Seismic validation of a novel fibre-optic gyroscope for measuring rotations

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ABSTRACT

This paper describes experimental research on the feasibility of the use of a novel fibre-optic gyroscope (FOG) to measure rotations in earthquake engineering. An FOG is a passive optical interferometer that uses the Sagnac effect to detect mechanical rotations such as tilts or torsions. Rotation rates measured by the FOG are absolute with respect to the local universe and, therefore, it does not require an external reference frame for operation. The measurement device is light, compact and easy to install. A series of shake table tests were performed on a four-storey one-fifth scale structure equipped with an FOG to investigate the suitability of the device for measuring structural rotations. Four different earthquake ground motions were used as input to the shake table. During the seismic testing, the FOG was attached to one of the first floor columns of the one-fifth scale structure to measure the rotation rates of the column. Relative displacements at the first floor were calculated from the rotation measurements provided by the FOG. The measurements were then compared with those obtained by a conventional linear potentiometer. A very good agreement was observed between both measurement techniques. The experimental results validated the accuracy of the measurements recorded by the FOG and its suitability for applications in earthquake engineering.

Keywords: Fibre-optic gyroscope, passive interferometer, Sagnac effect, seismic testing, rotation measurement.

INTRODUCTION

The effect of torsion caused by the asymmetries in buildings, where the stiffness centre differs from the mass centre, can be evaluated by using differential measurements of accelerometers. Traditionally, the effect of the structural rotations has been neglected in the studies on the seismic response of structures. Because their influence was thought to be small and there were no suitable devices available to properly measure the response of structures to rotations. Different types of inertial rotation sensors exploiting the Sagnac effect have now reached the necessary sensitivity to be used to investigate structural rotations in civil engineering.

Fibre-optic gyroscopes (FOGs) are passive interferometers where a beam of light is split into two equal beams. The two light beams then travel along several hundred metres of glass fibre coil around a closed circuit, one in the clockwise and the other in the anticlockwise sense. When the beam is recombined upon exiting the fibre, it shows a fringe pattern, which depends on the rate of rotation, but does not change with the translation. Rotation rates measured in this way are absolute with respect to the local universe.

Torsional rotations (rotations about a vertical axis) have the potential to lead to the catastrophic collapse of a structure. Since FOGs use the concept of Sagnac interferometry, they can provide the required rotational signal during large seismic events. The measurement devices are entirely insensitive to horizontal and vertical translations. FOGs are light, compact and easy to install. Besides, they do not require an external fixed reference frame to operate.

The first applications of FOGs to measure rotation rates, rotations, displacements and inter-storey drifts of civil engineering structures are described in this paper. During the shake table testing of a four-storey one-fifth scale structure, a novel FOG was attached to one of the first floor columns of the model structure. Four different earthquake ground motions were used in this experimental study. In order to excite the model structure with earthquake ground motions of different intensity levels, the amplitude of the earthquake records was scaled. The relative displacements at the first floor were calculated from the rotation measurements provided by the FOG.

A good agreement was observed between the measurements obtained with the FOG and those provided by a conventional linear potentiometer. The experimental results validated the accuracy of the measurements recorded by the FOG as well as the dynamic range of the sensor technology.

MEASUREMENT OF STRUCTURAL ROTATIONS

Structural rotations are an important measure of the response of civil engineering structures. Any torsional rotation in a building will cause the translational movement of the structural members located away from the centre of rotation. As a consequence, these structural translations need to be added to the translations of members associated with the horizontal components of the earthquake ground motion during the design process. The rotation of the column members of the building structures is measured as inter-storey drift. The inter-storey drift is the difference in horizontal displacement from one floor to the next and is usually divided by the inter-storey height. Typically, the inter-storey drift is expressed as a percentage of the storey height. The magnitude of the inter-storey drift is a measure of the damage expected in the structure due to earthquake excitation [1].

Measuring torsional rotations and inter-storey drifts on small-scale structural models is easy to a certain extent. However, it is difficult to measure the structural rotations on large-scale structural models and actual structures. In these type of structures, the torsional rotations can be measured by dividing the difference in the accelerations taken by two accelerometers by the distance between the two accelerometers in the direction perperdicular to the motion. The result is then integrated twice with respect to time to obtain the torsional rotations. However, the applicability of this measurement technique is limited due to the inherent sensor drift and the small offset from zero in the absence of an input signal.

