Laboratory and in-situ measurements of structural rotations using fibre-optic gyroscopes

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SUMMARY:
This paper will describe the first civil engineering applications of fibre-optic gyroscopes (FOGs) to measure structural rotations. FOGs use the Sagnac effect in a passive optical interferometer design to measure rotations with high precision. Since the rotations measured by FOGs are absolute with respect to the local universe, they do not require an external reference frame to operate. Besides, FOGs are light, compact and can be easily installed. Shake table tests were performed on a four-storey one-fifth scale structure equipped with a FOG to investigate its suitability for measuring rotation rates, rotations and displacements. The FOG was attached to one of the first floor columns of the four-storey one-fifth scale structure during the seismic testing. Relative displacements at the first floor were calculated from the measurements provided by the FOG and compared with those obtained by a conventional linear potentiometer. The measurement technique was then applied in the 328 m tall Sky Tower in Auckland (New Zealand). To evaluate lateral displacements caused by wind, the FOG was installed on the 54th and 60th floors of the tower structure. The FOG was also used to analyse the dynamic behaviour of a 70 m tall wind generator near Cuxhaven (Germany). Several measurements were carried out by placing the FOG in three different positions. The laboratory and in-situ measurements confirmed the accuracy and suitability of FOGs for applications in civil engineering.

Keywords: Fibre-optic gyroscopes, structural rotations, laboratory and in-situ measurements, seismology.

1. INTRODUCTION

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

Fibre-optic gyroscopes are passive interferometers where a beam of light is split into two equal beams. These 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 and, therefore, the measurement device does not require an external reference frame to operate.

This paper describes the first applications of FOGs to measure rotation rates, rotations, displacements and inter-storey drifts of civil engineering structures. FOGs are devices that utilise the Sagnac effect to detect mechanical rotations interferometrically from optical beams. They are compact, easy to install and, unlike conventional linear potentiometers, do not require a fixed reference frame for operation. Shake table tests were performed on a four-storey one-fifth scale structure fitted with an FOG. Four different earthquake ground motions were used in this experimental study. During the seismic testing, the FOG was attached to one of the first floor columns of the model structure. Relative displacements at the first floor were calculated from the measurements provided 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 experimental results validated the accuracy of the measurements recorded by the FOG as well as the dynamic range of the instrument.

The FOG was then installed on the Sky Tower in Auckland to evaluate the displacements of the tower structure. A series of measurements were carried out on the 54th and 60th floors during three days. The FOG was also used to investigate the dynamic behaviour of a wind generator near the city of Cuxhaven. Various measurements were performed by placing the FOG in three different positions. In-situ measurements taken by the FOG provided a very good signal to noise ratio of the measurement quantity. Furthermore, the in-situ measurements emphasised the importance of FOGs as an emerging sensor technology for the monitoring of civil engineering structures.

2. ROTATION MEASUREMENT

In civil engineering, the rotations are an important measure of the structural response. 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 building structures is measured as the inter-storey drift. The inter-storey drift is the difference in the 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 seismic excitation (Algan 1982).

The measure of torsional rotations and inter-storey drifts is reasonably easy on small-scale structural models. However, it is difficult to measure the structural rotations on large-scale structural models and actual structures. Torsional rotations can be measured by dividing the difference in the accelerations taken by two accelerometers by the distance between the 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 technique is limited due to the inherent sensor drift and the small offset from zero in the absence of an input signal.

In the laboratory, 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 can not be easily determined because there is no reference frame that may be used to measure the floor displacements. Although it is possible to set up a frame attached to the floor below in order to measure the relative displacement at the floor above, this is not a very 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 (McGinnis 2004). However, apart from the hardware complexity of this approach, it is also vulnerable to building deformations. The distortions may 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 to operate and, therefore, they can be installed in actual civil engineering 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 of significant importance 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.

3. SAGNAC EFFECT

Optical gyroscopes have replaced the conventional mechanical 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.

