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The Application of Piezoelectric Materials in Smart Structures in China

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Abstract

Piezoelectric materials have become the most attractive functional materials for sensors and actuators in smart structures because they can directly convert mechanical energy to electrical energy and vise versa. They have excellent electromechanical coupling characteristics and excellent frequency response. In this article, the research activities and achievements on the applications of piezoelectric materials in smart structures in China, including vibration control, noise control, energy harvesting, structural health monitoring, and hysteresis control, are introduced. Special attention is given to the introduction of semi-active vibration suppression based on a synchronized switching technique and piezoelectric fibers with metal cores for health monitoring. Such mechanisms are relatively new and possess great potential for future applications in aerospace engineering.

Key words: Piezoelectric materials, Vibration control, Energy harvesting, Structural health monitoring, Piezoelectric hysteresis

1. Introduction

A piezoelectric material responds to a mechanical force by generating an electric charge or voltage. This phenomenon is called the direct piezoelectric effect. However, mechanical stress or strain is induced when an electric field is applied to the material; this phenomenon is called the converse piezoelectric effect (Tani et al., 1998). Due to their excellent electromechanical coupling characteristic, piezoelectric materials have been widely used in structural vibration control, structural health monitoring, precision positioning, energy harvesting, and so on. The direct effect, the function enabling mechanical-to-electrical energy conversion, is used for sensing, energy harvesting or vibration damping. The converse effect, the function enabling electrical-to-mechanical energy conversion, is for actuation.

Due to their excellent frequency response, piezoelectric materials are very suitable for sensors and actuators in vibration and noise control. Piezoelectric sensors bonded on a structure can be used to directly measure the dynamic strain of the structure, which can be used as the feedback signal in active control. Though the output strains of piezoelectric actuators are relatively small compared to other functional materials, such as shape memory alloys and some electro-strictive polymers, they are still large enough for structural vibration suppression and noise reduction. Semi-active vibration control methods have recently attracted the attention of many researchers because of their low energy consumption. The electrical energy converted from the vibration energy of a structure by the direct piezoelectric effect is efficiently used for actuation in semi-active control.

Energy harvesting has been an active area of research in recent years due to growing awareness for environmental protection. Harvesting vibration energy based on piezoelectric materials utilizes the direct piezoelectric effect. In order to efficiently collect the low-quality electrical energy generated by a piezoelectric generator, the design of a high-performance electronic interface has been an important issue in energy harvesting. In addition, many studies have also been conducted in the design of mechanical structures for energy harvesters as well as the development of piezoelectric materials with high electromechanical factors. Structural health monitoring has also been an active area of research in the past 15 years. The methods for structural health

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monitoring (SHM) using piezoelectric materials can be divided into three main categories: those based on vibration characteristics, those based on impedances and those based on guided waves. Since the hysteresis of piezoelectric materials negatively affects control performance, its control has also been an active research area.

This article introduces the research activities and achievements attained through the application of piezoelectric materials in smart structures in China. The article is organized as follows: Section 2 introduces the studies in vibration control, including active methods and semi-active methods; Section 3 introduces the research on noise control using piezoelectric materials; Sections 4 and 5 provide the research in energy harvesting and structural health monitoring, respectively; modeling and control of piezoelectric hysteresis are introduced in Section 6 and a summary is given in Section 7.

2. Application in Vibration Control

2.1 Categorization of vibration control methods based on piezoelectric actuators

The methods of vibration control using piezoelectric transducers are divided into three categories: passive, active, and semi-active (Qiu et al., 2009a; Tani et al., 1998). In different vibration control systems, piezoelectric transducers play different roles. During passive control, an actuator is used to convert mechanical energy to electrical energy, which is dissipated in a shunt circuit so that the mechanical energy in the vibrating structure is reduced (Corr and Clark, 2003; Fleming and Moheimani, 2004; Hagood and von Flotow, 1991). Because the passive control system uses the principle of dynamic absorbers by tuning the resonance frequency of the shunt circuit to the natural frequency of the structural system, it is very sensitive to parameter variation. Hence the robustness of the passive control system is low.

During active control, the control command is applied to the piezoelectric actuator to generate a force and actively suppress the vibration. Usually active control methods produce high control performance and high robustness; however, the system requires sophisticated signal processing units and bulky power amplifiers (Fazelzadeh and Jafari, 2008; Qiu et al., 2009c; Zhang et al., 2004). These drawbacks make active control methods difficult to implement in many engineering structures, especially aerospace structures. However, semi-active methods overcome the disadvantages of complicated signal processing and bulky power amplifier in active vibration control. Additionally, semi-active methods bypass the sensitivity that the control performance of passive vibration control has to variations in parameters (Badel et al., 2006; Makihara et al., 2007; Qiu et al., 2009a). Usually semi-active methods provide comparable control performance and robustness to the active methods, and the systems are very simple to implement. Furthermore, such systems only consume a few milliwatts. This chapter introduces the research on active and semi-active vibration.

2.2 Active vibration control using piezoelectric actuators

The design of active piezoelectric control systems for structural vibration suppression generally involves several aspects: analysis and modeling of a piezoelectric structure, model reduction, location optimization of piezoelectric sensors and actuators, controller design based on different control theories, and system implementation. Research on active vibration control using piezoelectric actuators has been conducted accounting for these aspects.

2.2.1 Analysis and modeling of piezoelectric structure

Piezoelectric structural systems can either be lumped mass systems or distributed parameter systems, which are mathematically represented by ordinary differential equations and partial differential equations, respectively. Although methodologies for analysis and modeling of piezoelectric structures have been well developed, such methodologies are still necessary for all studies in active vibration control because of the requirement of state space models during the design of active controllers. Analytical methods of modeling have been used by Ji et al. (2009c, 2010b) for the cantilever piezoelectric beam and Fu and Zhang (2009) for microplates. For complicated structural systems, modeling based on analytical methods can be very complicated. Numerical methods, such as the finite element method (FEM), are preferable. FEM has been used by Qiu et al. (2009c) in the modeling of piezoelectric beams and by Shen and Liew (2004) and Zhao (2010) in the modeling of plant-like piezoelectric structures.

Model reduction is also an important step in the modeling process based on the FEM. The large number of degrees of freedom of FEM models is usually reduced using model reduction techniques, such as the singular value decomposition method (Wang et al., 2003), by removing insignificant modal coordinates. More sophisticated methods have been developed and can be found in the study by Dong and Meng (2005). The reduced model will still require further reduction for use in control system design and implementation. In control design, the model is converted to a state-space form and reduced by one of the reduction methods presently employed by the control community (Huang et al., 2005). In essence, these methods approximate a large dynamic system with fewer number of state variables.

2.2.2 Optimal placement of sensors and actuators

In active piezoelectric vibration control, placement of actuators and sensors on the structure is a very important issue because placement directly affects the efficiency of actuators and sensors in control. The location of sensors and actuators directly affects the observability and controllability of the system. For example, the sensor will not be able to observe a specific mode if it is located at the node of that mode. In multi-mode control, optimizing the locations of the sensors and actuators becomes extremely important in order to maximize the system's observability and controllability. Consequently, optimization increases the system's efficiency. Qiu et al. (2007) and Zhang and Erdman (2006) combined controllability and observability methods to optimize the locations of piezoelectric actuators and sensors for active vibration control of building floors. Chen et al. (2009) used the particle swarm optimizer to determine the positions of piezoelectric actuators for active vibration control of plates.

