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Online Phase Tracking of Interferometric Optical Fiber Sensors for Vibration Control

YOUNG-HWAN CHANG,[1] DO-HYUNG KIM,[2] JAE-HUNG HAN[1,*] AND IN LEE[1]

[1]*Department of Aerospace Engineering, Korea Advanced Institute of Science and Technology, 373-1 Guseong-dong Yuseong-gu, Daejeon 305-701, Korea*

[2]*Rotors System Department, Korea Aerospace Research Institute, 45 Eoeun-dong, Yuseong-gu, Daejeon 305-333, Korea*

ABSTRACT: Online phase tracking of an extrinsic Fabry–Perot interferometer (EFPI) and experimental vibration control of a composite beam with a sensing patch are investigated. EFPI sensors have nonlinearity due to their interferometric characteristics. We propose a new sensing patch for compensation of this interferometric nonlinearity. This newly developed sensing patch consists of an EFPI sensor and another sensor that can produce directional information. Therefore, it uses the advantages of their components used in conjuction in order to overcome the disadvantages of the components used separately. A sensing patch that comprises an EFPI sensor and a piezoceramic is fabricated, and the characteristics are experimentally investigated. A simple and practical logic is applied to real-time tracking of the optical phase of an interferometer. The experimental results show that the proposed sensing patch does not suffer from the nonlinear behavior of conventional EFPI sensors and the hysteretic behavior of piezoelectric materials. Moreover, it has excellent strain resolution and a wide dynamic sensing range. The application of a sensing patch has been also investigated: vibration control with this sensing patch has been performed using a fuzzy logic controller (FLC), and the possibility of using a sensing patch as a sensoriactuator is considered.

Key Words: sensing patch, EFPI, online phase-tracking, sensoriactuator, vibration control.

INTRODUCTION

RECENTLY, there have been many studies on sensing patches, which are combinations of existing sensors, in the field of smart structures and materials. These sensing patches utilize the advantages of their components used in conjuction and overcome the disadvantages of the components used separately. This article proposes a new sensing patch consisting of an extrinsic Fabry–Perot interferometer (EFPI) type of fiber-optic sensor and a piezoceramic.

Many research programs on the development and application of fiber-optic sensors are in progress: structural monitoring of large civil structures, aircraft and space structures, and so on. The optical fiber sensors have many promising properties compared to other types of sensors: small size, lightweight, nonconductivity, fast response, resistance to corrosion, lower power consumption, immunity to electromagnetic noise interference, and good installability onto or into host structures. Furthermore, the optical interferometer sensor is one of the most effective strain sensors in terms of resolution. Since the optical fibers can be inserted in the laminated composite structure, they can directly measure internal strain inside the structure as well as surface strain, unlike conventional strain sensors. Also, they can continuously monitor several conditions such as damage, strain, stress, crack formation, pressure, temperature, and so on.

Among the many kinds of optical fiber sensors, interferometric sensors are widely used. However, it is reported that they have the problem of inherent nonlinearity because of their interferometric characteristics. In order to extract true mechanical strain from an EFPI sensor output signal, several methods have been proposed including a novel fiber-optic vibration sensor (Doyle and Fernando, 1997), a cantilever-type optical fiber vibration sensor (Kimura and Toshima, 1998), a quadrature phase-shifted EFPI (Murphy et al., 1991), and a gold-deposited EFPI (Kim et al., 2003a). Several signal-processing techniques have also been proposed; usually, these techniques are based on the fringe-counting method (Kim et al., 2001) or phase-tracking method using a demodulation technique or neural network compensation (Kim et al., 2004). However, these signal-processing techniques are complex and cannot be easily applied to real-time dynamic strain measurement.

*Author to whom correspondence should be addressed.
E-mail: jaehunghan@kaist.ac.kr
Figures 8, 9, 14, 15, 17 and 18 appear in color online: http://jim.sagepub.com

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That is why studies on strain measurement using interferometric optical fiber sensors are limited to static or slow dynamic systems (Kim et al., 2003b).

This article presents a new sensing patch comprising an EFPI and a piezoceramic. By using the piezoelectric ceramic as a direction detector, a simple and practical phase-tracking logic is proposed for real-time strain measurements. An EFPI sensor itself has a nonlinear strain–intensity relationship, and a piezoelectric sensor shows hysteresis behavior. However, the sensing patch proposed in this study overcomes the problems that can arise in case of individual uses—it does not show nonlinear or hysteresis behavior. Moreover, it has good strain resolution and a wide dynamic sensing range. The performance of the proposed sensing patch is validated by the comparison with commercial laser sensors. Finally, the possibility of the use of the sensing patch as a sensoriactuator is considered. A sensoriactuator not only guarantees stabilities in 'direct-feedback control loops' but also leads to miniaturization of hardware.

Finally, vibration-control experiments were performed to show the effectiveness of the proposed sensing patch. In this study, fuzzy logic controller (FLC) and positive position feedback controller are used to suppress structural vibrations.

PRINCIPLE OF SENSING PATCH AND PHASE-TRACKING METHOD

In this study, an EFPI is fabricated and used as a part of the sensing patch in a vibration-control system. Its schematic diagram is shown in Figure 1. The reflected intensity, I, can be written using a sinusoidal function as follows:

$$I \propto A + B\cos\phi \tag{1}$$

where A and B are functions of the fiber core radius, the air gap separation, the transmission coefficient of the air–glass interface, and the numerical aperture; and ϕ is the optical phase. For small variations of air gap separation, A and B are constants, and can be easily obtained from measured EFPI sensor signals. The relation between optical phase, ϕ, and gap separation, s, is given as

$$\phi = 2ks \tag{2}$$

where k is the wave number defined as $2\pi n_c/\lambda_0$, n_c is the refractive index of an EFPI in the gage length, and λ_0 is the wavelength of the laser diode in a vacuum state. By using Equations (1) and (2), s can be written as follows:

