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DEVELOPMENT OF EXTRINSIC OPTICAL FIBER SENSORS FOR SEISMIC MEASURING

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ABSTRACT

This paper describes the development of two kinds of extrinsic optical fiber sensors for measuring seismic behavior of structures. The first one employs a vibrating wire whose tension can be modulated by external force, strain or vibration, and transformed into the change in frequency of wire vibration. The second one employs an electric LC circuit in the sensor head instead of the mechanical vibrating wire. Inductance L and capacitance C are connected in parallel in the sensor head, and the external displacement is transferred to the core of the solenoid for inductance. The oscillating frequencies of the vibrating wire and the LC circuit are detected by light sent through an optical fiber cable. The frequency is optically transmitted without attenuation or distortion through the optical fiber to recording and other devices. Various prototypes have been developed and their static and dynamic characteristics have been experimentally tested. Two prototypes were installed onto a steel frame on a shaking table to measure dynamic responses of strain and velocity. The experimental studies with prototypes demonstrate the high performance of the developed optical sensor in terms of accuracy, high frequency range, and other characteristics.

KEY WORDS

Optical fiber; optical fiber sensor; vibrating wire; extrinsic optical sensor; LC circuit; phase lock loop; shaking table test; strain meter; velocity meter; seismic measurement.

INTRODUCTION

Measuring technology has been playing an important role in earthquake engineering to reveal the dynamic behavior of the structures during earthquakes and dynamic experiments. Measured data might often involve errors or noise, which can be eliminated at the stage of analysis and data evaluation. Particularly, for the purpose of feedback control of the structural responses, however, it is necessary to remove such errors and noise in the measured response signal.

Conventional measuring systems, such as strain gauges, the Carlson system, differential transformer systems, etc. seem to have inevitable difficulties. These difficulties are caused by the systems that employ electrical devices in measuring heads, cables and sensor heads. Among those portions in the monitoring systems, the cables especially have unavoidable difficulties; i.e., (a)the cables act as long antennae to pick up electromagnetic fields and lightning strikes, even if the cables are carefully shielded, (b)they are heavy in weight, (c)electric sparks may ignite to a fire, if a cable is broken in an inflammable ambiance, (d) the cables have to be heavily water proofed, and (e) cabling cost accounts for a great deal of total monitoring cost, particularly in super large civil structures.

Compared with conventional sensing systems, optical fiber sensing system has shown great potential to overcome these difficulties. Generally, optical fiber sensors demonstrate the following superior performance: (1) Immunity to electromagnetic interference, (2) Lightweight compact size, low power, and reduced cable requirement, (3) Distributed property, (4)Ruggedness and durability, and (5)Potentially lower in components cost.

These advantages of optical fiber sensors are ideally suited to application in measuring dynamic behavior of civil structures. Unfortunately, only a limited number of attempts have been made to apply optical fiber sensors to civil structural systems so far. Among them, most of the researching efforts performed to date has focused on obtaining qualitative measurements such as detecting cracks within a concrete block. The research on quantitative measurements includes: measurement of strains in concrete beams using embedded fiber optic Fabry-Perot sensors (Yoshino *et al.* 1982; Claus *et al.*, 1992) in laboratory (Masri *et al.*, 1993); installation of multimode interferometric sensors to a building, a highway pavement system, and a bridge to measure vibrations, concrete curing, and other parameters (Huston *et al.*, 1992; Fuhr and Huston, 1993). These exploratory studies have demonstrated the applicability of optical fiber sensors and provided basic knowledge specifically related to the installation or embedment techniques. However, as these sensors were not originally developed for measuring civil infrastructure systems at present, the optical sensors stated above are not necessarily suitable for civil structures. These problems prevented easy application of these sensors to actual infrastructure systems on a large scale. Therefore, the development of optical fiber sensors more suitable for civil infrastructure applications is urgently needed. This paper proposes an innovative optical measuring system to bridge this gap and reports on the prototype development and preliminary experimental results.

CONCEPTS AND PRINCIPLES

To overcome the problems of the past optical fiber sensors, the authors have originated fundamental concepts for a new optical fiber sensor for civil structures as follows: (i) A resonant system is used whose oscillating frequency is determined by a single item of external disturbance, such as stress, strain, displacement, vibration and so on. (ii) The resonant frequency is optically detected and used to measure the external disturbance. (iii) A phase lock loop (P.L.L.) circuit is introduced to synchronize an exciting pulse signal spontaneously to the oscillating frequency. This circuit creates a series of pulses with the exact resonant frequency to excite the resonant system.