2.2.3 Active control methods

Active control methods can be divided into feedback methods and feed-forward methods. In most active vibration control studies, feedback methods have been used because the control input is generated based on the system output and no further information concerning the excitation force is required. The theories of feedback control include classical control theories (such as proportional-integral-derivative control), modern control theories based on state-space representation, robust control theories, neural network control theories, and fuzzy control theories. Recent studies on active vibration control using feedback methods include the study by Qiu et al. (2007) based on the proportion controller for vibration suppression of the flexible cantilever plate, the studies by Sheng and Wang (2009), Fu and Zhang (2009), and Mao and Fu (2010) using the positive position feedback scheme for vibration damping of piezoelectric structures. Qiu et al. (2007) also employed a variable structure strategy and Hu and Ma (2006) investigated the performance of an optimal controller for the active vibration control.

In feed-forward control, information concerning the vibration excitation is required for calculation of the control input. Since feed-forward controllers are always based on the model of the structure, the controllers can often achieve very high levels of vibration attenuation. Furthermore, adaptive feed-forward algorithms may exhibit satisfactory performance when they are applied to vibration control problems involving periodic disturbances. Studies on active vibration control using feed-forward methods include those by Zhang et al. (2003) and Zhao (2010) based on band-pass finite impulse response (FIR) filters for the vibration suppression of flexible linkage mechanism and plate, respectively.

2.3 Semi-active vibration control based on synchronized switch damping

Semi-active vibration control methods based on the piezoelectric actuators can be divided into state-switched methods and pulse-switched methods. In state-switched methods, the piezoelectric actuator is switched between an open-circuit state and a short-circuit state according to the displacement and velocity of the vibration. In the pulse-switched method, the voltage on the piezoelectric actuator is processed nonlinearly. This study will only discuss the pulse-switched method.

2.3.1 Classical synchronized switch damping

The synchronized switch damping (SSD) method, also called pulse-switched method, entails the nonlinear processing of the voltage on a piezoelectric actuator. It is implemented with a simple electronic switch synchronously driven with the structural motion. This switch, which is used to cancel or inverse the voltage on the piezoelectric element, allows a brief connection to a simple electrical network (short circuit in SSDS, inductor in SSDI, and voltage sources in SSDV) to the piezoelectric element (Badel et al., 2006; Faiz et al., 2006; Lallart et al., 2009; Lefeuvre et al., 2006a; Makihara et al., 2006; Onoda et al., 2003; Richard et al., 2000). Due to this process, voltage magnification is obtained and a phase shift appears between the strain in piezoelectric patch and the resulting voltage, as shown in Fig. 1. The force generated by the resulting voltage is always opposite to the velocity of the structure, thus creating net mechanical energy dissipation. The dissipated energy corresponds to the part of the mechanical energy that is converted into electric energy. Maximizing this energy is equivalent to minimizing the mechanical energy in the structure under a given excitation.

The role of the additional constant voltage sources in the SSDV technique is to increase the voltage amplitude, which increases the damping effect. In the original SSDV technique, the sign of the continuous voltage source is changed so that it will increase the piezovoltage during the inversion process (Lefeuvre et al., 2006a). However, its absolute value remains constant, which can lead to stability problems. In reality, when the vibration level is very low, the original SSDV approach may excite the structure instead of damping its vibrations. Hence, in the enhanced SSDV proposed by

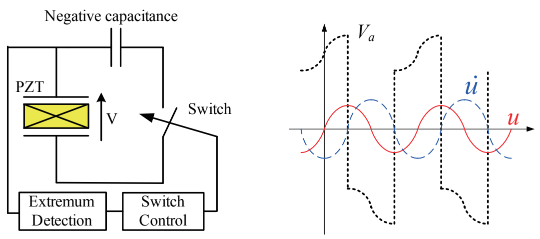


Fig. 1. The principle of synchronized switch damping technique.

Badel et al. (2006), which is shown in Fig. 1, the voltage source is proportional to the vibration amplitude as shown in following equation.

$$V_{cc} = -\beta u_M \tag{1}$$

where β is the voltage coefficient.

2.2.2 Adaptive SSDV

For a given value of parameter β in Eq. (1), the damping is not sensitive to the amplitude of the applied force. This is the critical point of the enhanced SSDV. But it must be noted that for large values of β, the above theoretical expressions are no longer valid because the displacement of high-order modes cannot be neglected any longer compared to the fundamental one. The experimental results exhibited that the optimal value of the voltage coefficient β depends on many factors, such as the noise level of the measured signal and the property of the switch (Ji et al., 2009a, 2009b). Hence, in order to achieve optimal control performance, the voltage coefficient should be adjusted adaptively according to the vibration amplitude and other experimental conditions.

An adaptive enhanced SSDV technique, in which the voltage coefficient is adjusted adaptively to achieve optimal control performance, has been proposed by Ji et al. (2009a). The basic principle of the adaptive SSDV technique is that the coefficient β is adjusted based on the sensitivity of the vibration amplitude with respect to β: the more the vibration amplitude is sensitive to β, the more β is increased. If the variation of amplitude is Δu_{Mi} due to an increment of the voltage coefficient $\Delta\beta$i, the sensitivity is defined as $\Delta u_{Mi}/\Delta\beta_i$. The increment of the voltage coefficient, $\Delta\beta_{i+1}$, in the next step is defined as

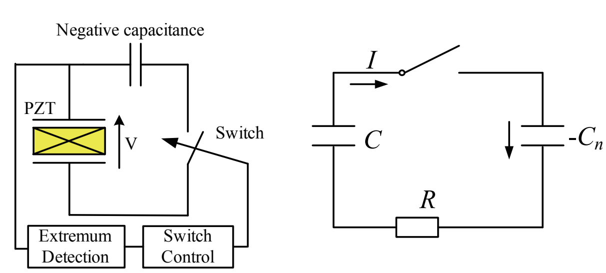
$$\Delta\beta_{i+1} = -\eta \frac{\Delta u_{Mi}}{\Delta\beta_i} \tag{2}$$

where η is the convergence rate factor. The larger the factor η is, the faster the convergence rate is. But when η is too large, the iteration process may become unstable. The physical meaning of the algorithm defined in Eq. (2) is similar to the Newton-Raphson method in numerical analysis.

In the derivative-based adaptive SSDV, the voltage coefficient β is optimized to achieve satisfactory damping control performance. The final goal of optimizing the voltage coefficient β is to obtain the optimal voltage. A novel adaptive SSDV method based on a least mean square (LMS) algorithm to directly adjust the voltage source or voltage coefficient was proposed by Ji et al. (2009b). In the LMS-based adaptive SSDV, a FIR filter is used to optimize the voltage V_{cc} or the voltage coefficient β. Their values are defined at each switching point (each displacement extrema), not the discrete sampling time n. Hence the detected displacement amplitude u_M (which is used as a sensor signal to control the switch action), instead of the displacement u itself, is used as the error e to the FIR filter. The output y of the FIR filter is the voltage or the voltage coefficient β at the switching times, instead of the voltage value at each discrete time, and the calculated voltage is held constant until the next switching time so that a rectangular wave is generated automatically by the switching circuit.

