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'Measuring the Monument' – Fibre Optic Sensor Systems show why Hooke's and Wren's plans for a Giant Telescope within the Monument in London failed

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ABSTRACT

Fibre optic sensor systems have often been used for structural health monitoring applications, usually on bridges, in tunnels and sewers and in various infrastructure where installation is usually only affected by access. This work has tackled a problem of structural monitoring on one of London's iconic historic buildings, where installation of the chosen fibre optic sensors had to be very carefully planned and agreed with the building owners who imposed severe limits to avoid creating any damage to the structure. Given these restrictions, a fibre optic sensor system was designed and installed to enable the accurate determination of the structural parameters of the building, solving a 350-year-old question of why the building was not able to be used for its original subsidiary purpose, from its design by Robert Hooke and Christopher Wren, as a telescope. Results of on-going research and analysis are reported.

Keywords: FBG-based fibre optic sensor; structural health monitoring; historic buildings

1. INTRODUCTION AND BACKGROUND

Figure 1. The Monument to the Great Fire of London.

The Monument is one of London's most famous landmarks, created as a monument to the Great Fire of London. Originally designed by Christopher Wren and Robert Hooke, it is often not known that it was not only intended as a monument to the Great Fire of London of 1666, but also a zenith telescope - the aim was to use it to prove that the Earth revolves around the sun.

However, it ultimately failed as an instrument to do so as it was insufficiently stable for the measurements to be made. The key question is why the Monument proved not to be sufficiently stable as a scientific instrument – could this have been foreseen, and would it be possible to rectify the problem today?

What Robert Hooke wanted to prove was that the Earth orbited the Sun rather than the other way round. At the time, the Copernican idea had been accepted by serious scientists, but a papal court had put Galileo under house arrest for life for promoting this view – and only less than 50 years before. Hooke wanted to use stellar parallax to prove his point. Hooke's chosen "nearby" star for the experiment was the very bright Gamma Draconis. (It is now known that this is 154.3 light years, or 900 x 10^{12} miles, away – and so, even though the earth moves by 186 million miles over a six-month period, the change in Gamma Draconis's apparent position in the sky is still tiny).

Hooke believed that the giant telescope that was the Monument could be used for the measurements needed to prove his hypothesis. However, the problem he faced was one of the stability of the Monument, and it had been believed that vibration from surrounding traffic, such as on the crowded and well-used London Bridge, even as far back as the 17th century was to blame – a problem exacerbated by the significant increase in traffic in the area since the late 19th century (and of course, potentially still a current issue with the even greater volume and weight of traffic across nearby London Bridge). An alternative theory was put forward by historian Lisa Jardine [1] that weather changes experienced at the monument were to blame, which contradicts the view widely disseminated (and seen in Wikipedia) that 'vibrations from heavy traffic nearby rendered the experimental conditions unsuitable (for Hooke's experiments)'.

To date, few quantitative studies of the vibration experienced at the Monument have been made over the years. As a listed building, there is naturally no facility to affix sensors to the structure itself, due to the potential for damage that they could cause. However, a recent study published in 2020 by researchers from Queen Mary University of London used the shaft of the monument stairwell to measure deformation in a hanging wire [2]. By twisting and untwisting a wire hanging down the shaft of the stairwell, they were able to detect deformation at less than 9 parts per billion – equivalent to a one-degree twist over the length of the 160-foot (50 m) wire. However, this experiment did not tackle directly the fundamental question of the source of the vibration problem. Whatever the source, those problems always prevented the Monument from being effective as a telescope as the vibration affected the observations and caused blur in the images.

2. METHODOLOGY – THE NEED FOR FIBRE OPTIC SENSORS

The key measurement question, for which there is the need for new sensor systems is – could the Monument still be used in its original purpose? To do so, an accurate measurement of the vibration that has been causing problems in the almost 350 years since the Monument was built is needed so that a solution, perhaps using adaptive optics, could be used. (Adaptive optics uses a deformable mirror in the optical path that eliminates dynamically the blurring of the light (caused by the vibration), by changing the light path dynamically to cancel out the effects of vibration). In light of that, the objective of this project has been to design, fabricate and make ready a fibre optic-based *sensor system* to measure the vibration accurately and in a dynamic way – to do so by installing a number of fibre-optic-based tilt sensors and accelerometers at the top of The Monument (where the tilt would be most evident) and placing the sensors along several axes of the building to gain maximum information on the vibration of the structure. The data obtained were analyzed, with a view to understanding the parameters needed for designing a stable telescope.

