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Communication

2-2 Piezoelectric cement matrix composite: Part II. Actuator effect

Dong Zhang[a,*], Zongjin Li[b], Ke-Ru Wu[a]

[a]*State Key Lab of Concrete Materials Research, School of Materials Science and Engineering, Tongji University, Shanghai, 200092, China*
[b]*Department of Civil Engineering, Hong Kong University of Science and Technology Clear Water Bay, Kowloon, Hong Kong, China*

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Abstract

In this paper, experimental results of the actuator effect of a 2-2 piezoelectric cement matrix composite are presented. A desirable actuator effect was observed in the composite. In the first part of this study, the actuator effect of the composite under free conditions was studied. It was found that the amplitude of the response increases, but the phase angle of the response decreases, both almost linearly with the frequency of the actuator effect. The second part of the study focused on the behavior of the actuator in a structure. Distinct differences were observed in the behaviors of the composite under free conditions and in a structural system (simulated by precompression in the frame of an MTS machine). Clearly, the behavior of the actuator in a structure is influenced by factors including the properties of other components of the structure and the interaction between the actuator and other components, which was represented here by the precompression level in the experiment. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Recently, "intelligent" structures have been receiving much attention from researchers in the civil engineering field [1–3]. High-performance structures, such as high-rise buildings and long-span bridges, and some buildings whose failure would cause disasters, such as nuclear waster containment structures, dams, and bridge decks, are the most probable candidates for the application of the intelligent structures. As a simple definition, intelligent structures are structures with the ability to sense, assess, and react to internal and external changes and as a result to maintain their design functions. In an intelligent structure, the materials that perform the sensing and reacting (actuating) tasks are called smart materials. Today's smart materials include piezoelectric materials, shape memory alloys, fiber optics, electrostrictive materials, magnetostrictive materials, and electro- and magnetorheological fluids. Due to the advantages of fast response, large force output, high bandwidth, and compactness, piezoelectric materials have been amongst the most widely used smart materials.

Compared to conventional actuators, such as proof mass actuators, hydraulic actuators, torque motors, and thrusters, actuators made of piezoelectric materials have the advantages of light weight, rapid response, large bandwidth, large force output, little power consumption, and high resolution [4–6]. In the literature relating to piezoelectric actuators, there are many studies on the interaction of the actuators and the host structures both theoretically and/or experimentally [7–11]. One of the conclusions that can be drawn from these investigations is that the actuator efficiency depends strongly on the match of the stiffness between the actuator and the host structure, the frequency, and the piezoelectric coupling coefficient. In our previous studies [12,13], a synthesis of the cement matrix and a piezoelectric ceramic has been shown to be a promising way to make piezoelectric materials suitable for concrete structures with regard to the matching of impedance and volumetric stability between the smart materials and the host structures. The fabrication and the sensory effect of 0-3 and 2-2 cement matrix piezoelectric composites have been presented in earlier reports [12,13]. The present paper is mainly focused on the actuator effect of the 2-2 piezoelectric cement matrix composite under a free condition and a precompression

* Corresponding author. Tel.: +86-21-6598-4191; fax: +86-21-6598-0530.

E-mail address: zhangdng@mail.tongji.edu.cn (D. Zhang).

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condition as an approximate simulation of the situation in a real structure.

2. Composite fabrication and experimental approach

A detailed description of the fabrication of the 2-2 piezoelectric cement matrix composite can be found in our previous report [13]. Briefly, ceramic plates were embedded into a cement matrix at a spacing of 1.1 mm. These ceramic plates were connected mechanically in series but electrically in parallel. Refer to the earlier report [13] for details of the sizes, shape, and internal structure of the composite.

