

Finite Element Analysis of Piezoelectric Composite Actuators

2011-01-0218

Published
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doi:10.4271/2011-01-0218

ABSTRACT

Piezoelectric materials are smart materials that can undergo mechanical deformation when electrically or thermally activated. An electric voltage is generated on the surfaces when a piezoelectric material is subjected to a mechanical stress. This is referred to as the 'direct effect' and finds application as sensors. The external geometric form of this material changes when it is subjected to an applied voltage, known as 'converse effect' and has been employed in the actuator technology. Such piezoelectric actuators generate enormous forces and make highly precise movements that are extremely rapid, usually in the micrometer range. The current work is focused towards the realization and hence application of the actuator technology based on piezoelectric actuation. Finite element simulations are performed on different types of piezoelectric actuations to understand the working principle of various actuators. The displacements produced by the multilayered actuators are sometimes insufficient compared with the total displacement requirements such as in injector control valve applications in automotive engine environment, therefore it calls for design of an amplification system to increase the stroke using existing multilayered stacks. Thus FE simulation procedures play key role in designing such smart actuating systems. Investigations on various types of displacement amplification systems have been made.

INTRODUCTION

"Piezoelectricity" is an electromechanical phenomenon, which relates electric polarization in the material to mechanical stress/strain. Piezoelectric materials convert electrical energy into mechanical energy or vice versa, referred to as "converse effect" and "direct effect", respectively. When a mechanical force deforms a piezoelectric material, a small but measurable electrical discharge is produced. Alternately, when an electrical voltage is applied across the thickness of a piezoelectric material, it experiences a significant increase in size (up to a 4% change in volume). Examples of piezoelectric materials include lead zirconate titanate (PZT) and poly vinylidene fluoride (PVDF) [1, 2].

In piezoelectric material, the electric dipoles are arranged randomly and it has a characteristic curie temperature. When heated above this temperature and placed in a strong electric field, the poling occurs, which remains in the material even after it is cooled. Further, when this poled ceramic is maintained below its curie temperature and subjected to a small electric field, the dipoles respond collectively to produce a macroscopic expansion along the poling axis and contraction perpendicular to the poling axis due to Poisson's effect (d_{31} effect). It may be noted that the strain changes direction with the change of direction of the applied field. The poling process is shown in [Figure 1](#).

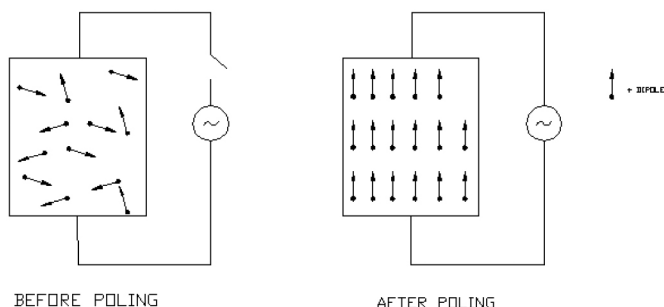


Figure 1. Poling in the piezoelectric crystal [1].

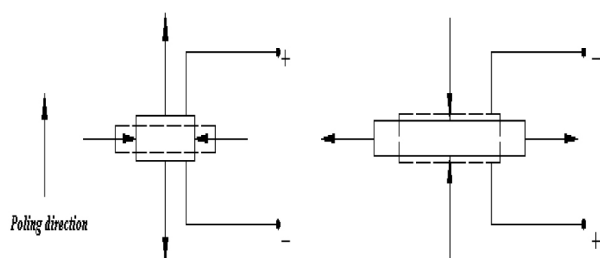


Figure 2. Deformation of piezoelectric crystal [1].

During the poling process, a strong DC electric field is applied across the electrodes of the piezoelectric crystal. This applied field causes most of the randomly aligned polar domains in the crystal to align with the applied field. The piezoelectric crystal is now said to be poled in the direction of the poling field. Upon applying an electric field along the poling direction, the material expands along the poling direction and contracts along the transverse direction. Reversing the electric field reverses the effect. The deformation patterns of poled crystal to such electric voltage configurations are presented in [Figure 2](#).

