant d_{31} is the major

material parameter to displacement; hence, to identify the variation of displacement as a function of d_{31} , Eq. 6.26 is simplified for subsequent analysis.

In the simplification process, both dielectric constant ϵ_{33}^T (or electric field E_3) and Young's modulus Y are taken as constants, i.e.,

$$E_{3(1)} = E_{3(2)} = \dots = E_{3(n)} = E_3 \quad (6.27)$$

$$Y_{(1)} = Y_{(2)} = \dots = Y_{(n)} = Y \quad (6.28)$$

Taking Eqs. 6.27 and 6.28 into the radius of curvature expression Eq. 6.11, the radius of curvature is simplified to be

$$\frac{1}{\rho} = \frac{6E_3}{n^2 h} \sum_{i=1}^n d_{31(i)} (n - 2i + 1) \quad (6.29)$$

Combining with the deflection expression in Eq. 6.25, we finally have

$$\begin{aligned} \delta &= \frac{3E_3 l^2}{n^2 h} \sum_{i=1}^n d_{31(i)} (n - 2i + 1) \\ &= \frac{3V l^2}{n^2 h^2} \sum_{i=1}^n d_{31(i)} (n - 2i + 1) = K \sum_{i=1}^n d_{31(i)} (n - 2i + 1) \end{aligned} \quad (6.30)$$

When n is equal to 2, Eq. 6.30 becomes

$$\delta = \frac{3V d_{31} l^2}{2h^2} \quad (6.31)$$

which is consistent with the classical expression for the displacement of a bimorph actuator.

We now obtained the simplified displacement expression Eq. 6.30, which is only a function of the piezoelectric constant d_{31} . In latter section, this equation will be further discussed to identify the effect of d_{31} distribution on the bending displacement of the monomorph.

6.2 Dynamic modeling

In the static modeling, the frequency effect is not considered. However, in dynamic applications, the displacement of the monomorph will vary with frequency. This is the frequency dependent property of the monomorph. In this section, the effect of

frequency is included, which gives the dynamic model for the monomorph. Euler-Benoulli beam theory, which is the typical thin beam theory, is appropriate for the present long and thin monomorph beam configuration (the ratio between the length and height of the bar is relatively large, usually more than 10) [174-180]. This theory is also most commonly applied because it is simple and provides reasonable engineering approximations for a variety of applications.

6.2.1 Free vibration

Fig. 6.4 illustrates the Euler-Benoulli beam model. A small element (Fig. 6.4 (b)) at position x in the beam is driven by the shear force $F(x,t)$, external distributed force $f(x,t)$, moment $M(x,t)$, and generates transverse displacement in the y direction. The displacement is denoted as $u(x,t)$. The element studied also has an acceleration of $\rho A dx \partial^2 u(x,t)/\partial t^2$ in the transverse y direction.

Fig. 6.4. Euler-Benoulli beam model

$$u(x, t) = Y(x)q(t) \quad (6.34)$$

where $Y(x)$ is the spatial response and $q(t)$ is the time response. Substituting Eq. 6.34 into the governing Eq. 6.33,

$$EIq(t)\frac{\partial^4 Y(x)}{\partial x^4} + \rho AY(x)\frac{\partial^2 q(t)}{\partial t^2} = 0 \quad (6.35)$$

Rearranging Eq. 6.35, the spatial function $Y(x)$ and time function $q(t)$ can be separated as

$$\frac{EI}{\rho AY(x)} \frac{\partial^4 Y(x)}{\partial x^4} = -\frac{1}{q(t)} \frac{\partial^2 q(t)}{\partial t^2} \quad (6.36)$$

Following the classical mechanical vibration theory, both sides of Eq.6.36 can be set to equal to the separation constant ω^2 [181], the following relations are then obtained

$$\begin{cases} \ddot{q}(t) + \omega^2 q(t) = 0 \\ EIY'''' - \omega^2 \rho AY = 0 \end{cases} \quad (6.37)$$

where $\ddot{q}(t)$ is the second order derivative of time function $q(t)$ on t and Y'''' is the fourth order derivative of spatial function $Y(x)$ on x . The solution of the second ordinary deferential equation in the above Eqs. 6.37 can then be expressed as

$$Y(x) = C_1 \cosh \lambda x + C_2 \sinh \lambda x + C_3 \cos \lambda x + C_4 \sin \lambda x \quad (6.38)$$

where C_i ($i = 1$ to 4) are constants and the eigenvalue λ has the following relation with the frequency ω as [181]

$$\omega = \lambda^2 \sqrt{\frac{EI}{\rho A}} \quad (6.39)$$

To identify the unknowns of C_i and λ , we derive the various order of derivatives for Y ,

$$\begin{cases} Y' = \lambda C_1 \sinh \lambda x + \lambda C_2 \cosh \lambda x - \lambda C_3 \sin \lambda x + \lambda C_4 \cos \lambda x \\ Y'' = \lambda^2 C_1 \cosh \lambda x + C_2 \lambda^2 \sinh \lambda x - C_3 \lambda^2 \cos \lambda x - C_4 \lambda^2 \sin \lambda x \\ Y''' = \lambda^3 C_1 \sinh \lambda x + C_2 \lambda^3 \cosh \lambda x + C_3 \lambda^3 \sin \lambda x - C_4 \lambda^3 \cos \lambda x \end{cases} \quad (6.40)$$

Under clamped-free boundary condition, the conditions are

$$\begin{matrix} Y = 0 \\ Y' = 0 \end{matrix} \bigg|_{x=0} \quad (6.41)$$

$$\begin{matrix} Y'' = 0 \\ Y''' = 0 \end{matrix} \bigg|_{x=l} \quad (6.42)$$

Applying these boundary relations, Eq. 6.38 (the spatial response expression) and 6.40 (the various order of derivatives for Y) can be expressed in a matrix form as

$$\begin{bmatrix} \cosh \lambda 0 & \sinh \lambda 0 & \cos \lambda 0 & \sin \lambda 0 \\ \lambda \sinh 0 & \lambda \cosh \lambda 0 & -\lambda \sin \lambda 0 & \lambda \cos \lambda 0 \\ \lambda^2 \cosh \lambda l & \lambda^2 \sinh \lambda l & -\lambda^2 \cos \lambda l & -\lambda^2 \sin \lambda l \\ \lambda^3 \sinh \lambda l & \lambda^3 \cosh \lambda l & \lambda^3 \sin \lambda l & -\lambda^3 \cos \lambda l \end{bmatrix} \begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \end{bmatrix} = 0 \quad (6.43)$$

From Eq. 6.43, it is obtained that

$$\cosh \lambda l \cos \lambda l + 1 = 0 \quad (6.44)$$

For the solution of first order vibration, it is

$$\lambda_1 l = 1.8751 \quad (6.45)$$

From Eq. 6.43 and considering Eq. 6.45, the following relation can also be obtained

$$\alpha = \frac{C_2}{C_1} = -\frac{\cosh \lambda l + \sin \lambda l}{\sinh \lambda l + \sin \lambda l} = -\frac{\sinh \lambda l - \sin \lambda l}{\cosh \lambda l + \cos \lambda l} = -0.7341 \quad (6.46)$$

As a result, the spatial response Eq. 6.38 can also be expressed as

$$Y(x) = C_1 [\cosh \lambda x - \cos \lambda x + \alpha (\sinh \lambda x - \sin \lambda x)] \quad (6.47)$$

where C_1 can be absorbed into time response $q(t)$ or cancelled in the following derivation. So in the following part it was omitted.

6.2.2 Forced vibration

In this analysis, the effects of both damping and external force are considered. Applying the governing Eq. 6.32 and taking the displacement relation Eq. 6.34 into the governing Eq. 6.32, we arrive at

$$EIq(t)\frac{\partial^4 Y(x)}{\partial x^4} + C\rho AY(x)\frac{\partial q(t)}{\partial t} + \rho AY(x)\frac{\partial^2 q(t)}{\partial t^2} = f(x,t) \quad (6.48)$$

According to time and spatial response relations Eq. 6.37, we have

$$EIY'''' = \omega^2 \rho AY \quad (6.49)$$

Taking Eq. 6.49 into Eq. 6.48,

$$q(t)\omega^2 \rho AY(x) + C\rho AY(x)\dot{q}(t) + \rho AY(x)\ddot{q}(t) = f(x,t) \quad (6.50)$$

Multiplying the both sides of Eq. 6.50 with $Y(x)$, and integrates from 0 to l ,

$$\omega^2 q \int_0^l \rho AY^2 dx + C\dot{q} \int_0^l \rho AY^2 dx + \ddot{q} \int_0^l \rho AY^2 dx = \int_0^l Yf(x,t)dx \quad (6.51)$$

we obtain

$$\omega^2 q + C\dot{q} + \ddot{q} = \frac{\int_0^l Yf(x,t)dx}{\int_0^l \rho AY^2 dx} \quad (6.52)$$

Assuming

$$C = 2\omega\xi \quad (6.53)$$

where ξ is called damping ratio, Eq. 6.52 is then expressed as

$$\ddot{q} + 2\omega\xi\dot{q} + \omega^2 q = \frac{\int_0^l Yf(x,t)dx}{\int_0^l \rho AY^2 dx} \quad (6.54)$$

If a moment $M(x, t)$ is applied to exert on the beam, the term $Y(x)f(x,t)$ in Eq. 6.54 should be replaced with MY' [178, 181-182]. As the effect of piezoelectricity is equivalent to a moment applied to the end of the monomorph [182], MY' can be expressed as

$$M(x,t)Y' = M_0 \cos(\omega t)\delta(x-l) \cdot Y' \quad (6.55)$$

where M_0 is the moment exerted to the end of the transducer which is equivalent to the effect of the voltage applied to the transducer. Integrating from 0 to l , we get

$$\int_0^l M(x,t)Y'dx = \int_0^l M_0 \cos(\omega t)\delta(x-l)Y'dx = M_0Y'(l)\cos(\omega t) \quad (6.56)$$