Following the fundamental concepts, two principles have been proposed, and experimental tests are carried out using prototype sensors so far. The first principle employs a vibrating wire for the resonant system; and the second one employs an electric LC circuit.

Vibrating Wire Sensor

An optical sensing system has been designed, based on the above mentioned concept. As shown in Fig. 1, the sensor system consists of the following parts: (1) a steel vibrating wire stretched between top and bottom portions of a frame through which the external disturbance (force, strain, pressure, vibration, etc.) is transformed into the change in tension of the wire, (2) a magnetic exciter to keep the wire vibrating, whose energy comes from an L.S. (light source), (3) an optical detector to measure the frequency of the wire vibration in which light from an L.S. is sent to and reflected from the wire through an optical fiber to an L.D. (light detector), and (4) a frequency adjusting circuit called P.L.L. that adjusts the exciting frequency to instantaneously match the resonant frequency of the wire varying with the external disturbance.

The relationship between the tension of the wire T and frequency of the vibrating wire f can be calculated by the following equation.

$$f = \frac{1}{n\ell}\sqrt{\frac{Tg}{\rho}} \quad . \tag{1}$$

Where ℓ is the wire length, ρ is weight per unit length of the wire, g is the gravitational acceleration, and n represents vibration mode of the wire with n = 2, 1, 2/3, ... respectively for the 1st, 2nd, 3rd, ... mode. Since the wire is supported by a frame where the external load is applied, as shown in Fig. 2, the tension of the wire T and the external load F has the following relationship:

$$\frac{T_0 - T}{k_1} = \frac{F}{k_1 + k_2} \ , \tag{2}$$

where T_0 is the initial tension of the wire, k_2 is the stiffness of the supporting frame and k_1 is the stiffness of the wire which is calculated by

$$k_1 = \frac{EA}{\ell} \ , \tag{3}$$

where E is Young's modulus and A is the area of cross section of the wire.
The relationship between the load F and the wire frequency f is then derived from Eqs. (1) and (2) as

$$f = \alpha\sqrt{T_0 - \frac{k_1}{k_1 + k_2}F} \quad (4)$$

Where α is an experimental constant. As a result, this sensor basically works as a force meter, which can be applied to various sensors by means of outer jigs.

