Hindawi Publishing Corporation
Smart Materials Research
Volume 2011, Article ID 236719, 7 pages
doi:10.1155/2011/236719

Research Article

Electrical Response of Cement-Based Piezoelectric Ceramic Composites under Mechanical Loadings

Biqin Dong,[1] Feng Xing,[1] and Zongjin Li[2]

[1] *Department of Civil Engineering, The Key Laboratory on Durability of Civil Engineering in Shenzhen, Shenzhen University, Shenzhen, Guangdong 518060, China*
[2] *Department of Civil Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong*

Correspondence should be addressed to Feng Xing, xingf@szu.edu.cn

Received 1 December 2010; Accepted 26 January 2011

Academic Editor: C. R. Bowen

Electrical responses of cement-based piezoelectric ceramic composites under mechanical loadings are studied. A simple high order model is presented to explain the nonlinear phenomena, which is found in the electrical response of the composites under large mechanical loadings. For general situation, this nonlinear piezoelectric effect is quite small, and the composite is suitable for dynamic mechanical sensor as holding high static stability. The experimental results are consistent with the relationship quite well. The study shows that cement-based piezoelectric composite is suitable for potential application as dynamic mechanical sensor with excellent dynamic response and high static stability.

1. Introduction

Civil infrastructural systems age and deteriorate during their service life due to factors such as ageing of materials, excessive use, overloading, environmental conditions, and deficient maintenance. As a result, structural health monitoring of civil infrastructures is of considerable importance in view of the immense loss of life and property that may result from structure failure. The unique feature of large size and complexity of most civil infrastructures renders visual inspection very tedious, expensive, and sometimes unreliable. The need for quick assessment of the state of health of civil infrastructures has necessitated research for the development of an automated, real-time, and in situ health monitoring technique. This kind of technique allows the system to monitor its own structural integrity while the infrastructures are in service, and also the monitoring can be performed throughout the service life of the infrastructures. Such a structural health monitoring system is useful not only to improve reliability but also to reduce the costs of maintenance and inspection for infrastructural systems [1].

In such a structure, sensor is an essential component for structural health monitoring purposes. Among the techniques used in sensors, piezoelectricity has been proved to be one of the most efficient mechanisms for most applications in smart structures [2–5]. For a typical piezoelectric material sensor, its two-part model with electrical-mechanical phase can be revealed as shown in Figure 1; whereas, in civil engineering, cement-based material concrete is the most popularly used structural material. But normal piezoelectric composites (such as polymer-based piezoelectric composites) are not suitable for civil engineering application because of their distinct differences in the volume stability from concrete. To meet the requirement of civil engineering structures, a 0–3 cement-based piezoelectric ceramic composite has been developed and studied in HKUST for the first time in the world [6–9]. The experimental results show that the composite is effective and applicable both in piezoelectric properties and compatibility, and it can be suitable for potential sensor application in concrete structures.

In this paper, electrical responses of cement-based piezoelectric ceramic composites under mechanical loadings are studied. Moreover, a simple high-order model is presented to explain the nonlinear phenomena of the electrical response of the specimens under large mechanical loadings. Actually, the generalized Hamilton's principle, which incorporates different electric boundary conditions as well as mechanical boundary conditions, is utilized to obtain the governing

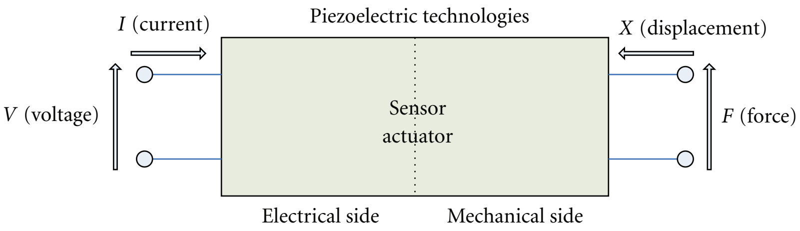


Figure 1: Schematic representation of two-part model of piezoelectric sensor.

Figure 2: The specimens of cement-based piezoelectric ceramic composite (left: uncoated with silver paint; middle: coated with silver paint; right: after poling).

