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Mini Review

Piezoelectric Material Non-Linear Characteristics, Compensation Methods and Application

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Abstract

Piezoelectric materials are capable of converting the mechanical stress to the electrical charge and vice versa. These piezoelectric effects made them useful for sensors and actuators in many applications, such as in the control of structural vibration. Nonlinear hysteresis is one of the inherent characteristics of the piezoelectric material, which affect their performance. This characteristic has been widely studied and can be compensated using operator-based or differential-based models. Another important characteristic to be considered is creep. It has caused slow drift in the actuation process. In general, the compensated method can be divided into two group; open and closed loop methods. The non-linear characteristics of the piezoelectric material is important to be characterized and compensated, in particular for used in the Active Vibration Control (AVC) system.

Keywords: Piezoelectric materials; Hysteresis; Creep; Structural vibration

Introduction

Piezoelectric material has been widely used as sensor and actuator in many applications such as in structural vibration reduction [1-3], control of flexible structures [4,5], positioning control [6,7] and energy harvesting [8]. This is due to the piezoelectric effects which converted the mechanical energy to the electrical energy (i.e., sensing ability) and conversely from electrical energy to the mechanical energy (i.e., actuating ability). These piezoelectric effects were firstly discovered but only been used in 1940 (Figure 1a & 1b). Show both of the piezoelectricity working principle of sensing and actuating abilities, respectively. From these Figure 1a & 1b, the first effect is due to the mechanical stress which transfers the energy to the electrical charge across the material and the second effect is conversely due to the applied electrical charge to the material resulting in mechanical stress [9].

The detail of piezoelectric constitutive equations in the stress-charge form are given by:

$$\sigma = c_E S - e_p E_e \quad (1)$$

$$D_e = e_p^T S + \epsilon_s E_e \quad (2)$$

Where S is the strain, σ is the stress, D_e is the electric displacement, E_e is the electric field strength, e_p is the piezoelectric coupling coefficient in the stress-charge form, c_E contains stiffness coefficients under constant electric field and ϵ_S is the electric permittivity matrix under constant strain. Subscripts E indicates zero or constant electric field and σ is the zero or constant stress field, while superscript T denotes matrix transposition. Piezoelectric actuators are known for their various shapes, flexibility, high frequency response and high stiffness but very limited on displacement [10-12]. Thus, they are suitable for the vibration isolation of stiff structures. For example, piezoelectric actuator has been used to control the vibration in automotive [13,14], aerospace [1,15], robotic [7] and civil structures [16].

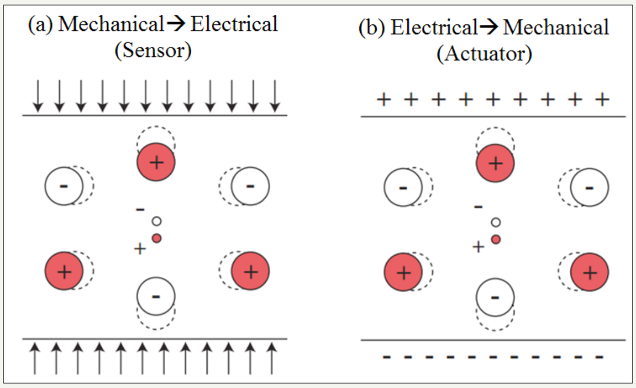

Figure 1: Sensing and actuating abilities from piezoelectric effect [10].

Non-linear hysteresis and creep are the inherent characteristic of the piezoelectric actuator, which affect their performance and these characteristics will be described in the next section. In general, there are three types of piezoelectric materials which can be used as an actuator such as ceramics, polymers or composites. Poly vinylidene fluoride (PVDF), Lead Zirconate Titanate (PZT) and Lithium Niobate (LN) are the examples of piezo polymer, piezo crystal and piezo composite, respectively [17]. All of them can be used as an actuator due to their characteristics which are lightweight and flexible and suitable for many applications. From all these materials, PZT (i.e., ceramic material) is still the most widely used material compared to the PVDF and LN due to lower voltage consumption for the actuation process [12]. Piezoelectric actuators in the market are available in various prices and shapes.

The price depends on the complexity, size and function of the piezoelectric actuator. In term of shape, there are many types of piezoelectric actuators that have been developed, such as stack, patch, bender, tube and shear-type piezo actuators [18]. The force and displacement of the actuator depend on the diameter and length, respectively. The high blocking force of the piezo stack actuator made it suitable for the control of instrumentation such as rotors and fuel injector. For example, two piezo stack actuators were used as control actuators in the Active Vibration Control (AVC) of the rotating machines for both steady-state and transient motions [19]. For the rail diesel engine, piezo stack actuator is used to actuate the fuel injector resulting in improved efficiency and emission reduction [20].