In the Sagnac's demonstration, a beam of light was split into two 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 (interferogram) was detected that depended on the precise rotation rate of the turntable and the size of the area.

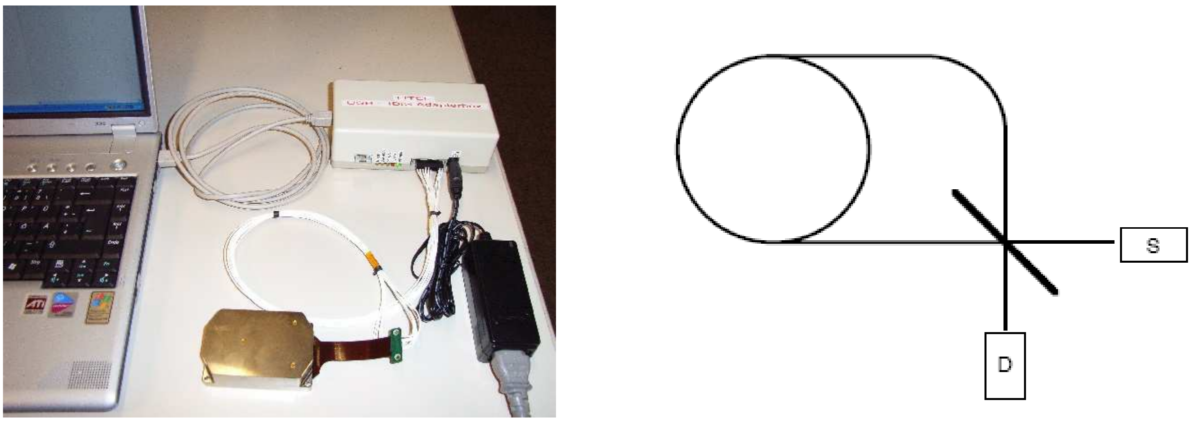
Sagnac interferometers are absolutely referenced to the local universe. Therefore, they do not require an external reference frame to operate. Gyroscopes using the Sagnac effect began to appear in the late 1960s, following the invention of the laser and development of fibre optics (Lefevre 1993). Today, 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 to operate. In comparison, FOGs are small, robust and their sensitivity is fully sufficient to investigate the behaviour of structures subjected to wind and earthquake loads (Schreiber et al. 2009).

4. FIBRE-OPTIC GYROSCOPES

4.1 Test Device

A fibre-optic gyroscope is a passive Sagnac interferometer employed to detect mechanical rotations such as tilts or torsions. The sensor houses a coil of about 0.5 km of optical fibre. Two beams of light travel along the fibre in opposite directions. Due to the Sagnac effect, the beam travelling against the rotation experiences a slightly shorter path than the other beam. The resulting phase shift is a measure of the rate of rotation when the beams are recombined (Lefevre 1993).

The test device utilised 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 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 1a.



a. µFORS-1 model

b. Operation principle

Figure 1. Fibre-optic gyroscope.

4.2 Operation Principle

The operation concept of the FOG is entirely based on optical signals and thus 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 (Schreiber et al. 2009).

The principle of operation of the FOG is very simple. However, the actual sensor design is highly complex in order to obtain high sensor stability and resolution. A schematic of the operation principle of the FOG is shown in Figure 1b. A narrow spectral line-width light beam is generated by a light source (S) and passed on to a 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 beams are superimposed again by the same beam splitter and steered onto a photo-detector (D).

If the entire apparatus is at rest, each of the light beams travels the same distance and there is no phase difference between the two beams. However, if the FOG is rotating around the normal vector of the fibre coil, the two light 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. Therefore, a modulation technique, pulsed operation and $\pi/2$-phase shifting for one sense of propagation are used to achieve maximum sensitivity. Additionally, the sensor is operated in a closed loop configuration to ensure a wide dynamic range (Lefevre 1993).