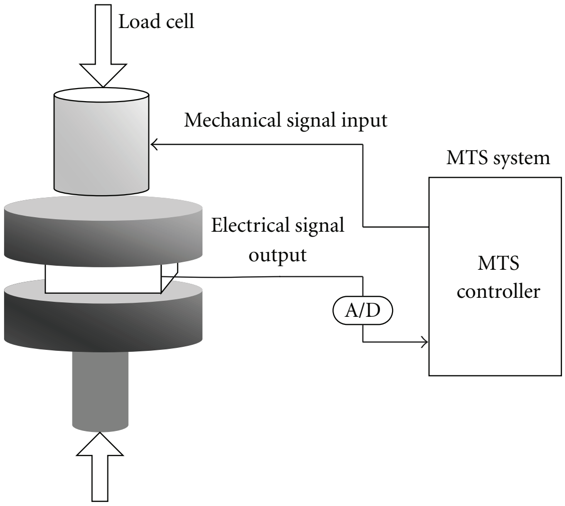


Figure 3: Illustration of MTS for mechanic-electrical response measurement of cement-based piezoelectric ceramic composite.

equations of motion. And deduction of the governing equations for piezoelectric beams, plates, and circular cylindrical shells from the high-order piezoelectric generic shell theory is discussed by many researchers [10–13]. The study will help us state the nonlinear turbulence of cement-based piezoelectric composites with large mechanical boundary.

2. Experiment

Lead zirconate titanate (PZT) piezoelectric ceramic powders (Hong Kong Functional Ceramic Co. LTD.) and cement (H.S.L. Enterprises Co. LTD.) were used to prepare cement-based piezoelectric composites.

Piezoelectric ceramic powder and white cement (white cement is chosen as major matrix in our experiment, and take Portland cement as a comparison) are mixed together to make 0–3 type cement-based piezoelectric ceramic composites. In order to improve the fluidity of the fresh mixture, a superplasticizer (W19, W. R. Grace) was used. Using a normal mixing (mixing duration is about 2 min), piezoelectric ceramic powder could be incorporated into the composites with different ratios of ceramic/cement. To achieve a uniform mixture, cement and piezoelectric ceramic particles were mixed thoroughly first, then water and superplasticizers were added into the mixture. The mixing process was continued until the mixture became uniform. Then the mixture was compacted into the 13 mm $*$ 13 mm $*$ 3 mm model. After casting, the specimens were put in the curing room with a temperature of 65°C and relative humidity of 98% for 24 hours.