2.2.3 The SSD technique based on negative capacitance

Negative capacitance has been widely used in passive vibration damping systems (Behrens et al., 2003; Lin and Ermanni, 2004; Park and Baz, 2005; Park and Park, 2003; Wu, 2000). But in semi-active vibration control, a negative capacitance $-C_n$ is used instead of an inductance for voltage inversion. When a negative capacitance $-C_n$ is used in a switching shunt circuit instead of an inductance, the circuit is purely capacitive. However, the voltage on the piezoelectric element can still be effectively inverted by briefly closing the switch, though the mechanism for voltage inversion is different. The schematic of the SSDNC system is shown in Fig. 2(a) and its equivalent circuit is shown in Fig. 2(b), where C is the equivalent capacitance of the piezoelectric element, C_n is the absolute value of the negative capacitance, R is the resistance in the shunt circuit. Negative capacitance can only



(a) The schematic of a SSDNC system (b) The equivalent circuit

Fig. 2. Principle of synchronized switch damping on negative capacitance (SSDNC) technique.

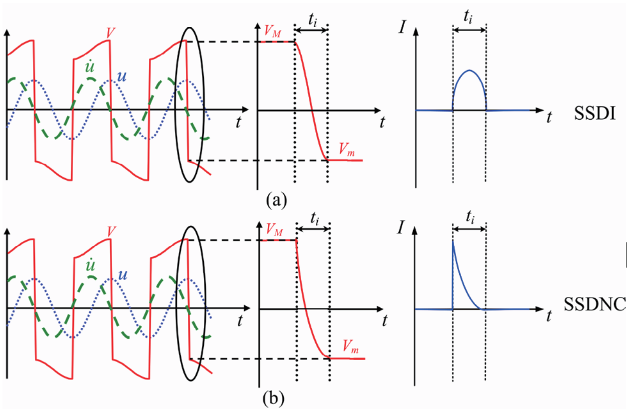


Fig. 3. The waveforms of the voltage on the piezoelectric actuator and the current in the circuit of synchronized switch damping on inductance and synchronized switch damping on negative capacitance.

be realized by synthetic circuit (Ji et al., 2010a).

The waveforms of the voltage on the piezoelectric element and the current in the circuit of SSDI are illustrated in Fig. 3(a). The SSDNC system is fundamentally first order because the electric circuit is purely capacitive (Ji et al., 2010a). No electrical oscillation occurs in the circuit. The magnitude of the voltage after inversion is independent of the quality factor of the circuit, but dependent upon the capacitance ratio $C/(C_n–C)$. If the value of the negative capacitance, C_n, is slightly larger than the capacitance of the piezoelectric element, C, the amplification factor can be very large. This is the advantage of SSDNC. The waveforms of the voltage and current are illustrated in Fig. 3(b).

2.2.4 Multi-mode vibration control

Though most studies in semi-active methods were devoted to single-mode control, the switching laws can be used for multi-mode control. However, due to the energy loss during voltage inversion, these switching laws are not optimal for multi-mode control as demonstrated by experimental results (Guyomar and Badel, 2006; Ji et al., 2009c, 2010b). Better control performance can be obtained by skipping some of the switching points, which are determined from these switch control laws. Hence special switch control laws are necessary for multi-modal control.

Although good control performances were achieved by using probability and statistics methods (Guyomar and Badel, 2006; Guyomar et al., 2007), the amount of calculation in these methods are relatively larger because the probabilistic distribution of displacement or voltage in a given period needs to be calculated for switch control. A simpler approach based on a displacement threshold has been proposed by Ji et al. (2009c) for two-mode control. In the proposed method, the voltage on the piezoelectric element is inverted only when the displacement satisfies the following conditions:

$$\frac{du}{dt}=0 \quad \text{and} \quad |u|>u_{M0} \tag{3}$$

where u_{M0} is the displacement threshold for switching action. Equation (3) indicates that switching actions take place at the displacement extrema which are larger than the threshold. The important issue is how to decide the displacement threshold in a real system. Displacement threshold should be adjusted automatically according to the vibration level and control state. For example, the amplitude threshold is calculated from average amplitude of latest ten switching points. A method based on energy threshold has also been proposed by Ji et al. (2010b).

3. Noise Control

3.1 Principles and classification of noise control

Active noise control can be traced back to 1936 when the German scientist, Lueg (1936), proposed this idea. In one active noise control system, a second source is introduced to cancel/minimize the primary source. Research on active techniques calls for multidisciplinary studies, including vibration, acoustics, control, signal processing, sensors, and actuators. Traditional or passive techniques are relatively ineffective in low frequencies. For instance, when using sound absorbing materials, the thickness of these materials must be comparable to the acoustic wavelength (in other words, when the frequency of sound is 100 Hz, the wavelength can be as long as 3.4 meters). However, this requirement leads to a large, bulky, expensive and unpractical system.

The benefits of using active noise control are promising; this system is an effective method to attenuate low frequencies, and the control band is basically confined within 1 kHz. Basically, there exists two active control methods according to the secondary source: one is an acoustic secondary source and the other is a direct forcing source. Also, the former is usually called active noise control (ANC); the latter is usually called active structural acoustic control (ASAC), in which structurally radiated sound is directly controlled by active structural inputs (Fuller et al., 1996). However, the reason why the active vibration control methods, which are powerful techniques for suppressing structural vibration, are not chosen is that different vibration modes of a structure have different radiation efficiencies, and thus simple vibration control may not lead to noise reduction. Actually, Knyazev and Tartakovskii (1967) demonstrated that active vibration control can lead to an increase in radiated sound levels.

When we want to suppress the sound transmission into some kind of enclosure or downsizing the enclosure noise environment globally, such as aircraft or automobile cabins, ASAC is usually more preferred than ANC. This is because as the frequency increases, the sound field becomes more complicated, and more acoustic actuators, usually loudspeakers, are needed to obtain global reductions (Elliott, 1994). Moreover, loudspeakers can be relative large and bulky when in comparison to piezoelectric actuators, which are widely used in active structure acoustic control (ASAC). For example, a loudspeaker with a diameter of 0.17 meters can weigh as much as 1-2 kilograms. This makes the whole active system relatively larger and more bulky than piezoelectric actuators. In summary, controlling the radiation of a vibration structure is very useful in many circumstances and smart materials. Piezoelectric materials can be used as both sensors and actuators for the control of sound.

In China, studies have also been conducted regarding active techniques for the past 30 years. Sha et al. (1981) designed a new active absorber to control the sound in a duct. Supposedly, this is the first paper published in China using ANC techniques. Chen et al. (1995) summarized some advances in the active control of structure-induced sound. Firstly, active control of free-filed noise radiated/transmitted by structural vibration and enclosed-space field noise generated by the inner noise sources and the external forces were discussed. Secondly, the physical mechanism and effects for the active control of sound by sound sources and force sources were compared.