5. LABORATORY MEASUREMENTS

5.1 One-Fifth Scale Structure

Shake table tests on scaled models of 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 laboratory floor. 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. 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 fibre-optic gyroscopes 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 2a. The photograph also shows five conventional linear potentiometers utilised to measure the floor displacements of the test structure during the shake table tests. The linear potentiometers were mounted on a steel reference frame that was fixed to the laboratory floor. The reference frame is also shown in Figure 2a.

The four storey one-fifth scale structure was designed by Kao (1998). 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 seismic loading. The model building is a 2.1 m high three-dimensional four-storey frame structure. The frames are built utilising 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 the 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, while 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 (Fig. 2a).

a. One-fifth scale structure

b. FOG attached to column

Figure 2. Laboratory measurements.

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 seismic excitation (Kao 1998). 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.

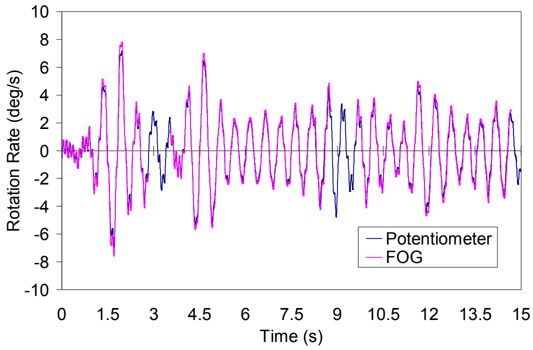
The test structure was subjected to four different earthquake ground motions, namely El Centro 1940 NS, Taft 1952 S21W, Sylmar County 1994 and Kobe 1995 N000E. The amplitude of the earthquake records was scaled in order to excite the model structure with earthquake ground motions of different intensity. Various linear potentiometers and accelerometers were used to measure the response of the model structure and the motion of the shaking table. As shown in Figure 2b, a fibre-optic gyroscope was attached to the centre column of the first floor of the test structure to measure the rotation rates of the 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. Earthquake intensities were so selected to prevent inelastic deformations in the one-fifth scale structure during the seismic testing (Franco-Anaya et al. 2007).

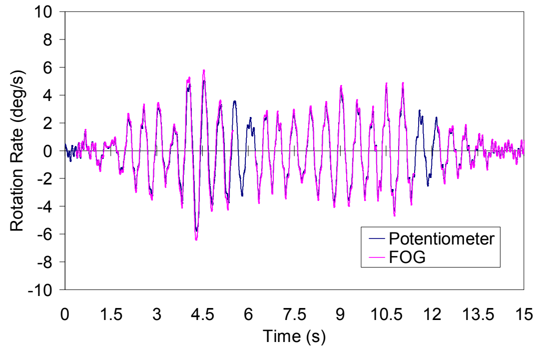
An assessment of the accuracy of the FOG's measurements is made by comparing the measurements provided by the FOG with those delivered by a conventional linear potentiometer attached to a fixed reference frame (Fig. 2a). The column's rotation is obtained by numerical integration of the rotation rate (degrees per second) measured by the FOG 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 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. The 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 of 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 the result of a software problem in the data logger of the FOG, which was identified only later on during the data analysis (Franco-Anaya et al. 2008). Experimental data recorded by the FOG is sampled at 1 kHz.

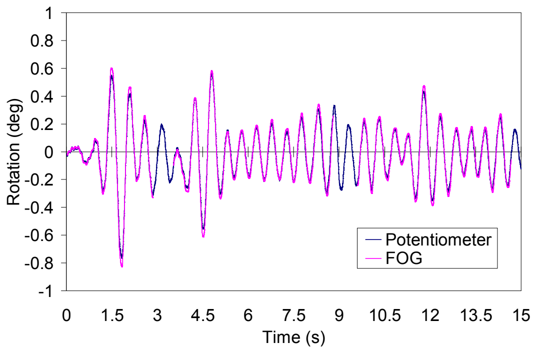
The displacement measurement at the first floor was used to demonstrate the measurement concept without the complications of building deflection and deformation. In actual applications, more than one rotation sensor would be installed throughout the building. The observed differences between several sensors would in turn provide the benefit of identifying building deflection and deformation, which would indicate the locations of energy dissipation (Schreiber et al. 2009).