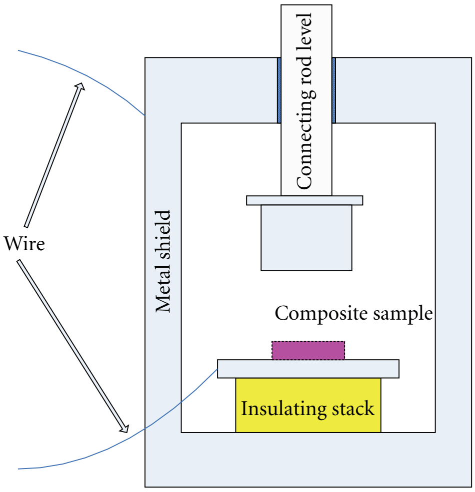
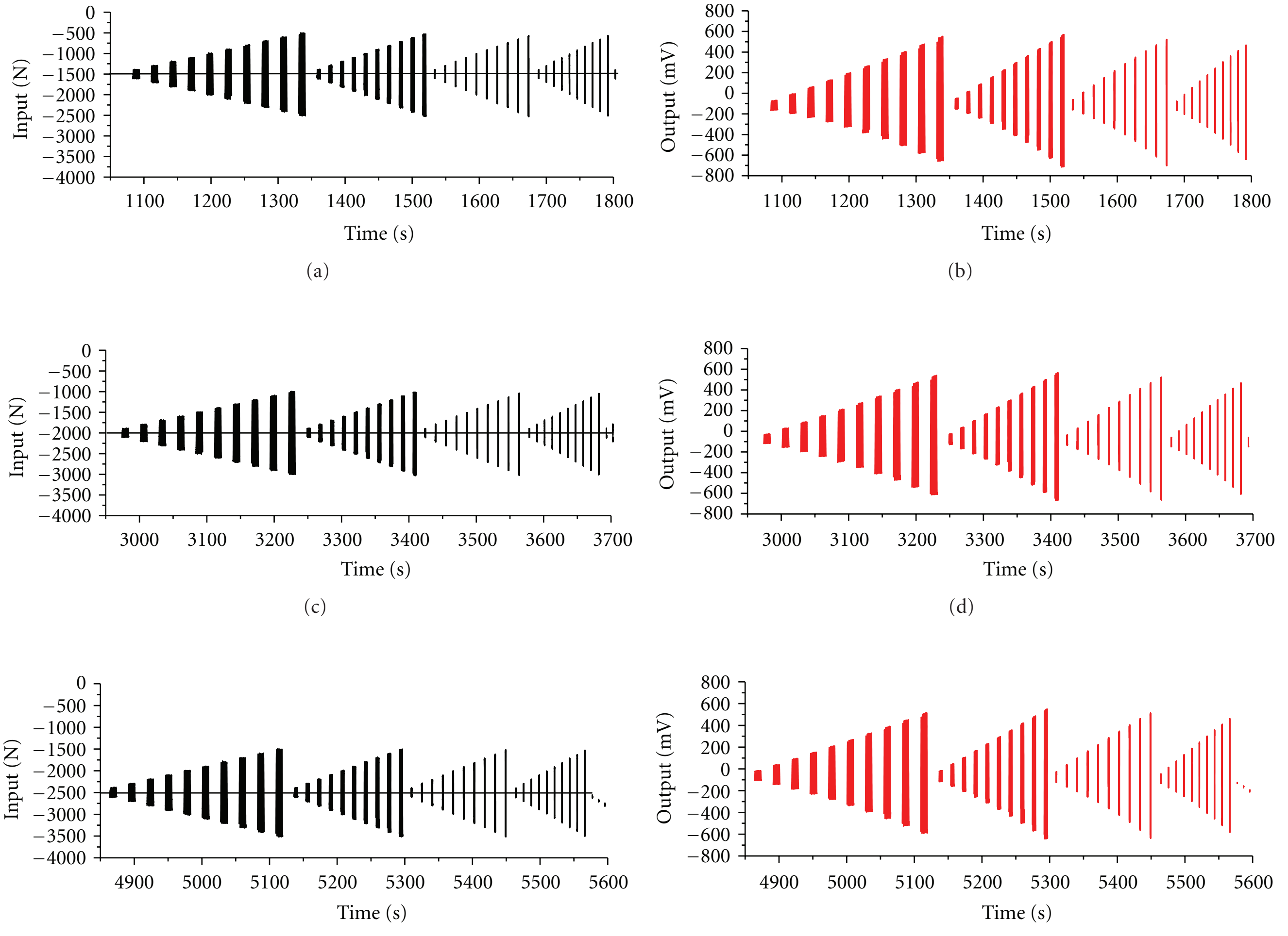


Figure 4: The frame for mechanic-electrical response measurement.



(a) (b)

(c) (d)

(e) (f)

FIGURE 5: Mechanical loading scheme for different mean loading levels (1500 N, 2000 N, 2500 N) and corresponding electrical output of cement-based piezoelectric ceramic composites.

A key technique for fabrication of piezoelectric materials is polarizing procedure. Polarizing was carried out in a silicon oil bath with a temperature of 160°C. After polarization the specimens were immersed in cold silicon oil to get a fast cooling in order to maintain the status of polarization. Then the polarized specimens were wrapped with aluminum foil to eliminate remnant charge generated during polarizing process. The specimens can be seen in Figure 2.

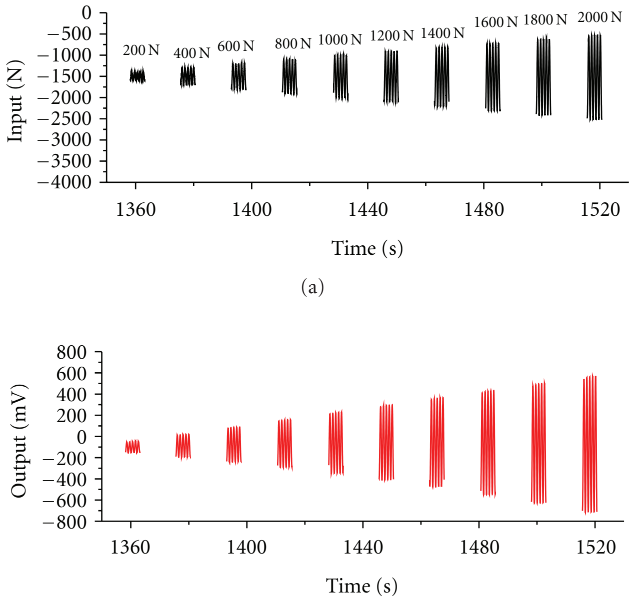
The mechanic-electrical response measurement of cement-based piezoelectric ceramic composite are carried out with MTS. The illustration of test can be seen in Figure 3. Different types of mechanical dynamic loadings are applied by MTS, and the output voltage is collected by PC through a charge amplifier. In order to eliminate the influence of environmental electric magnetic wave (normally, for 50 Hz AC), a metal frame is designed as shown in Figure 4.

