

A suite of optical fibre sensors for structural condition monitoring

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ABSTRACT

This paper is to review the research activities at City University London in the development of a range of fibre Bragg grating (FBG)-based sensors, including strain, temperature, relative humidity, vibration and acoustic sensors, with an aim to meet the increasing demands from industry for structural condition monitoring. As a result, arrays of optical fibre sensors have been instrumented into various types of structures, including concrete, limestone, marine propellers, pantograph and electrical motors, allowing for both static and dynamic monitoring and thus enhanced structural reliability and integrity.

Keyword List: Fibre Bragg grating, structural condition monitoring, optical fibre sensors

INTRODUCTION

Fibre Bragg Gratings (FBGs) have been explored widely for various structural condition monitoring [1][2]. This is due to their key characteristics of producing wavelength encoded signals that are not susceptible to instrumentation drift or environmental variations. In addition, they offer the capability of multiplexing multiple sensors on to a single length of fibre and allow for the share of the same light source and detector. Coupled with the intrinsic advantages offered by the fibres, into which the FBGs are written, including small size, light weight, immunity to electromagnetic interference and inert to harsh working conditions, FBGs have demonstrated to be suitable for monitoring various types of structures, in particular in those where their electrical counterparts have shown limitations.

This paper covers both the operational principles of a suite of FBG-based sensors that has been developed at City University London and a number of case studies, highlighting their potential for wide industrial applications.

FBG-BASED TEMPERATURE AND STRAIN SENSORS

Optical fibre Bragg gratings (FBGs) are used as a basis for simultaneous temperature and strain measurement [12]. An FBG is a structure with the fibre core being periodically modulated and which reflects the light at a wavelength termed the Bragg wavelength (λ_B) that satisfies the Bragg condition, given in equation (1).

$$\lambda_B = 2n_{eff}\Lambda \quad (1)$$

where n_{eff} is the effective refractive index of the fibre core and Λ is the grating period, where *both* are affected by strain/vibration and temperature variations, a feature that is reflected in the sensor design.

When the FBG is used for measurement of strain and/or temperature, equation (1) can be replaced by equation (2)

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - P_e)\varepsilon + [(1 - P_e)\alpha + \xi]\Delta T \quad (2)$$

where P_e is the photoelastic constant of the fibre, ε is the strain induced on the fibre, α is the fibre thermal expansion coefficient and ξ is the fibre thermal-optic coefficient. The first term of equation (2) represents the longitudinal strain effect on the FBG and the second term represents the thermal effect, which comprises a convolution of thermal expansion of the material and the thermal-optic effect.

One of the key features that FBG-based sensors have demonstrated is their multiplexing capabilities. Figure 1 shows a typical FBG-based sensor layout based on the wavelength-division-multiplexing (WDM) with each grating (sensor point) being encoded with a specific wavelength. This characteristic is of particular importance for large-scale structural condition monitoring, allowing for simultaneous multi-point multi-parameter measurement over a long distance yet with limited number of fibres ('wires'). As indicated in equation (2), each Bragg wavelength shift, induced either by the strain or temperature variation, is associated with the specific Bragg wavelength that is location dependent as illustrated in Figure 1. Compared to conventional strain gauge-based techniques, the optical fibre Bragg grating-based quasi-distributed sensing approach has shown significant advantages in terms of ease of handling/installation and the interrogation of a large number of sensing points, i.e. FBG strain/temperature sensors, and coupled to a single source and interrogated by a single detector. In addition, there is no need to post-process the FBG raw data obtained due to their high signal-to-noise ratio compared to those from strain gauges. As illustrated in Figure 1, a Wavelength Division Multiplexing (WDM) scheme [4] can be used very effectively to address the gratings and yield both the strain/vibration/temperature values of multiple sensors and, through prior calibration, their physical locations on the target structure.

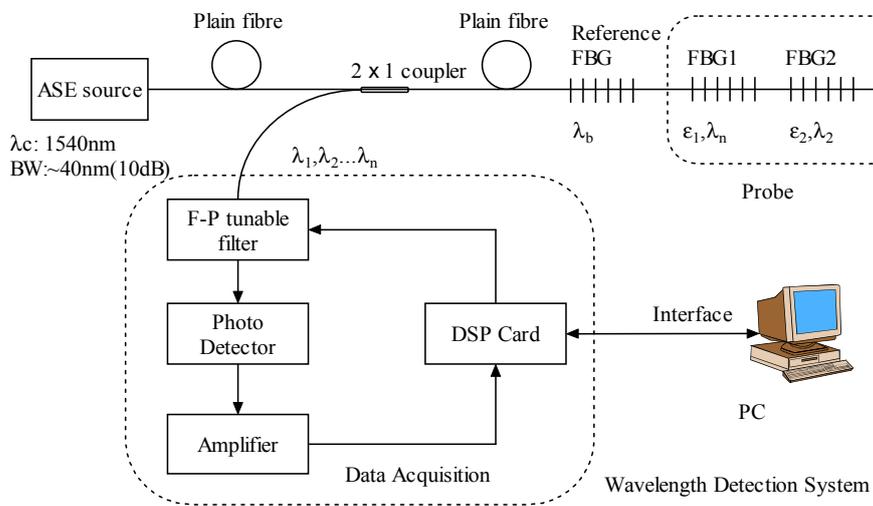


Figure 1. Quasi-distributed FBG-based sensor system with each sensor being encoded with a specific wavelength

