VIBRATION MEASUREMENT USING OPTICAL FIBER SENSORS

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ABSTRACT

There have been increasing interests in vibration measurement and control of structural systems using smart materials. In order to realize these functions of smart structures, many researchers have studied functional materials and their characteristics. Among several functional materials, the optical fibers have been intensively studied as highly accurate sensors for a variety of applications such as health monitoring, vibration measurement and nondestructive testing. In this study, the vibration sensing characteristics of extrinsic Fabry-Perot interferometers (EFPI) and fiber Bragg grating (FBG) sensors have been investigated. In addition, the optical fiber sensors have been applied to the vibration control. In order to use EFPI sensors over wider dynamic ranges, methods of compensating its non-linearity for the vibration control have been investigated. An FBG sensor system with a passive detection scheme has been developed and applied to the suppression of flow-induced vibration.

KEY WORDS: extrinsic Fabry-Perot interferometer, fiber Bragg grating, vibration measurement

INTRODUCTION

The key terms of smart structure is sensing, actuating, and thinking capabilities. Usually sensing and actuating capabilities are implemented using embedded smart materials such as electroactive materials, shape memory alloy, optical fiber sensors and so on. As to thinking capabilities only simple control logics or data reduction processors can be embedded within the structural members at present. True thinking capabilities inside the structures have not been perfectly implemented so far. The development of micro engineering will facilitate the internal implementation of thinking capabilities of smart structures.

Among several proposed functionalities of smart structures, the vibration and deflection control is considered as one of the most important features since excessive vibration and deflection of structures might degrade system performance and even yield structural failure sometimes. Hence, the capability of the vibration measurement is essential to the smart structural systems. Among several functional materials, optical fibers are the preferred sensor materials that can produce sensors that are small, lightweight, less power consumed, immune to electromagnetic interference and easily installable onto/into host structures. Recently, optical fiber sensors have been increasingly studied for a variety of applications: vibration measurement, nondestructive testing as well as health monitoring.

This article presents some efforts toward investigating dynamic application of optical fiber sensors to the measurement and suppression of structural vibration. Among various kinds of optical fiber sensors, extrinsic Fabry-Perot interferometer (EFPI) and fiber Bragg grating sensors are considered. The dynamic characteristics of fiber optic sensors are explored and vibration suppression experiments are performed.

NON-LINEAR EFFECTS OF EFPI SENSOR

EFPI sensors are widely used because they have many advantages like other optical sensors and can be constructed with reasonable prices. However, it is reported that they have the problem of representing vibrational amplitudes and directions because of their interferometric characteristics as shown in Fig. 1. S1 is an example 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 because of the initial optical phase of EFPI. You can easily notice from S3 and I3 that the EFPI sensor shows non-linearity whenever the strain amplitude is large enough. In order to extract true mechanical strain from the EFPI sensor output signal, several methods have been proposed including quadrature phase-shifted EFPI [1], absolute EFPI(AEFPI) [2] and passive quadratic signal processing using two read-out interferometers [3]. Several signal processing techniques have also been used based on fringe counting method [4]. Such algorithms can be applicable for the strain measurement of quasi-static system, but is not practical for the real-time feedback control system. That is the why the studies on the vibration control using interferometric optical sensors are limited to small disturbance cases [5, 6].

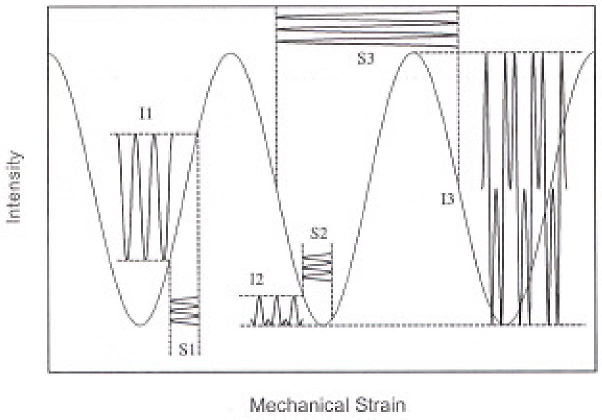


Fig. 1 Relation between sensor output intensities and strain variations.