A test system composed of an MTS machine, a signal generator, a linear amplifier, an oscilloscope, and a personal computer was used to test the electromechanical behavior, including the piezoelectric effect and the inverse piezoelectric effect. In this system, the signal generator and linear amplifier were used to impose a driving voltage onto the composite samples. The sinusoidal electrical signal from the signal generator was enlarged by 20 times the linear amplifier, with the frequency unchanged. Then the output of the linear amplifier, that is, the enlarged electrical signal, was applied to the two electrodes of the composite, which were connected to the electrodes of the parallel ceramic plates embedded in the cement matrix. The ceramic plates vibrated under the electrical excitation, which caused the composite to quiver in turn. Two extensometers and a load cell in the MTS system were used to detect the strain of the vibrating composite under free conditions and the force generated by the composite under precompression conditions. The electrical stimulus, strain, and force signals were all recorded onto the computer's hard disk through the oscilloscope in the test. A more detailed description about the test system, including a schematic illustration, can be found in our previous report [13].

3. Results and discussion

3.1. Free condition

Fig. 1 shows some typical results of the strain response of the composite samples under the free condition, stimulated by the sinusoidal electrical excitation at different frequencies. In this figure, the electrical signal and the strain signal are plotted as functions of time. The amplitude and waveform of the electrical excitation did not change during the