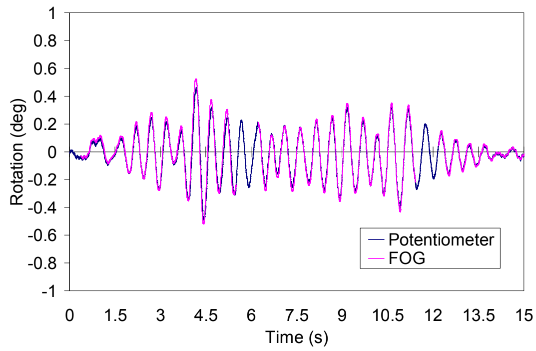
a. Rotation rate of centre column



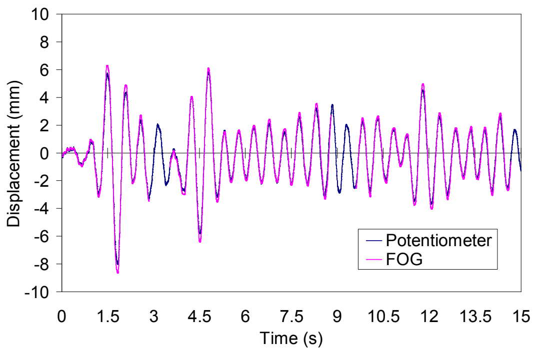
a. Rotation rate of centre column



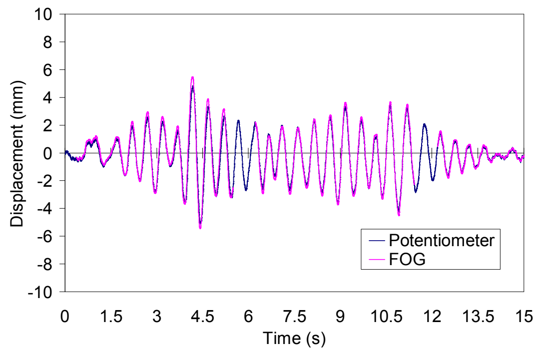
b. Rotation of centre column



b. Rotation of centre column



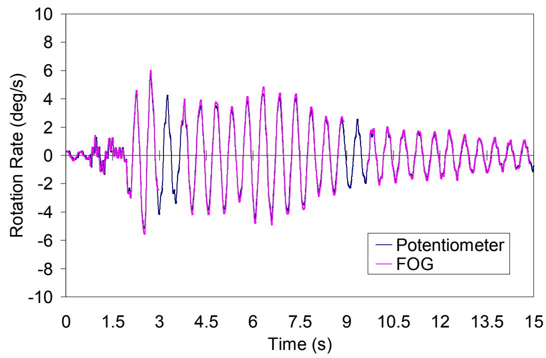
c. Relative displacement at first floor



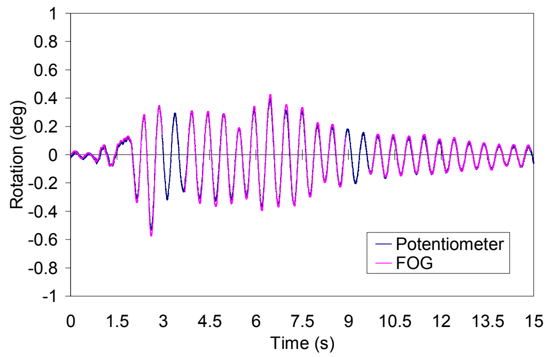
c. Relative displacement at first floor

Figure 3. Measurements for El Centro 30%.