Different sine function loadings are applied by MTS, and corresponding electrical outputs of composites are measured, along with the influence of all parameters for mechanic-electrical response. Figure 5 shows the mechanical loading scheme for different mean loading levels (1500 N, 2000 N, 2500 N) and corresponding output voltage of cement-based piezoelectric ceramic composites. For every segment, different magnitude is varied from 200 N to 2000 N (peak to peak value, 200 N, 400 N, 600 N, 800 N, 1000 N, 1200 N, 1400 N, 1600 N, 1800 N, 2000 N); the details can be seen in Figure 6. In addition, the applied frequency is changed from 1 Hz to 10 Hz. For all variables, five cycles loading are executed, and the relationship between mechanical force input signal and electrical voltage output signal is studied (see Figure 7).

3. Results and Analysis

A linear constitutive equation of piezoelectric materials with mechanical clamped motion and electrical short circuit is expressed as [14–17]:

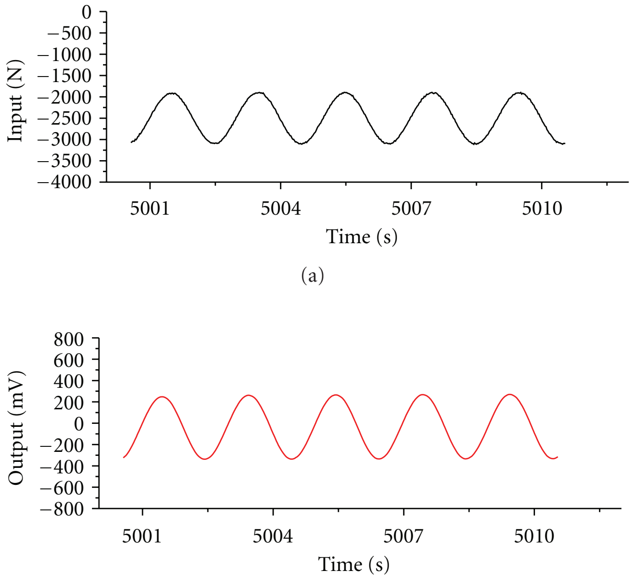
$$\begin{aligned} T_j &= c_{ji}^{E} S_i - e_{jn} E_n, \\ D_m &= e_{mi} S_i + \varepsilon_{mn}^{S} E_n, \end{aligned} \qquad (1)$$



(a)

(b)

Figure 6: Sinusoidal mechanical loading scheme with different magnitude (from 200 N to 2000 N, peak to peak) and corresponding electrical output of cement-based piezoelectric ceramic composites.