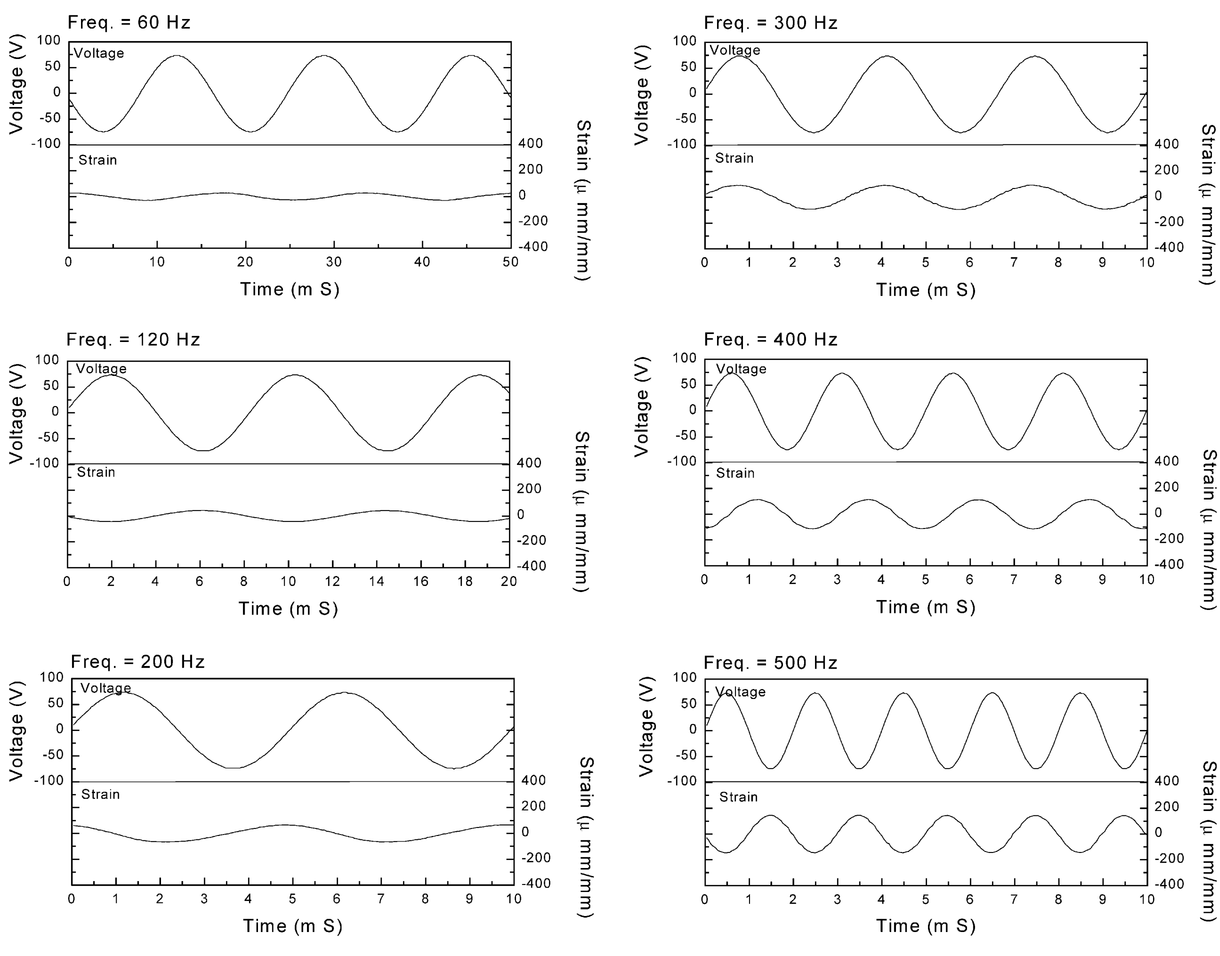

Fig. 1. The electrical stimulus and strain of the composite samples under free condition at different frequencies.

test, and the peak-to-peak amplitude of the electrical excitation was 150 V. The only parameter of the electrical stimulus that changed was frequency, which increased from 10 to 800 Hz during the test. As the frequency increases, the amplitude of the strain signal increases gradually, and the phase angle also changes.

In Fig. 2, the relationship between the amplitude and phase angle of strain and frequency of the electrical stimulus is depicted more directly. It can be seen that the amplitude of strain, that is, the mechanical response, increases almost linearly with the increase in frequency of the electrical stimulus. A similar phenomenon was also found in our previous study [13] of the sensory effect of the same composite, where the amplitude of the electrical response, that is, piezoelectric voltage, also increased linearly with the frequency of the mechanical stimulus. However, the phase angle in the present work behaves in a different style compared to that of the sensory effect of the composite. As reported in our previous paper [13], the phase angle of the electrical response increased asymptotically to a constant with increasing frequency of the mechanical stimulus. But it can be seen in Fig. 2 that the phase angle of strain, the mechanical response, decreases with increasing frequency of the electrical stimulus.

As shown in Figs. 1 and 2, the composite samples will expand or contract when stimulated by electrical voltage under the free condition, and no accompanying stress will be generated. But if the composite sample is mechanically clamped, no strain or displacement is allowed to occur. Mechanical clamping means that the size of the composite sample is restored to its original value by an external force. So, according to the theory of elasticity, stress or force will be generated in the samples. In Fig. 3, the y-axis intercept represents the amplitude of the displacement of the composite samples stimulated by the sinusoidal electrical voltage under the free condition. This displacement amplitude is the product of strain amplitude and the thickness of the ceramic plate array (= 25 mm). The force generated in the composite samples under a mechanical clamping condition

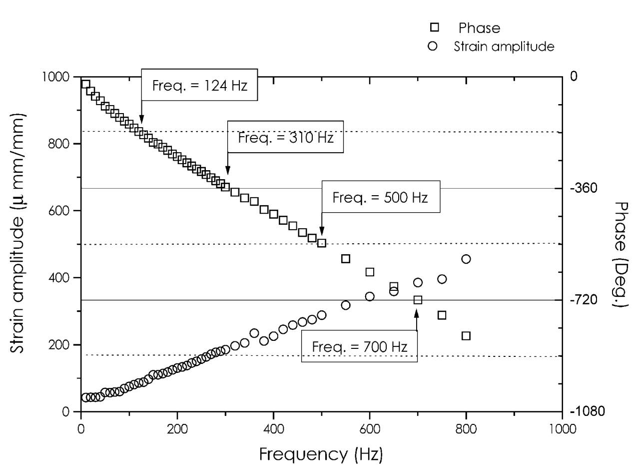

Fig. 2. The amplitude and phase of strain signal vs. frequency.