In laboratory testing, the inter-storey drifts can be calculated from displacements measured by conventional potentiometers that require a fixed reference frame. However, for real structures, the inter-storey drifts cannot be easily determined because there is no reference frame that can be utilised to measure the floor displacements. Although it is possible to set up a frame attached to the floor below to measure the relative displacement at the floor above, this is not a practical solution. Another approach is to set up a light source near the ceiling and to direct it to a grid-like receiving device, located on the floor, that detects the movement of the light source [2]. However, apart from the great hardware complexity of this approach, it is also vulnerable to the building deformations. The distortions could cause the light source to tilt, which would be amplified by the length of the light beam.

Unlike conventional linear potentiometers, the FOGs do not require a fixed reference frame for operation and, therefore, they can be installed in actual civil structures easily. In the case of the differential measurements of two accelerometers mentioned before, the geometry of the measurement arrangement with respect to the centre of rotation is significant for the resolution of the measurement technique. In contrast, the FOG can provide the correct angle of rotation even when the centre of rotation is a long way off from the sensor. Furthermore, the FOG can also be used to detect and monitor damage in structures. If several FOGs are placed on each storey or on discrete locations along the height of the building, any difference in the rotation rate between the parts of the building will be an indication of energy dissipation and, therefore, potential structural damage.

THE SAGNAC EFFECT

Conventional mechanical gyroscopes have been replaced by the optical gyroscopes in commercial jetliners, booster rockets and orbiting satellites. Such devices are based on the Sagnac effect (also called the Sagnac interference), first demonstrated by the French physicist Georges Sagnac in 1913 [3]. In the Sagnac's demonstration, a beam of light was split into two light beams so that one beam travelled clockwise, while the other beam travelled anticlockwise around the same area in a rotating platform. Although both light beams travelled within a closed loop, the beam travelling in the direction of the rotation of the platform returned to the point of origin slightly after the beam travelling in the opposite direction to the platform's rotation. As a result, a "fringe interference" pattern, known as interferogram, was detected that depended on the precise rotation rate of the turntable and the size of the area.

Sagnac interferometers are absolutely referenced to the local universe. Therefore, they do not require an external reference frame to operate. Gyroscopes using the Sagnac effect began to appear in the late 1960s, following the invention of the laser and the development of the fibre optics [3]. Today, FOGs are the most prominent representatives for passive optical Sagnac interferometers, while ring laser gyroscopes represent the group of active Sagnac devices. Ring laser gyroscopes characterise the most sensitive and most stable class of gyroscopic devices. However, they are large and very delicate for operation. In comparison, FOGs are small, robust and their sensitivity is fully sufficient to investigate the rotations of structures subjected to wind and earthquake loads [4].

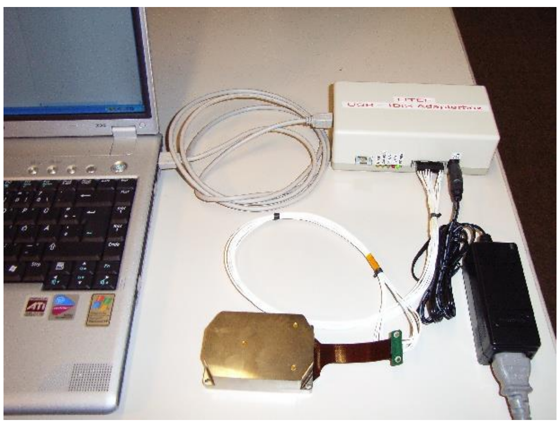
FIBRE-OPTIC GYROSCOPE

A fibre-optic gyroscope (FOG) is a passive Sagnac interferometer employed to detect mechanical rotations such as tilts or torsions. The sensor houses a coil of about 500 m of optical fibre. Two light beams travel along the optical fibre in opposite directions. Due to the Sagnac effect, the light beam travelling against the rotation experiences a slightly shorter path than the other light beam. The resulting phase shift is a measure of the rate of rotation when the light beams are recombined [3].