$$s = \frac{1}{2k}\cos^{-1}\left(\frac{I - A}{B}\right) \tag{3}$$

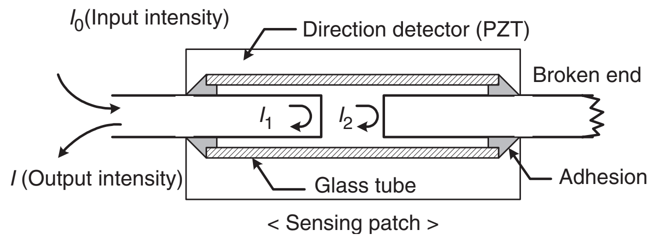

Figure 1. *Schematic diagram of a sensing patch.*

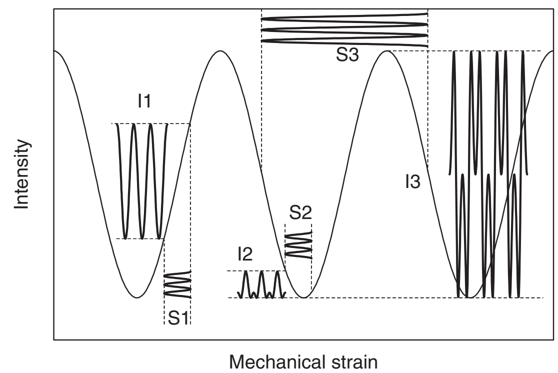

Figure 2. *Signal fading in fiber interferometers.*

Owing to the characteristics of interferometric optical fiber sensors, the output intensity of an EFPI does not have a linear relationship with mechanical strain, as explained in Figure 2 (Kim et al., 2004). S1 is a possible mechanical strain for a vibrating system, and I1 is the corresponding output intensity. S2 indicates another example of mechanical strain that has the same amplitude as S1. However, the corresponding intensity, I2, shows a distorted behavior, according to the initial optical phase of an EFPI. One can easily notice from S3 and I3 that the EFPI sensor shows severe nonlinearity whenever the strain amplitude is large enough.

In order to extract the mechanical strain from an EFPI sensor output signal, we can use Equation (3) in a discrete time step and accumulate the phase change. But, the arccosine function in Equation (3) has value between 0 to π. Therefore, at the discontinuous points, information about the direction of structural strain is necessary to keep up online phase tracking. In order to get the strain directional information, any sensor that produces real strain direction can be used. Among the several possible sensor materials, piezoelectric material is used in this study. The overall online phase-tracking sequence is shown in Figure 3. By using an EFPI sensor signal and strain rate information, the optical phase, which corresponds to the mechanical strain, is obtained as follows:

$$\phi_{k+1} = \phi_k + \mathrm{sign}(\text{strain rate}) \times \left|\cos^{-1}\left(\frac{I_{k+1} - A}{B}\right) - \cos^{-1}\left(\frac{I_k - A}{B}\right)\right| \tag{4}$$

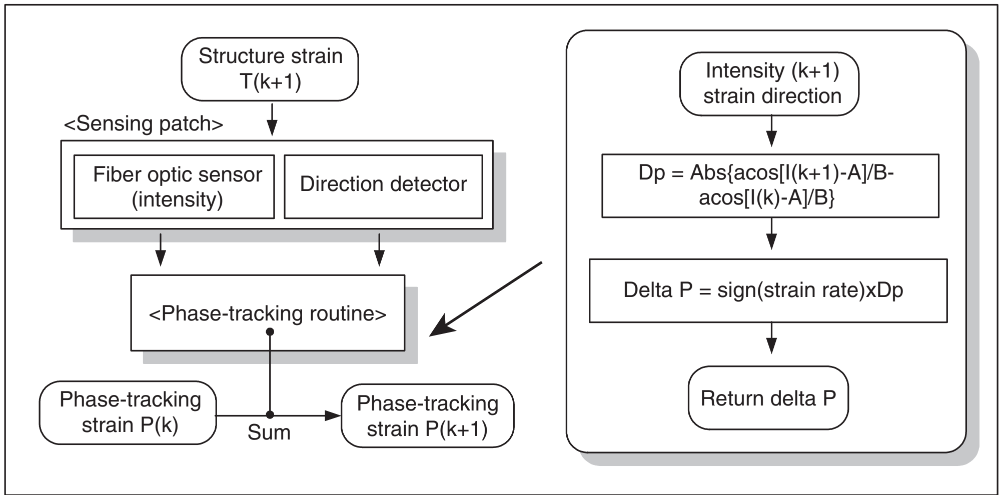

Figure 3. *Flow chart for the phase-tracking method.*

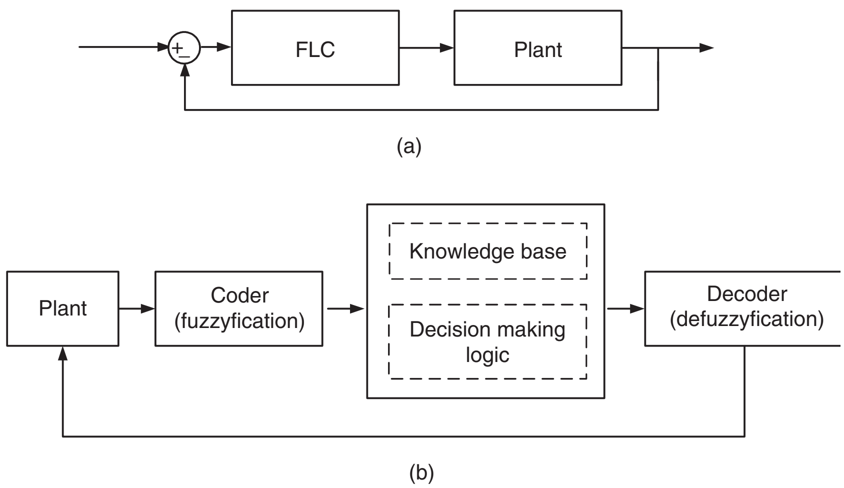

Figure 4. *Basic structure of an FLC: (a) fuzzy logic control system and (b) basic structure of a FLC.*

where $\phi_k(= 2ks_k)$ is the optical phase at the kth step. A high-pass filtering is applied to remove any possible error that can arise in phase tracking.