Qiu and Sha (1996) summarized the development of active structural acoustic incidence control. The conclusion followed that the feedback method which is effective to pure tone is also effective to broadband random incident noise transmission, while the feed-forward control method is only effective to pure tone incident noise transmission. Hansen et al. (2007) developed a hierarchy of active noise and vibration control system design clearly (Fig. 4). This figure indicates that the performance of an active noise system is confined by many limits, and it is an optimization process from design to implementation.

3.2 Recent studies of noise control using piezoelectric actuators

Qiu et al. (2008) proposed a method for the active noise isolation of a plate structure without using acoustic sensors. Sound pressures were estimated from the piezoelectric sensor outputs by neural networks. Furthermore, these pressures were used as feedback signals. The new noise isolation system without acoustic sensors exhibits the same noise control performance as the conventional system using microphone sensors. Thus, the control system became more compact than before. With the theory of radiation modes, piezoelectric ceramics were used as control actuators in the system of active control of sound radiation by Wu et al. (2009). According to the characteristics of the first four radiation mode shapes, four groups of actuators are presented. While controlling the sound power of the first four radiation modes, these actuators can convert the complicated multi-input and multi-output (MIMO) control system into several simple and independent single input and single output (SISO) systems.

Jin et al. (2009) carried out an experimental study on ASAC based on distributed structural volume velocity sensors. They used a simply supported rectangular plate and analyzed the relationship between structural surface velocity and sound power radiated by the plate in the wave-number domain. They also presented an approach for a volume velocity sensor using polyvinylidene fluoride (PVDF) piezoelectric film and orthogonal property of trigonometric function, and excellent control effects were obtained. The feasibility of

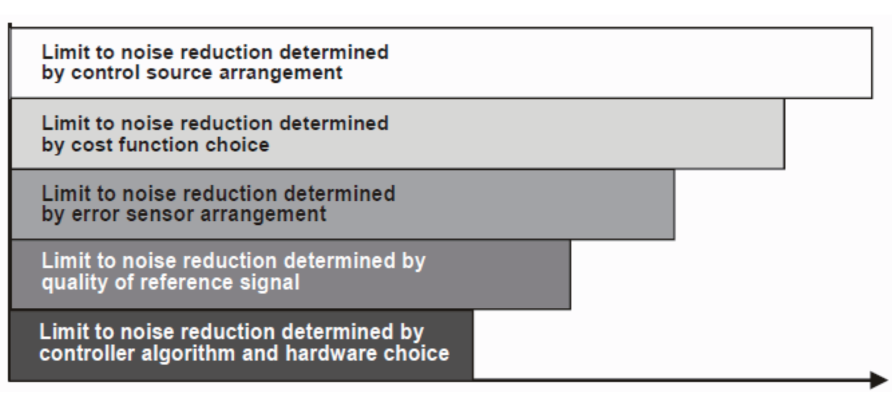


Fig. 4. Hierarchy of active noise and vibration control system design.

using synthesized structural acoustic sensors (SSAS) for ANC inside irregularly shaped enclosures was investigated by Li and Cheng (2010). A cylindrical shell with a floor partition, which can be used to model an aircraft cabin, was used as a test case. PZT actuators are used as control actuators. Both SISO and MIMO control systems were optimally designed using genetic algorithms and implemented with a filtered-X feed-forward LMS controller. Results showed that with an optimally designed SSAS, an active structural acoustic system can effectively reduce noise inside the enclosures without using any acoustic transducers.

Various algorithms in active control have also been designed to make the whole system more robust and effective; the most famous is the filtered-X LMS algorithm. Many modified algorithms have also been proposed to enhance the controller's performance. For instance, Qiu and Hansen (2003) presented the feasibility of a method for applying effort constraints on an adaptive feed-forward control. Tu and Fuller (2000) used multiple reference feed-forward active noise to cope with the environment with multiple noise sources. An adaptive de-correlation filter based on the Wiener filter theory and Gram-Schmidt orthogonalization theorem was constructed to implement the reference signal preprocessing step.

Qiu et al. (2006) discussed the implementation of delay-less sub-band ANC algorithms. Wideband ANC systems usually have hundreds of taps in the control filters and the cancellation path models, which results in high computational complexity and low convergence speed. To overcome these shortcomings, sub-band adaptive filtering was developed to reduce the computational complexity and to increase the convergence speed. Chen et al. (2008) proposed a new analysis method for the performance of multi-channel feed-forward ANC system in the frequency domain.

4. Energy Harvesting

Vibration energy harvesting based on piezoelectric materials can potentially be applied to power supplies for low-power electronic devices, such as structural health monitoring systems, wireless devices and semi-active vibration control systems. Desirable electromechanical coupling characteristics of piezoelectric materials facilitate the conversion of mechanical energy to electrical energy. Some non-linear techniques for piezoelectric voltage can be used to enhance the electromechanical conversion.

4.1 The principle of piezoelectric energy harvesting

The power generated by a piezoelectric element cannot be directly used by other electric devices; therefore, some electric interface is necessary for the energy harvesting system to ensure the voltage is compatible with electric load or energy storage element. There are many different schemes for an electric interface developed for energy harvesting such as an AC-DC rectifier or a voltage doubler (Guyomar et al., 2005; Qiu et al., 2009b). This section describes the principle of piezoelectric energy harvesting systems based on the most commonly used interface, "standard interface," which simply rectifies the AC voltage to DC voltage. The circuit of a piezoelectric energy harvesting system based on the standard interface is shown in Fig. 5(a).

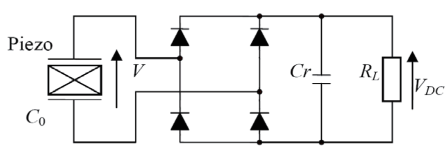
As shown in Fig. 5(a), the standard interface includes a diode rectifier and a filter capacitor. The terminal electric load is modeled by an equivalent resistor R_L. To calculate the power output of the interface under the condition of single mode vibration, some assumptions should be made. First, the mechanical displacement u must be purely sinusoidal and the open-circuit voltage V on the piezoelectric must also be sinusoidal. However, the rectifier is in the blocked state and the piezoelectric element is on the open-circuit state when the absolute value of V is lower than V_{DC}, the voltage across the capacitor. When the absolute value of V is above V_{DC}, a current I flows through the diodes. The current is divided into two parts, one to the capacitor and the other to the load. The energy E generated in a period T can be estimated by calculating the integration of product of V and I during a period, therefore the power can be obtained by dividing E by T and expressed as

$$P = \frac{4\alpha^2 u_m^2 \omega^2 R_L}{(2R_L C_0 \omega + \pi)^2} \tag{4}$$

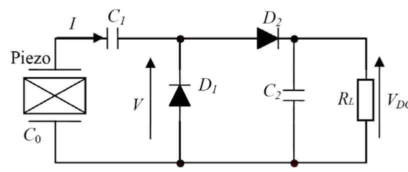
where u_m is the displacement amplitude of mechanical vibration. The other three popular interfaces are the voltage double interface (Ji et al., 2008), a synchronous electric charge extraction (SECE) (Lefeuvre et al., 2006b), and synchronized switch harvesting on inductor (SSHI) (Guyomar et al., 2005; Lefeuvre et al., 2006b) are shown in Fig. 5(b-d).