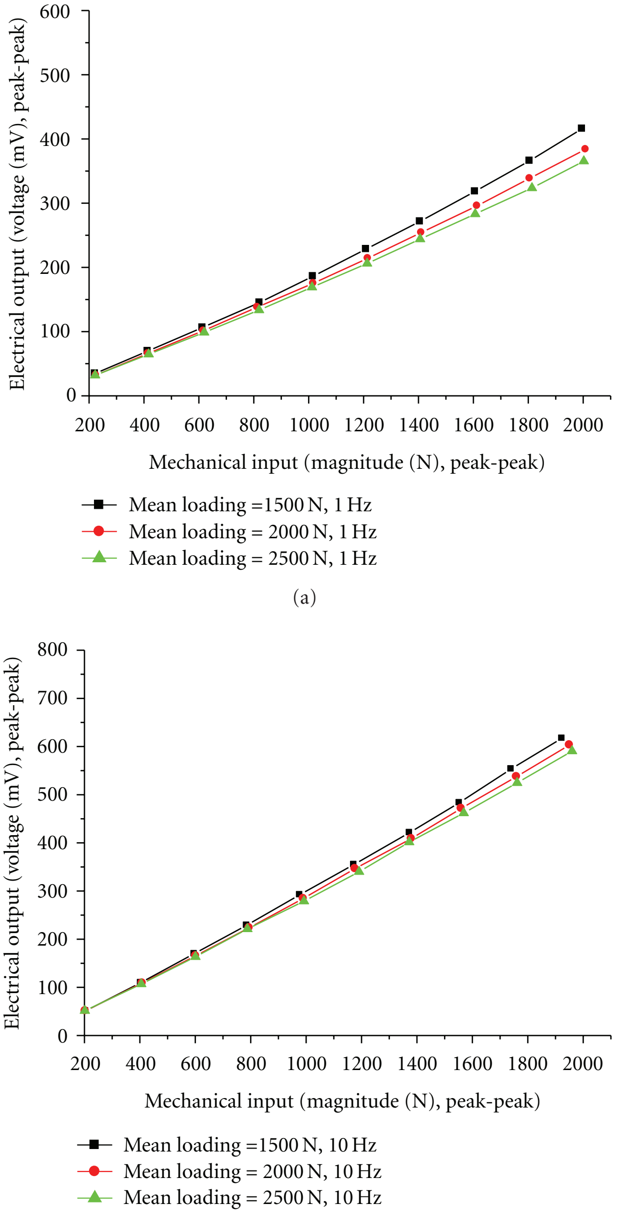
(a)

(b)

Figure 7: Sinusoidal mechanical loading and its electrical output of cement-based piezoelectric ceramic composite.

where c_{ji}^E is elastic stiffness coefficient with constant electrical field, ε_{mn}^S is dielectric coefficient with constant strain, e_{mi} and e_{jn} are piezoelectric stress coefficient, T_j is stress, D_m is electrical displacement, S_i is strain, and E_n is electrical field. This means that any effect, including mechanical or electrical excitation, will change the value of the electrical displacement. In cement-based piezoelectric ceramic composite, the piezoelectric property is not affected by cement material and only determined by the kind of piezoelectric ceramic and the volume proportion of ceramic in the composite [18]. As a result, it is feasible to apply the constitutive equation of piezoelectric materials to cement-based piezoelectric ceramic composites. In order to characterize the mechanic-electrical response of composite, we only apply mechanical loading, and (1) can be rewriten as:

$$D_m = e_{mi} S_i. \tag{2}$$



(a)

(b)

Figure 8: The influence of mean loading on magnitude of mechanical-electrical response of cement-based piezoelectric ceramic composite (a) 1 Hz, (b) 10 Hz.

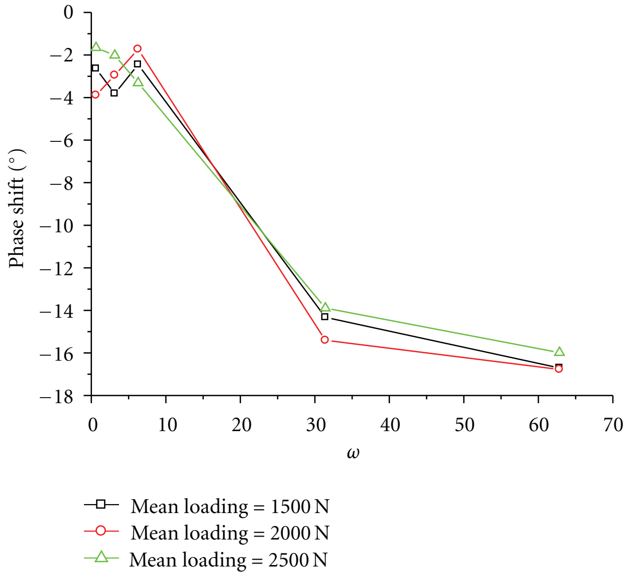


FIGURE 9: The influence of static loading on phase shift of mechanical-electrical response of cement-based piezoelectric ceramic composites.