PRINCIPLES OF PIEZOELECTRIC ACTUATORS

The commonly used forms of piezoelectric actuators are the *Unimorph*, *Bimorphs* and *Multilayer /stack* actuators. *Unimorphs* are single layer piezoelectric crystals, in which upon application of an electric field along the initial poling direction of the material, the layer expands along the thickness direction (also referred to as the longitudinal direction) and contracts in the transverse direction. The motions are reversed with the reversal of the applied electric field. The motion along the thickness direction will be relatively less as compared to the motion along the transverse direction which will be in the order of a few microns. The transverse motion is often exploited in the structural control systems. Further, two layers of piezoelectric material may be connected back to back and with appropriate poling and electrode connections, *extension motors* and *benders* may be realized. Any number of piezoelectric layers may be stacked together which upon subjected to an electric field delivers a

motion proportional to the number of layers in the stack along the longitudinal direction and is called the *multilayer/stack* actuator [1, 3].

Piezoelectric extension motors

These are two layer motors and make use of the d_{31} effect as both layers expand or contract together. The electric field is applied parallel to the initial poling direction of the material. Based on poling directions of the piezoelectric layers and the electrode connections two types of extension motors may be realized. [Figure 3](#) below shows the expansion of a piezoelectric layer along the length upon application of an electric field parallel to the poling direction which is along the thickness [1, 3].

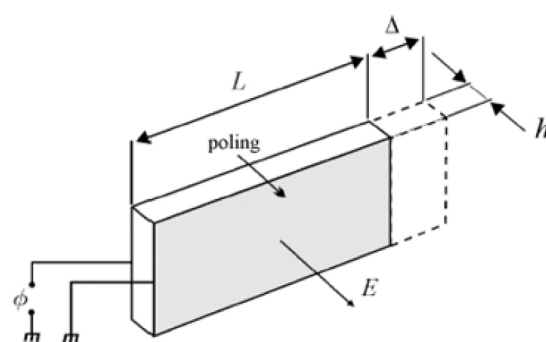


Figure 3. Extension actuators.

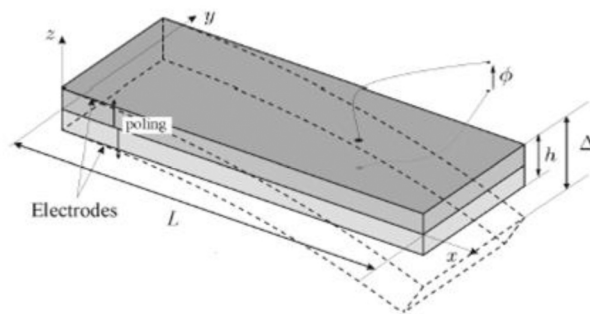


Figure 4. Bimorph actuators.

Piezoelectric bimorphs or benders

In a bimorph configuration, an electric field is applied in the direction parallel to the initial poling direction of the piezoelectric material. Also referred to as “extension-mode bending actuators”; these benders mainly use the d_{31} effect. In construction a bimorph consists of a pair of laminated piezoelectric layers with the top and bottom layers appropriately poled with electrode surfaces. Upon application of an electric field across the two layers of the bender, one layer extends while the other layer contracts generating a moment and hence the required bending effect. [Figure 4](#) shows a typical bimorph actuation [2].