FUZZY LOGIC CONTROL

A fuzzy logic control system has been applied as one of the effective control systems in various fields including vibration control of structures. The advantage of the fuzzy logic control system is its inherent robustness and ability to handle nonlinearities and uncertainties in structural and loading conditions.

In this section, the design of an FLC has been discussed in order to suppress vibration using the proposed sensing patch. An FLC is incorporated into a closed-loop control system as shown in Figure 4(a). The basic structure of a typical FLC is illustrated in Figure 4(b). The various components of this controller are defined as follows (Lee, 1990; Naghdy et al., 1998).

Fuzzification

This unit maps the measured inputs, which may be in the form of crisp values, into fuzzy linguistic values, using the fuzzy reasoning mechanism. The fuzzification interface involves the following functions:

1. measures the values of input variables,
2. performs a scale mapping that transfers the range of values of input variables into corresponding universes of discourse, and
3. performs the function of fuzzification that converts input data into suitable linguistic values, which may be viewed as labels of fuzzy sets.

Knowledge Base

The knowledge base comprises a knowledge of the application domain and the attendant control goals.

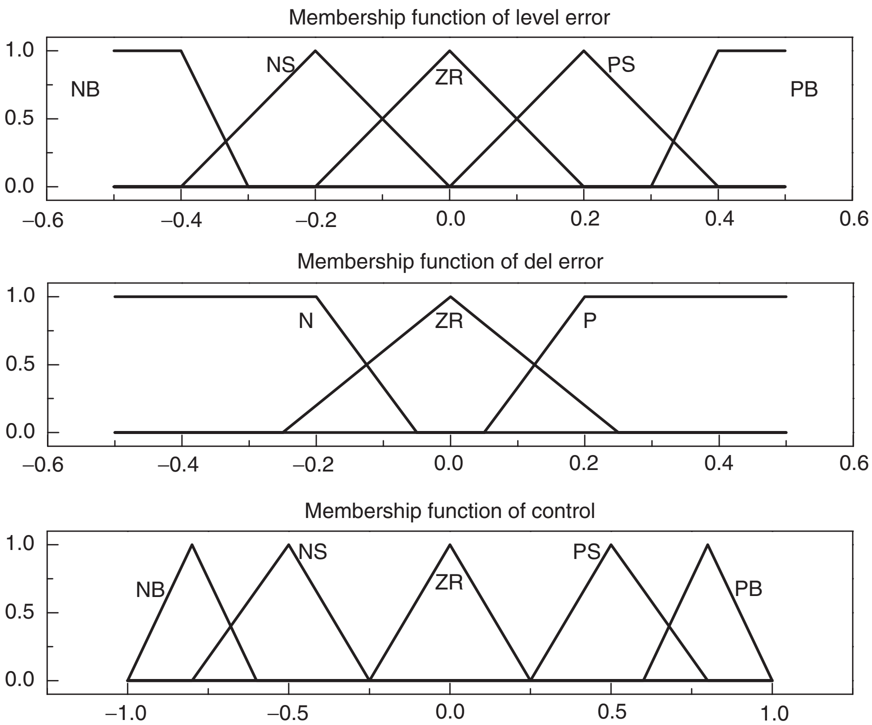

***Figure 5.** Membership Functions for displacement, velocity, and control.*

It consists of a 'data base' and a 'linguistic (fuzzy) control rule base.'

1. The data base provides necessary definitions, which are used to define linguistic control rules and fuzzy data manipulation in an FLC.
2. The rule base characterizes the control goals and control policy of domain experts by means of a set of linguistic control rules.

Decision Making

This unit is the fuzzy reasoning mechanism that performs various fuzzy logic operations to infer the control action for a given fuzzy input; it has the capability of simulating human decision making, based on fuzzy concepts and of inferring fuzzy control actions employing fuzzy implication and the rules of inference in fuzzy logic.

Defuzzification

The inferred fuzzy control action is converted into required crisp control value in this unit. The defuzzification interface performs the following functions:

1. a scale mapping, which converts the range of values of output variables into corresponding universes of discourse, and
2. defuzzification, which yields a nonfuzzy control action from an inferred fuzzy control action.

Table 1. Fuzzy variables.

ZR = zero
PS = positive and small
PB = positive and big
NS = negative and small
NB = negative and big

Table 2. FAM for the fuzzy controller.

		Del error		
		N	ZR	P
Level error	**NB**	PB	PB	ZR
	NS	PS	PS	ZR
	ZR	ZR	ZR	ZR
	PS	ZR	NS	NS
	PB	ZR	NB	NB

In fuzzy vibration control, displacement (x) and velocity ($\dot{x}$) information are used as feedback to the FLC. The output of the controller is the required control force (u). The membership functions chosen for input and output variables are triangular and trapezoidal shapes, as illustrated in Figure 5. The fuzzy variables used to define the fuzzy space are described in Table 1.

In this study, the fuzzy controller is designed using intuitive methods. The rule base of the control system is developed by observing the behavior of the excited system and adopting the necessary control action to suppress the vibration. The fuzzy associative memory (FAM) is shown in Table 2. The output of