The technical approach proposed by the authors and deemed suitable for installation on this listed historic building by the City of London was a fibre optic based sensor system, designed around the use of Fibre Bragg Grating (FBG) technology, offering advantages over the use of conventional strain gauges. Straining the sensor causes a change in the grating pitch and therefore in the wavelength of the reflected signal, the latter being a measure for the amount of strain applied [3]. When needed, such sensors can readily be multiplexed along a single fibre optic cable, in that way reducing the need for the installation of a large number of cables (as would be the case for electronic strain gauges, for example). Both the tilt and acceleration sensors are based on the movement of a suspended mass causing strain (positive or negative) in the fibres attached to a pivot mechanism. This basic principle can be implemented in many ways (swinging rod, diaphragm, spring, etc.) depending on the desired accuracy and sensitivity. This is illustrated schematically in Figure 2.

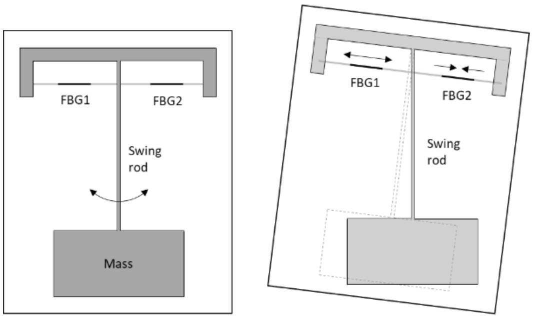

Figure 2. Simplified schematic of the design of fibre-optic tilt and acceleration sensors used.

Installation issues: Installing a sensor system on a 350-year-old listed building, with all the restrictions that this brings, required careful design of a system that could first be installed, then left for long periods (in a building to which the public continued to have access). In consultation with the City of London, a solution was agreed whereby no holes were being drilled, no epoxies used, and no permanent attachments installed. This contrasts the installation with many industrial situations where the constraints described do not apply.

In light of the constraints, a careful design of the sensor system was undertaken, in which two tilt sensors were securely fixed to a mounting bracket and oriented perpendicular to one another. To meet the constraints, the bracket was then fixed in the centre of a metal grille that spanned the cross-section of the Monument, near the top of the staircase in the Flame Room above the visitor gallery (as shown in Figure 3). A compass was used to align the tilt sensor axes with the adjoining Fish Street Hill, which runs approximately north to south, and along the line from Monument Street to Monument Square, running approximately east to west. In this way, two fibre optic based accelerometers were also fixed to the grille, oriented horizontally and vertically, i.e. perpendicular and parallel to the central axis of the Monument itself.

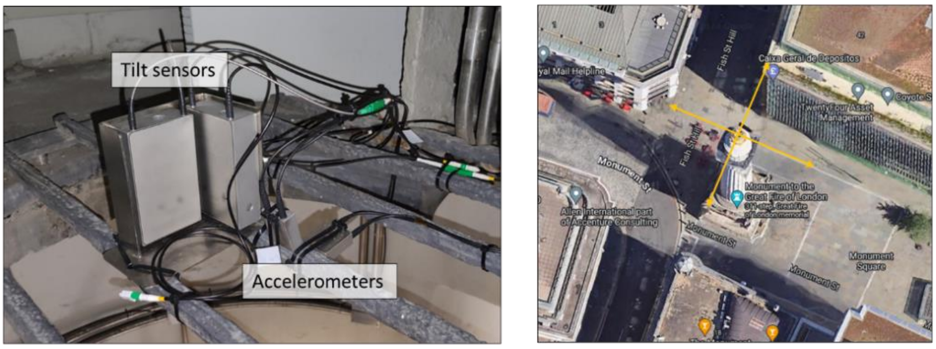

Figure 3. Sensors installed in the flame room of the monument (left). Orientation of the tilt sensors (right) with respect to the surrounding buildings.