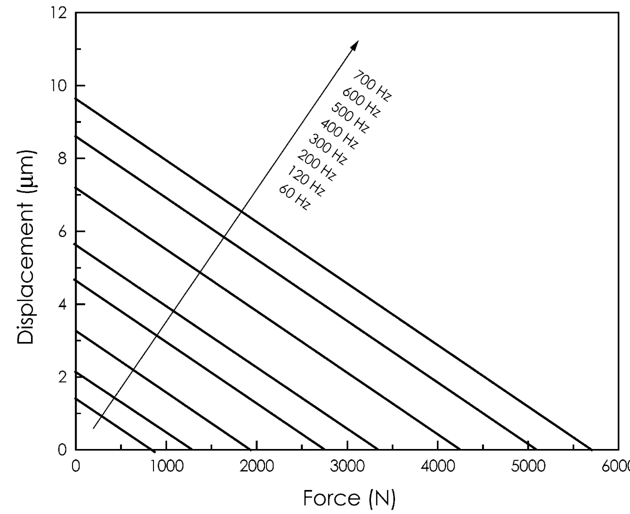

Fig. 3. Displacement vs. force of the composite samples at different frequencies.

is represented by the x-axis intercept in Fig. 3, which is determined by the following equation.

$$F = \varepsilon EA$$

where ε is the strain amplitude, E is the modulus of elasticity of the composite (20.5 GPa) [13], and A is the side face area (680 mm^2) [13]. The frequency of the electrical stimulus has a significant influence on the force or displacement of the composite samples. As the frequency increases, relatively large forces will be generated in the composite samples, which is very useful for intelligent structures in civil engineering.

3.2. Precompression condition

In the previous section, the behavior of the composite samples under the free condition was described. At the end of the section, a theoretical calculation was applied to the properties of the composite under clamped conditions, using the test results of strain amplitude and modulus of elasticity of the composite samples. In fact, such an absolute restriction can rarely be realized in practical applications. In most situations, the actuators are partially restricted to different degrees in different structures.

In order to simulate the partial restriction, the behavior of the composite under the so-called precompression condition was then studied. Here, the term ‘‘precompression condition’’ means that the composite sample was first compressed to some degree, for example, 1000 or 2000 N, before it was electrically excited. The precompression, provided by an MTS machine, was used to simulate partial restriction. In the tests, the electrical voltage and force variations were recorded. Fig. 4 shows some typical results; it can been seen clearly that the frequency of the electrical stimulus greatly influences the amplitude of the mechanical