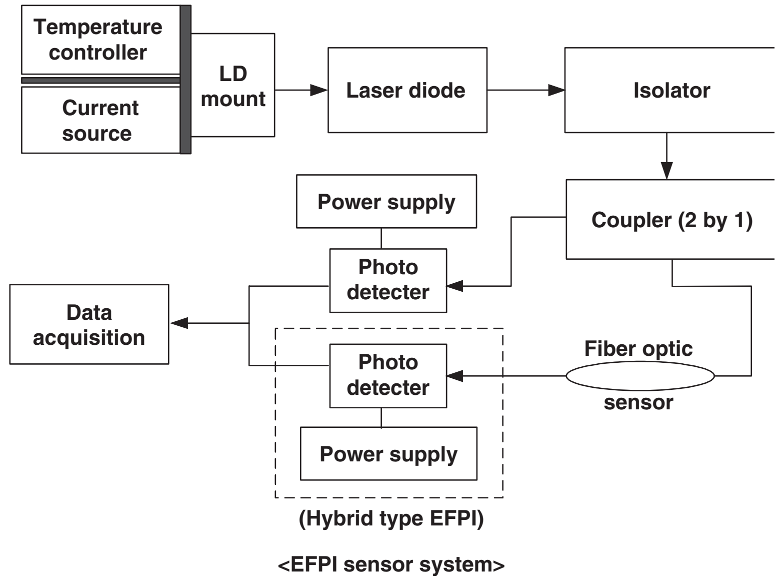

Figure 6. *EFPI sensor system.*

the system is the control force required to drive the actuator.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 6 shows the schematic diagram of the EFPI sensor system. In order to keep the wavelength of the laser diode constant, the sensor system includes a temperature controller. During the experiment, the laser diode temperature was maintained at 25°C, and a 17 mA current drives the laser diode.

The test model was a composite beam structure (graphite/epoxy $[0]_8$, 2 cm width and 20 cm length) with a piezoceramic actuator and a sensing patch as shown in Figure 7. The sensing patch was manufactured as shown in Figure 1 and attached on the beam structure 4 cm above the clamping position. In order to monitor and compare obtained sensing patch signals with real vibration signals, a laser displacement sensor (LB041, Keyence) and an electric strain gage were used. The displacement sensing point was set 9 cm below the beam tip, and the strain gage was attached to the sensing patch.

Figure 8 shows an overall experimental setup consisting of an EFPI sensor system, a laser displacement sensor, a PC-based digital data acquisition and real-time control system, a piezo amplifier, and the test model.

Sensing patch Verification

Several simulations were performed using MATLAB/Simulink block in order to verify the proposed phase-tracking method. Figure 9(a) and (b) show the simulation results of the phase-tracking method when excitation frequencies are 50 and 100 Hz. In simulations,