As indicated clearly in equation (2) that a FBG has a cross-sensitivity, i.e. it is sensitive to both strain and temperature; therefore when strain measurement is required using a FBG, its temperature effect is required to be compensated. The latter has triggered a large number of publications in relation to the diversity of compensation mechanisms proposed.

Figure 2 shows a typical example of using FBGs for monitoring a structure where its electromagnetic (EM) interference would cause a problem to electrical temperature sensors, e.g. thermocouples. Figure 2(a) shows an electric motor stator instrumented with 17 FBGs mapped on the inner circumference and Figure 2(b) the zoom-in photo, showing both the FBG sensors and their fibre connection to an interrogation system, as illustrated in Figure 1. For cross-comparison, several thermocouples are also included in the test for temperature measurement.

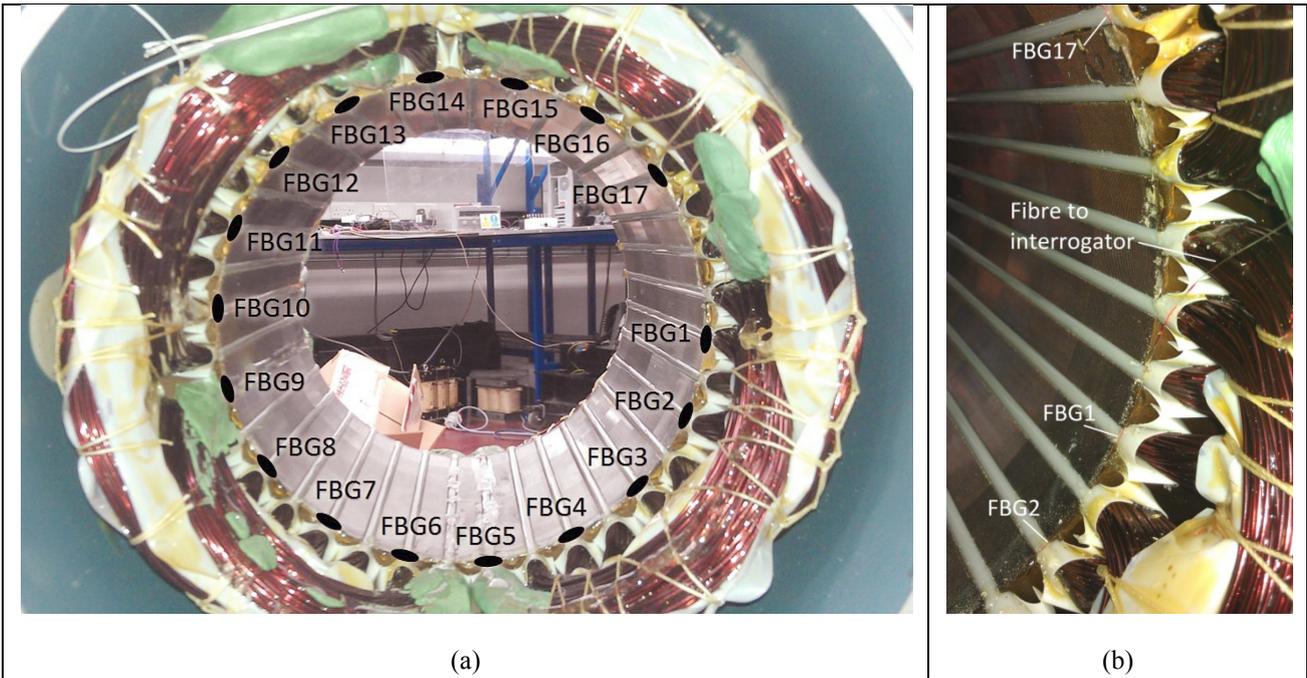


Figure 2 (a) An electric motor instrumented with 17 FBGs mapped on the inner circumference of a stator; (b) zoom-in picture, showing both the FBG sensors and their fibre connection to an interrogator