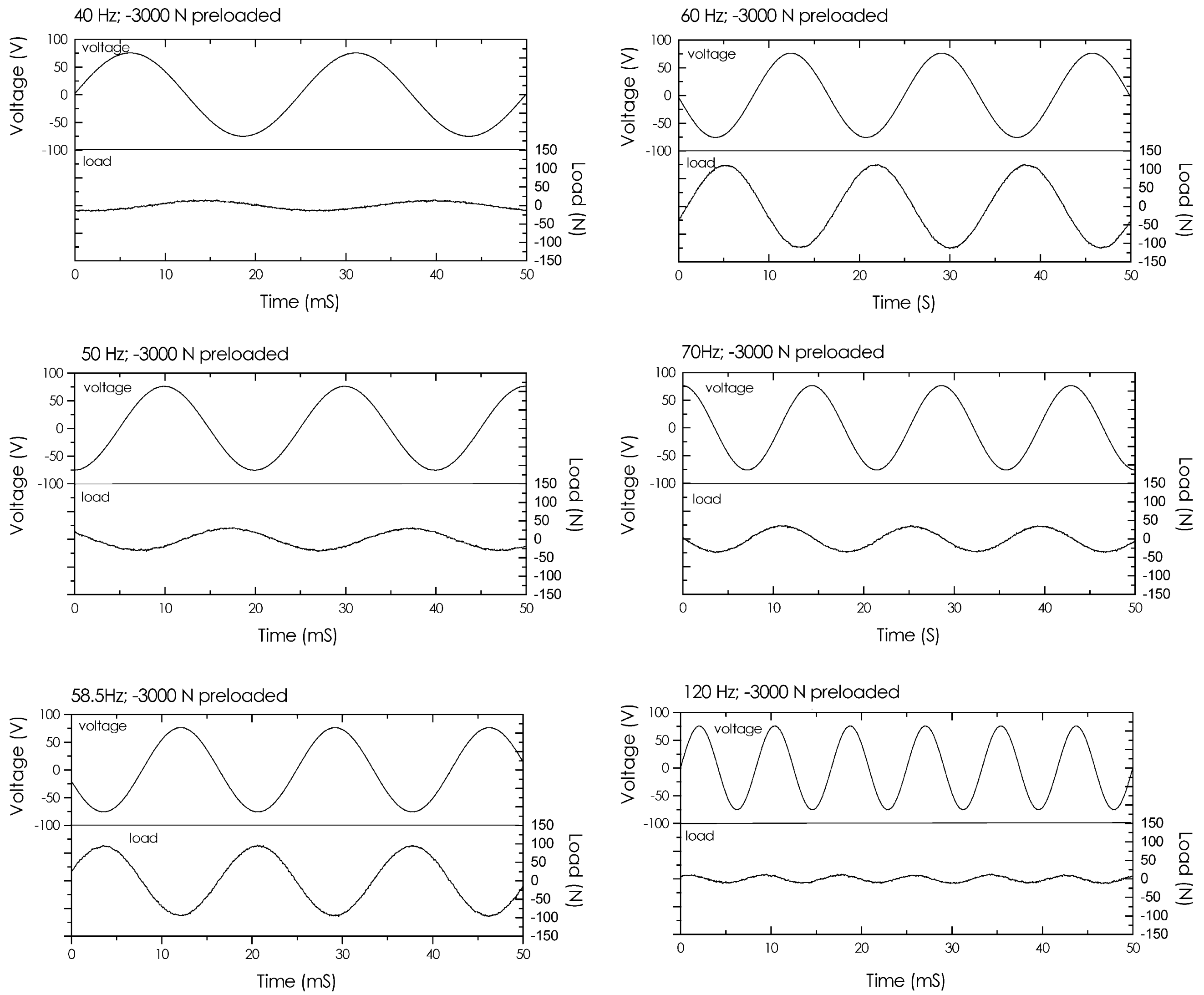

Fig. 4. Typical results of precompression test.

response. The amplitude of the response reaches its maximum at some particular frequency; above or below this frequency, the amplitude becomes smaller. For example, in Fig. 4, when the precompression level is 3000 N, the position of the peak of the amplitude of the mechanical response is around 60 Hz.

In Fig. 5, the amplitude and phase angle of the load variation of the composite samples under precompression conditions of different levels are plotted against the frequency. Comparing Figs. 2 and 5, there exist distinct differences between the converse piezoelectric behaviors of the composite samples under free conditions and those under precompression conditions.

1. *Phase angle*. There is only one common point between Figs. 2 and 5 regarding the phase angle of the mechanical response. They both display a trend of decreasing as the frequency increases. But in Fig. 2, the decrease is monotonic, smooth, and gradual, almost linear. In contrast, in Fig. 5, for the precompression condition, there exists a steep drop and a peak during the gradually decreasing course of the phase angle.

2. *Amplitude*. The difference in the amplitudes of the mechanical response caused by different conditions (free and precompression) is much more evident. In Fig. 2, the amplitude of the mechanical response increases almost linearly with the frequency for the free condition. But as shown in Fig. 5, for the precompression condition, there is no increasing trend for the amplitude of the mechanical response as the frequency increases. Instead, there exists a peak in the amplitude curves corresponding to the steep drop in the phase angle curves at the same frequency position. And around the frequency position of the peak in the phase angle curves, there is a pair consisting of a valley and a peak in the amplitude curves.