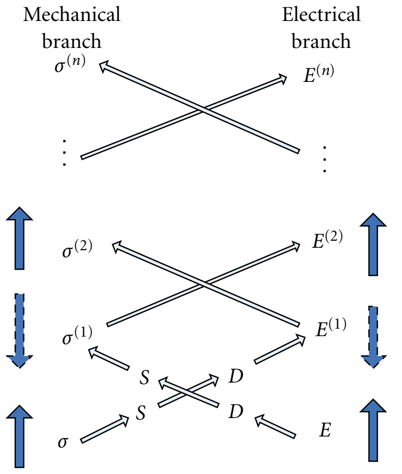


FIGURE 10: The inducing procedure of initial stress field and electrical field in cement-based piezoelectric ceramic composites.

For one-dimensional (33 direction) input-output relationship

$$D_3 = e_{33} S_3. \tag{3}$$

Then, an electrical potential U calculated at a distance along the 3 directions will now be nonzero as shown in,

$$U = E \cdot d, \tag{4}$$

where U is the voltage and d is the distance of dipole moment, which are directly relative to the electrical displacement D. From (3) and (4) and basic stress-strain relationship, we can obtain a linear relationship between electrical output and mechanical input:

$$U(t) = \alpha \cdot F(t), \tag{5}$$

where α is the convert constant of mechanical signal $F(t)$ to electrical signal $U(t)$.

According to basic electrical knowledge, it is defined that any voltage output is attributed to the variety of electrical potential ($V = \Delta U$). Then for dynamic mechanical loading, if we only consider the magnitude, (5) evolves to

$$V = \Delta U = \alpha \cdot \Delta F, \tag{6}$$

where V is voltage output, ΔF is the magnitude of dynamic loading force. Different mean loading level (static) is applied to test the stability of the composite specimens under the mechanic loads. Varying the mean loading at different frequencies is added, and the results are shown in Figures 8 and 9. All plots indicate that mechanic-electrical dynamic response of cement-based piezoelectric composites match a linear relationship very well. And for all mean loading we measured, the curves show no much difference in both magnitude and phase angle.

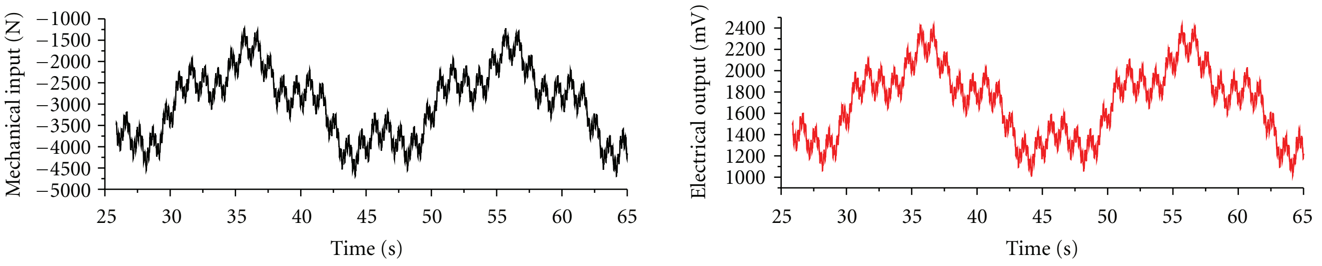
The experimental data reveal that the response of cement-based piezoelectric ceramic composite holds a similar behavior despite the mean loading level. This result is consistent with a linear relationship, whereas a small voltage output difference (see Figure 8) appears in our measurement, especially, in large input signal. This phenomenon is called nonlinear piezoelectric effect (or high-order piezoelectric effect), which is studied by many researchers and lots of papers are published [10–13]. A simple explanation is that after polarization, an electrical equilibrium appears between dipole moment and ambient charge in cement-based piezoelectric ceramic composites, whereas, if a stress field (initial, zero order) is applied, the electrical equilibrium will break, and an induced electrical field (one order) will come forth, which is opposite to the direction of the stress field. Similarly, the one-order electrical field will cause a second stress field. Based on the above, we can know that $(n-1)$-order stress field induces n-order electrical field. If initial electrical field is applied, the same circs will come forth. The whole procedure can be seen in Figure 10.