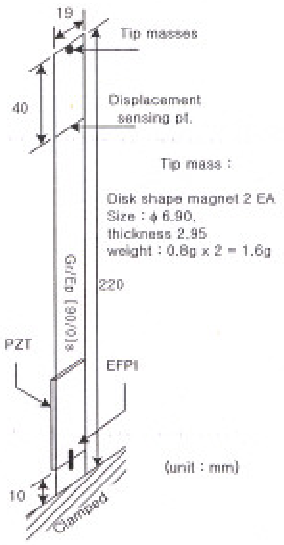


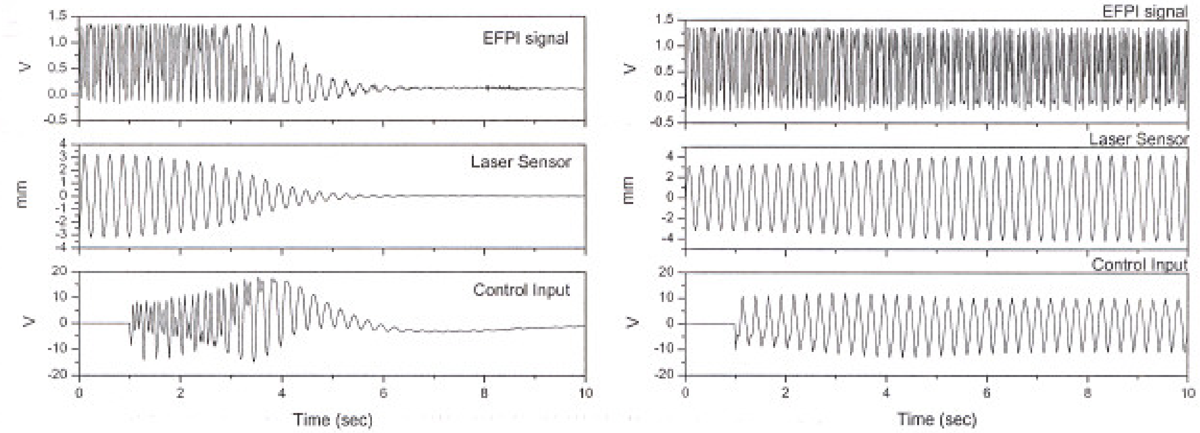
Fig. 2 Schematic diagram of the specimen.

In the present study, we experimentally investigated vibration control performances using EFPI sensor signals. Utilizing the neural network controller for the compensation of the sensor non-linearity, we can successfully suppress vibration, which cannot be controlled by conventional controllers, without any additional signal processing except high-pass filtering used to remove D.C. components.

The schematic diagram of the specimen is shown in Fig. 2. The specimen comprises a composite base structure (graphite/epoxy $[90/0]_s$), a PZT actuator (C8, Fuji Ceramics), an EFPI sensor and tip masses for the reduction of resonant frequencies and the increase of vibrational amplitude. In the experiment, EFPI output is used as feedback signal and a laser displacement sensor (LB041, Keyence) is used for the monitoring of real deflections.

The neuro-adaptive controller used in the present study is similar to the authors' previous work [7]. The control system consists of the neuro-identification model and the neuro-controller. The role of the neural network model (identifier) for the plant is to obtain mathematical representation of the real plant. The weights of the neural network model are adjusted so that the output of the neural network model should be the same as that of the plant. After completing the forward modeling, the tuning for weights of the neuro-controller is performed. The designed neural network controller is implemented using a DSP board (DS1102, dSPACE) and the weights are updated at every 0.01 sec.

The EFPI sensor output signal becomes distorted as the vibration amplitude increases. Vibration control experiments have been performed for small and large amplitude cases, that is, for slightly and highly non-linear cases. When the excitation amplitude is small, the EFPI signal is slightly distorted and both controllers can suppress the vibration successfully. But, the LQG controller makes the system unstable as the excitation amplitude is increased as shown in Fig. 3.



(a) Neuro-controller.

(b) LQG controller.

Fig. 3 Control result of the nominal system (Excitation voltage = 12 V).

The conventional linear controller fails in vibration reduction with the compensation of the EFPI sensor non-linearity when the excitation level is high. However, the neural network controller has the ability to compensate the non-linearity of an EFPI sensor in vibration control problems.

FLUTTER SUPPRESSION USING FBG SENSOR

For lightweight and flexible structures, it is important to measure and suppress the flow-induced vibrations caused by interactions between fluid and structures. Dynamic aeroelastic instability, flutter, involves aerodynamic, inertia and elastic forces of flight structures. Because flutter may cause disastrous structural failure in flight, the prediction of stability boundary and the suppression of flutter are very important in flight structures.