Piezoelectric Non-Linear Characteristics and Compensation Methods

Piezoelectric actuator suffers from the non-linear hysteresis which can negatively affect its performance. Hysteresis is defined as a dynamic lag phenomenon between the input voltage and output displacement or force of the piezoelectric actuator in the time domain operation [12]. The hysteresis characteristic of the piezoelectric actuator was noticeable when operating in the large voltage range with slow or fast speed motion, which can bring about large positioning error [10]. The hysteresis of the piezoelectric actuator occurred in both static and dynamic operations. Figure 2 shows the typical hysteresis curve of the piezoelectric actuator when operating in open-loop condition. From the Figure 2, there are two mechanisms to characterize the hysteresis of the piezoelectric actuator; displacement and voltage. When the piezoelectric actuator was energized, the displacement of the piezoelectric actuator will move from the position 1 to position 2 with the maximum supplied voltage of 50V and return back to the position 1 when the piezoelectric actuator was de-energized.

However, the increment route (from position 1 to position 2) and the decrement route (from position 2 to position 1) are not the same due to the hysteresis effect. This effect become worse when operating the piezoelectric actuator in a larger voltage range as shown by position 3 (i.e., maximum voltage of 75V) and position 4 (i.e., maximum voltage of 100V) in Figure 2. To date, many of dynamic models have been developed to predict the hysteresis behavior of the piezoelectric actuator. The models can be categorized in two types which is operator-based control and differential-based control.

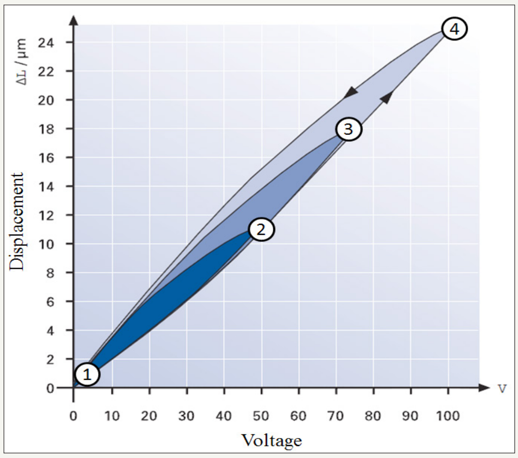

Figure 2: Typical hysteresis curve of an open-loop piezoelectric actuator [12].

For operator-based hysteresis models, such as Prandtl-Ishlinski, Preisach and Preisach have successfully model the hysteresis and a lot of works have been reported. Generally, it involves the integration models which the kernel has infinite number of hysteretic operators, which can describe hysteresis shape accurately. Whereas, differential-based models such as Duhem and Bouc-Wen models are alternate in modelling this non-linear characteristic. In this approach, the model will have finite dimensional and easily extended to continuous input using approximation and a limited process that avoid computation time [21-25]. The advantage and disadvantages of the different types of hysteresis models are summarized as in Table 1.

Table 1: List of the compensation methods for hysteresis characteristics.

	Types of Model	Advantages	Disadvantages	References
Operator-based control	Prandtl-Ishlinski	1. Simplicity with ease of implementation and used for real application 2. Applicable for stationary and nonstationary application. The errors contribute up to 3.9% and 7.5% for stationary and nonstationary controls, respectively.	1. High computation time due to increase of number backlash operators. 2. The model has singularity when the slope of hysteresis curve become zero. Also, near this singularity is highly sensitive to noise and required precaution step in order to avoid modelling error	[22-25]

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	Preisach	1. In hysteresis characterization, the model shows good performance even though at narrow frequency range or no-load condition 2. The model can capture a large class of hysteresis maps with complex behaviour using integral model with infinite numbers of hysteretic operators	1. Total data collected will influence the accuracy of the model 2. The model uses double integrator which when constructing the inverse model is very difficult.	[21-23], [26-28]
Differential-based model	Bouc-Wen	1. The model can be applied with different types of controllers	1. Construction of inverse model is difficult. 2. In classical model such as Bouc-Wen model is applicable for symmetrical. Unfortunately, many hysteresis problems in piezoelectric such as piezo-stack, piezotube scanner and multimorph cantilever are non-symmetrical. 2. The asymmetric model is not easily extending to multi-degree of freedom system. This can lead to very complex calculation and implementation to compensator	[23], [28-30]
	Duhem	1. For input responses, the model is robust as the signal can sinusoidal or triangle which essential in comparing tracking reference. 2. In feedforward compensation and compared with Bouc-Wen model, this model effectively alleviates cross-coupling effects between the X and Y of axis actuation	1. The hysteresis is model in more complex way compared to Bouc-Wen and other models. 2. Difficulty to find functions of input voltage that influence on both model performance and hysteresis loop	[23,28,31]