4.2 Improving efficiency and power generation through piezoelectric configuration

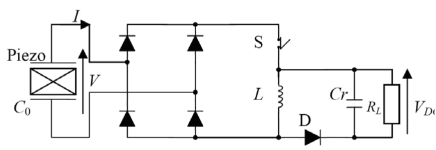
Many studies have been conducted on the modelling and analysis of the piezoelectric configuration. Kan et al. (2008) established an analysis model to simulate the influence of the exciting method, the structural parameters and the material properties of the piezoelectric cantilevers on energy generation. The results indicate that there are different optimal thickness ratios for the piezoelectric monomorph cantilever generator and piezoelectric bimorph (PB)



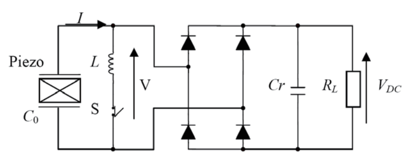
(a) Standard interface



(b) Voltage double interface



(c) SECE interface



(d) SSHI interface

Fig. 5. Four electrical interfaces for energy harvesting. SECE: synchronous electric charge extraction, SSHI: synchronized switch harvesting on inductor.

cantilever generator to obtain maximal electrical energy in the same dimension and excitation, and the maximal energy generated from the PB cantilever generator is about twice as much as that from the piezoelectric monomorph cantilever generator.

Yuan et al. (2008) studied the piezoelectric cantilever under a vibration environment. In comparison to the rectangular layer piezoelectric cantilever, the trapezoidal piezoelectric cantilever generated higher power with the same force and the volume as the PZT. Li et al. (2009) also studied an energy harvesting structure based on a rectangle piezoelectric micro-cantilever. Analytical results showed that increasing the mass and decreasing the length of micro-cantilever manifests into low-frequency resonance and maximum power in the actual design. He et al. (2009) established a mathematical model of a cantilever piezoelectric generator used in rotary machines. The effects of the axial extension force on the stiffness of the beam and the frequency of the generator were analyzed, and the formulas of the frequency, output voltage and output power of the cantilever piezoelectric generator were derived. The results showed that the maximum output power of the generator was about 35 μW at the rotation frequency of about 14.25 Hz. The output power quickly decreased when the rotation frequency deviated from the frequency of the generator.

Hu et al. (2007a) proposed a piezoelectric energy harvester consisting of a spiral-shaped piezoelectric bimorph that transforms mechanical energy into electric energy. The spiral-shaped harvesting structure is very useful in the microminiaturization of advanced sensing technology. Hu et al. (2008a) proposed a corrugated PVDF bimorph power harvester with the harvesting structure fixed at the two edges in the corrugation direction and free at the other edges. Statistical results show that the adaptability of a harvester to the operating environment can be improved greatly by designing the harvesting structure with an adjustable resonant frequency. A maximal output power of about 24.2 mW can be obtained from the trapezoidal piezoelectric cantilever at an operating frequency of 130 Hz across a resistive load of 80 kΩ with a cyclic stress of 1 N.

Hu et al. (2007b) studied a technique adjusting the performance of a PB vibrating in the flexural mode through axial preloads, which is useful for a power harvester to effectively scavenge energy from ambient mechanical vibrations/noise with varying-frequency spectra. Xue et al. (2008) presented a novel approach for designing broadband piezoelectric harvesters by integrating multiple PBs with different aspect ratios into a system.

4.3 Improving efficiency and power generation through circuitry

In addition to improving power harvesting efficiency and energy generation capabilities by improving the mechanical configuration of the device, recent research has also focused on designing a new electrical interface to improve efficiency. Hu et al. (2008b) studied the performance of an energy harvester with a PB and a real electrochemical battery (ECB); both are connected as an integrated system through a rectified DC-DC converter (DDC). To raise the output power density of PB, a SSHI is used in parallel with the harvesting structure to reverse the voltage through charge transfer between the output electrodes at the transition moments from closed-circuit to open-circuit. It was found that the introduction of a DDC in the modulating circuit and an SSHI in the harvesting structure can raise the charging efficiency by several times.

Shen et al. (2010a) presented a technique called enhanced synchronized switch harvesting (ESSH) to further improve the efficiency of the double synchronized switch harvesting

Fig. 6. A self-powered energy harvesting circuit.

(DSSH) (Lallart et al., 2008). The general circuit of DSSH includes two parts, each of which corresponds to the interface circuit of the series SSHI proposed by Taylor et al. (2001). An intermediate capacitor, C_{int}, was used to temporarily store the harvested energy between the two parts. Compared to the standard technique of energy harvesting, the DSSH dramatically increases the harvested power by almost 300% at resonance frequencies under the same vibration conditions, and also ensures an optimal harvested power for the load connected to the microgenerator. In the DSSH, all the energy stored in the intermediate capacitor is transferred by the second stage of SSHI to the storage capacitor, so that the voltage became zero. However, the efficiency of harvesting depends on the voltage on the intermediate capacitor. In ESSH, the voltage on it is optimized to further increase the efficiency. Furthermore, a self-powered circuit which implements the technique (ESSH) is proposed, as shown in Fig. 6. In addition, the overall power dissipation for the control circuitry is relatively low (only about 121 μW).

4.4 Applications

Research communities have shown great interest in the development of wireless sensors and communication node networks. Conventionally, such devices are powered by electrochemical batteries. However, batteries not only increase the size and weight of wireless sensors, but also suffer from the limitations of a brief service life and the need for constant replacement, which is not acceptable or even possible for many practical applications. Thus, the need to power remote systems has motivated many research efforts to focus on harvesting electrical energy from various ambient sources. Compared to other available sources, vibration energy harvesting using piezoelectric materials directly converts applied mechanical energy into usable electric energy and is easily integrated into micro-systems. As a result, the use of piezoelectric materials for scavenging energy from ambient vibration sources has recently experienced a dramatic rise for energy harvesting.

This section discusses the recent development for applying piezoelectric materials in vibration energy harvesting to practical devices. In terms of practical applications, many researchers focused on the power supply in microelecromechanical systems (MEMS) and vibration damping system without an external power supply.

In order to develop a micro-scale power harvester, Wu et al. (2008) presented a MEMS device that generates electrical power from mechanical energy garnered from environmental vibrations. The design utilizes a single crystal silicon beam covered with sol-gel PZT film. The device was fabricated on (110) silicon wafer, on which an optional cuboid silicon mass can be formed beneath the cantilever using a simple wet etching process. The proof mass improves the output electrical power and decreases the natural frequency of the device. The test results show that power greater than 1 nW was generated at a frequency of 1,673 Hz and amplitude of 11 nm. Shen et al. (2008) discussed a piezoelectric micro energy harvesting device which based on MEMS technology. This device works in low frequency environments. When excited by vibration, the device converts mechanical energy into electrical energy, demonstrating the feasibility of micro energy harvesting in low frequency environments. Zhang and San (2009) presented a hybrid vibration-powered microgenerator combining the structures of a piezoelectric generator and an electrostatic generator. The simulated results reveal that the hybrid power generator provided higher output power than that of the two energy harvesting mechanisms at a special resonant frequency. For a resonant frequency of 282 Hz, the simulation result shows the output power from the hybrid mechanism was 4.85 μW, which is double the power generated from the original capacitive mechanism (2.11 μW).