Replacing $Yf(x,t)$ in Eq. 6.54 with $M(x,t)Y'$ and using Eq. 6.56, Eq. 6.54 becomes

$$\ddot{q} + 2\omega\xi\dot{q} + \omega^2q = \frac{M_0Y'(l)\cos(\omega t)}{\int_0^l \rho AY^2 dx} = \frac{M_0Y'(l)}{\int_0^l \rho AY^2 dx} \cos(\omega t) \quad (6.57)$$

Solving Eq. 6.57 which is an ordinary differential equation, we have

$$\begin{cases} q = \frac{M_0Y'(l)}{\int_0^l \rho AY^2 dx} \frac{\cos(\omega t - \phi)}{\omega_n^2 \sqrt{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + 4\xi^2 \left[\frac{\omega}{\omega_n}\right]^2}} \\ \tan(\phi) = \frac{2\xi\omega_n\omega}{\omega_n^2 - \omega^2} \end{cases} \quad (6.58)$$

in which

$$\omega_n = \lambda_n^2 \sqrt{\frac{EI}{\rho A}} \quad (6.59)$$

where the subscript n in ω_n and λ_n represents the n th order vibration. In this work, only the first order is considered. Replacing $q(t)$ with Eq. 6.58, the general displacement Eq. 6.34 is given to be

$$u(x,t,\omega) = Y(x)q(t) = Y(x) \frac{M_0Y'(l)}{\int_0^l \rho AY^2 dx} \frac{\cos(\omega t - \phi)}{\omega_n^2 \sqrt{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + 4\xi^2 \left[\frac{\omega}{\omega_n}\right]^2}} \quad (6.60)$$

Considering eigenvalue functions Eqs. 6.44, 6.45, spatial function 6.47, natural frequency relation 6.59, Eq. 6.60 can be simplified to be

$$u(x,t,\omega) = 0.2227Y(x) \frac{M_0}{EI} l^2 \frac{\cos(\omega t - \phi)}{\sqrt{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + 4\xi^2 \left[\frac{\omega}{\omega_n}\right]^2}} \quad (6.61)$$

This equation (Eq. 6.61) describes the response of the beam as a function of time, frequency and position. At the free tip of the beam, the bending displacement can be derived to be

$$u(l, t, \omega) = 0.4454 \frac{M_0}{EI} l^2 \frac{\cos(\omega t - \phi)}{\sqrt{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + 4\xi^2 \left[\frac{\omega}{\omega_n}\right]^2}} \quad (6.62)$$

To find the maximum displacement at the free tip of the beam when frequency varies, the simple approach is to find the minimum value of the following expression

$$\Delta = \left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + 4\xi^2 \left[\frac{\omega}{\omega_n}\right]^2 \quad (6.63)$$

which is a part of Eq. 6.62. Then we have

$$\frac{d\Delta}{d\omega} = -2\omega_n^2 + \omega^2 + 2\xi^2 \omega_n^2 = 0 \quad (6.64)$$

Hence, the resonant frequency for the maximum bending displacement can be found to be

$$\omega_r = \sqrt{1 - 2\xi^2} \omega_n \quad (6.65)$$

where ω_n and ω_r are the natural frequency and the resonant frequency of the beam, respectively. For maximum displacement, i.e., displacement at resonant frequency, taking Eq. 6.65 into general displacement Eq. 6.62, $u(l, t, \omega_r)$ is obtained as

$$u(l, t, \omega_r) = 0.4454 \frac{M_0}{EI} l^2 \frac{\cos(\omega_r t - \phi)}{2\xi \sqrt{1 - \xi^2}} \quad (6.66)$$

The mechanical quality factor Q_m can then be defined from Eq. 6.66 as [181]

$$Q_m = \frac{1}{2\xi \sqrt{1 - \xi^2}} \quad (6.67)$$

where Q_m represents the loss of the transducer. A high Q_m allows low loss and large vibration amplitude. If ξ is small in Eq. 6.67, Q_m can be simplified as

$$Q_m \approx \frac{1}{2\xi} \quad (6.68)$$

Thus, at the resonant frequency, the bending displacement can be simplified as

$$u(l, t, \omega_r) = 0.4454 \frac{M_0}{EI} l^2 Q_m \cos(\omega_r t - \phi) \quad (6.69)$$

6.2.3 Equivalent moment and bending stiffness

From above analysis, it is found that the dynamic displacement is related to the equivalent moment M_0 , which is exerted at the end of the monomorph, and the equivalent bending stiffness EI . It is noted that the monomorph developed here has a layered structure and each layer has its own properties. To obtain the equivalent moment M_0 and bending stiffness EI , the results obtained from static modeling could be applied. First, taking Eqs. 6.8 (the neutral plane position) and 6.20 (the electric field in i th layer) into Eq. 6.10 (the simplified moment equation), and rearranging the results, we obtain

$$\left[\frac{h^3 w}{4n^3} \frac{\left[\sum (2i-1)Y_{(i)} \right]^2}{\sum Y_i} - \frac{wh^3}{3n^3} \sum (3i^2 - 3i + 1)Y_{(i)} \right] \frac{1}{\rho} + \frac{h^2 w}{2n^2} \left[\frac{\sum \frac{Y_{(i)} d_{31(i)} nV}{h \epsilon_{33(i)}^T \sum_1^n 1/\epsilon_{33(i)}^T} \sum (2i-1)Y_{(i)}}{\sum Y_{(i)}} - \sum \frac{(2i-1)Y_{(i)} d_{31(i)} nV}{h \epsilon_{33(i)}^T \sum_1^n 1/\epsilon_{33(i)}^T} \right] = 0 \quad (6.70)$$

According to the classical theory of strength of materials [172], the following equilibrium relation exists

$$-EI \frac{1}{\rho} + M_0 = 0 \quad (6.71)$$

Comparing Eqs. 6.70 and 6.71, the equivalent moment and bending stiffness can be expressed as

$$h^2 w \left[\sum \frac{Y_{(i)} d_{31(i)} n V}{h \varepsilon_{33(i)}^T \sum_1^n 1 / \varepsilon_{33(i)}^T} \sum (2i-1) Y_{(i)} \right] \quad (6.72)$$

$$EI = \frac{h^3 w}{3n^3} \sum (3i^2 - 3i + 1) Y_{(i)} - \frac{h^3 w}{4n^3} \frac{\left[\sum (2i-1) Y_{(i)} \right]^2}{\sum Y_{(i)}} \quad (6.73)$$

Now we obtained the full expression of the bending displacement at the free tip of the beam from M_0 and EI , which can be placed into the displacement governing Eq. 6.62,

$$u(l, t, \omega) = 2.6724 \frac{l^2 V n^2}{h^2} \times \frac{\sum \frac{Y_{(i)} d_{31(i)}}{\varepsilon_{33(i)}^T \sum_1^n 1 / \varepsilon_{33(i)}^T} \sum (2i-1) Y_{(i)} - \sum Y_{(i)} \sum \frac{(2i-1) Y_{(i)} d_{31(i)}}{\varepsilon_{33(i)}^T \sum_1^n 1 / \varepsilon_{33(i)}^T}}{4 \sum (3i^2 - 3i + 1) Y_{(i)} \sum Y_{(i)} - 3 \left[\sum (2i-1) Y_{(i)} \right]^2} \times \frac{\cos(\omega t - \phi)}{\sqrt{\left[1 - \left(\frac{\omega}{\omega_n} \right)^2 \right]^2 + 4 \xi^2 \left[\frac{\omega}{\omega_n} \right]^2}} \quad (6.74)$$

6.3 Experimental verification

6.3.1 Static response

To verify the theories derived above and also explain the results obtained in Chapter 5, the experimental results were compared with the theoretical values calculated using the equations derived earlier in this section.

In the present section, we compare the experimental displacement with the theoretical values obtained from three approaches. They are:

- 1) Static: the static displacement Eq. 6.26 was applied to calculate the displacement, where the materials properties, Y , d_{31} , and ϵ_{33}^T , measured for individual layers were utilized. The properties have been listed in Table 6.1.

Table 6.1. Parameters of the PZT materials applied for theoretical calculation

	Static				Simplified static		
Material No.	d_{31} (10^{-10} m/V)	Y (10^{10} Pa)	ϵ_{33}^T (10^{-8} F/m)	ρ (10^3 g/m ³)	d_{31} (10^{-10} m/V)	Y (10^{10} Pa)	ϵ_{33}^T (10^{-8} F/m)
5	-1.220	7.77	7.00	7.539	-12.20	7.77	7.00
6	-1.236	7.41	7.22	7.526	*	**	***
7	-1.041	7.32	6.90	7.512			
8	-0.969	6.86	6.82	7.459			
9	-0.908	6.49	6.65	7.423			
10	-0.798	5.67	6.60	7.397			
11	-0.625	5.47	6.36	7.390	-6.25	5.47	6.36

* $-1.220 + (-0.625 + 1.220)/n \times i$; ** $7.77 + (5.47 - 7.77)/n \times i$; *** $7.00 + (6.36 - 7.00)/n \times i$;
n = 2, 4, 6; i = 1, 2, 3, ...n

- 2) Simplified static: In this approach, for simplicity, Y , d_{31} , and ϵ_{33}^T were considered to be linearly distributed in the monomorph in the static displacement Eq. 6.26. This approach provides a simpler relationship compared to the earlier one and is noted to provide reasonably good estimates.
- 3) Dynamic: As discussed in Section 6.2, the equivalent bending stiffness EI and bending moment M_0 were first obtained from the dynamic curve when frequency is zero measured in Chapter 5 and using the following Eq. 6.76, which is obtained from Eqs. 6.59 (natural frequency relation) and 6.62 (general bending displacement expression)

$$\begin{cases} EI = \rho A \left(2\pi f_r \left(\frac{l}{1.8751} \right)^2 \right)^2 \\ M_0 = \frac{|u(l,t,0)|}{0.4454l^2} EI \end{cases} \quad (6.76)$$

where f_r is the resonant frequency; $|u(l,t,0)|$ is the vibration amplitude at zero frequency. Then displacement can be calculated.