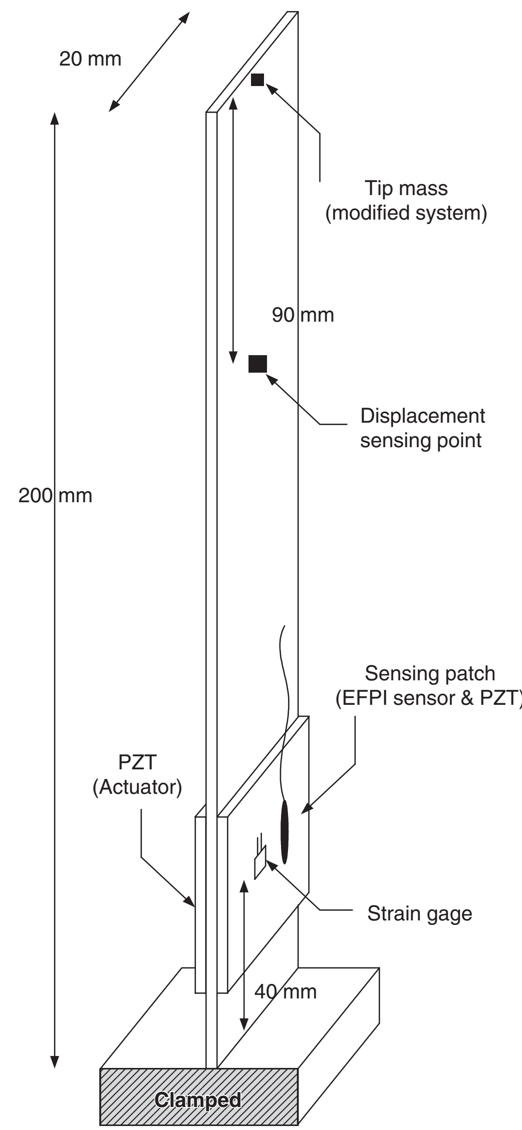

Figure 7. *Schematic diagram of the test model.*

Figure 8. *Overall experimental setup.*

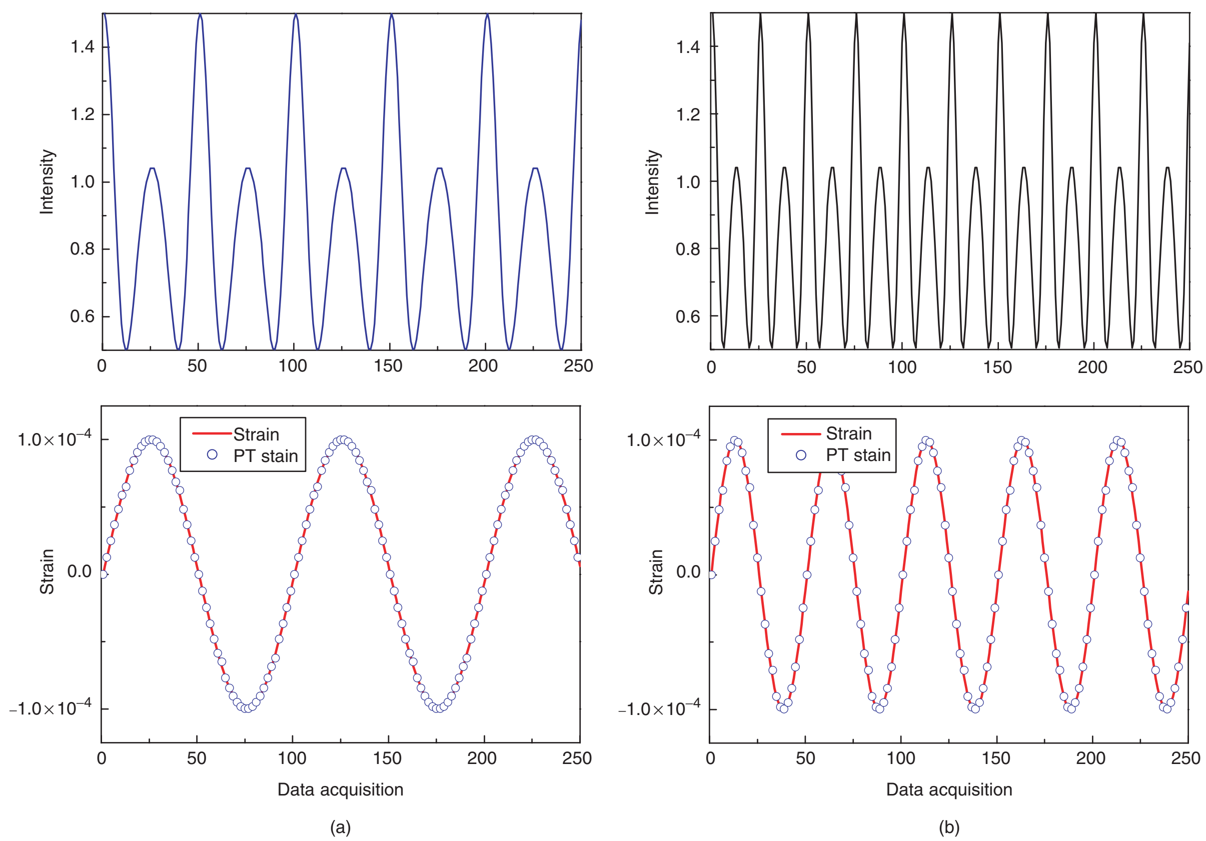

Figure 9. *Simulation results for the phase-tracking method: (a) excitation frequency = 50 Hz and (b) excitation frequency = 100 Hz.*

the sampling frequency is 5 kHz. The phase-tracked signals are in good agreement with true strain signals, while the raw intensity signal of the EFPI presents the fading effect or nonlinear behavior.

Before the experimental verification of the sensing patch, it is necessary to verify the hysteretic effect of piezoelectric material on the phase-tracking method. Because the phase-tracking method uses the strain rate

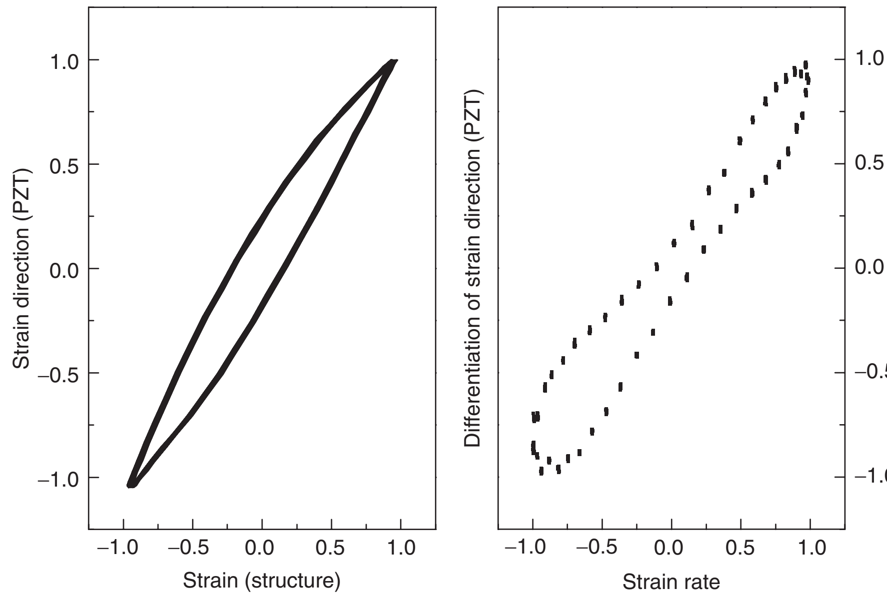

***Figure 10.** Hysteretic behavior of the piezoelectric material.*

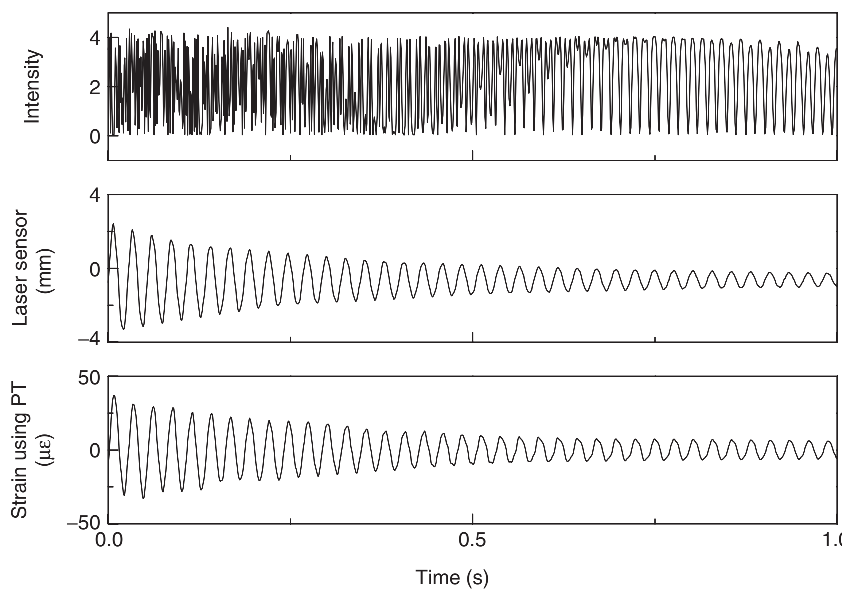

***Figure 11.** Experimental result of phase tracking during free vibration.*

signal from a piezoelectric material, the hysteretic behavior of piezoelectric material may have an adverse influence on phase tracking. The left-hand side of Figure 10 shows hysteresis of the piezoelectric material, and the right-hand side shows the relation between strain rate signal and differentiation of directional signal of piezoelectric material in general behavior (normalized result). Using the sine excitation test at several frequency bands with a laser Doppler velocimeter and piezoelectric material, these general behaviors are experimentally obtained from several tens to hundreds of Hz. Because the sensing patch uses only the strain rate signal, the hysteretic behavior of piezoelectric material has negligible effect on the phase-tracking method.