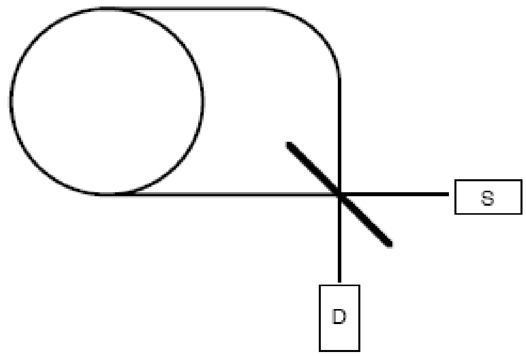
The test device used in this research was a µFORS-1 model manufactured by Northrop Grumman LITEF GmbH in Germany. The sensor has a random walk noise error level of less than 0.1 degrees per square root Hz, which becomes visible for signals of periods of approximately 50 seconds or longer. For the here presented measurements, this error source is far too small to be detected. The test device is approximately 100×80×25 mm in size and needs to be connected to a computer and a power supply. A photograph of the test device is shown in Figure 1(a).

The operation of the FOG is entirely based on optical signals and, therefore, there are no mechanical moving parts inside the sensor. The FOG works efficiently over a wide range of excitation frequencies between 0.001 Hz and 2 kHz. Furthermore, a well-defined reference to the north can be obtained from the FOG's measurements, which provides an additional advantage of using the FOG for the long term monitoring of structural stability [4].

The operation principle of the FOG is very simple. However, the actual sensor design is highly complex for obtaining high sensor stability and resolution. A schematic of the operation principle of the FOG is shown in Figure 1(b). A narrow spectral line-width light beam is generated by a light source (S) and passed on to a light beam splitter of equal intensity. The two light beams generated are then guided around a monomode fibre coil in opposite directions. After passing through the fibre, the two light beams are superimposed again by the same beam splitter and steered onto a photo-detector (D).



(a) Test device



(b) Operation principle

Figure 1. Fibre-optic gyroscope.

If the entire apparatus is at rest, each of the light beams travels the same distance and there is no phase difference between them. However, if the FOG is rotating around the normal vector of the fibre coil, the beams do not travel the same distance and a phase shift between the beams can be seen. Since the signals travel at the speed of light, the phase shift obtained is very small. Thus, a modulation technique, pulsed operation and $\pi/2$-phase shifting for one sense of propagation are used to achieve maximum sensitivity. In addition, the sensor is operated in a closed loop configuration to ensure a wide dynamic range [3].

ONE-FIFTH SCALE STRUCTURE

Shake table tests on scaled models of building structures are widely utilised to study their behaviour during an earthquake ground motion. The inter-storey drifts of the model structure can be precisely determined under these controlled laboratory tests. For this purpose, a rigid reference frame is mounted on the fixed floor of the laboratory. By using several displacement transducers attached to the reference frame, it is possible to measure the displacements of the structural model along the axis of translation of the shake table. The inter-storey drifts of the model structure are then determined from the displacements measured by the transducers. Since the FOGs do not require a reference frame, they can measure the inter-storey drift as a rotation around the normal vector of the fibre coil.

To evaluate the suitability of the FOGs for civil engineering structures under seismic excitations, a series of shake table tests were performed on a four-storey one-fifth scale structure. A photograph of the test structure is shown in Figure 2(a). The photograph also shows five conventional linear potentiometers used to measure the floor displacements of the test structure during the shake table tests. The linear potentiometers were mounted on a steel reference frame. The frame was fixed to the laboratory floor. The reference frame is also shown in Figure 2(a).

The four storey one-fifth scale structure was designed by Kao [5]. The main feature of this steel moment-resisting frame structure is the incorporation of replaceable fuses located in critical regions of the structure to show the effects of inelastic structural performance under earthquake loading. The model building is a 2.1 m high three-dimensional four-storey frame structure. The frames are built using square hollow steel sections for beam and column members. The fuses, beam-column joints and other connecting components are made of steel flat bars. Two frames in the longitudinal direction provide lateral load resistance. Each frame has two bays with 0.7 m and 1.4 m long spans. The short bay is to show earthquake dominated response. The long bay is to show gravity dominated response by having an extra concentrated load induced by a transverse beam at the mid-span at each level. In the transverse direction, three one-bay frames with 1.2 m long span provide lateral stability and carry most of the gravity load. A one-way floor slab provides a significant proportion of the model mass. The slab is made of steel planks and is connected to a rigid steel plate that acts as a diaphragm. The planks are simply supported on the beams of the transverse frames and on the intermediate beam supported by the long span beams of the longitudinal frames of the four-storey one-fifth scale structure.

(a) One-fifth scale structure

(b) FOG attached to column

Figure 2. Measurement instrumentation.