Figs. 6.5 to 6.7 are the comparisons of static displacement between the measured results and theoretical derivations. The results are for the 2-layer, 4-layer and 6-layer monomorphs obtained in Chapter 5. The displacement was measured at different voltage from 20 V to 100 V as shown in Figs. 6.5 to 6.7. These monomorphs were characterized in Chapter 5 and were marked as A1, A2, A3 (2-layer system), B1, B2, B3 (4-layer system), C1, C2 and C3 (6-layer system). It should be noted that for the 2-layer system, the static case is equivalent to the simplified static case as there are only two materials applied. From the figures, it can be found that under low applied voltage, for all the nine monomorphs, the experimentally measured displacement is close to the theoretical values. This implies that taking the measured properties of each layer into our derived equations in static model or using the equivalent parameter in dynamic model, the bending displacement of the monomorph actuator can be predicted with reasonable accuracy. It is also noted that the simplified static approach provides accurate predictions.

Fig. 6.5. Comparison of theoretical and measured displacement at different applied voltages of 2-layer system monomorph

Fig. 6.6. Comparison of theoretical and measured displacement at different applied voltages of 4-layer system monomorph

Fig. 6.7. Comparison of theoretical and measured displacement at different applied voltages of 6-layer system monomorph

6.3.2 Effect of material and geometry properties in static response

Both the static displacement Eq. 6.26 and data distribution are complicated in this study, we will examine and discuss the factors that affect the above outcomes and also reveal more indications using the established model in the following part.

(a) Material factors of Y , d_{31} and ε_{33}^T

In this section, effect of Young's modulus Y , dielectric constant ε_{33}^T and piezoelectric constant d_{31} on the bending displacement was theoretically discussed. In this study, the dimensions of FGM monomorph actuators were arbitrarily selected as length $l = 10$ mm and thickness $h = 0.25$ mm. As the simplified static analysis shows reasonably good description of the displacement behavior, for simplicity this analysis was performed using Eq. 6.26 considering the linear distribution of the material properties. To check the significance of each individual parameter, when one or two parameters were examined, the others were kept constant as shown in Fig. 6.8, where the curves in the figure represent

Line 1 – d_{31} changes, but ε_{33}^T and Y keep constant;

Line 2 – Y changes, d_{31} and ε_{33}^T keep constant;

Line 3 – ε_{33}^T changes, but Y and d_{31} keep constant;

Line 4 – d_{31} , Y change, ε_{33}^T keeps constant;

Line 5 – d_{31} , ε_{33}^T change, Y keeps constant;

Line 6 – ε_{33}^T and Y change, but d_{31} keeps constant;

Line 7 – d_{31} , ε_{33}^T and Y change.

Fig. 6.8. The functions of parameter Y , d_{31} and ε_{33}^T on the displacement according to

Eq. 6.26

The effect of each material property parameter is discussed below:

- 1) If only the piezoelectric constant d_{31} varies, the displacement as a function of voltage is shown in line 1. It can be seen that the displacement is the maximum among all the studied conditions under the same voltage. This indicates that d_{31} is the most essential parameter that contributes to the displacement.
- 2) If only Young's modulus Y varies, it is found that the displacement is almost zero as shown in line 2. This implies the Young's modulus has little contribution to the displacement.
- 3) If only ε_{33}^T varies, the displacement as a function of voltage is shown in line 3. The ε_{33}^T induced displacement can be explained by using the electric field Eq. 6.17 derived earlier

$$E_{3(i)} = \frac{\varepsilon_{33(1)}^T}{\varepsilon_{33(i)}^T} E_{3(1)} \quad (6.17)$$

where $E_{3(1)}$ is the electric field of the first layer in the monomorph; $E_{3(i)}$ is that of the i th layer. This equation implies that in different layers with different dielectric constants, the electric field will be different. So even the d_{31} in the different layers are same, there are still deflections because the strain $S_1 = d_{31}E_3$, where E_3 is variable in different layers. From line 3, it is found that displacement linearly decreases with the increase of voltage, which is opposite to line 1. This indicates that the contribution of d_{31} and ε_{33}^T to displacement is opposite. If the monomorph is bending at the positive direction by the effect of d_{31} , the magnitude could be degraded by the effect of ε_{33}^T . It is also found that the absolute value of displacement in line 3 is much smaller than that in line 1. This shows that the effect of ε_{33}^T is insignificant compared with the piezoelectric constant.

- 4) If two or three of the three parameters were considered, line 4, 5, 6 and 7 were then obtained. It is found that line 4, 6 and 7 are superimposed with line 1, 3 and 5, respectively, and line 5 and 7 are positioned between line 1 and 3. This again shows that Young's modulus Y has less contribution to the displacement and the contribution of d_{31} and ε_{33}^T to displacement is opposite.

The above discussion tells us that to obtain a high bending displacement, control of the distribution of the piezoelectric constant is most important. This also confirms that

our consideration of selecting the material systems based on the piezoelectric constant distribution to form the FGM structure in Chapter 3 is reasonable.

(b) Geometrical factors

It is noted from Eq. 6.26 that displacement is also a function of length l , thickness h and number of layers n of the monomorph. In this section, the effect of these parameters is discussed using the verified model discussed earlier.

The displacement of the monomorph increases parabolically with the length l as can be seen from Eq. 6.26. Hence, the longer the length, the larger the displacement. This is also confirmed by the experimental results as shown in Figs. 6.5 to 6.7. For example, monomorph B2 and B3 have the same thickness (0.26 mm) but different length (B2, 15 mm and B3, 19 mm). Monomorph B3 generates larger displacement than B2 under the same voltage.

Eq. 6.26 also indicates the displacement is inversely proportional to the square of the thickness if the material properties, applied voltage, length and number of layers are fixed. As a result, thinning the thickness can greatly increase the displacement. In addition, thinning the thickness is more advantageous in device miniaturization.

Fig. 6.9 models the theoretical bending displacement of monomorph actuators with thickness varying from 0.1 mm to 0.4 mm, and length 10 mm, at different voltages. The simplified static estimation was again applied to evaluate the displacement. Young's modulus Y , dielectric constant ϵ_{33}^T and piezoelectric constant d_{31} are all included in the calculation. It can be seen that the thickness significantly affects the magnitude of displacement. For example, at 100 V, the displacement of an actuator with thickness of 0.4 mm is only about 1.97 μm . However, when the thickness is reduced to 0.1 mm, the displacement can reach 31.56 μm , where as much as 16 times improvement is obtained. Thus, it can be concluded that thinning the thickness is an efficient and effective method to increase the displacement. This is advantageous for the miniaturization of the component and our fabrication technique EPD is proved to be a good technique to fabricate thin FGM monomorph.

Fig. 6.10 shows the bending displacement modeling result as a function of number of layers. In this simplified static simulation, the layer number varies from 2 to 100 for a FGM monomorph actuator with 0.25 mm in thickness and 10 mm in length at the applied voltage of 100 V. It is apparent that the bending displacement decreases abruptly with the number of layers in the early stage. However, with the increase in

the number of layers, the bending displacement tends to saturate at a low value, which is approximately 68% of the maximum value. This trend is consistent with the result analyzed using FEM given in the literature for symmetric monomorph study [136]. The maximum displacement happened at two layers, indicating that if a large displacement is expected, the number of layers should be restricted to as few as possible. However, the continuous layer composition is advantageous to the optimization of the stress distribution over the cross section. The study on stress distribution will be further investigated in the following chapter.

Fig. 6.9. Displacement as a function of applied voltage at different thickness varying from 0.1 mm to 0.4 mm according to Eq. 6.26

Fig. 6.10. Bending displacement as a function of the number of layers according to Eq. 6.26

From the simplified Eq. 6.30, it can also be found that a monomorph with even number of layers is better than the one with odd number of layers. The reason is that, for example, if the layer number is odd, such as 5, substituting each d_{31} in the simplified displacement Eq. 6.30, the following relation is obtained:

$$\delta = K(4d_{31(1)} + 2d_{31(2)} + 0d_{31(3)} - 2d_{31(4)} - d_{31(5)}) \quad (6.78)$$

Thus, the middle layer does not contribute to bending displacement. Hence, an even number of layer is a better choice, and this is the reason why we choose even layer systems as the studied objects. The displacement is mainly induced by the difference of d_{31} in the layers at the two sides of the middle layer. The larger the difference is, the larger the displacement can be obtained. In all the layers, the first layer and the last layer provide the most contribution.

6.3.3 Dynamic response

Fig. 6.11 is the comparison between the measured amplitude of the dynamic displacement from the frequency 100 Hz to 700 Hz and the fit curve calculated using the following Eq. 6.79 that is obtained from Eqs. 6.62:

$$\frac{|u(l, t, \omega)|}{|u(l, t, 0)|} = \frac{1}{\sqrt{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + 4\xi^2 \left[\frac{\omega}{\omega_n}\right]^2}} \quad (6.79)$$

Fig. 6.11. The bending displacement of the monomorph in the frequency ranging from 100 Hz to 700 Hz

From the figure, we can find that the two curves are basically consistent, indicating the dynamic modeling is reasonable. To be noted, there are deviations between the two curves. This is because the viscoelastic damping assumptions, which assume the damping force proportional to the vibration velocity, do not accurately describe the damping behaviors of the monomorph [8, 36, 181].