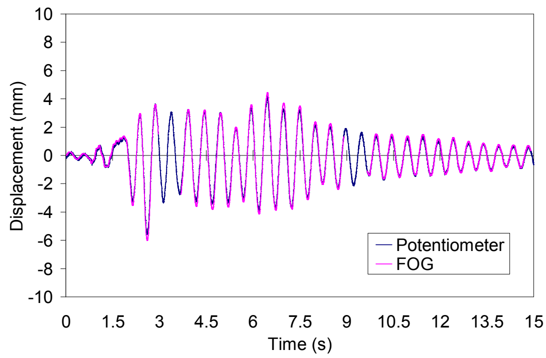
Figure 4. Measurements for Taft 40%.



a. Rotation rate of centre column

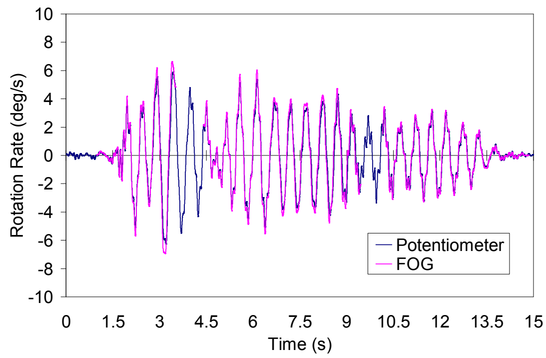


b. Rotation of centre column

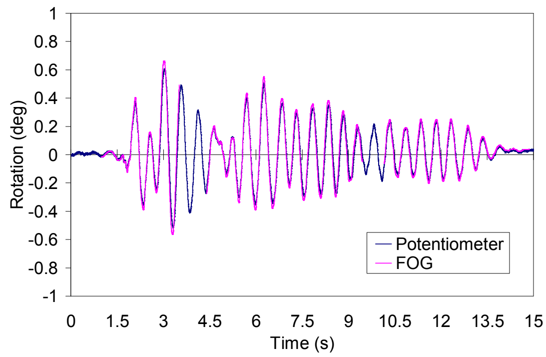


c. Relative displacement at first floor

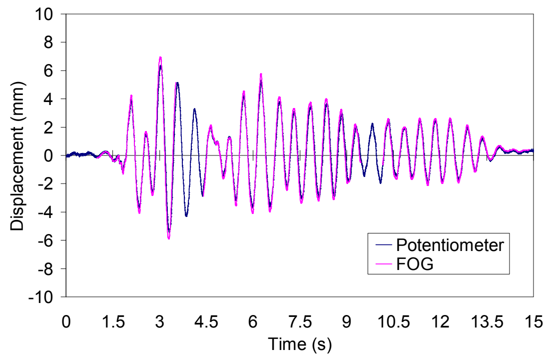
Figure 5. Measurements for Sylmar 10%.



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 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.

6. IN-SITU MEASUREMENTS

6.1 Sky Tower

The FOG was then used to measure the displacements of the 328 m tall Sky Tower in Auckland, New Zealand. Figure 7a shows a photograph of the Sky Tower. The device was clamped to antenna frames on the outside of the tower at level 54 and to window supports at level 60. It only took a few minutes to set up the test sensor and start taking readings from the Sky Tower. The resonance frequency of the rocking mode of the Sky Tower is 0.165 Hz which corresponds to a period of approximately 7 s.

During a three-day period of time, a number of measurement series with durations between 6 and 12 minutes were taken under calm wind conditions. Wind speeds varied between 24 and 36 km/h. The computer recorded the instantaneous rotation rate measured by the FOG around the axis perpendicular to the coil of the glass fibre at one-millisecond intervals. The FOG was orientated in such a way that it was sensitive to the rocking mode of the structure in the north-south direction.