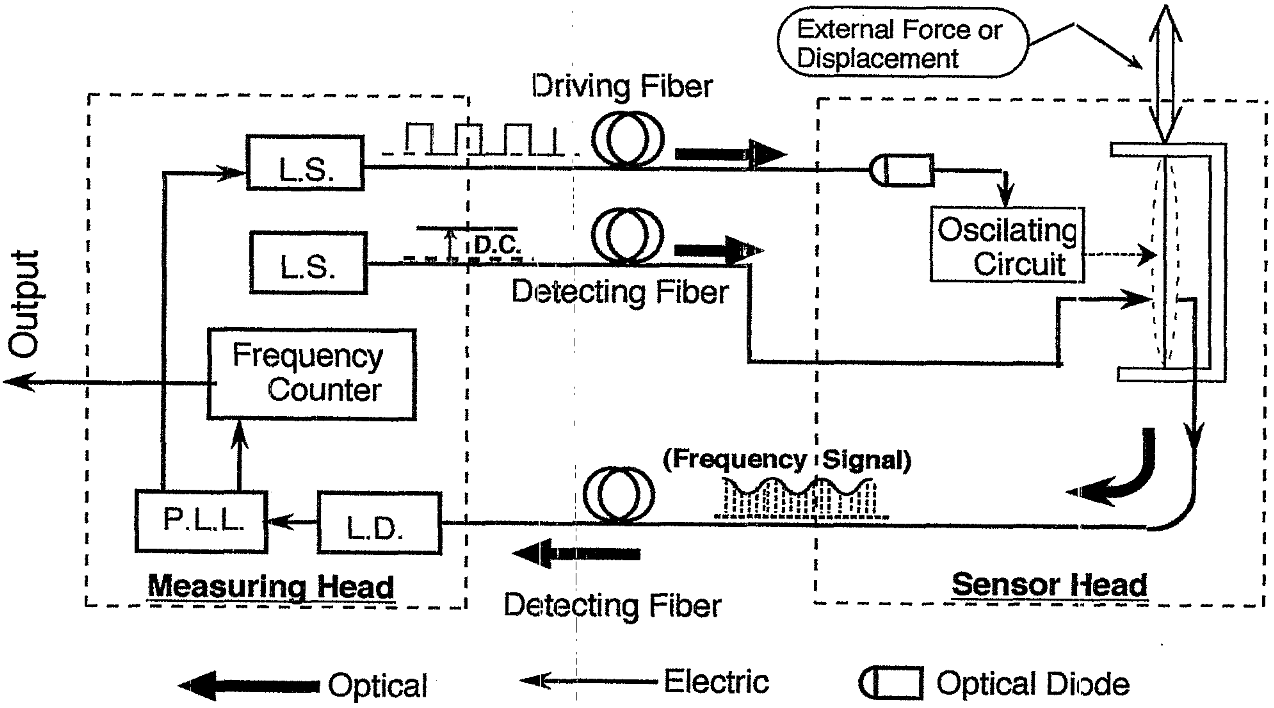

Fig. 1. Conceptual configuration of vibrating wire optical sensor

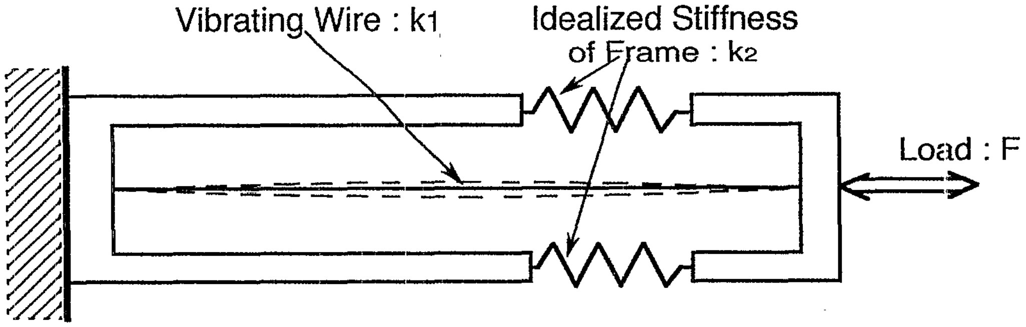

Fig. 2. Vibrating wire optical sensor and its supporting frame

Electric LC Circuit Sensor

An electric LC circuit sensor employs a circuit of a ferrite core built-in solenoid as an inductance component of L(H) and a condenser as a capacitance component of C(F), which are connected in parallel as resonant system in a sensor head. The resonant frequency f for the circuit is given by

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (5)$$

The built-in core can be displaced by a surrounding disturbance. In the case of measuring micro displacement, a combination of a fixed L and a variable C can be employed. It is found that this sensor works basically as a displacement sensor, which can be applied to various sensors by means of outer jigs. A conceptual drawing for the LC circuit system is depicted in Fig. 3.