In an effort to develop a self-powered vibration damping system, Shen et al. (2010b) presented a vibration damping system powered by harvested energy with implementation of the so called SSDV technique. By supplying the energy collected from the piezoelectric materials to the switching circuit, a new low-power device using the SSDV technique was realized. Compared to the original self-powered SSDI, such a device significantly improved vibration control. Its effectiveness in the single-mode resonant damping of a composite beam is validated by experimental results.

5. Structural Health Monitoring

According to principle, the methods of SHM using piezoelectric materials can be divided into three main categories: those based on vibration characteristics, those based on impedances and those based on guided waves.

Research in SHM is distributed into different aspects for each category, including mechanism and principle, sensing technology, wireless data transmission, signal processing, etc. This section introduces recent research in SHM conducted in China.

5.1 Monitoring based on piezoelectric impedance and vibration characteristics

When damages occur in a structure, its vibration characteristics will change. The electrical impedance of a surface bonded or embedded piezoelectric transducer will also change due to the electro-mechanical coupling between the transducer and the structure. By measuring the vibration characteristics of the structure using the piezoelectric transducer or measuring the electrical impedance of the piezoelectric transducer, the damages on the structure can be identified. Xu et al. (2010) proposed an identifying technology for structural damage based on the impedance analysis of a piezoelectric sensor. The variation of structural crack damage can be observed effectively using this damage metric. For monitoring the structural health of composite structures, quickly and accurately identifying the impact load whenever there is an impact is an important feat. Yan and Zhou (2009) put forward a genetic algorithm-based approach for impact load identification, which can identify the impact location while simultaneously reconstructing the impact force history.

Since piezoelectric transducers are only sensitive to nearby cracks, surface-bonded transducers may not be able to accurately detect the deep damages, especially in large size structures. Yu et al. (2010) conducted a numerical study of SHM using surface-bonded and embedded PZT transducers. The results show that the proposed method using embedded PZT transducers effectively identifies cracks in large-sized concrete structures and possess great potential in structure health monitoring. Due to the complexities of the damaged structures and the difficulties in high-frequency analysis, further information about the nature of damage cannot be obtained using electro-mechanical impedance in its conventional non-model-based way. A hybrid technology combining the electro-mechanical impedance technique and reverberation matrix method is proposed by Yan et al. (2007, 2009, 2011) to quantitatively correlate damage in beam structures with high-frequency signatures for SHM. Different types of sensors were adopted to provide reliable monitoring of large scale engineering structures.

Reinforced concrete (RC) structures are one of the most familiar engineering structures within the civil engineering community. Such structures often suffer crack damage during their service lives because of factors such as overloading, excessive use, and poor environmental conditions. Thus, early detection of crack damage in RC structures warranted the attention of many researchers. Zhu et al. (2008) proposed an identification technique for micro-damage of concrete/steel structures based on piezoelectric monitoring signals, which was expected to provide a reliable and accurate basis for the health monitoring of concrete structures. A health monitoring method based on PZT admittance signals was proposed by Wang et al. (2009), which used the electromechanical coupling property of piezoelectric materials. An experimental study monitoring the health of an RC beam was implemented based on the PZT admittance signals. From the obtained PZT admittance curves, the presence of an incipient crack could be captured and the cracking load of the RC beam could also be determined. From the experimental study, it was concluded that the health monitoring technique was effective and sensitive for RC structures, which indicated its favorable application foreground in civil engineering.

Based on the actuation and sensing function of piezoelectric ceramic materials, PZT active health monitoring for fatigue accumulative damage of concrete beam containing nano-particles (TiO_2) for pavement was experimentally studied by Zhang et al. (2007). The test results indicated that the vibration signals received by PZT patches contained three development stages: the damage-formation stage, the damage-steady- growth stage and the damage-sharp-growth stage, which showed that the PZT patch could monitor the whole course of the formation and growth of cracks in concrete and the failure of the concrete beam.

5.2 Health monitoring based on guided wave

The active monitoring technology based on the piezoelectric sensors (PZT) and guided waves is an effective and popular method for monitoring structural health. Piezoelectric transducers are used to generate and sense guided waves. Xu et al. (2004) used an active Lamb wave detection technique to detect the damage in composite materials. The ellipse technique localizes two dimensional damages in structures. Three methods are applied to compute the time delay between differential signals and health signals. Experiments were conducted demonstrating that wavelet transformation analysis possessed greater advantages over the other methods: this analysis provided precise damage locations when the signal-to-noise ratio was small. A new method entitled the No-baseline Time Reversal Imaging Method was proposed by Wang and Yuan (2009). A back propagation piezoelectric (PZT) array arrangement method and time reversal window function were purposed to eliminate direct propagation waves and reflections from the boundaries to intercept the inner scattering waves in the structural responses. Based on time reversal theory, current structural responses are used to realize damage location and imaging by suitable piezoelectric array and window functions. This method does not require a baseline.

Zhang and Wang (2005) proposed a piezoelectric wafer model based on Lamb waves providing a means for nondestructive evaluation of micro cracks. Multi-agent system (MAS) based SHM technology was researched in order to manage diverse, heterogeneous and distributed information. Zhao et al. (2008, 2009) introduced an evaluation on a MAS to validate the efficiency of multi-agent technology. Through the cooperation of different agents and different subsystems, the whole system fused the information acquired from three sensors . Such sensors comprised a strain gauge sensor, fiber optic sensor and a piezoelectric sensor. A new damage localization method was proposed by Liu et al. (2010) by using a new metal core piezoelectric fiber sensors. The details are discussed in the following section.

5.3 A new piezoelectric sensor for health monitoring

5.3.1 Metal-core piezoelectric fiber transducers

Metal-core piezoelectric fiber (MPF) transducers were first developed through an extrusion method by Qiu et al. (2003) and the hydrothermal method by Sato et al. (2004). The transducers possessed small diameters ranging from 150 μm to 400 μm, in order to be easily bonded on or integrated with a host structure to overcome the brittleness of conventional piezoelectric fibers (Qiu et al., 2003). A single MPF can be used as a sensor or an actuator with two electrodes (the central metal core and the outer metal layer), and it can be used in two different modes that correspond to two different surface electrode geometries. When the outer surface of a piezoelectric fiber is fully coated, the fiber is simply called a metal core piezoelectric fiber (MPF) and is used in the longitudinal mode, as shown in Fig. 7(a). When the outer surface is half coated, the piezoelectric fiber is called a half coated metal core piezoelectric fiber (HMPF), and it is used in the bending mode, as shown in Fig. 7(b). The MPF sensors used during Lamb wave detection were fully coated metal core piezoelectric fibers with diameters within the vicinity of 300 μm, and a length of 20 mm. Since the strain occurs along the length of the fiber and the electric field is in the radial direction, the MPF sensors work in the 3-1 mode.