6.4 Concluding remarks

In this chapter, the electromechanical constitutive relationship between the bending displacement, material properties, geometry properties and excitation conditions, was established both in static and dynamic cases using standard theory of piezoelectrics, as well as vibration and strength of materials. In the static modeling, the equation was derived to predict the bending displacement under Clamped-Free boundary condition. In the dynamic modeling, the frequency dependent properties of the bending displacement were analyzed. The comparison between the experimental and theoretical values was also performed. The factors that affect the displacement amplitude of the monomorph were discussed using both the experimental data and the equations derived earlier in this chapter. Some important equations and conclusions obtained are summarized below:

(a) The static bending displacement of the monomorph actuator can be expressed as

$$\delta = \frac{3l^2 n^2 V}{h^2} \frac{\sum_{i=1}^n \frac{d_{31(i)} Y_{(i)}}{\varepsilon_{33(i)}^T \sum_{j=1}^n 1/\varepsilon_{33(j)}^T} \sum_{i=1}^n (2i-1) Y_{(i)} - \sum_{i=1}^n \frac{(2i-1) d_{31(i)} Y_{(i)}}{\varepsilon_{33(i)}^T \sum_{j=1}^n 1/\varepsilon_{33(j)}^T} \sum_{i=1}^n Y_{(i)}}{4 \sum_{i=1}^n (3i^2 - 3i + 1) Y_{(i)} \sum_{i=1}^n Y_{(i)} - 3 \left[\sum_{i=1}^n (2i-1) Y_{(i)} \right]^2} \quad (6.26)$$

(b) The displacement is mainly contributed by d_{31} , which affects the bending displacement by the following relation

$$\begin{aligned} \delta &= \frac{3E_3 l^2}{n^2 h} \sum_{i=1}^n d_{31(i)} (n - 2i + 1) \\ &= \frac{3V l^2}{n^2 h^2} \sum_{i=1}^n d_{31(i)} (n - 2i + 1) = K \sum_{i=1}^n d_{31(i)} (n - 2i + 1) \end{aligned} \quad (6.30)$$

(c) The dynamic constitutive relationship of the monomorph is

$$u(x, t, \omega) = 0.2227Y(x) \frac{M_0}{EI} l^2 \frac{\cos(\omega t - \phi)}{\sqrt{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + 4\xi^2 \left[\frac{\omega}{\omega_n}\right]^2}} \quad (6.61)$$

where

$$M_0 = \frac{h^2 w}{2n^2} \left[\sum \frac{(2i-1)Y_{(i)} d_{31(i)} nV}{h\varepsilon_{33(i)}^T \sum_1^n 1/\varepsilon_{33(i)}^T} - \frac{\sum \frac{Y_{(i)} d_{31(i)} nV}{h\varepsilon_{33(i)}^T \sum_1^n 1/\varepsilon_{33(i)}^T} \sum (2i-1)Y_{(i)}}{\sum Y_{(i)}} \right] \quad (6.72)$$

$$EI = \frac{h^3 w}{3n^3} \sum (3i^2 - 3i + 1)Y_{(i)} - \frac{h^3 w}{4n^3} \frac{\left[\sum (2i-1)Y_{(i)}\right]^2}{\sum Y_{(i)}} \quad (6.73)$$

$$Y(x) = \cosh \lambda x - \cos \lambda x + \alpha(\sinh \lambda x - \sin \lambda x) \quad (6.47)$$

The bending displacement is frequency dependent, at low frequency, it does not vary significantly. At resonant frequency, the bending displacement reaches maximum. This relation is shown in Eq. 6.79

$$\frac{|u(l, t, \omega)|}{|u(l, t, 0)|} = \frac{1}{\sqrt{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + 4\xi^2 \left[\frac{\omega}{\omega_n}\right]^2}} \quad (6.79)$$

(d) The bending displacement of the monomorph is shown to be a function of material properties such as piezoelectric constant d_{31} , dielectric constant ε_{33}^T and Young's modulus Y . d_{31} is the key parameter to produce large displacement. The dielectric constant ε_{33}^T degrades the bending displacement produced by the inverse piezoelectric effect and the Young's modulus gives very less contribution to the displacement. The results showed that the top and bottom layers significantly affect the displacement, the larger the difference in d_{31} for the top and bottom layers, the larger the overall displacement can be obtained. As a result, appropriate

arrangement of d_{31} in each layer can result in huge improvement in the displacement.

- (e) The displacement of FGM monomorph actuator is also shown to be a function of geometrical parameter of length l , thickness h and number of layers n . The bending displacement of the monomorph actuator is directly proportional to the square of length l and inverse proportional to the square of thickness h . The number of layers also greatly influences the displacement. The displacement decreases with the increase of number of layers. The displacement drops quickly with the initial increase of number of layers and finally levels at approximately 68% of the initial displacement.

Chapter 7 Analysis on Stress Distribution

When the bending actuator is working, mechanical stresses will be induced in the device. This is due to the fact that some layers are contracted, and the others are stretched. The occurrence of high and uneven mechanical stresses might lead to reduced lifetime and low reliability of the device. In addition, the interfacial stress inherent to these designs will result in the reduced mechanical integrity [137]. In this chapter, the stress distribution of the monomorph actuator developed in the present work was analyzed. It should be noted that in this chapter, not only the stress in static case was analyzed, the dynamic situation, which is seldom addressed in the literature, was also studied. As a reference, the conventional bimorph was first analyzed using finite element analysis (FEA). Then, the monomorph actuator developed in the present work was analyzed and compared with that from bimorph actuator. Finally, including both stress and displacement results obtained earlier, the studied material system actuators were analyzed and discussed.

7.1 Stress distribution of a bimorph actuator

In conventional theory of strength of materials and piezoelectric theories, for a long and thin beam as shown in Fig. 7.1, the following relations for various stress states exist [131, 172, 183-184]:

$$\begin{cases} T_1 \neq 0 \\ T_2 = T_3 = T_4 = T_5 = T_6 = 0 \end{cases} \quad (7.1)$$

where the subscript 1, 2, and 3 denote the normal stress along the x-, y- and z-directions, respectively, and 4, denote the shear stress associated with y- and z-directions, 5 for that at z- and x-directions, and 6 for x- and y-directions. In the following analysis, the main stress component, T_1 (also denoted as σ_x), was analyzed using finite element analysis method.

Fig. 7.1 The schematic structure of a beam

7.1.1 Modeling process

The FEA software ANSYS/Multiphysics was applied in the present work. The analysis procedure has three distinct steps [185-186] as explained next. The first step is to build a model, which involves the preparation of all required data to be processed during the solution solving phase of the computer program. The second step is to apply load, define boundary condition on the structure and obtain the solution. The final step is to review the results. The detailed process is introduced below [187-191].

(a) Defining the element type

The ANSYS element library contains more than 150 different element types. The element type determines the element degree of freedom and whether the element lies in two- or three- dimensional space. In the present work, the coupled-field-element SOLID5 was applied. SOLID5 has a three-dimensional magnetic, thermal, electric, piezoelectric, and structural field capability with limited coupling between the fields. For the bimorph case, both structural and piezoelectric fields are involved in. The element has eight nodes with up to six degrees of freedom at each node. When used in structural and piezoelectric analysis, SOLID5 has large deflection and stress stiffening capabilities. In the present analysis of the bimorph, the element has degrees of freedom with UX, UY, UZ and VOLT.

(b) Defining material properties

For three-dimensional analysis, several basic material properties are required to be input by 'material model' function in ANSYS. They are density ρ , dielectric matrix $[\epsilon]$, piezoelectric matrix $[e]$ and stiffness matrix $[c]$.

The dielectric matrix $[\epsilon]$ is a 3×3 diagonal matrix for a 3D model and the data are entered into ANSYS as a material data table with the labels PERX, PERY and PERZ. It is given in the following format

$$[\epsilon]^s = \begin{bmatrix} \epsilon_{11} & 0 & 0 \\ 0 & \epsilon_{11} & 0 \\ 0 & 0 & \epsilon_{33} \end{bmatrix} \quad (7.2)$$

The piezoelectric matrix $[e]$ relates the electric field to stress, and for a 3D model, $[e]$ is a 6×3 matrix and is entered as a material data table, PIEZ. It is expressed in the following format

$$[e] = \begin{bmatrix} 0 & 0 & e_{13} \\ 0 & 0 & e_{13} \\ 0 & 0 & e_{33} \\ 0 & 0 & 0 \\ 0 & e_{42} & 0 \\ e_{51} & 0 & 0 \end{bmatrix} \quad (7.3)$$

The stiffness matrix $[c]$ is a 6×6 matrix and the data is entered as a material data table, ANEL. It is expressed as

$$[c]^E = \begin{bmatrix} c_{11} & c_{21} & c_{31} & 0 & 0 & 0 \\ c_{21} & c_{11} & c_{23} & 0 & 0 & 0 \\ c_{31} & c_{23} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{66} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{44} \end{bmatrix} \quad (7.4)$$

(c) Creating the model geometry

The structure of the bimorph actuator was created as shown in Fig. 7.2. It has a dimension of 15 mm in length, 3 mm in width and 0.6 mm in thickness. The bimorph was meshed with 1350 elements and 1792 nodes automatically using the 'sweep' function of ANSYS. The poling direction of the bimorph is along the thickness direction, i.e., z-axis direction in the Cartesian coordinate system.