The experimentally acquired values for A, B in Equation (1) and the initial phase were 2.156, 2.125, and 2.4872 rad, respectively. In addition, wavelength was 1310 nm, gage length was 10 mm, air gap was 41 μm, and sampling frequency was 2 kHz. First, the phase-tracked signals were compared with laser displacement sensor signals for free decay condition. Second, when the specimen was excited at the first resonant frequency (38 Hz), the laser displacement signal and the signal from the sensing patch by using phase-tracking method are acquired. Figures 11 and 12 show the excellent correlation between the laser displacement sensor signals and phase-tracked signals: the top figures represent EFPI intensity signals, middle figures are the displacement signals, and bottom figures show the

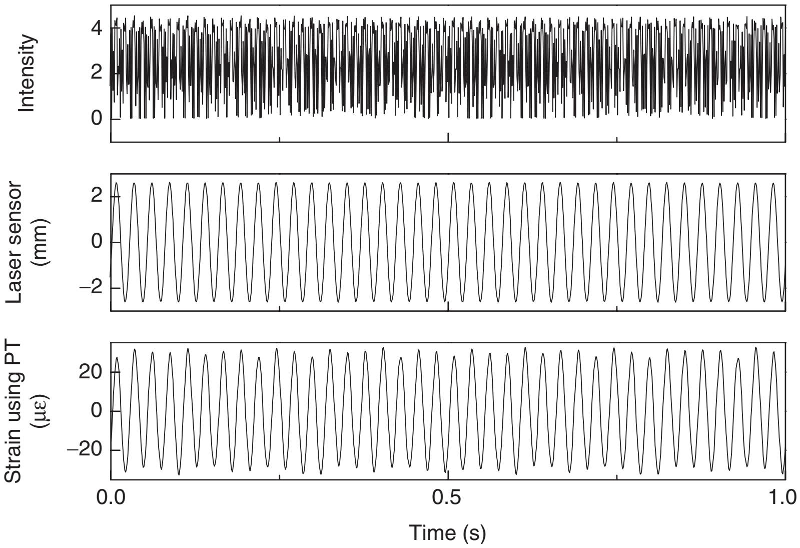

Figure 12. Experimental result of phase-tracking during sine excitation.

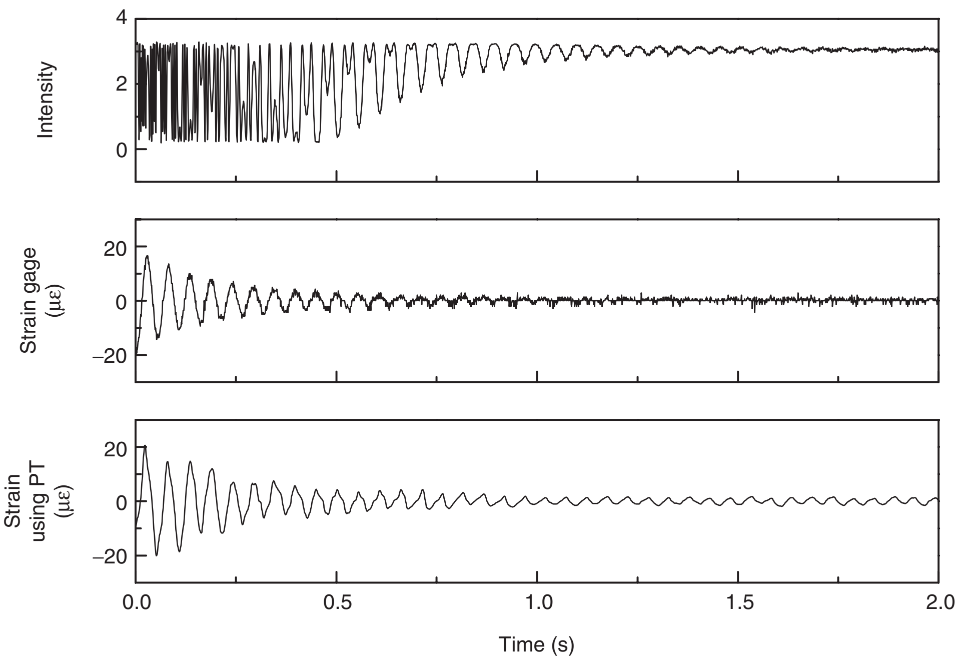

Figure 13. Experimental result of strain gage and phase-tracking signal.

phase-tracked signals. EFPI intensity signals show the fading effect, or nonlinear behavior. But phase-tracked signals using EFPI intensity signal show good agreements with displacement signals from commercial laser sensors. By this time, indirect comparisons of the sensing patch performance were made with a laser displacement sensor.

Figure 13 directly compares strain from the strain gage with the phase-tracked signal. It was difficult to sense minute strains using strain gages. In contrast, the sensing patch can sense minute strains because it uses an EFPI sensor with excellent resolution.

The results in Figures 10–13 validate the strain signals from the sensing patch using the proposed phase-tracking method. Therefore, the sensing patch is readily applicable to structural vibration monitoring and control.

Experimental Results for Vibration Control

In this study, the sensing patch and phase-tracking method are applied to the vibration control. The FLCs are applied and their performances are compared with those of the positive position feedback controller (Fanson and Caughey, 1990).