Software and remote data gathering: The sensors were connected to an optical sensing device (Micron Optics si155) and the data read out from the device by using a mini-PC. The data were saved as .csv files, which could be downloaded remotely, via a 4G USB dongle. The data files were analysed with MATLAB (Mathworks).

3. RESULTS AND DISCUSSION

Installation at the Monument: the sensor system was initially installed, and preliminary results were obtained over a period of 1 month in the Summer of 2024, where the data gathered represented a series of different conditions, including day and night, the building being open and closed to the public, various weather conditions, and various traffic levels on the nearby London Bridge. Further periods of study of the data gathered from the Monument are planned, but as discussed below, the data received over the initial month of study have provided some clear information about the movement.

The sensor data collected were subjected to a high-pass filter, with a cut-off frequency of 0.1 Hz, to remove tilt offsets as well as acceleration baseline drifts (due to the small temperature changes which were occurring). A frequency analysis of the data was also performed using a fast Fourier transform (FFT) approach. The filtered tilt and accelerometer sensor data which were obtained are shown in Figure (left), and the corresponding frequency spectra are shown in Figure Figure (right). The accelerometer data showed few features other than a large spike on one particular day (5th August), which were attributed to an unexplained event and therefore excluded from the discussion below.

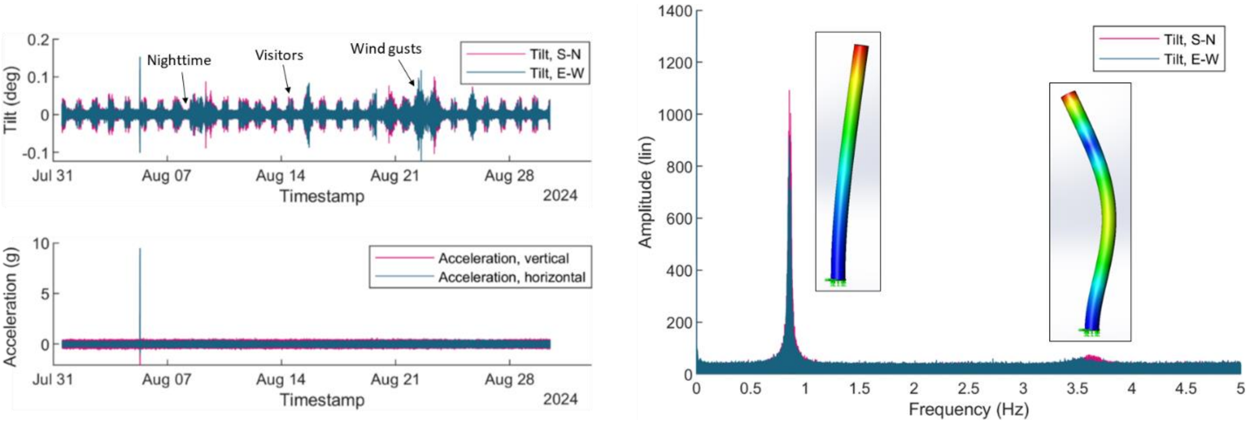

Figure 4. (left) Sensor signals vs time, after high-pass filtering, for the full 1-month measurement period. Top: tilt angle vs time; bottom: acceleration vs time. (right) Frequency spectra of tilt sensor data. Insets: results from FEM modelling indicating the first and second order bending modes of a column of similar proportions to the Monument (exaggerated deformations visualized).

The following fibre optic sensor data analysis focuses on the tilt sensor data as this can provide the most valuable information on the building movement. An analysis of the data to investigate the most significant frequency information was carried out. This frequency analysis indicated a consistent frequency of 0.85 Hz for the E-W tilt sensor, with a weaker frequency component at 3.5 Hz. (as can be seen clearly from Figure Figure (right)). The main frequency components of the S-N oriented tilt sensor are slightly shifted with respect to the E-W tilt sensor, with a main component at 0.86 Hz, and a weaker component at 3.6 Hz. An enlarged view of the tilt sensor data vs timestamp shows a clear near-sinusoidal oscillation.