Fig. 7.2. Loading conditions of the studied bimorph actuator with dimension of 15 mm in length, 3 mm in width and 0.6 mm in thickness

(d) Loading conditions and solution

As shown in Fig. 7.2, the bimorph was clamped at one end by setting the degrees of UX, UY and UZ zero at the end where $x = 0$ in structural load function. The electric loads, i.e., constant voltages of zero and 100 V were applied on bottom and top surfaces of the bimorph, respectively. Then, the static and harmonic analysis were performed.

7.1.2 Results and discussion

Fig. 7.3 illustrates the stress T_1 distribution of the bimorph actuator in the static case. In which, (a) is the view from y-direction, (b) is the enlarged view of a piece of the section, and (c) is the cross section view. The stress distribution is represented by the color variation. It can be seen that the stress is dependent on z (thickness direction) as color variation exists in z -direction, but basically independent on x (length direction) as the color is basically consistent in x -direction. Fig. 7.3 (d) shows the stress distribution of the bimorph over the cross section. It can be seen that maximum stress is located at the middle part of the bimorph or the interface of the two layers. Usually, the bimorph is fabricated by bonding two layers of plates using the epoxy at the interface. The maximum stress here will obviously reduce the reliability of the bimorph actuators. This is the main driving force for the development of a monomorph actuator.

(a)

(b)

(c)

(d)

Fig. 7.3. Stress distribution represented by the color variation of a bimorph actuator under static condition: (a) the view from y-direction, (b) the enlarged view of a piece of the section, (c) the cross section view, and (d) stress distribution over the cross section

Fig. 7.4 illustrates the stress distribution of the bimorph actuator in dynamic state. The stress distribution has been quite different from that of the static case. It can be seen that the color varies both in z- and x- direction, indicating that the normal stress is not only dependent on z but also on x. The maximum stress arises at the position $x = 0$. Fig. 7.4 (d) shows stress distribution over the cross section at position $x = 0$. Different from the static case, the stress is basically linearly distributed and maximum stress occurs at the bottom and top surfaces. This indicates that the interface problem should not be as significant as that in the static case.

(a)

(b)

(c)

(d)

Fig. 7.4. Stress distribution represented by the color variation of a bimorph actuator under dynamic condition, (a) the view from y-direction, (b) the enlarged view of a piece of the section, (c) the cross section view, and (d) stress distribution over the cross section

7.2 Stress distribution analysis using theoretical model

In this section, the stress distribution of the traditional bimorph and FGM monomorph actuator developed in the present work were analyzed using the theoretical modeling established in Chapter 6. The results of the bimorph were compared with the reference analysis earlier using FEA. The configuration of the monomorph analyzed is shown in Fig. 7.5. It has n layers, with normal stress T_1 (σ_x) in the x (1)-direction.

Fig. 7.5. Schematic structure and normal stress T_1 of a FGM monomorph actuator

7.2.1 Static stress distribution

Recalling Eq. 6.8 (neutral plane position expression), 6.11 (the curvature radius expression) and 6.20 (electric field expression) derived in Chapter 6 earlier, the neutral plane position d_0 , radius of curvature ρ and electric field $E_{3(i)}$ can be evaluated as:

$$d_0 = \frac{\rho \sum_{i=1}^n Y_{(i)} d_{31(i)} E_{3(i)} + \frac{h}{2n} \sum_{i=1}^n Y_{(i)} (2i-1)}{\sum_{i=1}^n Y_{(i)}} \quad (6.8)$$

$$\frac{1}{\rho} = \frac{6 \left[\sum_{i=1}^n d_{31(i)} E_{3(i)} Y_{(i)} \sum_{i=1}^n (2i-1) Y_{(i)} - \sum_{i=1}^n d_{31(i)} E_{3(i)} Y_{(i)} (2i-1) \sum_{i=1}^n Y_{(i)} \right]}{\frac{4h}{n} \sum_{i=1}^n (3i^2 - 3i + 1) Y_{(i)} \sum_{i=1}^n Y_{(i)} - \frac{3h}{n} \left[\sum_{i=1}^n (2i-1) Y_{(i)} \right]^2} \quad (6.11)$$

$$E_{3(i)} = \frac{nV}{h \epsilon_{33(i)}^T \sum_{i=1}^n 1/\epsilon_{33(i)}^T} \quad (6.20)$$

Then, using the strain and stress relations derived earlier in Chapter 6, the stress at position z over the cross section of the monomorph can be found as

$$\begin{cases} S_1 = -\frac{z - d_0}{\rho} \\ T_{1(i)} = Y_{(i)} S_{1(i)} - Y_{(i)} d_{31(i)} E_{3(i)} \end{cases} \quad (7.5)$$

Based on the above analysis, the 2-, 4- and 6-layer monomorph with the same configuration mentioned earlier in Chapter 3 were analyzed under same bending displacement condition for comparison. The material properties in each layer were listed in Table 6.1. The dimension of the three monomorphs is the same as that of the bimorph mentioned in this chapter. The results of the stress at position z were then obtained by inputting the geometrical and material properties in the strain and stress relation Eq. 7.5.

The distribution of the normal stress T_1 inside the bimorph is shown in Fig. 7.6 (a). It can be seen that the normal stress distribution of the bimorph actuator is independent on the position x . This is consistent with the previous analysis on the bimorph actuator using FEA. Fig. 7.6 (b) illustrates the stress distribution in the thickness direction. As expected, the maximum stress occurs at the interface for the bimorph actuator as analyzed earlier. This normal stress distribution of the bimorph is also consistent with that of the previous analysis using FEA. These consistent results obtained for the bimorph have shown the theoretical models established in the present work provide a reasonably accurate estimate to the stress states in the system, which hence is appropriate to extend to the prediction for our developed monomorph's performance.

The theoretical modeling results for the monomorph are shown in Fig. 7.7. The comparison of the monomorphs with bimorph on stress distribution is shown in Fig. 7.8. It can be seen that the stress distribution within the monomorph is smoother than that of the bimorph. Both the mechanical stresses near the interfaces between the layers and the stresses at the surfaces of the samples have obviously been reduced. The analysis has also shown that the stress distribution also becomes smoother with the increase of the number of layers. The stress reduction is the main advantage of FGM monomorph over the bimorph, as the large mechanical stress occurs at the interface will reduce the life and reliability of the bending actuator.

(a)

(b)

Fig. 7.6 Normal stress distribution of bimorph in static case calculated using Eqs. 6.8, 6.11, 6.20 and 7.5, (a) normal stress distribution in x-z plane, (b) normal stress distribution in thickness direction

(a) 2-layer monomorph

(b) 4-layer monomorph

(c) 6-layer monomorph

Fig. 7.7. Normal stress distribution of FGM monomorph actuators in static case calculated using Eqs. 6.8, 6.11, 6.20 and 7.5

Fig. 7.8. Normal stress distribution of bimorph and monomorph actuator in the thickness direction under static conditions calculated using Eqs. 6.8, 6.11, 6.20 and

7.5

The effect of the number of layers on the maximum stress induced in the system is also evaluated and shown in Fig. 7.9. It can be seen that with increasing number of layers, the maximum normal stress is reduced. For example, the maximum stress has been reduced to 97% that of the bimorph for a 2-layer monomorph, and down to 52% and 41% for a 4- and 6-layer monomorph, respectively.

Fig. 7.9. Dependence of the maximum stress on the number of layers under static conditions calculated using Eqs. 6.8, 6.11, 6.20 and 7.5

7.2.2 Dynamic stress distribution

In the dynamic state, the deflection curve of the monomorph is different from that of the static state. As derived in Chapter 6, the dynamic response of the monomorph has the following relation

$$u(x, t, \omega) = 0.2227Y(x) \frac{M_0}{EI} l^2 \frac{\cos(\omega t - \phi)}{\sqrt{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + 4\xi^2 \left[\frac{\omega}{\omega_n}\right]^2}} \quad (6.61)$$

and $Y(x)$ can be expressed as

$$Y(x) = \cosh \lambda x - \cos \lambda x + \alpha(\sinh \lambda x - \sin \lambda x) \quad (6.47)$$

Thus, at the resonant frequency, applying Eq. 6.47, the deflection curve can be expressed as

$$\begin{aligned} u(x) &= 0.2227 \frac{M_0}{EI} l^2 Q_m (\cosh \lambda x - \cos \lambda x + \alpha (\sinh \lambda x - \sin \lambda x)) \\ &= K (\cosh \lambda x - \cos \lambda x + \alpha (\sinh \lambda x - \sin \lambda x)) \end{aligned} \quad (7.6)$$

where

$$K = 0.2227 \frac{M_0}{EI} l^2 Q_m \quad (7.7)$$

$$\lambda_1 l = 1.8751 \quad (6.45)$$

$$\alpha = -0.7341 \quad (6.46)$$

Hence the radius of curvature ρ becomes

$$\frac{1}{\rho} = \frac{du^2}{dx^2} = \lambda^2 K (\cosh \lambda x + \cos \lambda x + \alpha (\sinh \lambda x + \sin \lambda x)) \quad (7.8)$$

and the neutral plane position d_0 can also be expressed as

$$d_0 = \frac{\rho \sum_{i=1}^n Y_{(i)} d_{31(i)} E_{3(i)} + \frac{h}{2n} \sum_{i=1}^n Y_{(i)} (2i-1)}{\sum_{i=1}^n Y_{(i)}} \quad (6.8)$$

Then, applying Eqs. 6.8 (the neutral plane position), 6.20 (electric field expression), and 7.8 (the radius of curvature expression) into the stress and strain relations Eq. 7.5, the normal stress distribution in dynamic state can be obtained for our evaluation.