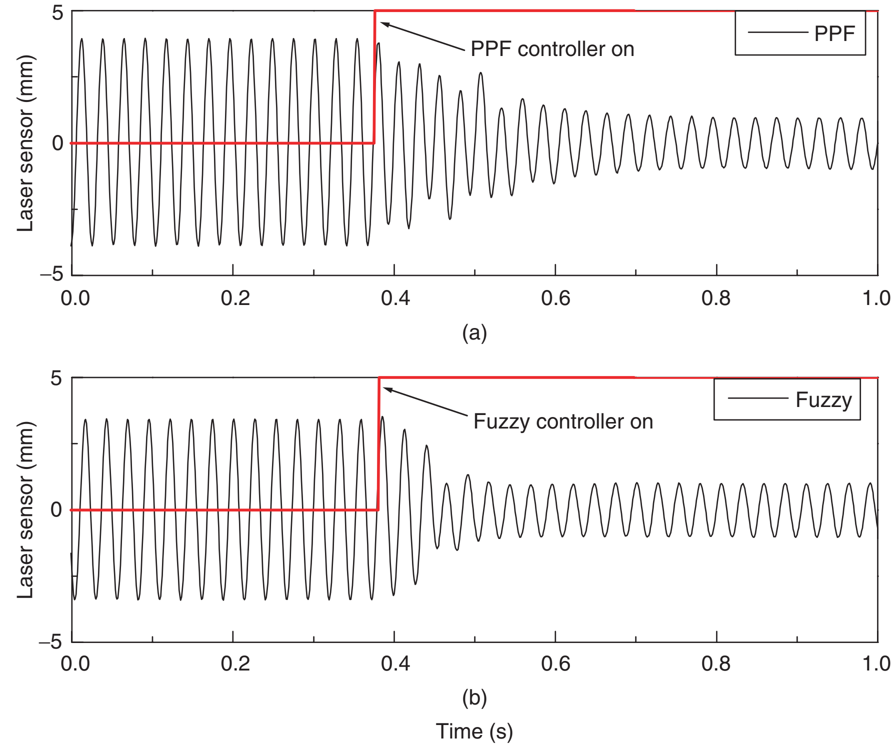

Figure 14. *Experimental results using sensing patch: (a) PPF control and (b) fuzzy control.*

NOMINAL SYSTEM

The positive position feedback controller is designed according to Fanson and Caughey (1990) for the nominal system:

$$H_{PPF}(s) = \frac{K\omega_f^2}{s^2 + 2\varsigma_f \omega_f s + \omega_f^2} \tag{5}$$

where ς_f is the filter damping ratio, ω_f is the filter resonance frequency equal to the first bending mode frequency, and K is the control gain. The FLC is also designed as described in the preceding section. As shown in Figure 14(a) and (b), when the beam structure is excited sinusoidally at the structure's resonant frequency, $f_1 = 38$ Hz, the FLC suppresses the vibration faster than the PPF controller. The controlled vibration levels are similar for both controllers.

MODIFIED SYSTEM

Designed controllers are applied to the modified system that has concentrated mass at the tip of beam. The first natural frequency of the system is changed to 20 Hz. In order to compare robustness performance, the control gains are fixed. As shown in Figure 15(a) and (b), the positive position feedback controller cannot suppress vibration because the controller is designed for a nominal system. But comparatively, FLC has a good performance because it disregards the frequency characteristics of the beam structure.

Possibility of Sensoriactuator

In this study, the sensing patch is used as a self-sensing actuator in free vibration, and their possibilities as a sensoriactuator are presented.

Generally, for piezoelectric transducers, the control input signal is very high compared to the signal generated due to pure mechanical strain. Therefore, it is difficult to extract a sensing signal from the piezoelectric actuator. So, in this experiment, the strain directional information was obtained from a simple extracting circuit based on the self-sensing bridge circuit (Lowell et al., 1994). Figure 16 shows the modified self-sensing bridge circuit: the measured signal (v_s) offers strain rate, and v_p and v_c signals represent the piezoelectric mechanical induced signal and the control voltage applied to the piezoceramic, respectively. The directional information needed for the phase tracking is given by the measured signal, v_s. The schematic diagram of overall experimental setup is shown in Figure 17. The test model was a composite beam structure (graphite/epoxy $[0_2/90_2]_s$, 2 cm width and 20 cm length, and tip mass). During the experiment, laser diode temperature was maintained at 30°C, and 0.476 mW power was applied to the laser diode. The sensing patch was attached on the beam structure 3.5 cm above the clamping position. Other experimental conditions were the same as the previous experiments.