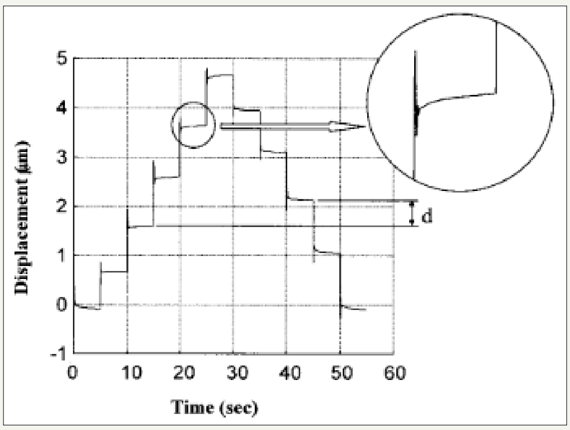

Figure 3: Step response of the piezoelectric actuator with displacement difference resulted from the hysteresis [34].

Onward, the fundamental task is to exploit the characteristics of these models and design the corresponding control that can mitigating the hysteresis effect [26-31]. Another non-linear characteristic of the piezoelectric actuator to be considered is a creep. It can define as phenomena with displacement drift without accompanying change in input voltage [32]. It appears as effect of piezoelectric viscoelastic material properties and also exist in both electrical and mechanical domains [33]. Found that constant input voltage lead to displacement creep of the piezoelectric as shown in Figure 3. The highlight circle shown clearly the creep effect in piezoelectric application [34]. Clearly, the presence of the creep can cause substantial errors especially in atomic force microscopes [35-37] and micro-manipulators [38].

In some applications, the creep effect can be removed using the sensor technology, but it will limit the performance especially

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for micro or nano-positioning applications. Nevertheless, the cost for the sensor with high accuracy and high bandwidth are very expensive and large in size such as interferometers, optical sensors and camera-microscope measurement systems [39]. Concerning the creep, there are several methods have been proposed. One of them is logarithmic function. The method aims to compensate the creep by having an opposite logarithmic model applied to the voltage so the final strain will remain constant. Another method to be considered is a dynamic operator. The method is composed of many elementary first order operators. The advantage and disadvantages of the different types of creep compensation methods are summarized as in Table 2.

Table 2: Comparison of different type of compensation method for creep.

Type of Model	Compensation Method	Advantages	Disadvantages	References
Open loop	Logarithmic function	1.Inexpensive method whereby it avoids the limitation of closed-loop which depend on the sensor	1. Applicable to one-degree of freedom model. 2. The difficulty in determination of voltage nominal constant input and creep factor for any desired displacement. 3. For obtaining reliable creep data, the researcher will have difficulty task.	[38,40]
Closed loop	Dynamic operator	1. Ease of identification and control	1. Applicable to one-degree of freedom model. 2. Expensive modelling as it required high precision bandwidth sensor.	[38,41]
N/A	Mutli-DOF	1. The creep is eliminated for every axis and decoupling between all axis. 2. The compensator is simple to commute and ease of implementation.	1. The model is not proved yet for 3-DOF.	[39]

In closed-loop method, it offers several advantages like accuracy, repeatability and vibration rejection. Indeed, it is an expensive option, whereby there is a requirement of sensor to be used. Second option (open loop) is a low-cost compensation method, whereby it does not used the sensor, but it subjected to low accuracy and problem in the reliability of the data. Based on the previous study, both closed and open loop share one limitation, only can be used for 1-DOF problems [40,41].

Conclusion

Non-linear hysteresis and creep are the inherent characteristic of the piezoelectric material which can negatively affect its performance. There are plenty of models that have been developed to characterize this characteristic of the piezoelectric actuator. This problem can be compensated using the method listed above. Future works should concentrate on other non-linear characteristics of the piezoelectric material and advanced control strategies to compensate them for the application as sensor and actuator in the AVC system.

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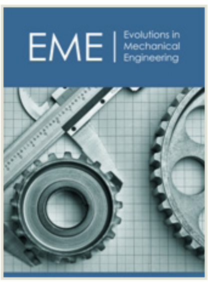

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