The four-storey model building was designed as a one-fifth scale structure. It was intended to model the structure as a typical four-storey reinforced concrete frame building, therefore, the natural period of the model structure was required to be within 0.4 s to 0.6 s to obtain similar response under earthquake excitation [5]. The equivalent static method, outlined in the New Zealand Loadings Standard NZS 4203: 1993, was employed to calculate the earthquake forces. The seismic weight of the one-fifth scale structure is 35.3 kN. A structural ductility factor of 6 was adopted for the structural design. Thus, the model structure was designed for a base shear force of 8.7% of its seismic weight.

SHAKE TABLE MEASUREMENTS

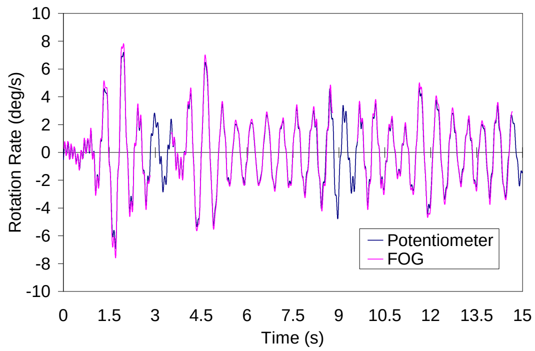
The test structure was subjected to four different earthquake ground motions, namely El Centro 1940 NS, Taft 1952 S21W, Sylmar County 1994 and Kobe 1995 N000E. The amplitude of the earthquake records was scaled to excite the model structure with earthquake ground motions of different intensity. As shown in Figure 2(a), various linear potentiometers and accelerometers were used to measure the response of the model structure and the motion of the shaking table. The FOG was attached to the centre column of the first floor of the model structure to measure the rotation rates of the column. Figure 2(b) shows a photograph of the FOG attached to the centre column.

Several shaking table tests were conducted utilising the above-mentioned earthquakes at various peak ground acceleration levels. In this research, response time-histories for the following ground motions are presented: El Centro 30%, Taft 40%, Sylmar 10% and Kobe 10% with corresponding peak ground accelerations of 0.10g, 0.07g, 0.08g and 0.08g, respectively. The earthquake intensities were so selected to prevent inelastic deformations in the structure during the seismic testing [6].

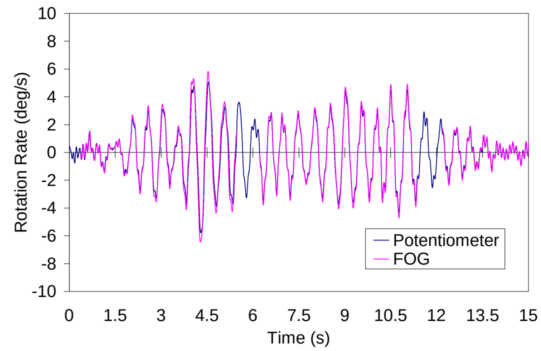
An assessment of the accuracy of the FOG's measurements is made by comparing the measurements provided by the FOG with those delivered by a conventional linear potentiometer attached to a fixed reference frame. The column's rotation is obtained by numerical integration of the rotation rate (degrees per second) measured by the FOG device without an external reference frame. The relative floor displacement is then calculated by multiplication of the column's rotation by the height of the first floor. In the same way, the column's rotation is calculated with the inverse tangent of the displacement at the first floor, obtained by conventional linear potentiometers, divided by the storey height. The rotation rate is then determined by numerical differentiation of the column's rotation. It is assumed that the centre column of the model structure is undergoing rigid rotation. Displacements caused by any other type of deformation such as beam bending or joint rotation are considered to be insignificant.

Figures 3 through 6 show a comparison in terms of rotation rates, centre column's rotations and first floor displacements measured by the FOG with those provided by a conventional potentiometer. An excellent agreement is observed between both sensors for all the records used in the seismic testing. Small discrepancies can be observed between the displacement obtained with the potentiometer and the displacement computed from the rotation rate measured by the FOG at peak values of the graphs. However, this reflects a systematic effect caused by deformations of the potentiometer arms under maximum strain. The breaks that might be observed in the FOG's data are result of a software problem in the data logger of the FOG, which was identified only later during the data analysis [7]. Experimental data recorded by the FOG is sampled at 1 kHz.