So, for single mechanical loading, the total electrical output (voltage) of cement-based piezoelectric ceramic composite can be derived from

$$V_{\text{total}} = F\left(\sigma + E^{(1)} + E^{(3)} + \cdots + E^{(n)}\right), \tag{7}$$

where n is odd value, and from Figure 9 we can know that the direction for all orders of induced electrical field is opposite to the initial stress field. And the direction for all orders of induced stress field is the same to the initial stress field. Moreover, for higher initial stress field applied, corresponding induced electrical field will be larger, which means that electrical output (voltage) will decrease but mechanical output (strain) will increase with improving stress field level. So comparing (7) to the linear constructive equation (5), it is clear that

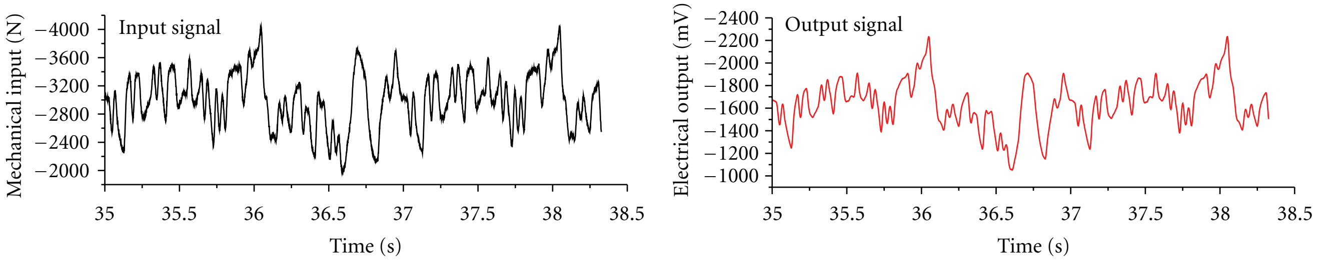
$$V_{\text{total}} < V = F(\sigma). \tag{8}$$



(a)

(b)

FIGURE 11: Multiple sine wave inputs and corresponding electrical output for cement-based piezoelectric ceramic composite.



(a)

(b)

FIGURE 12: Random wave inputs and corresponding electrical output for cement-based piezoelectric ceramic composite.

For general situation, this nonlinear piezoelectric effect is quite small and can be neglected. It shows that the composite is suitable for dynamic mechanical sensor as holding high static stability.

With the linear system, the principle of superposition states that a linear combination of input signals produces an output signal that is simply that linear addition of the separate output signals that would result if each input term had been applied separately [19]. The extensive studies are carried out with multiple sine input function, according to the following form:

$$F(t) = 3000 + 1000\sin(0.1\pi t) + 400\sin\left(0.4\pi t + \frac{\pi}{3}\right) + 300\sin\left(2\pi t + \frac{2\pi}{3}\right) + 200\sin(10\pi t + \pi) + 200\sin\left(40\pi t + \frac{4\pi}{3}\right). \quad (9)$$

Every component of multiple sine function signals is listed in Table 1. The relationship of input/output waveform is expressed in Figure 11. The plots show that electrical output signal can reproduce the mechanical input signal with quite complex waveform without any visible distortion.

More practical measurement is focused on the random wave test, which is reciprocal to the common dynamic loading, such as earthquake. The waveform is generated by PC and is added to composite specimen through MTS. Both input signal and output signal are plotted in Figure 11. Comparing with input/output waveform in Figure 12, we can know that electrical signal is quite close to the mechanical signal due to the instinct of composite as its linear mechanic-electrical relationship.

TABLE 1: The components of multiple sine function signals.

No.	Frequency (Hz)	Mean loading (N)	Peak-peak amplitude (N)	Phase (degree)
1	0.05	3000	2000	0
2	0.2	3000	800	60
3	1	3000	600	120
4	5	3000	400	180
5	20	3000	400	240

4. Conclusion

In this paper, mechanic-electrical response of cement-based piezoelectric ceramic composite is studied. As a typical linear smart material, it possesses an excellent dynamic performance to mechanical loading within whole frequency range of civil engineering application. Some conclusions can be drawn as follows.

(1) A high-order response of cement-based piezoelectric ceramic composite exists under mechanic loads. For general situation, this nonlinear piezoelectric effect is quite small and can be neglected. It shows that the composite is suitable for dynamic mechanical sensor as holding high static stability.

(2) The experimental results show that electrical output signal can reproduce the mechanical input signal with quite complex waveform without any visible distortion.

(3) Measurement with multiple function inputs indicates that cement-based piezoelectric ceramic composite holds an excellent performance to dynamic signals in frequency range for general civil engineering applications.