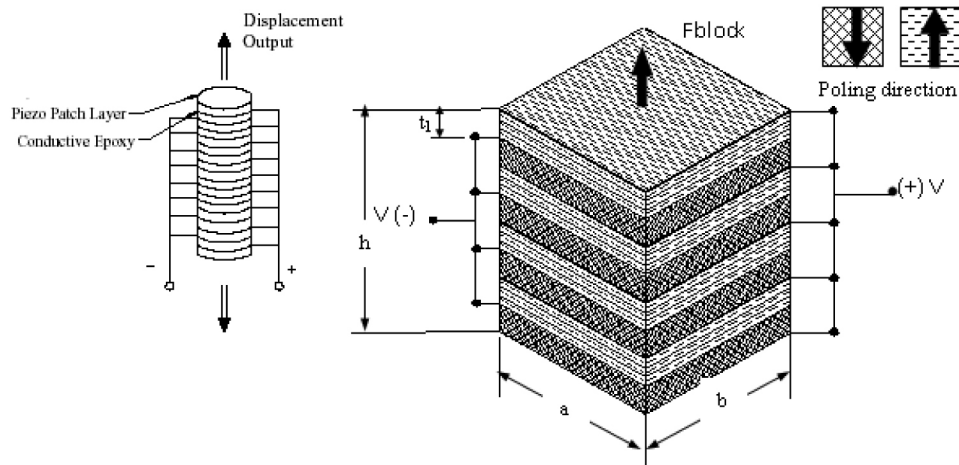


Figure 5. Stack actuator with parallel connection.

Multilayer / Stack actuators (MLA)

These are solid-state actuators that convert electrical energy directly into motion of extremely high resolution. Actuators of this kind show displacements in the range between 10-300 μm , with large blocking forces, up to several kN, requiring low driving voltages. Each stack (thickness t_1) is made up of several piezoceramic layers of definite thickness that are poled in the same direction. All the layers in a stack share the total applied voltage. These stacks are then arranged with opposite poling direction and electrodes are provided at the interface of the stacks as shown in Figure 5 [1, 5].

Piezoelectric stack actuator design will make use of increase of ceramic thickness in the direction of the applied electrical field (d_{33} effect). Stacking of several layers towards building a multilayered structure increases equivalently the total stroke. In practice, axial strain rates up to 2%, of stack's length can be achieved under certain conditions. Piezoelectric stack actuators provide a displacement proportional to an applied voltage. These actuators are generally capable of providing large forces across small displacements over a large frequency bandwidth [6]. The operation range of a typical stack actuator revolves around the relationship shown in Figure 5 [5], which illustrates the ability of a stack to provide a force at a given displacement.

The free displacement (x) is the displacement produced by the actuator at the maximum specified voltage at zero block force (i.e. force generated in the actuator is zero). Blocked force (F_{blocked}) is defined as the maximum force generated by the actuator at maximum voltage when the actuator is fully constrained (i.e. not allowed to undergo any deformation). Piezoceramic stacks are capable of providing their largest force when they are constrained to produce zero displacement. Conversely, the stack can produce no force at its maximum displacement. The optimal operating region, with regards to efficiency of operation over a cycle, of a

piezoceramic actuator is around the shaded region shown in Figure 6 that is bounded by $x_{\text{max}} / 2$ and $F_{\text{blocked}} / 2$. Work is said to be done by the actuator when it develops a force for a given displacement. Thus, a piezo-ceramic stack whose blocked force is as twice the calculated maximum required actuator force and whose maximum displacement is twice the maximum displacement required for the purpose will be required to ensure that the actuator would always be able to provide the necessary displacements and forces.

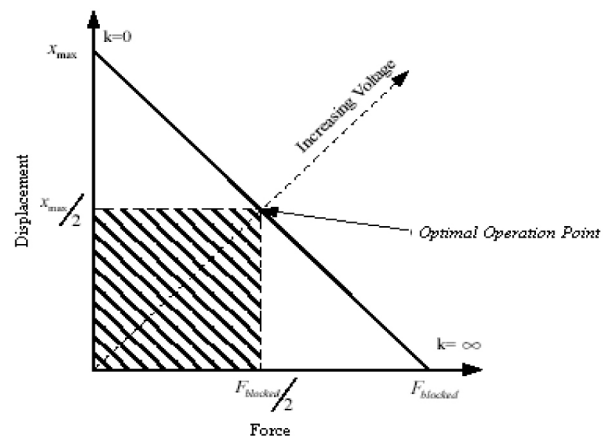


Figure 6. Displacement vs. force for the piezoelectric actuator.