One important feature of the MPF sensor is its high directivity. The experimental setup in Fig. 8(a) was used to investigate the directivity of MPF sensor. The result in Fig. 8(b) shows excellent directivity of the MPF in sensing the Lamb

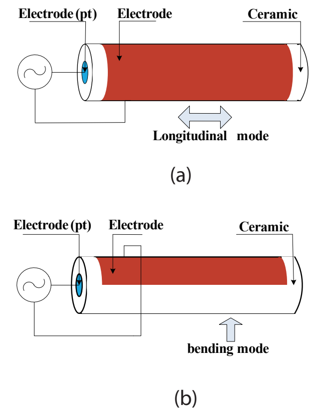


Fig. 7. Metal-core piezoelectric fiber with geometrical reference for (a) full coated electrode and (b) half coated electrode.

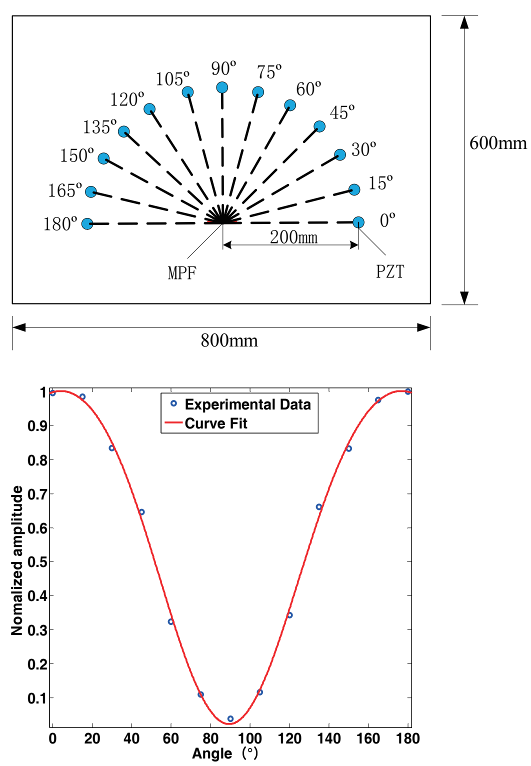


Fig. 8. Configuration of experimental setup and directional sensitivity of the metal-core piezoelectric fiber.

wave. Such directivity behavior can be exploited to greatly simplify both active-passive damage detection systems based on diffraction measurements (Lemistre and Balageas, 2001; Liu et al., 2010), and passive-only, acoustic emission damage/impact detection systems. In both cases, the use of rosette-like detection modes based on unidirectional sensors would avoid the necessity for prior knowledge of the wave velocity in the medium, which is particularly appealing when anisotropic materials are involved.

5.3.2 MPF rosettes for the wave source localization

Strain rosettes based on electrical strain gages are commonly used in structural analysis. For arbitrary loading conditions, the rosette configuration allows the determination of the directions and values of the principal strains (Timoshenko and Goodier, 1969). Based on the same principle, a rosette-type configuration of MPFs has been proposed by Liu et al. (2010) as a means for directly determining the direction of acoustic wave propagation. The MPFs are especially suitable for rosette applications due to their high directivity. The layout of the MPF rosette is shown in Fig. 9. As discussed above, the MPF is capable of picking up strain fields associated with Lamb wave propagation in the structure. From the recorded signals, one should be able to extract strain amplitude, frequency and also the arrival time of the acoustical waves in case of burst excitation. However, the strain amplitudes of the fibers are required in order to determine the direction of wave propagation when using only the rosette technique. It is sufficient to record the peak-to-peak amplitude of the signal for each individual MPF within the rosette. The 120° set-up enables a normalized measurement that is independent of the magnitude of the transmitted acoustical strain field.

The advantage of the proposed source location scheme (Zhao et al., 2009) is that no absolute signal values are needed. It is expected that the sensitivity of the MPF will be dependent of the relative orientations of the acoustic wave propagation direction and MPF axis, since the direction of maximum strain will be parallel to the propagation direction. This angular relationship was determined by launching Lamb waves from PZT transducers located at various angles (φ) to the MPF. From the angular relationship, two suitably spaced rosettes can be used to locate the source of the ultrasound by taking the intersection of the directions given by the two rosettes, as shown in Fig. 10. The new method of localization does not need the velocity of wave propagation and is especially useful in anisotropic media.

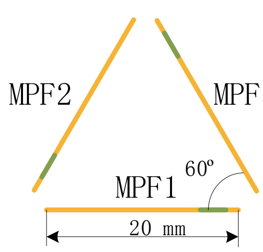


Fig. 9. Layout of metal-core piezoelectric fiber (MPF) rosette.

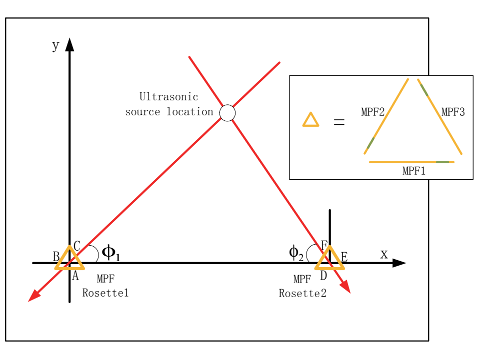


Fig. 10. Layout of the sample and definition of a coordinate system.

6. Nonlinear Hysteresis Control

Due to their characteristics of high displacement resolution, high stiffness, and high-frequency response, piezoelectric actuators have been widely used in high-precision positioning devices and tracking systems, such as scanning tunneling microscopy, and diamond turning machines. However, piezoelectric actuators exhibit hysteretic behavior, which severely limits system precision. A typical hysteresis loop is shown in Fig. 11. Hence, active control of nonlinear hysteresis of piezoelectric actuators has become an active area of research. Research on hysteresis control of piezoelectric actuators has mainly focused on hysteresis model and its inverse control.

6.1 Neural network control

Artificial neural networks have been widely and successfully used in systems identification because of its ability to infer from imperfect, noisy, or incomplete data used in network training. Theoretically multilayer feed-forward neural network, with sigmoid transfer functions in the hidden layer and linear transfer functions in the output

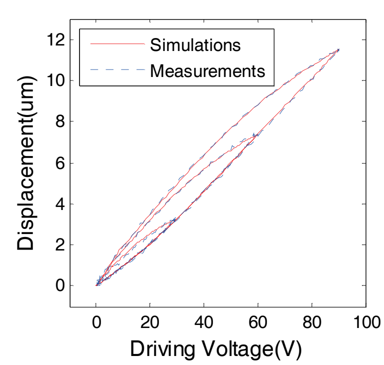


Fig. 11. The typical hysteresis loop of piezoelectric actuator.

layer, can approximate virtually any function of interest to any degree of accuracy, provided sufficient number of neurons are used in the hidden layer. However, neural networks can only approximate one-to-one mapping and multi-to-one mapping, and cannot directly approximate multi-value mapping such as hysteresis nonlinearity (Hagan et al., 1996). Many new mapping methods have been developed for neural networks in order to describe the hysteresis, such as accumulated generation operation of grey theory (Dang and Tan, 2005b), hybrid neural network (Liu et al., 2006b), neural network in three-dimension coordinates (Qu et al., 2005), radial basis function neural networks (Yang and Chang, 2006), Winner model (Wei et al., 2004), chaotic neural network (Liu et al., 2006b). Some of these neural network models have been programmed to design controllers for hysteresis compensation. Chen et al. (2010) designed a combined controller, which consists of a feed-forward loop to describe the inverse hysteresis by neural networks and a feedback loop to reduce the error accumulated by the inverse hysteresis model. Lin et al. (2006) designed an adaptive control with hysteresis estimation and compensation using recurrent fuzzy neural network to improve the control performance of the piezoelectric actuator. Yang and Chang (2006) designed a trajectory tracking controller composed of adaptive neural network and PI controller for a nano-positioner driven by a piezoelectric actuator.