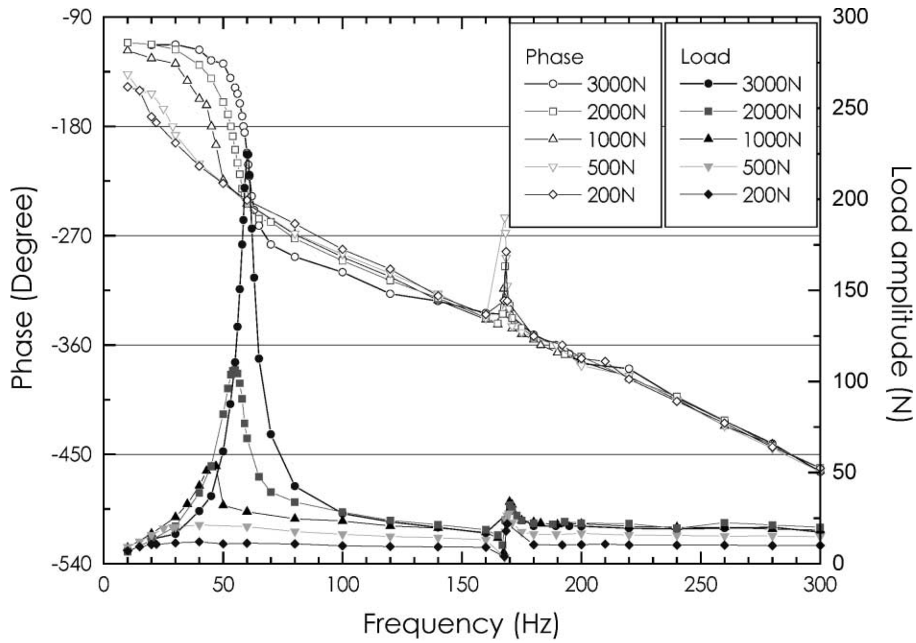

Fig. 5. The load amplitude and phase vs. the frequency.

3. *Characteristic frequencies*. Consider the precompression condition at the level of 2000 N as an example. Fig. 6 shows the derivative of the phase angle and the load amplitude of the mechanical response of the composite samples under the 2000-N precompression condition. It can be seen that the peak and valley in the load amplitude curve coincide exactly with the valley and peak, respectively, in the curve of the derivative of phase angle, which means that the peak or valley in the load amplitude curves corresponds to the steepest parts of the phase angle curves. There exist three characteristic frequencies in the low-frequency range (Fig. 6).

4. *The influence of the precompression level*. The precompression level represents the strength of the interaction between the composite sample and the other components of the structure. It can be seen that the precompression level greatly influences the first peak in the load amplitude curves and the steep drop in the phase angle curves. As the level