The bimorph and monomorph mentioned earlier were both analyzed in the dynamic state. Based on the above theoretical relations, the mapping of the stress is shown in Fig. 7.10. It can be seen that in the dynamic situation, the normal stress is dependent on both thickness position z and length position x (color varies both in z - and x -direction). The most significant variation and maximum stress appears at position $x = 0$. In addition, different from the static case, where the maximum stress arises in the

middle contact layer, in this case, the maximum stress happens at the top and bottom surface of the actuator for the dynamic situation.

(a) Bimorph

(b) 2-layer monomorph

Fig. 7.10. Normal stress distribution of bimorph and 2-, 4- and 6-layer monomorph under dynamic condition calculated using Eqs. 6.8, 6.20, 7.5 and 7.8

Fig. 7.11 shows the normal stress distribution over the cross section at position $x = 0$. It can be found that the maximum stress is reduced as the number of layers increases. However, this reduction is only about 10-20% and less pronounced than that observed in the static case. So the configuration of FGM monomorph is more effective to smooth stress distribution in the static case than in the dynamic case.

Fig. 7.11. Stress distribution of bimorph and 2-, 4- and 6-layer monomorph at position $x = 0$ under dynamic condition calculated using Eqs. 6.8, 6.20, 7.5 and 7.8

7.3 Discussion

From the discussion and analysis in the previous and in this chapter, we have noted that there are two contradiction trends existing in the FGM monomorph structure. The FGM monomorph structure is advantageous in smoothing the stress distribution which will result in the improvement of reliability and life span of the actuator. However, as we observed from experiments and discussed from the theoretical models, the increase of the number of layers decreases the bending displacement of the actuator. For usual applications, both factors should be considered.

Fig. 7.12 shows the relative values of displacement and maximum stress observed under the same applied voltage of the monomorphs developed in this work. It can be seen that both stress and displacement decrease with increasing the number of layers.

However, when the number of layers increases from two layers to four layers, the stress reduced nearly 50%. But from 4 layers to 6 layers, the reduction is only about 10%. In other words, the reduction in stress becomes less significant when the number of layers is more than 4. As for the displacement, the reductions from 2-layer to 4-layer and from 4-layer to 6-layer are 17.5% and 13.6%, respectively. Based on this analysis, if the large displacement is the primary requirement for the application, the 2-layer system is the primary selection. However, if large displacement is not so vital a requirement, 4-layer will be a much better choice considering both the factors of displacement and stress distribution. Furthermore, large displacement can be obtained by increasing the applied voltage or length of the monomorph for 4-layer system too. The fabrication procedure of the 4-layer system is also simpler than that of the 6-layer system. Hence, we conclude that the 4-layer monomorph will be a good choice for most applications.

Fig. 7.12. Displacement and stress as a function of number of layers calculated using Eqs. 6.26, 6.8, 6.11, 6.20 and 7.5

7.4 Concluding remarks

In this chapter, the stress distributions of the bimorph and monomorph actuators were analyzed. Essential conclusions are drawn below:

- a) The actuators exhibit different stress distributions when in static and in dynamic case. In static case, the maximum stress arises at the interface of different layers. In dynamic case, the stress is both thickness position and length position dependent. The maximum stress occurs at the bottom or top surface of the clamped end of the actuator. The stress distribution basically follows a linear relationship.
- b) The maximum stress decreases with increasing number of layers in both static and dynamic cases. However, in static case, the reduction in stress is significant and the stress distribution is also smoother. Nevertheless, in the dynamic case, this reduction is not so obvious.
- c) Considering the requirement of large displacement and small maximum stress, the 4-layer monomorph developed in this project is considered to be a good choice for most applications.

Chapter 8 Conclusions

In this work, piezoelectric FGM monomorph actuators were fabricated, characterized, modeled and discussed. From the characterization results of the starting materials, three material systems were identified to fabricate the monomorph using electrophoretic deposition. The prepared monomorph was characterized both in physical and electromechanical properties. The constitutive modeling was also established to analyze, discuss and predict electromechanical behavior and stress distribution of the monomorph actuators. Based on this work, the important conclusions are summarized below:

(1) Material properties distribution

Compositional selection and variation could form 2-layer, 4-layer and 6-layer monomorph actuator systems, which exhibit gradient distribution of both microstructure and material properties, including Young's modulus Y , piezoelectric constant d , and dielectric constant ϵ^T . This will then result in functional gradient

(b) The developed monomorph actuator has advantages of larger sensitivities, lower applied voltage and larger maximum displacement than diffusion-couple type monomorph actuator reported in the literature.

(c) The dynamic displacement is found to be frequency dependant and reaches maximum at resonant frequency. The 2-layer system generates the largest displacement and the 6-layer system gives the smallest displacement under their resonant frequencies.

(4) Establishment of the constitutive relations

(a) The static bending displacement of the monomorph actuator is derived to be

$$\delta = \frac{3l^2 n^2 V}{h^2} \frac{\sum_{i=1}^n \frac{d_{31(i)} Y_{(i)}}{\epsilon_{33(i)}^T \sum_{j=1}^n 1/\epsilon_{33(j)}^T} \sum_{i=1}^n (2i-1) Y_{(i)} - \sum_{i=1}^n \frac{(2i-1) d_{31(i)} Y_{(i)}}{\epsilon_{33(i)}^T \sum_{j=1}^n 1/\epsilon_{33(j)}^T} \sum_{i=1}^n Y_{(i)}}{4 \sum_{i=1}^n (3i^2 - 3i + 1) Y_{(i)} \sum_{i=1}^n Y_{(i)} - 3 \left[\sum_{i=1}^n (2i-1) Y_{(i)} \right]^2} \quad (6.26)$$

(b) The dynamic constitutive relationship of the monomorph is derived to be

$$u(x, t, \omega) = 0.2227 Y(x) \frac{M_0}{EI} l^2 \frac{\cos(\omega t - \phi)}{\sqrt{\left[1 - \left(\frac{\omega}{\omega_n} \right)^2 \right]^2 + 4 \xi^2 \left[\frac{\omega}{\omega_n} \right]^2}} \quad (6.61)$$

where

$$M_0 = \frac{h^2 w}{2n^2} \left[\sum_{i=1}^n \frac{(2i-1) Y_{(i)} d_{31(i)} n V}{h \epsilon_{33(i)}^T \sum_{j=1}^n 1/\epsilon_{33(j)}^T} - \frac{\sum_{i=1}^n \frac{Y_{(i)} d_{31(i)} n V}{h \epsilon_{33(i)}^T \sum_{j=1}^n 1/\epsilon_{33(j)}^T} \sum_{i=1}^n (2i-1) Y_{(i)}}{\sum_{i=1}^n Y_{(i)}} \right] \quad (6.73)$$

$$l^3 \left[\sum_{i=1}^n (2i-1) Y_{(i)} \right]^2$$

(c) The bending displacement is a function of material properties. In which, d_{31} is the most important parameter for obtaining large displacement. A distribution of d_{31} with larger value in the top layer and smaller value in the bottom is appropriate. Dielectric constant ε_{33}^T degrades the bending displacement by producing the inverse displacement and the Young's modulus gives no significant effect to the displacement.

(d) The bending displacement is geometry dependent. It increases with the ratio of length to thickness and decreases as the number of layers increases.

(e) The bending displacement is proportional to the applied electric field.

(f) The bending displacement is frequency dependent. At low frequency, it does not vary significantly. At resonant frequency, the bending displacement reaches maximum.

(4) Analysis on stress distribution

(a) The actuators exhibit different stress distributions in static and dynamic cases. In the static case, the stress distribution is position dependent in thickness direction and the stress reaches maximum at the interfaces of the layers. In the dynamic case, the stress is both in-thickness and in-length position dependent. The stress distribution is close to a linear curve in the studied cross section with maximum value at the bottom or top surface of the clamped end of the actuator.

(b) The maximum stress decreases with increasing number of layers both in the static and dynamic cases. However, the reduction in maximum stress is more significant in static case than in the dynamic case.

(c) Considering the requirement of large displacement and small maximum stress, the 4-layer monomorph developed in this work provides the appropriate properties.

Chapter 9 Future Work

The present work has made an attempt to establish an effective procedure to fabricate FGM monomorph and property-performance constitutive relationship for the FGM monomorph. General relationships have been derived and validated by experimental results. Despite the reasonable accuracy and description provided by the present relationships, several aspects of further work could further improve the study. In this chapter, these areas are discussed.

9.1 Dynamic vibration behavior of the system

The monomorph actuator can work both in static and dynamic modes. In the present work, we have placed our focus on the static condition. However, it is indicated in our present dynamic study, the behavior of the transducer could be quite different from that in static case. The essential parameters resulted in the difference of dynamic performance of the transducer mainly include: (1) the vibration amplitude is frequency dependent; (2) mode shape varies; (3) damping behavior, which results in the energy dissipation. A general model based on the conventional Euler-Benoulli beam theory has been derived in the present work. In this established model, the higher order vibration mode was neglected. And for simplicity, the damping was

also increases, which results in heat generation, temperature rise, large stress and more loss in the system. As a result, the materials will degrade and the reliability of the system will also drop. As a result, a better understanding at high-power performance and identifying the limitation of the transducer both in static and dynamic conditions are necessary. This includes investigating the material characteristics under high electric field, finding the threshold of the electric field, and the mapping of the temperature profile of the transducer. These investigations are useful to improve the stability and life span of the actuators.

Constant current or voltage method can be used to investigate the electromechanical properties of the materials under high electric field and high vibration level [30-35, 192]. In this method, the fundamental bending vibration mode of the transducer can be applied. The frequency-admittance curve can also be measured. Therefore, electromechanical properties can be determined. Meanwhile, the vibration velocity can be measured with an optical displacement sensor; the temperature can be measured with a thin thermocouple. Graphically, the relations between the piezoelectric properties, vibration level and electric field can be found. Thus, the upper limit for the electric field, maximum vibration velocity and maximum temperature rise can be determined.