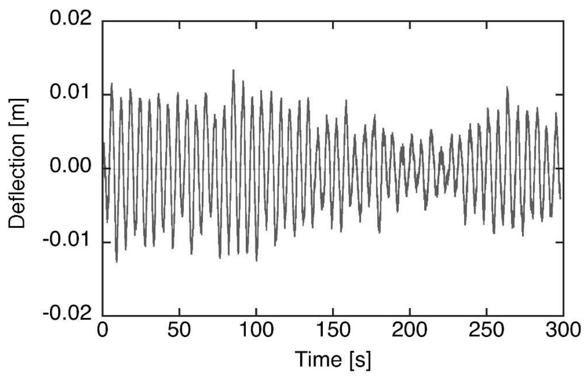
a. Sky Tower

b. Wind generator

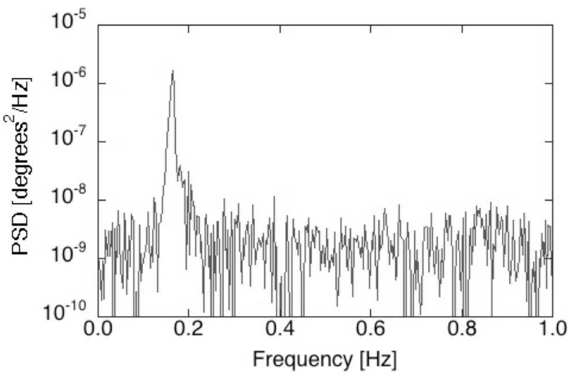
Figure 7. In-situ measurements.

Figure 8 shows one sample out of approximately 20 data sets obtained over the three-day period. The measured rotation rate was integrated to yield the excursion angle of the structure and then converted to a structural displacement as a high-resolution function of time. The displacement time-history at level 54 is shown in Figure 8a. It can be seen that the typical excursions reach a level of approximately 2 cm peak to peak over periods of about 7 s. The envelope of these excursion measurements shows the response of the Sky Tower to wind gusts.

A power spectrum was obtained from the displacement time-history at level 54 of the Sky Tower. The power spectral density (PSD) describes how the power of the signal is distributed with frequency. The resonance frequency of 0.165 Hz that corresponds to the rocking mode of the structure can clearly be seen in Figure 8b. It is important to note that the measurements have a very good signal to noise ratio despite the small overall values (Franco-Anaya et al. 2008).



a. Displacement time-history

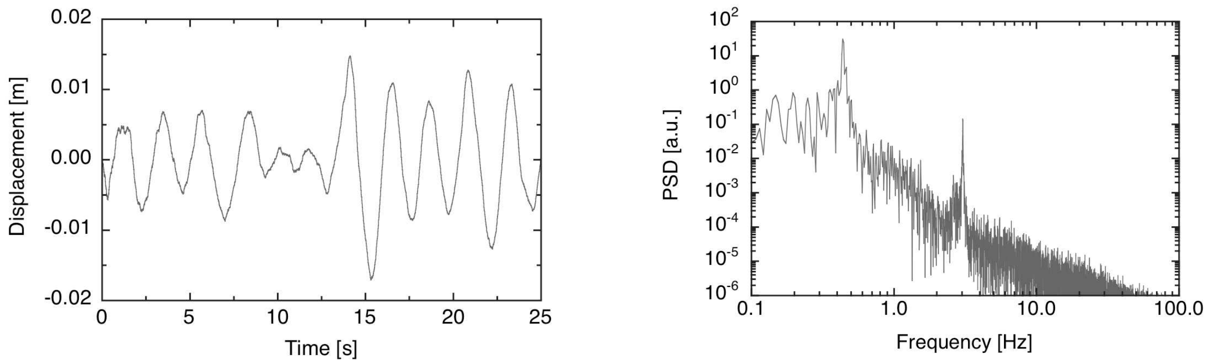


b. Power spectrum

Figure 8. Measurements at level 54 of the Sky Tower.