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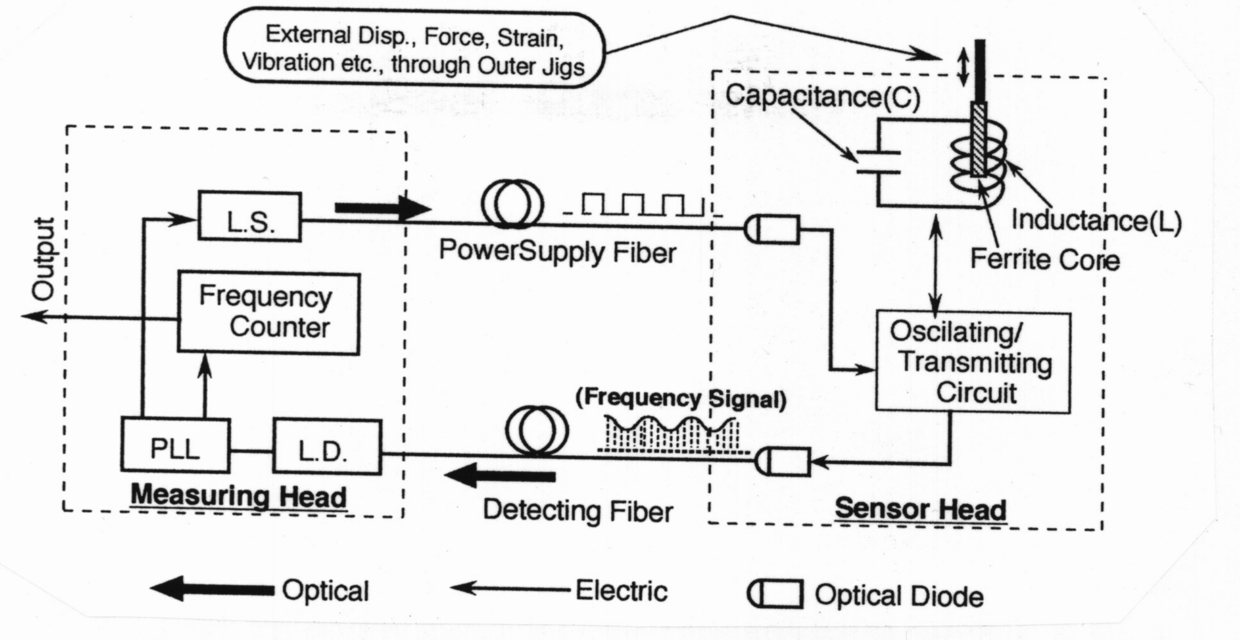

Fig. 3. Conceptual configuration of electric LC circuit optical sensor

PROTOTYPE DEVELOPMENT

Five prototypes have been developed so far. Prototypes #1 through #3 utilize the vibrating wire principle, and prototypes #4 and #5 utilize the LC circuit principle. Figure 4 shows the prototype #1 developed to demonstrate the feasibility of the basic concept of the proposed sensor. A steel wire is stretched between two flanges of a channel shape ( ] shape) frame and is oscillated by a solenoid that is driven by a series of laser pulses from a light source. The preliminary tests have confirmed that it is possible to excite the wire and to measure its frequency using the optical sensor.

Figure 5 shows a lineup of prototypes #2 through #5. Prototype #2 was developed to test its basic characteristics as a sensor for acquiring both its static and dynamic properties. It has basically the same configuration as that of #1. Prototype #3 has a cylinder shape that is similar to prototype #2. It is carefully sealed to become water-proof in order to be embedded into a concrete specimen. Prototypes #4 and #5 are a strain meter and a velocity meter, respectively. These two sensors are tested attached to a steel frame structure on a shaking table.