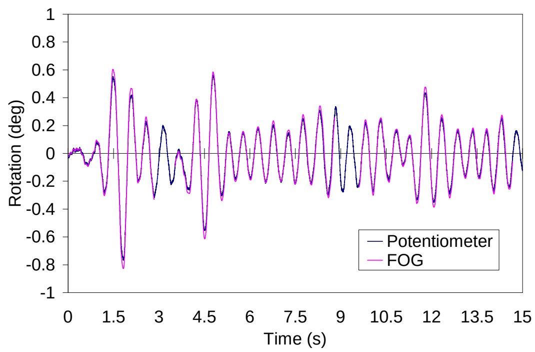
The displacement measurement at the first floor was used to demonstrate the measurement concept without the complications of building deflection and deformation. In actual applications, more than one rotation sensor would be installed throughout the building. The observed differences between several sensors would in turn provide the benefit of identifying the building deflection and deformation, which would indicate the locations of energy dissipation [4].



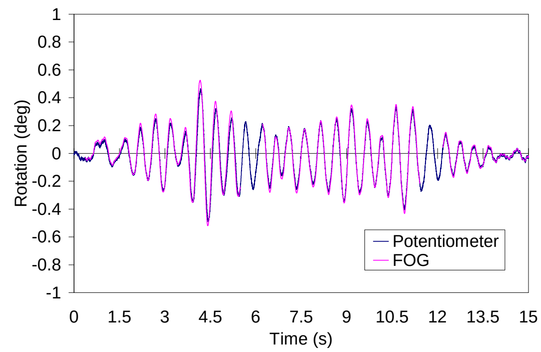
(a) Rotation rate of centre column



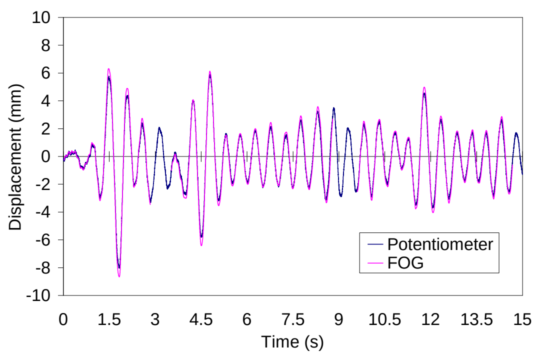
(a) Rotation rate of centre column



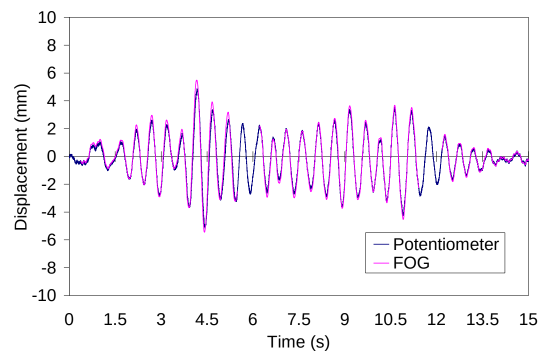
(b) Rotation of centre column



(b) Rotation of centre column



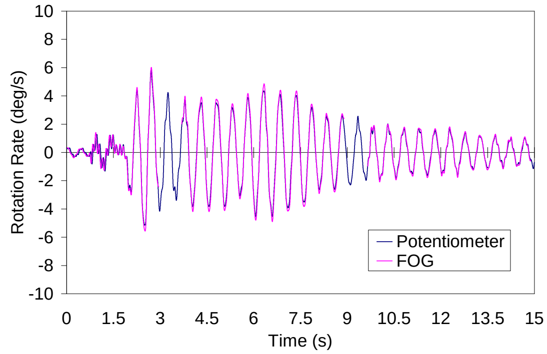
(c) Relative displacement at first floor



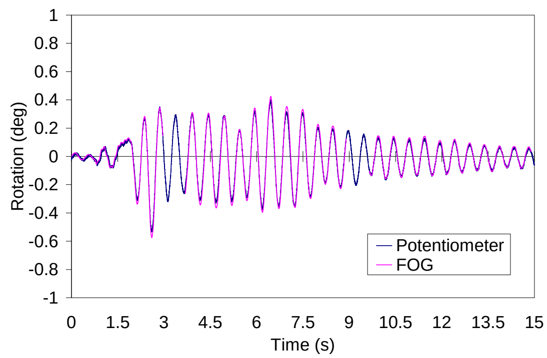
(c) Relative displacement at first floor

Figure 3. Measurements for El Centro 30%.