6.2 Wind Generator

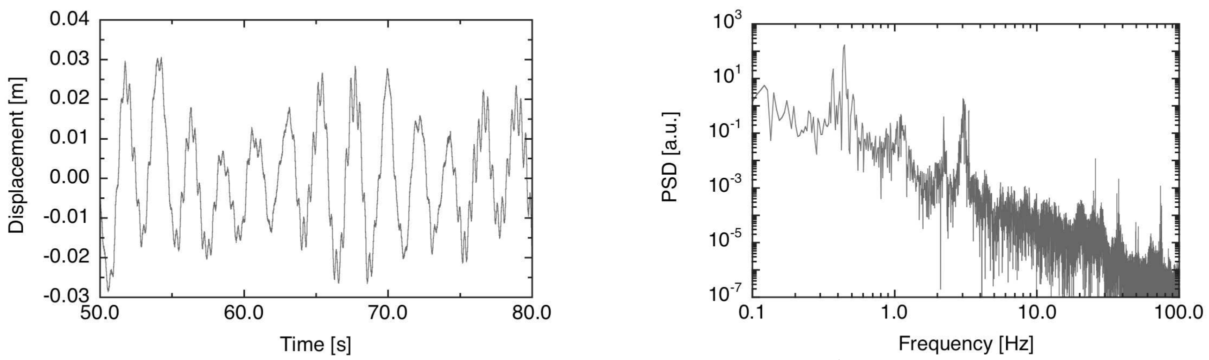
The FOG was also installed on a 70 m tall wind generator to investigate the dynamic behaviour of the structure. The wind generator is located in northern Germany near the city of Cuxhaven. The structure has three wind turbine blades. The wind generator is usually operated at a rate of 20 revolutions of the rotor blades per minute. A photograph of the wind generator can be seen in Figure 7b. The FOG was operated under moderate wind conditions in three different orientations. Wind speeds varied between 25 and 40 km/h. During the first measurement series, the sensitive axis of the FOG was orientated parallel to the main shaft of the wind generator. It was then rotated by 90° so that the FOG was still orientated vertically, but in a direction parallel to the plane in which the blades were rotating. In the third measurement series, the normal vector of the fibre coil of the FOG was pointed upwards so that the torsion around the horizontal plane could be measured (Schreiber et al. 2009).



a. Displacement time-history b. Power spectrum

Figure 9. Measurements at the wind generator (turn off).

The rotor blades were stopped during the first measurement series to determine the natural vibration mode of the wind generator. The rotation rates measured by the FOG were integrated numerically to obtain the angle of rotation as a function of time. To determine the displacement of the structure, the tangent of the angle of rotation was then multiplied by the height of the structure. Figure 9a shows the displacement time-history at the top of the wind generator during the first measurement series. The maximum displacement is about 2 cm. The corresponding power spectrum is shown in Figure 9b. The natural vibration mode has a frequency of 0.44 Hz and the second mode is excited at 3.04 Hz. There are no further frequency components evident in the data set.



a. Displacement time-history b. Power spectrum

Figure 10. Measurements at the wind generator (turn on).

Once the wind generator was turn on again, it was observed that the structural response showed larger displacements and the second mode frequency of 3.04 Hz became more noticeable. Besides, there was a clear division between the first vibration mode at 0.44 Hz and a low frequency mode at 0.36 Hz. The latter frequency was presumably caused by the first vibration mode of the rotor blades. The respective diagrams are shown in Figure 10. There is another signal that also started to show up at a frequency of

1 Hz. However, it is not as sharply defined as all the signals previously mentioned. This signal can be associated with the effect of the rotor blades passing in front of the shaft of the generator (Schreiber et al. 2009).

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 used in actual civil engineering applications.

Shake table tests were performed on a four-storey one-fifth scale structure to evaluate the suitability of the FOGs for 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 potentiometer. The shake table results validated the accuracy of the measurements taken by the FOG.

The FOG was then used to measure displacements in the Sky Tower in Auckland. The Sky Tower was considered a challenging target because of the demands involved for the measurement technique. The FOG was installed on the 54th and 60th floors of the structure. Under calm wind conditions, several sets of measurements were carried out during a three-day period of time. The FOG was also installed on a wind generator near Cuxhaven to investigate its dynamic behaviour. Various measurements were performed under moderate wind conditions in three different positions of the FOG. Measurements recorded by the FOG at both tower structures provided a very good signal to noise ratio. The in-situ measurements confirmed the suitability of the FOG for applications in real structures.

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