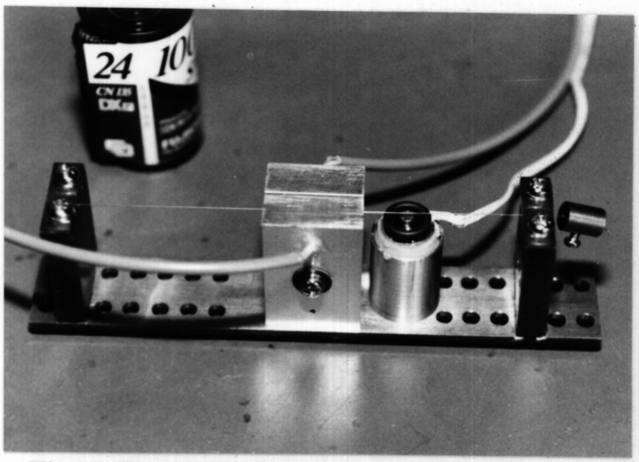

Fig. 4. Prototype #1 for demonstrating feasibility of vibrating wire sensor

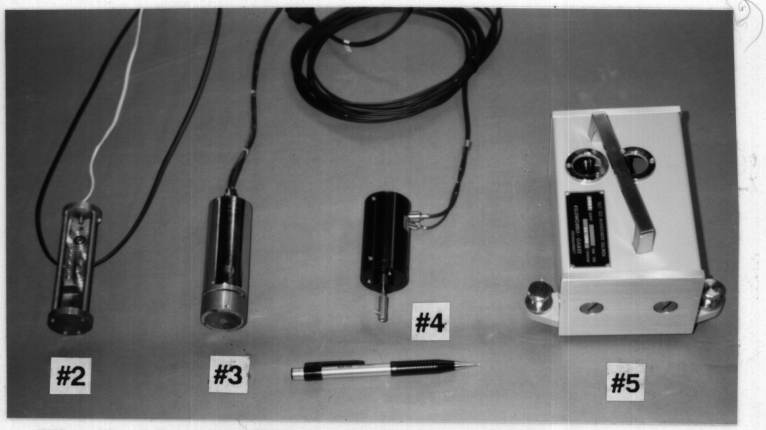

Fig. 5. Lineup of optical sensors #2 through #5

EXPERIMENTAL TESTING

Static Characteristics of Vibrating Wire Sensor

First, the static relationship between external force and frequency of the vibrating wire is tested using prototype #2. One end of the optical sensor is attached to a conventional load cell, and the axial load is applied to the other end by a screw jack where the force is controlled by a handle. Figure 6 compares the voltage applied to the solenoid (Fig. 6; upper) and the corresponding voltage detected by the L.D. (light detector) which transforms the light signal reflected from the vibrating wire into voltage (Fig. 6; lower). From comparing the distorted exciting signal and the harmonic reflected signal, it is observed that the vibrating wire is very robust and reliable.

The relationship between the applied external force (which is measured by the conventional load cell) and the corresponding vibration frequency of the wire is shown in Fig. 7. The open squares indicate the experimental data and the solid line shows the theoretical result from Eq. (4). It is observed that the experimental result perfectly agrees with the theoretical one. The theoretical relationship calculated according to Eq. (4) is $f=95.22\sqrt{216.0-F}$, while the relationship from the regression analysis based on the experimental results is $f=95.30\sqrt{215.8-F}$ with a correlation coefficient as high as 0.99998.

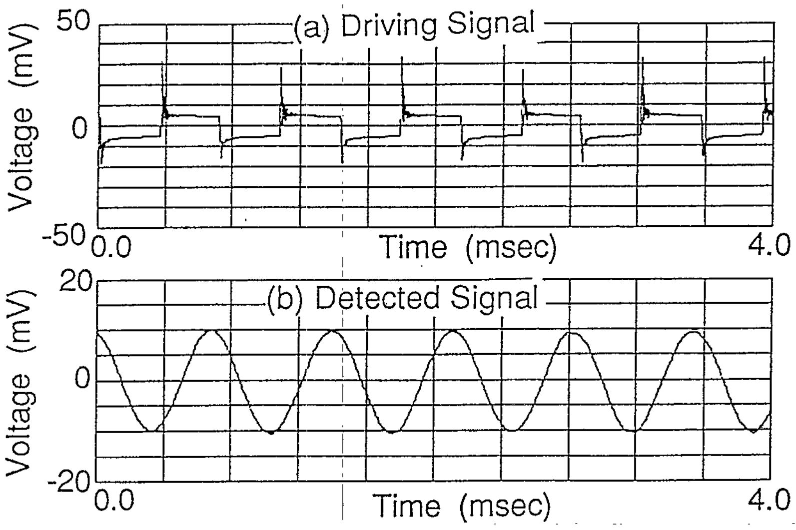

Fig. 6. Exciting signal and detected signal of the vibrating wire

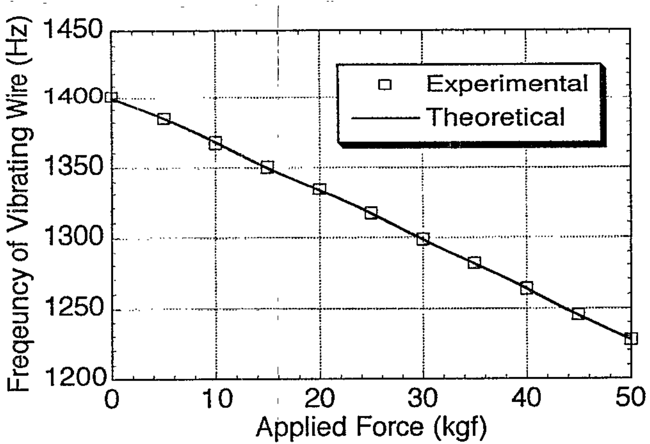

Fig. 7. Relationship between applied force and frequency of the vibrating wire

Dynamic Characteristics of the Vibrating Wire Sensor

The dynamic characteristics of the developed sensor (prototype #2) are examined for future applications in which the responses of civil structures are to be measured under dynamic external loads such as winds and earthquakes. The testing facilities are similar to the one used for static testing, except for the screw jack that is replaced by a hydraulic actuator. Sweeping excitation tests are conducted in which the sinusoidal load applied by the actuator has a constant amplitude with frequencies varied from 1 to 100 Hz within a time span of 10 seconds.