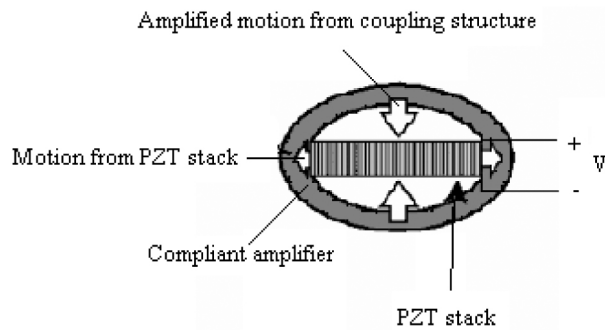


Figure 7. Flextensional actuator.

Often the displacement produced by these candidate piezo stacks is insufficient compared with the total displacement requirements required for certain applications such as the fuel injector valve in an automotive engine, in which circumstances the following options may be considered

- Select much larger stacks that can produce higher displacements
- Design an amplification system to increase the stroke using existing stacks
- Search for the best fit of prevailing piezo stack capability with emerging fuel injector technology

The first option is deemed impractical because of the physical limitations of the stack sizes, higher capacitance and higher current and also available space limitations. The intermediate solution is deemed to be a reasonable approach in spite of considerations for implied energy losses and system complexities. Of the various approaches that are available for displacement amplification viz. mechanical, hydraulic, and hybrid, an amplification system such as amplified piezo actuator (APA) which is a flextensional amplifier, developed by CEDRAT® Technologies, and purely based on mechanical amplification is preferred [7]. The mechanical amplification system is a better option because of its simplicity and inherently improved control of design issues. The structural configuration and the working principle of an amplified piezo actuator are shown in [Figure 7](#) [7].

Amplified piezoelectric actuators [7] consist of stacks that are pre-stressed inside a steel elliptic frame, which produce a natural amplification ratio of the displacement (between 2 and 5 according to the two axes ratio). This principle will obtain deformation between 0.3 and 3 percent with only a slight decrease of the force capability, while other piezoelectric principles have strokes up to a maximum of 0.1 percent of their total length.

The main advantages of APAs are their relatively high displacements combined with their large forces and compact size along the active axis (shell short axis). Their deformation reaches 0.3% (30µm/cm) to 5% (50µm/mm), in comparison

to the MLA deformation of 0.1% (1µm/mm). For example, on a 200V range, the APA200M actuator produces free displacements up to 200µm and blocked forces up to 50N along its short axis, which is only 17mm high. This corresponds to an apparent strain of more than 1.4% along the short (active) axis [7].

Another advantage is the robustness of the actuators, and the ability to withstand both transverse forces (because such forces do not produce flexure in the stack and are entirely supported by the shell,) and transient forces (because the stack is pre stressed). The high displacements of APAs combined with their high forces show that these actuators achieve displacement amplifications of 2 to 10 with a good mechanical efficiency. They achieve equivalent output energy to mass ratio as conventional stacked actuators [7].

FINITE ELEMENT SIMULATIONS OF PIEZOELECTRIC ACTUATORS

The piezoelectric actuators discussed thus far are simulated using the ABAQUS Finite Element Analysis software [8]. Eight-node hexahedral element C3D8E having electromechanical coupling capability was used to model the actuator. Appropriate mechanical constraints and electrical boundary conditions were applied to realize various actuator configurations.

Piezoelectricity, which is basically a combination of electrical behavior and mechanical Hooke's law of the material, may be written in the coupled form as

$$\{S\} = [s^E] \{T\} + [d^t] \{E\} \quad (1)$$

$$\{D\} = [d] \{T\} + [\epsilon^T] \{E\} \quad (2)$$

where S = Strain

S^E = Elastic compliance at constant electric field

T = Stress

d = Piezoelectric strain per unit of electric field

E = Electric field

D = Electric charge displacement

ϵ = Permittivity at constant stress

The above form is the “strain-charge” form of coupled piezoelectric constitutive equation. [Equation \(1\)](#) describes the converse piezoelectric effect and [Equation \(2\)](#) the direct piezoelectric effect. In addition there also exists the “stress-charge” form of coupled piezoelectric constitutive equation.