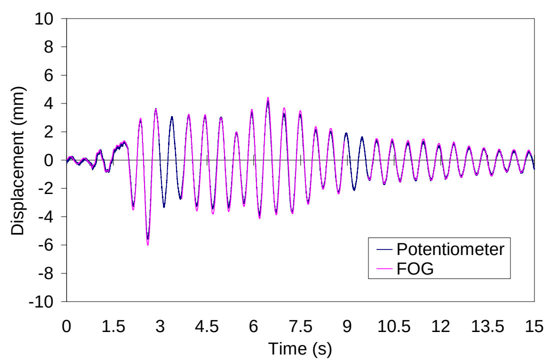
Figure 4. Measurements for Taft 40%.



(a) Rotation rate of centre column

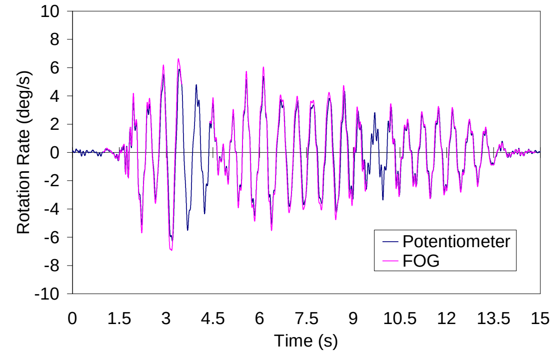


(b) Rotation of centre column

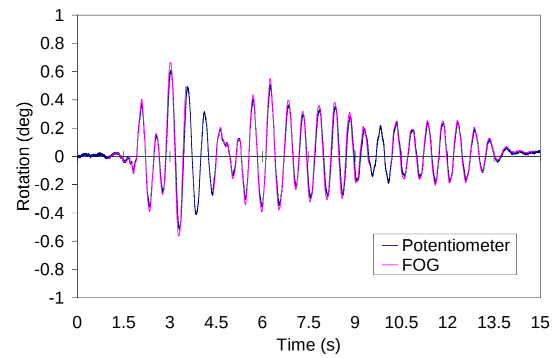


(c) Relative displacement at first floor

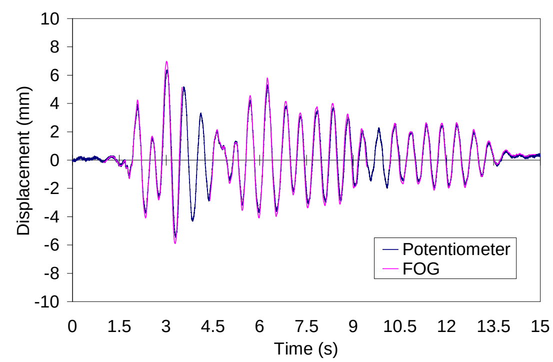
Figure 5. Measurements for Sylmar 10%.



(a) Rotation rate of centre column



(b) Rotation of centre column



(c) Relative displacement at first floor

Figure 6. Measurements for Kobe 10%.

Whereas displacement measurement using the conventional transducers is readily available in a laboratory environment, it is almost impossible in an actual earthquake scenario. In contrast, for applications of the FOG, there is no difference between the displacement measurement in a laboratory experiment and that in a tall building structure.

The test device was later attached to the third floor to check the torsional rotations of the one-fifth scale structure. However, there were only very small torsional rotations detected because the model structure is symmetric, and the seismic excitation was applied in one direction only [7].

CONCLUSIONS

This paper has described a novel measurement concept that uses a fibre-optic gyroscope type μFORS-1. It is small, easy to install and has sufficient sensitivity. The FOG is entirely an optical device and, therefore, does not have any mechanical moving parts. It works efficiently over a range of excitation frequencies between 0.001 Hz and 2 kHz. Since the FOG is absolutely referenced to local universe, it does not require an external reference frame for operation. Therefore, the FOG can be easily installed in actual civil engineering structures.

Shake table tests were performed on a four-storey one-fifth scale structure to evaluate the suitability of the FOGs for civil structures under earthquake excitations. Four earthquake records at different levels of intensity were used to investigate the accuracy of the measurements recorded by the FOG. The device was attached to the first floor centre column of the structure. Column rotations and displacements at the first floor were calculated from the rotation rates measured by the FOG. A very good agreement was observed between the measurements obtained with the FOG and those provided by a conventional linear potentiometer. The shake table results validated the accuracy of the measurements taken by the FOG and its potential use in civil and earthquake engineering applications.

ACKNOWLEDGMENTS

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