A typical set of signals measured by the load cell and by the optical sensor is compared in Fig. 8, where the actuator excitation frequency is 10 Hz and the axial load is around 10kgf. The signal from the optical sensor excellently agrees with that from the load cell. The transfer function of the signal from the optical sensor over

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that from the load cell is obtained (Feng *et al.*, 1994; Feng *et al.*, 1995). The magnitude remains to be approximately unity up to f=25 Hz where the discrepancy reaches a 10% level. The dynamic characteristics of the load cell used in this test are known to be adequate up to a 20 Hz range and therefore it is concluded that the vibrating wire sensor can be used as a sensor to measure the dynamic response at least up to 20 Hz. This represents a sufficient range for civil structures.

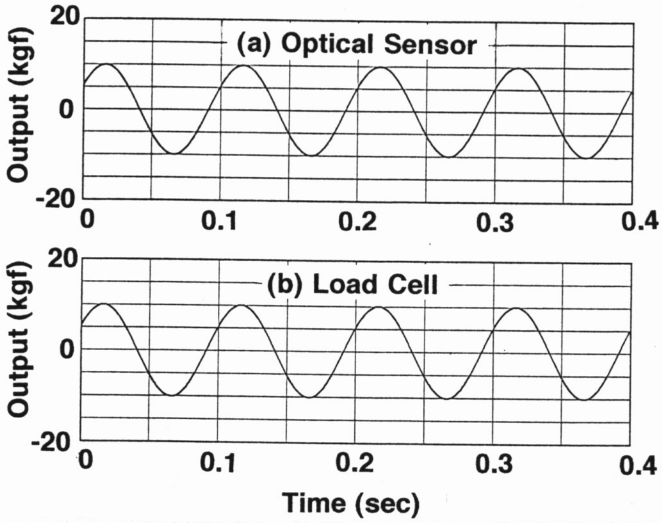
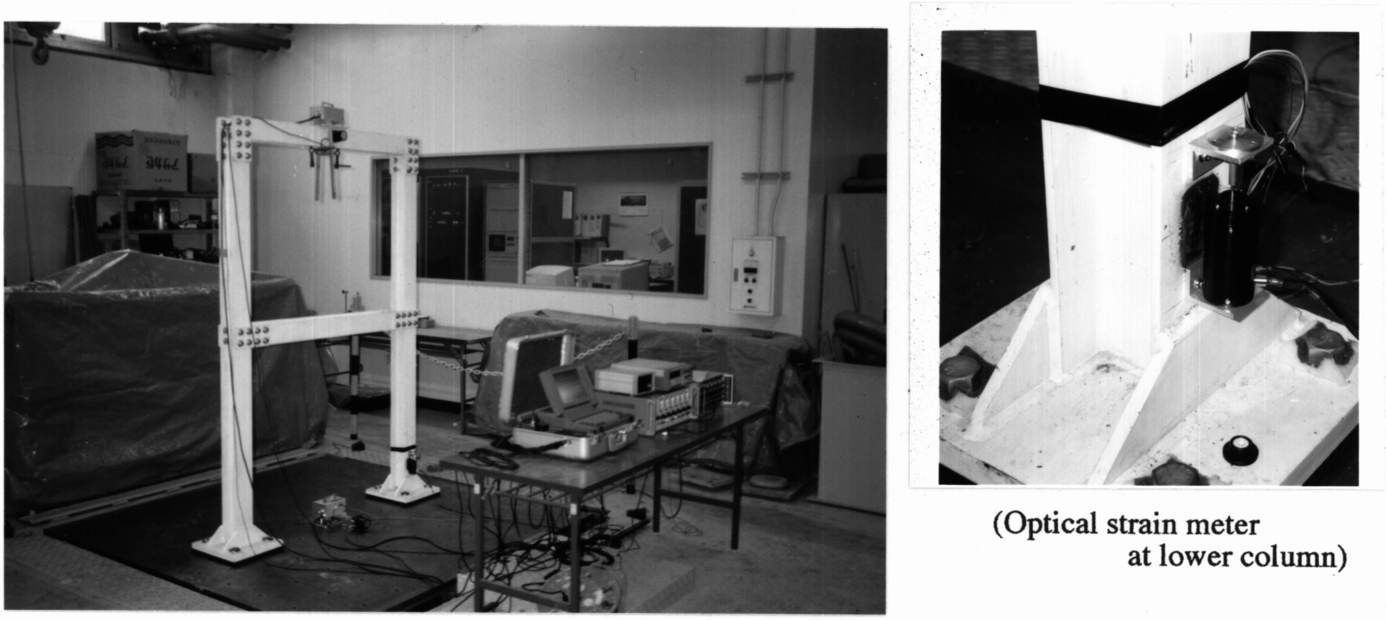