6.2 Preisach model

Zhou et al. (2007) designed a piezoelectric electro-hydraulic servo valve system with a feed-forward control based on the Preisach hysteresis nonlinear model and high-precise fuzzy feedback control. Li et al. (2007) identified the Preisach model by analyzing the first order reversal curves. Gong et al. (2007) designed a tracking control system of a giant magnetostrictive administered by Preisach inverse compensation. Zheng et al. (2003) described hysteresis behavior of piezoelectric actuators using the Preisach model. Zhang et al. (2002) studied the hysteresis properties of a piezoelectric actuator based on the Preisach model. Wei and Tao (2004) studied the Preisach model of hysteresis in a piezoelectric actuator and designed a feed-forward controller based on this model. Wei (2004) researched an open-loop precision positioning control of a micro-displacement platform based on piezoelectric actuators using the Preisach model. The key parameters of this model were identified by a neural network. Cao et al. (2005) designed a piezoelectric positioning control system based on the Preisach model.

Zhao and Tan (2006) developed a neural network approach for identifying Preisach-type hysteresis. This method introduced a hysteresis operator that transformed the multi-valued mapping of hysteresis into a one-to-one mapping so that neural networks could be applied to the approximation of the conditions. Dang and Tan (2005a) developed a dynamic hysteresis model for a piezoceramic actuator, which was obtained by combining the Preisach model with diagonal recurrent neural networks. The structure of this model is based on the structure of the Preisach model, in which the rate-independent relay hysteresis operators are replaced by the rate-dependent hysteresis operators of a first-order differential equation. Therefore, the proposed model not only possesses the properties of the Preisach model, but also can be used to describe dynamic hysteresis behavior.

Liu et al. (2006a) designed a micro-positioning controller based on the Preisach model for piezoelectric actuators. Li et al. (2007) discussed the generalized Preisach model for hysteresis nonlinearity of a piezoceramic actuator and its numerical implementation. Hu et al. (2005) used an operator representing the inverse dynamics of hysteretic effects inherent to piezoceramic actuators in order to enhance the tracking accuracy of piezoceramic-driven positioning system. Li et al. (2008) extended the classic Preisach model into a mixed model.

6.3 Prandtl-Ishlinskii model

Su et al. (2004) presented a forward neural net structure. By using recursive least squares to regulate the net weights, this net structure modeled hysteresis without accounting for the underlying physics. Simulation results suggest the effectiveness of the modeling and controlling methods. Hu and Chen (2006) designed an adaptive inverse control scheme for the hysteresis characteristics of a piezoelectric cantilever. This displacement control system was constructed based on the hysteretic model and its inverse model which introduced backlash operators by the adaptive LMS filter. This approach contained good characteristics pertaining to self-learning and control actions.

Chen et al. (2006) established the static and dynamic models between the displacement of microgripper and the external electric field and force, and designed a hybrid controller for mocro assembly. Wang and Mao (2008) designed an adaptive sliding model control for a hysteresis system based on the Prandtl-Ishlinskii model. Qin and Hu (2004) established the Maxwell hysteresis model of a piezoelectric actuator. Dang and Tan (2007) researched the dynamic hysteresis model by combining the Gamma filter and the structure of the Prandtl-Ishlinskii model. Guo and Dang (2008) developed a dynamic Prandtl-Ishlinskii model by introducing a first-order lag operator.

A modified Prandtl-Ishlinskii model was proposed by Jiang et al. (2010) based on two asymmetric hysteresis operators.

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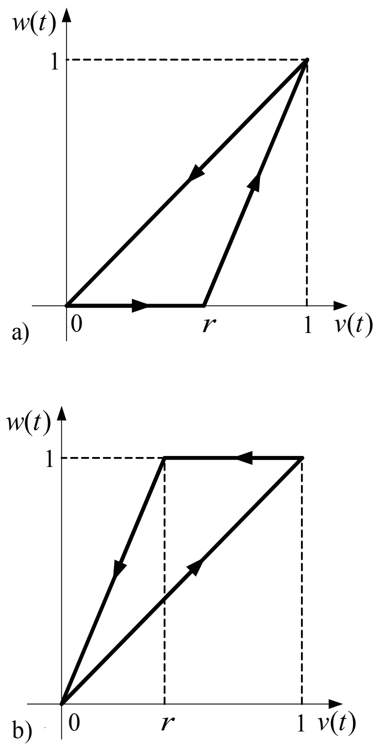

Fig. 12. The transfer characteristic of a right-side play operator and left-side play operator.

The two asymmetric hysteresis operators separately modeled the hysteresis of an ascending branch and a descending branch. When combined, these branches modeled the full loop hysteresis. The proposed model satisfied the wiping-out property but does not satisfy congruency property. The identification of the proposed model is based on an iterative method, exhibiting that the proposed model's identification procedure is faster and simpler than the identification procedures of other classical hysteresis models. The proposed model also exhibits a very high accuracy in characterizing the hysteresis nonlinearity of piezoelectric actuators. From those results, it can be concluded that the modified Prandtl-Ishlinskii model can be a new option for modeling and control of hysteresis in piezoelectric actuators.

6.4 Coordinate transform

Because the minor loop and major loop is similar in shape, the minor loop can be achieved by transforming the coordinate of the major loop. Cui et al. (2004) and Jia, et al. (2002) adopted the coordinate transform to model the hysteresis nonlinearity between the displacement and the voltage across a piezoceramic actuator. Zhao and Tan (2004) used the coordinate transformation method to realize the mapping between the input set and the output set of the hysteresis. The mapping between the input and output sets can be proven to be bijective with the set theory. The affine mapping theory was applied to model a class of hysteresis, which is stimulated by smooth periodic signals. Both the hysteresis and its inverse dynamic model can be constructed with the proposed method. The simulation results indicate the effectiveness of the method. Badel et al. (2008) used two simple hyperbola functions with only three parameters to describe the ascending branches and descending branches of hysteresis, and designed an inverse controller of piezoelectric actuators.

7. Summary

Due to their excellent electromechanical coupling characteristics and their ability to directly convert mechanical energy and electrical energy, piezoelectric materials have become the most attractive functional materials for sensors and actuators in smart structures. In recent years, scholars in China have actively engaged in the research of smart materials and structure. This article presents the studies on applications of piezoelectric materials in smart structures, including vibration control, noise control, energy harvesting, SHM, and hysteresis control in China. Special attention was given to the introduction of semi-active vibration suppression based on synchronized switching techniques and health monitoring based on piezoelectric fibers with metal cores because of their promising potential for future application in aerospace engineering.

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