9.3 Loading effect of the system

In the current analysis, the actuator is working in the no-load and free state. However, in practice, usually a load, either a force or moment, will exert on the system. This may change the response of the system. An investigation on the performance of the monomorph in the loading state is thus required. Equivalent circuit is a powerful tool to perform the piezoelectric response in the loading condition. This method establishes the bridge between electrical and mechanical quantities, and represents the system using electrical parameters. Fig. 9.1 illustrates the equivalent circuit of a bender actuator. The relations of the mechanical and electrical parameters can be expressed as [193]

$$\begin{cases} F = AV - Zv \\ i_m = Av \end{cases} \quad (9.1)$$

in which A , V , i_m , F and v are force factor, voltage, motional current, force and vibration velocity of the bender. By identifying the necessary parameter, the response of the system can be predicted.

Fig. 9.1. Equivalent circuit of a bender actuator [193]

9.4 Stability and reliability of the system

Reliability and stability is important for the commercialization of the devices, especially when the actuator is applied in a critical system where the cost of failure is high. Due to fatigue and degradation of the materials, the performance of the actuator could drop or fail after long time cycling. An investigation on the time-dependent performance and failure mechanism of the actuator is thus necessary. This study is useful for system control and development of valid physical models to allow prediction of failures. To perform the reliability and stability test, the actuator can be run under a defined condition for a stated period of time. During the study of the failure characteristics, some accelerate-failure-mechanism can be applied, such as running the system in some extreme conditions, including high temperature, high voltage and high humidity.

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Appendix A ANSYS Input Listing

In this appendix, the examples of ANSYS input listing files are given. These data are from the ANSYS log file. They describe the procedure of ANSYS modeling.

(a) Static analysis of a bimorph actuator

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/BATCH
/input,menust,tmp,"",,,,,,,,,,1
/GRA,POWER
/GST,ON
/PLO,INFO,3
/GRO,CURL,ON
/REPLOT,RESIZE
*SET,1,0.015
*SET,w,0.003
*SET,h,0.0003
/PREP7
!*
ET,1,SOLID5
!*
BLOCK,0,1,0,w,0,h,
BLOCK,0,1,0,w,0,-h,
NUMMRG,KP,,,LOW
!*
MAT,1,
! /INPUT,.. \pzt1.SI_MPL
/NOP
/COM,Internal UNITS set at file creation time = SI (MKS)
TBDEL,ALL,_MATL
MPDEL,ALL,_MATL
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MPDATA,R5.0,1,DENS,_MATL ,1, 7600.00000 ,
MPTEMP,R5.0,1,1, 0.00000000 ,
MPDATA,R5.0,1,PERX,_MATL ,1, 4.071000000E-09,
MPTEMP,R5.0,1,1, 0.00000000 ,
MPDATA,R5.0,1,PERY,_MATL ,1, 4.071000000E-09,
MPTEMP,R5.0,1,1, 0.00000000 ,
MPDATA,R5.0,1,PERZ,_MATL ,1, 2.080000000E-09,
TB,PIEZ,_MATL ,,, 0
TBDAT, 1, 0.00000000 , 0.00000000 , -2.10000000
TBDAT, 4, 0.00000000 , 0.00000000 , -2.10000000
TBDAT, 7, 0.00000000 , 0.00000000 , 9.50000000
TBDAT, 10, 0.00000000 , 0.00000000 , 0.00000000
TBDAT, 13, 0.00000000 , 9.20000000 , 0.00000000
TBDAT, 16, 9.20000000 , 0.00000000 , 0.00000000
TB,ANEL,_MATL , 1,, 0
TBTEMP, 0.00000000 , 1
TBDAT, 1, 1.480000000E+11, 7.620000000E+10, 7.420000000E+10
TBDAT, 4, 0.00000000 , 0.00000000 , 0.00000000
TBDAT, 7, 1.480000000E+11, 7.420000000E+10, 0.00000000
TBDAT, 10, 0.00000000 , 0.00000000 , 1.310000000E+11
TBDAT, 13, 0.00000000 , 0.00000000 , 0.00000000
TBDAT, 16, 3.590000000E+10, 0.00000000 , 0.00000000
TBDAT, 19, 2.540000000E+10, 0.00000000 , 2.540000000E+10
/GO
!*
MPLIST,1
TBLIST,ALL,1
!*
MAT,2,
! /INPUT,.. \pzt2.SI_MPL
/NOP
/COM,Internal UNITS set at file creation time = SI (MKS)
TBDEL,ALL,_MATL
MPDEL,ALL,_MATL
MPTEMP,R5.0,1,1, 0.00000000 ,
MPDATA,R5.0,1,DENS,_MATL ,1, 7600.00000 ,
MPTEMP,R5.0,1,1, 0.00000000 ,
MPDATA,R5.0,1,PERX,_MATL ,1, 4.071000000E-09,
MPTEMP,R5.0,1,1, 0.00000000 ,
MPDATA,R5.0,1,PERY,_MATL ,1, 4.071000000E-09,
MPTEMP,R5.0,1,1, 0.00000000 ,
MPDATA,R5.0,1,PERZ,_MATL ,1, 2.080000000E-09,
TB,PIEZ,_MATL ,,, 0
TBDAT, 1, 0.00000000 , 0.00000000 , -2.10000000
TBDAT, 4, 0.00000000 , 0.00000000 , -2.10000000
/DIST, 1, 0.729000,1
/REP,FAST
/DIST, 1, 0.729000,1
/REP,FAST
/DIST, 1, 0.729000,1
/REP,FAST
/DIST, 1, 0.729000,1
/REP,FAST
CM,_Y,VOLU
VSEL,,, 2
CM,_Y1,VOLU
CMSEL,S,_Y
!*
CMSEL,S,_Y1
VATT, 1,, 1, 0
CMSEL,S,_Y
CMDELE,_Y
CMDELE,_Y1
!*
CM,_Y,VOLU
VSEL,,, 1
CM,_Y1,VOLU
CMSEL,S,_Y
!*
CMSEL,S,_Y1
VATT, 2,, 1, 0
CMSEL,S,_Y
CMDELE,_Y
CMDELE,_Y1
!*
FLST,5,2,6,ORDE,2
FITEM,5,1
FITEM,5,-2
CM,_Y,VOLU
VSEL,,,P51X
CM,_Y1,VOLU
CHKMSH,'VOLU'
CMSEL,S,_Y
!*
VSWEEP,_Y1
!*
CMDELE,_Y
CMDELE,_Y1
CMDELE,_Y2
!*
!*
ANTYPE,0
NSEL,S,LOC,X,0
FLST,2,112,1,ORDE,11
FITEM,2,87
FITEM,2,-88
FITEM,2,104
FITEM,2,-105
FITEM,2,151
FITEM,2,-152
FITEM,2,168
FITEM,2,394
FITEM,2,-453
FITEM,2,934
FITEM,2,-978
!*
/GO
D,P51X,0,,,UX,UY,UZ,,,
NSEL,S,LOC,Z,h
FLST,2,256,1,ORDE,4
FITEM,2,89
FITEM,2,-104
FITEM,2,169
FITEM,2,-408
/GO

```

```
TBDAT, 7, 0.00000000 , 0.00000000 , 9.50000000
TBDAT, 10, 0.00000000 , 0.00000000 , 0.00000000
TBDAT, 13, 0.00000000 , 9.20000000 , 0.00000000
TBDAT, 16, 9.20000000 , 0.00000000 , 0.00000000
TB,ANEL,_MATL , 1,, 0
TBTEM, 0.00000000 , 1
TBDAT, 1, 1.480000000E+11, 7.620000000E+10, 7.420000000E+10
TBDAT, 4, 0.00000000 , 0.00000000 , 0.00000000
TBDAT, 7, 1.480000000E+11, 7.420000000E+10, 0.00000000
TBDAT, 10, 0.00000000 , 0.00000000 , 1.310000000E+11
TBDAT, 13, 0.00000000 , 0.00000000 , 0.00000000
TBDAT, 16, 3.590000000E+10, 0.00000000 , 0.00000000
TBDAT, 19, 2.540000000E+10, 0.00000000 , 2.540000000E+10
/GO
!*
MPLIST,2
TBLIST,ALL,2
!*
/VIEW, 1 ,,1
/ANG, 1
/REP,FAST
```

```
!*
D,P51X,VOLT,0
NSEL,S,LOC,Z,-h
FLST,2,256,1,ORDE,4
FITEM,2,153
FITEM,2,-168
FITEM,2,709
FITEM,2,-948
/GO
!*
D,P51X,VOLT,100
ALLSEL,ALL
FINISH
/SOLU
/STATUS,SOLU
SOLVE
FINISH
/POST1
SET,,, ,1
SET,,, ,1
PLDISP,0
FINISH
```

(b) Harmonic analysis of a bimorph actuator