Fig. 8. Comparison of dynamic signal measured by the vibrating wire sensor and load cell

Testing with Steel Fame on a Shaking Table

A two-storied steel frame is placed on a shaking table, and prototypes #4 and #5 LC circuit optical sensors are tested. Figure 9 shows the setup of the frame, in which LC circuit strain sensors and velocity meters, and conventional strain gauges and servo type velocity meters are used.



(Optical strain meter
at lower column)

Fig. 9. Setup of steel frame on shaking table

Some examples of measured response waves are shown in Fig. 10. In this figure, recorded waves of the LC circuit optical fiber sensors and the conventional sensors are included. As a result, the recordings measured by the optical sensors show good agreement with measured by the conventional sensors. Through this experiment, the LC circuit optical sensors are confirmed to be used for measuring dynamic behavior of structures.

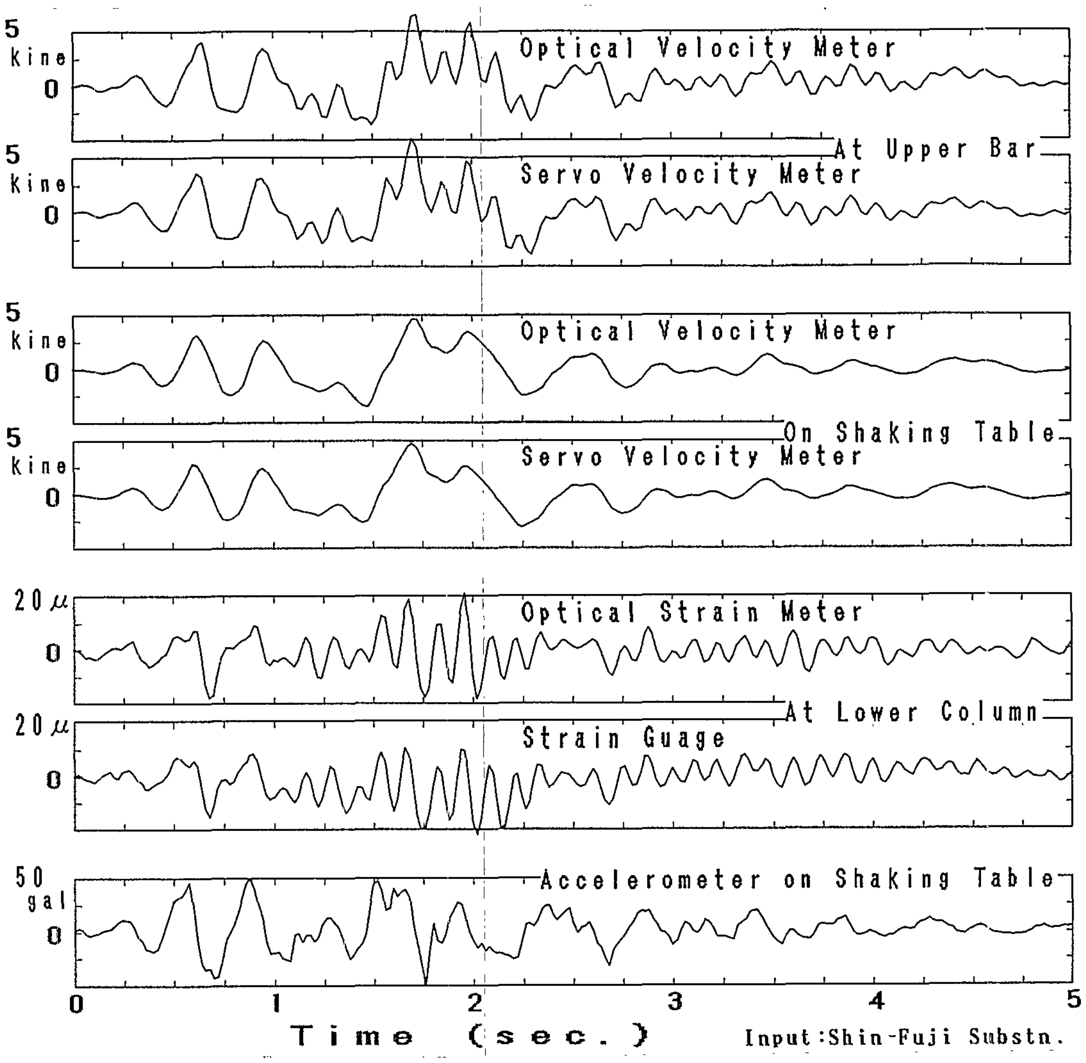


Fig. 10. Comparison of response waves measured by LC circuit sensors and conventional sensors

FUTURE IMPROVEMENTS

After the development and the experimental study, it is believed that these optical sensors can be utilized for in-situ and laboratory measurements. For application to other purposes of measurement, they can be used as anemometers, soil or water pressure sensors and others. Such sensors will find wider applications in civil structures including so-called smart structures. It is also required to realize that a large number of the units can be combined to form a distributed sensor net work. As the principles of the sensors described herein are in a "frequency signal transmission" system; if each of the resonant frequencies for each sensor head is recognizably different, these sensors can be designed as a distributed sensing system along a single fiber.

CONCLUSIONS

Two principles of optical fiber sensors for dynamic measurement of structures are proposed. These sensors are based on an innovative concept of using a vibrating wire and an LC circuit which are oscillated by a series of light pulses and whose oscillating frequency is detected optically. Five prototypes have been developed and experimental studies on their static and dynamic performances have been conducted. Experimental testings for the measurement of dynamic responses of a steel structure have also been performed. It is demonstrated that;