A simple, preliminary Finite Element Method (FEM) analysis was carried out and the results are shown schematically as insets in Figure (right). The results of this analysis correspond well to the experimental results which suggests that those frequencies correspond to the first two bending modes of the column. Because the wind gust data were only available from the published sources at 1-hour intervals, the tilt magnitude data were also divided into 1-hour time windows, from – 30 mins to + 30 mins around each wind gust speed data point. The maximum tilt magnitude within each 1-hour window was then plotted against the wind gust speeds, as shown in Figure 5 (left). This figure indicates a linear relationship between the tilt magnitude of the Monument and the wind gust speed (within experimental error). Linear fitting provided a sensitivity coefficient of 0.0009 deg/km/h, with $R^2 = 0.75$. A visualization of the tilt effect, i.e. the sway path of the top of the monument in Figure 5 (right) highlights the difference in magnitude of the identified contributing factors (traffic, visitors, wind).

4. DISCUSSION

It is evident from the data that traffic is the least contributing factor to the sway of the Monument (roughly equating in its effect to small-scale wind gusts, of up to 15km/h). Visitors have twice the effect on the structure (comparable to a typical gust of up to approximately 35km/h). Wind gusts stronger than 35km/h overshadow all other causes of the vibration of the Monument. At night-time wind can be considered as the only significant cause for vibration/sway of the Monument, (as visitors are excluded and traffic is light in that region of London). While on-going measurements are continuing, data have shown that the problems that Hooke and Wren experienced were fundamental to the nature of the building itself and could not have been overcome to create a stable telescope that they had designed, in spite of having access to the best large-scale lenses available globally at the time (from the workshop in the Netherlands of Constantijn Huygens, brother of Christiaan). Thus, a Monument it was – and a Monument is has remained – rather than being a working telescope.

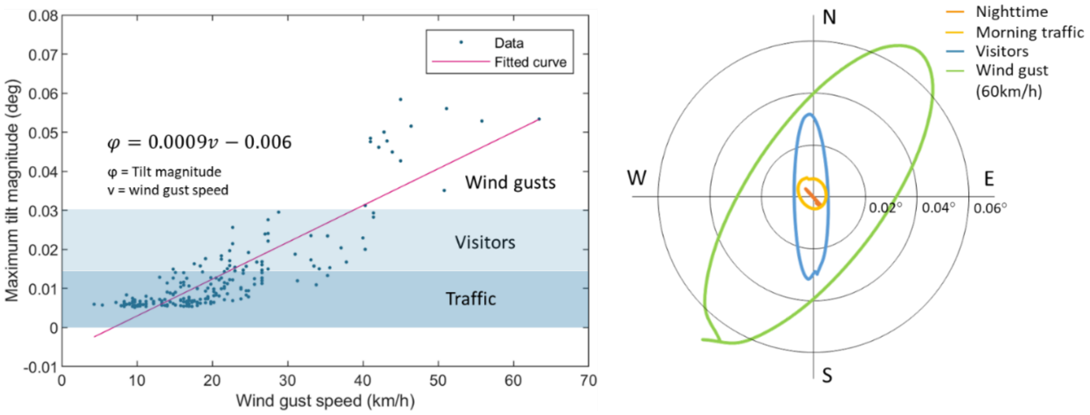

Figure 5. (left) Maximum tilt magnitude versus wind gust speed: including effects of local traffic (deep blue band); of visitors ascending stairs (light blue band); (right) Data visualization of several tilt effects (N-S and E-W axis shown).

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REFERENCES

[1] Jardine, J., “Monuments and microscopes: Scientific thinking on a grand scale in the early Royal Society,” Notes Rec. R. Soc. Lond., 55(2), 289-308, (2001).
[2] Ali, W., Liu, D., Li, J., Pery, A. D., Herrada, N., Mills, D., Owen, R. A., Burton, P. A., Dong, D., Gannaway, G., Bushby, A. J. and Dunstan, D. J., “Nanostrain sensitivity in a wire torsion experiment,” Rev. Sci. Instrum., 91(1), 013901, (2020).
[3] Rao, Y.-J., “In-fibre Bragg grating sensors”, Meas. Sci. Technol., 8, 355–375, (1997).