(4) The study shows that cement-based piezoelectric composite is suitable for potential application as dynamic mechanical sensor with excellent dynamic response and high static stability.

Acknowledgments

The authors would like to acknowledge the financial support provided by National Natural Science Foundation of China (nos. 50778114 and 50908149), Natural Science Foundation for the team project of Guangdong Province, 2009, and The team Programs for Science and Technology Development of Shenzhen University, 2009.

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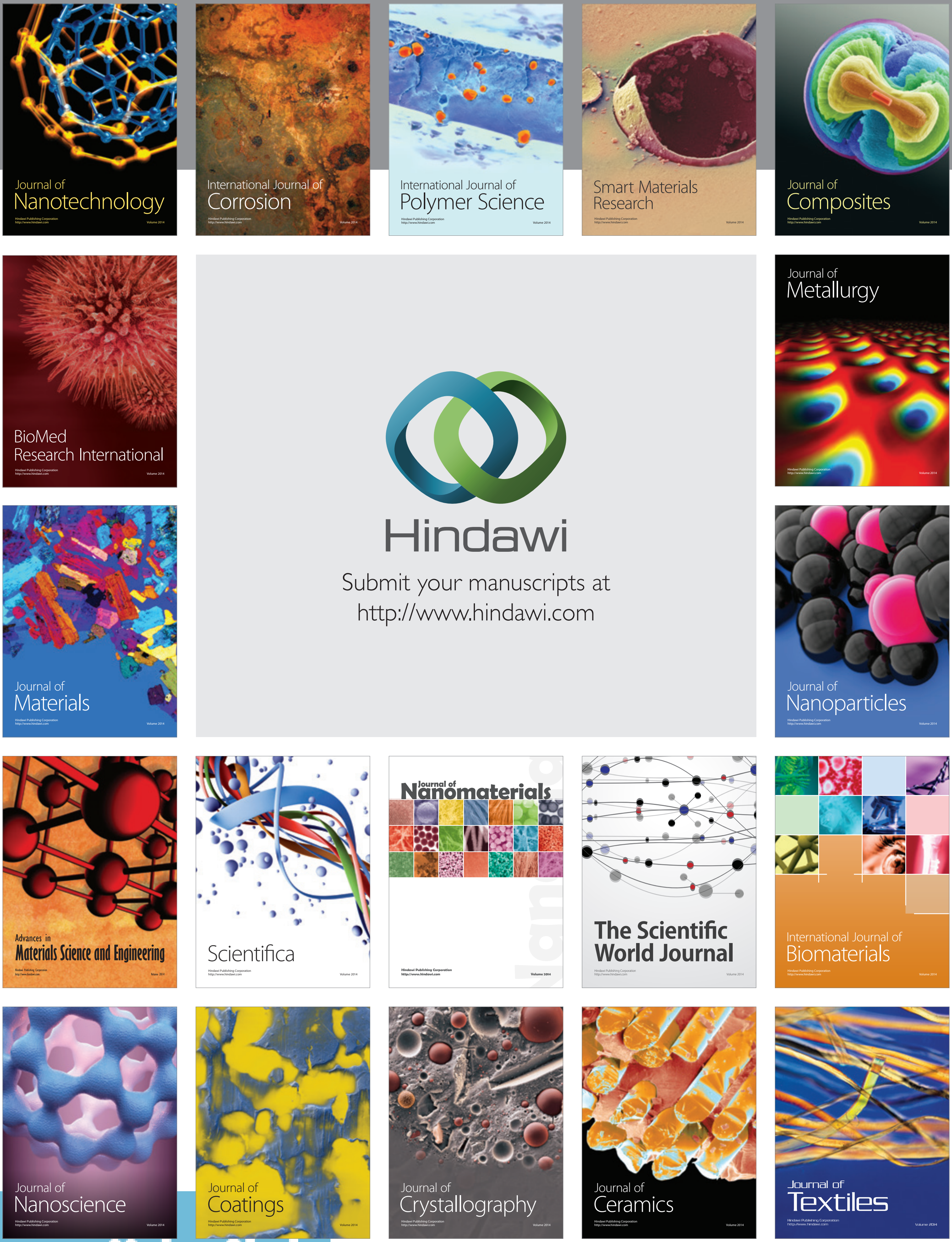
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