(1) The wire vibration and LC circuit oscillation can be accurately detected by an optical fiber. This makes the proposed sensor robust and reliable, and thus suitable for in civil infrastructure during earthquakes.
(2) The experimental results perfectly agree with the theoretical ones. The sensing mechanism allows easy and accurate calibration.
(3) The proposed optical sensors have sufficient accuracy and frequency range.
(4) The optical sensors are easy to install on steel structures, and their high accuracy is demonstrated.
(5) The configuration of the sensors is very simple and the cost is highly competitive.

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REFERENCES

Claus. R. O., Gunther, M. F., Wang, A. and Murphy, K. A. (1992). Extrinsic Fabry-Perot sensor for strain and crack opening displacement measurements from -200 to 900° C. *Smart Materials Structures,* ***Vol. I,*** 237 - 242.

Feng, M. Q. and H. Suzuki, H. (1994). An optical fiber sensor for monitoring civil infrastructure. *International Conference on Intelligent Materials.*

Feng, M. Q., Suzuki, H. and Yokoi, I. (1995). Development of optical sensing systems for smart civil infrastructure. *Smart Struct . & Mater. .* ***Vol. 4,*** A114 - A120.

Fuhr, P. and Huston, D.R.(1993). Intelligent civil structures efforts in Vermont - An overview. '93 *Smart Struct. & Materi. '93 Smart Sensing, Processing and Instrumentation* , 412 - 427

Huston. D.R., Fuhr, P.L., and Beliveau, J. G. (1992). Bridge monitoring with fiber optic sensors. *8th U.S. - Japan Bridge Engineering Symposium.*

Masri, S. F., Mustafa, M., Vries, M. J. and Claus, R. O. (1993). Experimental study of embedded fiber optic strain gages in concrete structures, Smart Structures and Materials. 428 - 434.

Yoshino, T., Kurosawa, K.. Itoh, K and Ose, T. (1982). Fiber-optic Fabry-Perot interferometer and its sensor applications. *IEEE Journal of Quantum Electron.* ***QE18,*** 1624 - 1632.