In this study, dynamic application of an FBG sensor system to the flutter boundary evaluation and suppression of a composite plate structure has been investigated. In practical situations, the modeling of an aeroelastic system is complicated and the dynamic characteristics of an aeroelastic system changes with respect to the airflow velocity. Therefore, the adaptiveness and the robustness are principal features for an aeroelastic control system. Neuro-adaptive feedback control algorithm is used for this purpose. The control system is the same as previously described. The effectiveness of the flutter suppression system is evaluated via wind tunnel testing.

The test model is a swept-back cantilevered composite plate with a surface-bonded FBG sensor and piezoceramic actuators. The base structure is graphite/epoxy (CU-125 NS, HANKUK FIBER) $[90_2/0_2]_s$ laminate. Two piezoceramics (C-82, Fuji Ceramics) and one FBG sensor (gauge length = 10 mm, λ_B = 1546 nm) are bonded on the root region as shown in Fig. 4. The principle of the FBG sensor is the measurement of the changes in reflective signal, which is the center wavelength of back-reflected light from a Bragg grating. The signal depends on the effective refractive index of the core and the periodicity of the grating. The wavelength detection mechanism used in the present study is based on two cavity lengths in Fabry-Perot read-out interferometers to produce two quadrature phase shifted signals from Bragg grating sensor. The detailed description can be found in Ref. [8] and [9].

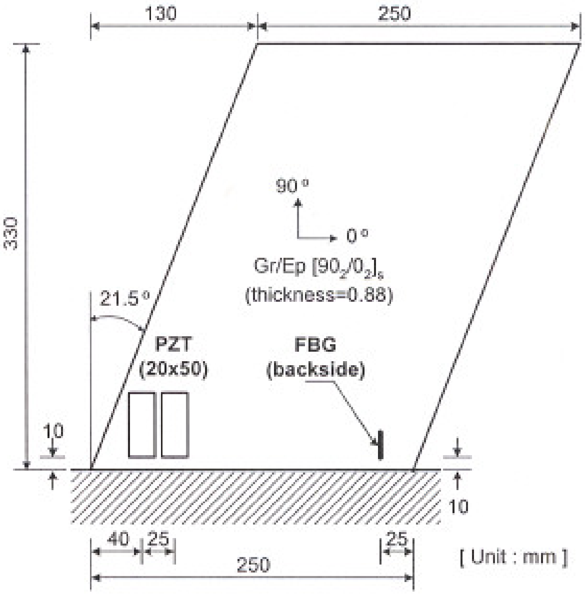


Fig. 4 Wind tunnel test model.

Wind tunnel test has been performed in the subsonic wind tunnel. The wind tunnel is an open-circuit tunnel with effective velocity ranges of 9 to 60 m/sec and closed test section. At first, aeroelastic responses according to airflow velocity has been investigated and the flutter prediction parameters are evaluated using sampled data. Secondly, flutter suppression experiment has been performed at the free stream velocities that cause limit cycle oscillations for the uncontrolled case.

When the airflow velocity is below 14.0 m/s, air damping is dominant and the aeroelastic system is stable. As the airflow velocity increases, the limit cycle oscillation occurs and the vibration amplitude increases. Power spectra of the FBG sensor data against airflow velocity are shown in Fig. 5. It can be seen that the vibration energy is concentrated in the second mode, which is flutter mode, and increases according to the airflow velocity.

In case of interpreting analytical result, the flutter phenomenon breaks out suddenly and the stability boundary is clear. However, in practical situation, there is a limit cycle oscillation region and it is difficult to determine the flutter point. In addition, limit cycle oscillation could lead to fatigue failure. Therefore, the prediction of dynamic aeroelastic stability boundary using experimental data that are sampled below critical speed is very important and practical. The stability boundary has been evaluated using the flutter prediction parameter, F_z, proposed by Torri and Matsuzaki [10]. The flutter prediction parameters using experimental data against dynamic pressure are shown in Fig. 6. The evaluated flutter speed is $V_F = 15.0$ m/s, which is close to the analytic result; analytical flutter speed using MSC/NASTRAN is $V_F = 15.4$ m/s.