```
/BATCH
/input,menust,tmp,",,,,,,,,,,,,,1
/GRA,POWER
/GST,ON
/PLO,INFO,3
/GRO,CURL,ON
/REPLOT,RESIZE
*SET,1,0.015
*SET,w,0.003
*SET,h,0.0003
/PREP7
!*
ET,1,SOLID5
!*
BLOCK,0,1,0,w,0,h,
BLOCK,0,1,0,w,0,-h,
NUMMRG,KP,,, ,LOW
!*
MAT,1,
!/INPUT,..pzt1.SI_MPL
/NO
/COM,Internal UNITS set at file creation time = SI (MKS)
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MPDEL,ALL,_MATL
MPTEMP,R5,0, 1, 1, 0.00000000 ,
MPDATA,R5,0, 1, 1, 7600.00000 ,
MPTEMP,R5,0, 1, 1, 0.00000000 ,
MPDATA,R5,0, 1, PERX,_MATL , 1, 4.071000000E-09,
MPTEMP,R5,0, 1, 1, 0.00000000 ,
MPDATA,R5,0, 1, PERY,_MATL , 1, 4.071000000E-09,
MPTEMP,R5,0, 1, 1, 0.00000000 ,
MPDATA,R5,0, 1, PERZ,_MATL , 1, 2.080000000E-09,
TB,PIEZ,_MATL , 1,, 0
TBDAT, 1, 0.00000000 , 0.00000000 , -2.10000000
TBDAT, 4, 0.00000000 , 0.00000000 , -2.10000000
TBDAT, 7, 0.00000000 , 0.00000000 , 9.50000000
TBDAT, 10, 0.00000000 , 0.00000000 , 0.00000000
TBDAT, 13, 0.00000000 , 9.20000000 , 0.00000000
TBDAT, 16, 9.20000000 , 0.00000000 , 0.00000000
TB,ANEL,_MATL , 1,, 0
TBTEM, 0.00000000 , 1
TBDAT, 1, 1.480000000E+11, 7.620000000E+10, 7.420000000E+10
TBDAT, 4, 0.00000000 , 0.00000000 , 0.00000000
TBDAT, 7, 1.480000000E+11, 7.420000000E+10, 0.00000000
TBDAT, 10, 0.00000000 , 0.00000000 , 1.310000000E+11
TBDAT, 13, 0.00000000 , 0.00000000 , 0.00000000
TBDAT, 16, 3.590000000E+10, 0.00000000 , 0.00000000
TBDAT, 19, 2.540000000E+10, 0.00000000 , 2.540000000E+10
/GO
!*
MPLIST,1
TBLIST,ALL,1
!*
MAT,2,
!/INPUT,..pzt2.SI_MPL
```

```
MPDATA,R5,0, 1, PERY,_MATL , 1, 4.071000000E-09,
MPTEMP,R5,0, 1, 1, 0.00000000 ,
MPDATA,R5,0, 1, PERZ,_MATL , 1, 2.080000000E-09,
TB,PIEZ,_MATL , 1,, 0
TBDAT, 1, 0.00000000 , 0.00000000 , 2.10000000
TBDAT, 4, 0.00000000 , 0.00000000 , 2.10000000
TBDAT, 7, 0.00000000 , 0.00000000 , -9.50000000
TBDAT, 10, 0.00000000 , 0.00000000 , 0.00000000
TBDAT, 13, 0.00000000 , -9.20000000 , 0.00000000
TBDAT, 16, -9.20000000 , 0.00000000 , 0.00000000
TB,ANEL,_MATL , 1,, 0
TBTEM, 0.00000000 , 1
TBDAT, 1, 1.480000000E+11, 7.620000000E+10, 7.420000000E+10
TBDAT, 4, 0.00000000 , 0.00000000 , 0.00000000
TBDAT, 7, 1.480000000E+11, 7.420000000E+10, 0.00000000
TBDAT, 10, 0.00000000 , 0.00000000 , 1.310000000E+11
TBDAT, 13, 0.00000000 , 0.00000000 , 0.00000000
TBDAT, 16, 3.590000000E+10, 0.00000000 , 0.00000000
TBDAT, 19, 2.540000000E+10, 0.00000000 , 2.540000000E+10
FITEM,2,151
FITEM,2,-152
FITEM,2,168
FITEM,2,394
FITEM,2,-453
FITEM,2,934
FITEM,2,-978
!*
/GO
D,P51X,,0,,,UX,UY,UZ,,,
NSEL,S,LOC,Z,h
FLST,2,256,1,ORDE,4
FITEM,2,89
FITEM,2,-104
FITEM,2,169
FITEM,2,-408
/GO
!*
D,P51X,VOLT,0,0
NSEL,S,LOC,Z,-h
FLST,2,256,1,ORDE,4
FITEM,2,153
FITEM,2,-168
FITEM,2,709
FITEM,2,-948
/GO
!*
D,P51X,VOLT,100,0
HARFRQ,1523,1623,
NSUBST,100,
KBC,1
!*
ALPHAD,0,
BETAD,0,
DMPRAT,0.0239,
!*

```

```
/NOP
/COM,Internal UNITS set at file creation time = SI (MKS)
TBDEL,ALL,_MATL
MPDEL,ALL,_MATL
MPTEMP,R5.0, 1, 1, 0.00000000 ,
MPDATA,R5.0, 1,DENS,_MATL , 1, 7600.00000 ,
MPTEMP,R5.0, 1, 1, 0.00000000 ,
MPDATA,R5.0, 1,PERX,_MATL , 1, 4.071000000E-09,
MPTEMP,R5.0, 1, 1, 0.00000000 ,

ALLSEL,ALL
/STATUS,SOLU
SOLVE
/REPLOT,RESIZE
FINISH
/POST1
SET,LIST
SET,,, ,100
PLDISP,0
FINISH
```

Appendix B ANSYS Input Data

In this appendix, the data [194] for the bimorph ANSYS are listed below:

$$\rho=7600 \text{ Kg/m}^3 \quad (\text{B.1})$$

$$[\varepsilon]^s = \begin{bmatrix} 4.071 & 0 & 0 \\ 0 & 4.071 & 0 \\ 0 & 0 & 2.080 \end{bmatrix} \times 10^{-9} \text{ (F/m)} \quad (\text{B.2})$$

$$[e] = \begin{bmatrix} 0 & 0 & -2.1 \\ 0 & 0 & -2.1 \\ 0 & 0 & 9.5 \\ 0 & 0 & 0 \\ 0 & 9.2 & 0 \\ 9.2 & 0 & 0 \end{bmatrix} \text{ (N/Vm)} \quad (\text{B.3})$$

$$[c] = \begin{bmatrix} 14.8 & 7.6 & 7.4 & 0 & 0 & 0 \\ 7.6 & 14.8 & 7.4 & 0 & 0 & 0 \\ 7.4 & 7.4 & 13.1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3.6 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2.5 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2.5 \end{bmatrix} \times 10^{10} \text{ (N/m}^2\text{)} \quad (\text{B.4})$$

Appendix C Nomenclature

k_{31}	electromechanical coupling factor
d_{31}	piezoelectric constant
ϵ_{33}^T	dielectric constant
Q_m	mechanical quality factor
Y (or E)	Young's modulus
D_3	electric displacement
T_1	stress
S_1	strain
s_{11}^E	elastic compliance constant
Q	shear force
M	moment
M_0	equivalent moment
N	axial force
d_0	position of the neutral plane
f_a	anti-resonant frequency
f_r	resonant frequency
ω	frequency
ω_r	resonant frequency
ω_n	natural frequency
ρ	density, radius of curvature
C^T	static capacitance
E_3	electric field
V	applied voltage
δ	bending displacement
δ_l	bending displacement per unit length
l	length
w	width
h	thickness
n	number of layers
r_{ou}	outer diameter
r_{in}	inner diameter

x, z	position
t	time
u	general expression of bending displacement
I	moment of inertia
ξ	the damping ratio

Appendix D Equipments and Experimental Techniques

Table D.1 Equipments and experimental techniques

Item	Technique	Equipments	Chapter
Synthesis of the materials	Mixed oxide		Chapter 3
Characterization of physical properties	XRD SEM	Shimadzu XRD-6000; JEOL JSM-5410LV	Chapter 3
Characterization of piezoelectric properties		HP 4194 A impedance analyzer; Densimeter (MD-200S) RT6000HVS ferroelectric tester (Radiant Technologies, Inc); MTI-2000 fotonic sensor (MTI Instruments); Vibraplane (RS Kinetic System)	Chapter 3
Characterization of suspension		pH meter (MP220 pH Meter, Mettler Toledo); ZetaPlus (Brookhaven Instruments); Acoustic Spectrometer DT-1200 (Dispersion Technology, Inc.)	Chapter 4
Fabrication of piezoelectric FGM monomorph actuators	EPD	DC power supply (KEPCO, Bipolar operational power supply/amplifier, Model BOP 1000M); Deposition cell	Chapter 4
Static displacement measurement		RT6000HVS ferroelectric tester (Radiant Technologies, Inc); MTI-2000 fotonic sensor (MTI Instruments); Vibraplane (RS Kinetic System)	Chapter 5
Dynamic displacement measurement		Function generator (FG300, YOKOGAWA); Oscilloscope (DL1520, YOKOGAWA); MTI-2000 fotonic sensor (MTI Instruments); Vibraplane (RS Kinetic system)	Chapter 5

List of Publications

- 1 Y. H. Chen and J. Ma, Electrophoretic deposition and characterization of a FGM piezoelectric monomorph actuator, *Materials Science Forum*, 437-438 (2003) 487-490
- 2 Y. H. Chen, T. Li and J. Ma, Investigation on the electrophoretic deposition of a FGM piezoelectric monomorph actuator, *Journal of Materials Science*, 38 (2003) 2803-2807
- 3 Y. H. Chen, J. Ma and T. Li, A functional gradient ceramic monomorph actuator fabricated using electrophoretic deposition, *Ceramics International*, 30 (2004) 683-687

4 Y. H. Chen, T. Li and J. Ma, Investigation on the electrophoretic deposition of a FGM piezoelectric monomorph actuator, *Ceramics International*, 30 (2004) 1807-1809

piezoelectric FGM monomorph actuator, *Ceramics International*, 30 (2004) 1807-1809

- 5 Y. H. Chen, T. Li and J. Ma, Electrophoretic deposited monomorph actuator, *The International Conference on Smart Materials (Smart Mat-' 04)*, Thailand, 2004
- 6 T. Li, Y. H. Chen and J. Ma, Characterization of a C-morph monolithic actuator,