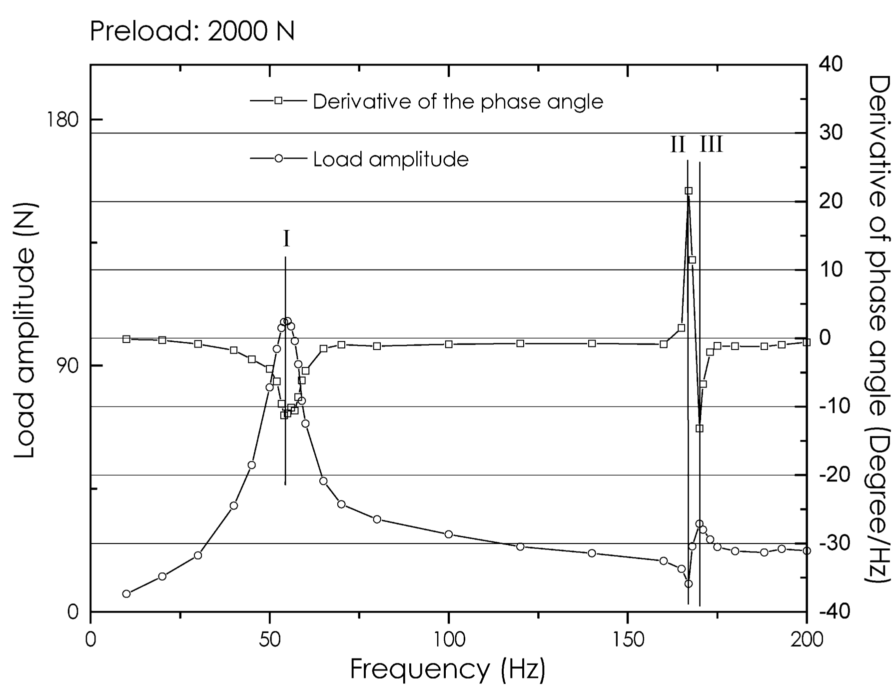

Fig. 6. Characteristic frequencies of the mechanical response under precompression condition.

increases from 200 to 3000 N, the height of the first peak in the load amplitude curves and the depth of the drop in the phase angle curves increase rapidly. As well, the peak frequency, that is, the first characteristic frequency (I), increases from 30 to 50 Hz. Meanwhile, the second and the third characteristic frequencies (II and III) are almost not influenced by the precompression level.

The composite sample is located and clamped in the structure (as in the frame of the MTS machine) in most real applications. So, its behavior should be looked upon as one part of the entire behavior of the system consisting of many components (such as the frame and the composite sample in this experiment). It is influenced by the properties of the other components and the coupling strength (such as the precompression level in the test) between the composite sample and the other components. Thus, a systematic viewpoint should be adopted of analyzing the behavior of an actuator in the host structure, instead of an isolated method based only on the properties obtained from tests in free conditions.

In this test, the frame of an MTS machine was used as a structure to provide a simulated situation for observing the behavior of the composite samples in a real structural system. Of course, because of the differences between a real structure and the frame of the MTS machine, only some qualitative results could be obtained. Experiments using real structures, at least small ones, are needed to acquire more accurate and quantitative knowledge of the behavior of a functional composite in host structures.

4. Conclusions

A 2-2 piezoelectric cement matrix composite has been fabricated successfully in the laboratory, with desirable sensory and actuator effects.

The experiment on the actuator effect was divided into two parts. In the first part, the actuator effect of the composite under a free condition was studied. It was found that the frequency greatly influences the amplitude and phase angle of the mechanical response, which is similar to the phenomena observed in previous experiments on the sensory effect with respect to the amplitude, but dissimilar with respect to the phase angle. Both for the sensory and actuator effects, the amplitude of the response increases almost linearly with the frequency. The phase angle of the response increases asymptotically to a constant in the sensory effect, but decreases almost linearly in the actuator effect, with increasing frequency.

In the second part of the experiment, the focus was on the behavior of the actuator in a structure. Here, the frame of an MTS machine was used to simulate the real situation in a structure. Distinct differences were observed in the behaviors of the composite under the free condition and in a simulated structural system. It was found that the phase angle decreases with the increasing frequency, but there exists a steep drop and a peak in the phase angle curves. The amplitude of the mechanical response does not increase monotonically as the frequency increases. Instead, there exists a peak in the amplitude curves corresponding to the steep drop in the phase angle curves at the same frequency position. Around the frequency position of the peak in the phase angle curves, there is a pair consisting of a valley and a peak in the amplitude curves. Three characteristic frequencies were found in the response curves of the actuator under precompression conditions. The position of the first characteristic frequency, the height of the first peak in the amplitude curves, and the depth of the drop in the phase angle curves are all influenced by the precompression level.

Experiments with real structures are needed to characterize the behavior of the composite as an actuator in real structures.

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