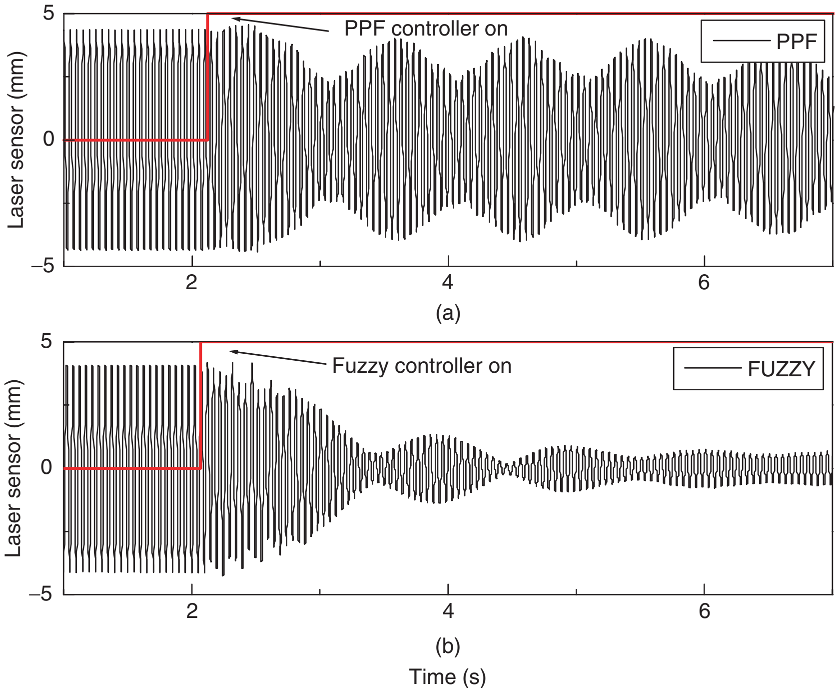

***Figure 15.** Experimental results using a sensing patch with perturbation: (a) PPF control and (b) fuzzy control.*

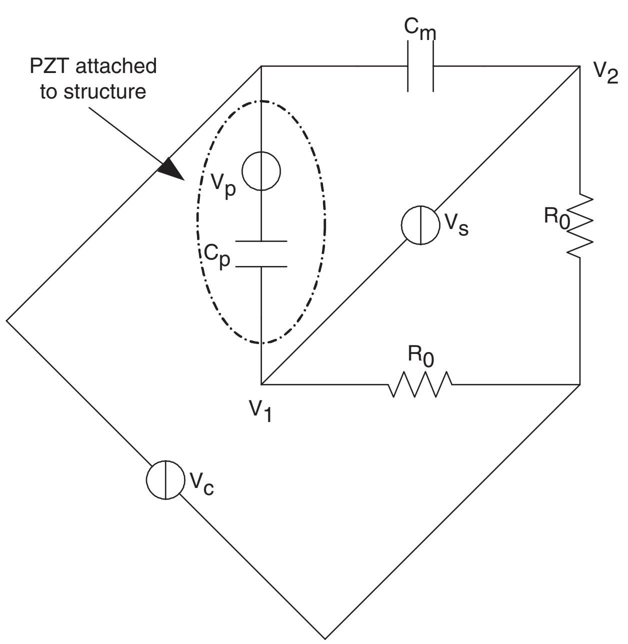

***Figure 16.** Self-sensing bridge circuit applied to the sensing patch.*

Figure 18 shows vibration-control experimental result using the sensing patch with the self-sensing bridge circuit in impulsive loading case. The dotted line shows free decay and the solid line shows the controlled result based on the phase-tracked signal. In this case, the sensing patch was used as a sensor and actuator simultaneously, and a relatively low voltage was applied to the self-sensing bridge circuit in order to suppress structural vibration. This experimental result shows that the proposed sensing patch with a self-sensing bridge circuit can suppress and monitor dynamic strains at the same time.

CONCLUSIONS

In the present study, a sensing patch is proposed for the compensation of interferometric nonlinearity of an EFPI sensor. The sensing patch utilizes the advantages of an EFPI sensor and piezoelectric material in order to overcome disadvantages when components are separately used. A simple and practical logic is applied to the real-time tracking of the optical phase of the interferometer. The proposed sensing patch provides an effective method of monitoring structural dynamic characteristics by providing a wider linear dynamic range, which cannot be achievable with a conventional EFPI sensor system.

A vibration-control experiment is also performed for the validation of the proposed sensing patch. In this paper, the FLC and positive position feedback controller were used to suppress structural vibration. Finally, the sensing patch is used as a self-sensing actuator in the free vibration test, and the possible extension to a sensoriactuator is presented.

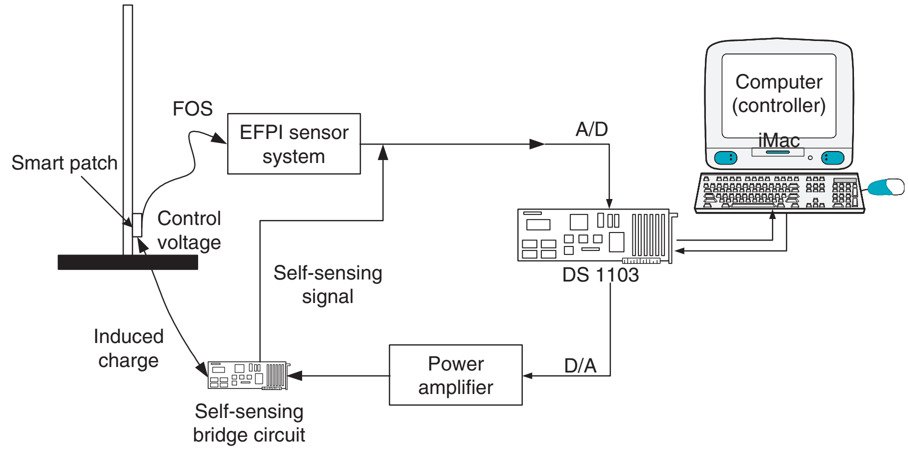

Figure 17. *Schematic diagram of the sensing patch with a self-sensing bridge circuit.*

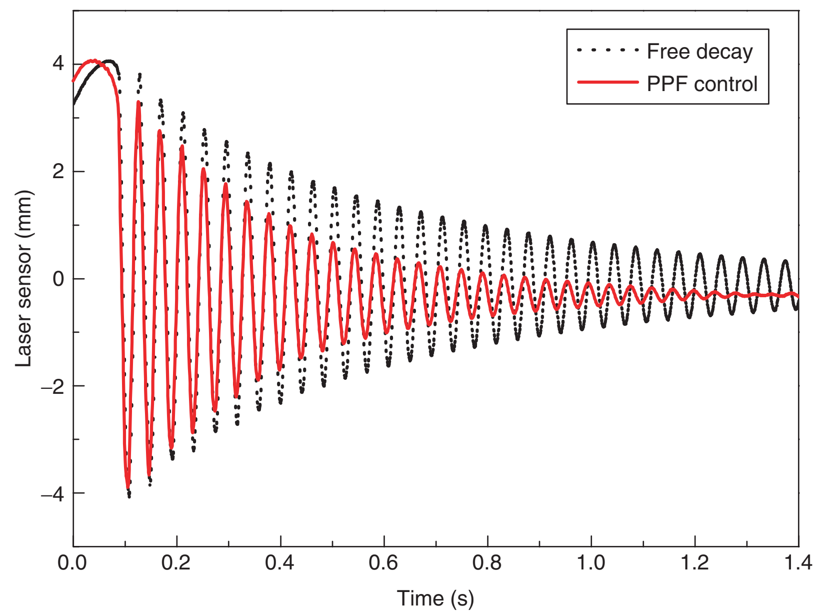

Figure 18. *Experimental result in impulsive loading case.*

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