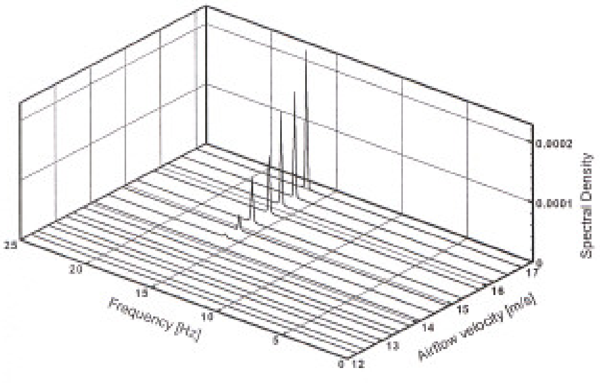


Fig. 5 Power spectra vs. airflow velocity.

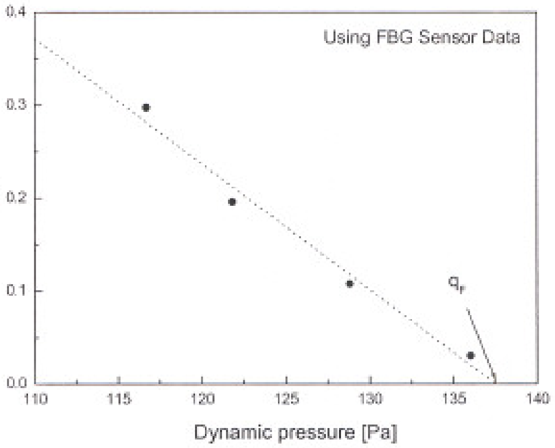
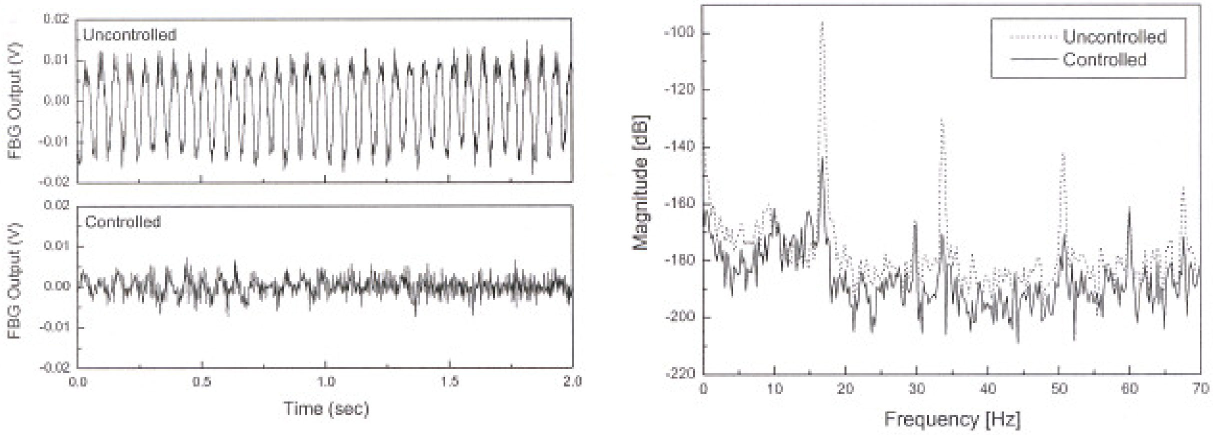


Fig. 6 Evaluated flutter prediction parameters.

The flutter suppression experiment has been performed at the airflow speed over the flutter boundary. Fig. 7 shows the control results at $U_\infty = 17.0$ m/s. The effectiveness of control system can be seen in both time and frequency domains. The amplitudes of the flutter mode and its harmonics are significantly reduced.



(a) Time history.

(b) Power spectrum.

Fig. 7 Flutter suppression result at $U_\infty = 17.0$ m/s.

CONCLUSION

The present study investigates the measurement and suppression of the structural vibrations using optical fiber sensor systems. Utilizing the neural network controller for the compensation of the sensor non-linearity of an EFPI sensor, we can successfully suppress vibration, which cannot be controlled by conventional controllers. In addition, the FBG sensor signal is used for the evaluation of aeroelastic stability boundary and the suppression of flutter. The real-time neuro-adaptive control algorithm effectively reduces the amplitude of flutter mode.

The optical fiber sensor systems can be constructed as multi-field sensors such as simultaneous measurement of temperatures and strains. The use of optical fiber sensors for the measurement and control of structural vibration will extend another practical function of fiber optic smart structures.

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