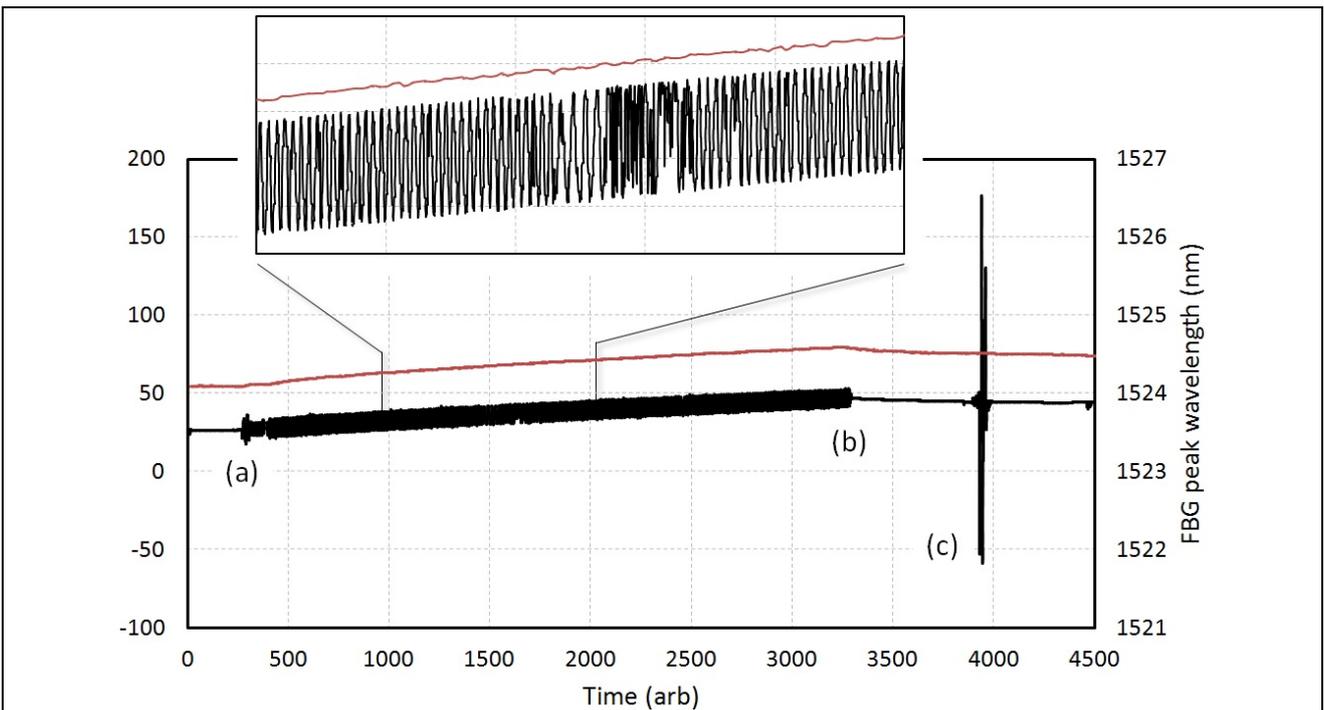


Figure 3 Preliminary experimental data obtained from a FBG-based temperature sensor (red), in cross-comparison with that from a thermocouple (black)

Figure 3 shows the experimental data obtained from a FBG-based temperature sensor, in cross-comparison with that from a thermocouple, when the motor is under various operational conditions. At (a), the power injected into the motor is ramped up and it is noticeable that the FBG (red curve) and thermocouple (black curve) both indicate the increase of temperature showing that the motor is heated up when it is in operation. However, the signal from the thermocouple (not shielded) is far noisier than that from the FBG, confirming that the optical sensor is immune to the EM interference, unlike the conventional thermocouple. At (b), the motor is switched off and both sensors indicate the motor cooling process, together with the disappearance of the EM effect on the thermocouple. At (c), the motor is switched on again, but unlike (a) in which the power is injected slowly, the step change of the power in this case leads to a massive scale of noises appeared at the thermocouple signal, but not at the optical sensor signal, demonstrating a clear advantage of optical fibre sensors being used for measurement in an environment where electromagnetic interference becomes an importance issue to conventional electrical sensors.

FIBRE OPTIC VIBRATION SENSORS

As indicated in equation (1), the Bragg wavelength shift is linearly proportional to the grating period and the variation of which is determined by the vibration of the object to which the FBG is attached. Figure 4 (a) shows a typical example by mapping arrays of FBGs (335 FBGs in total) on to a full marine propeller and using the layout illustrated in Figure 4 (b), in order to correlate the dynamic response of the Bragg wavelength shifts to the vibration of the propeller when it is excited by a fixed frequency. Therefore the modal shapes of the vibration of the blades can be determined by converting the time-domain signals of the FBGs into the natural frequencies of the propeller using a Fast Fourier Transform analysis approach.

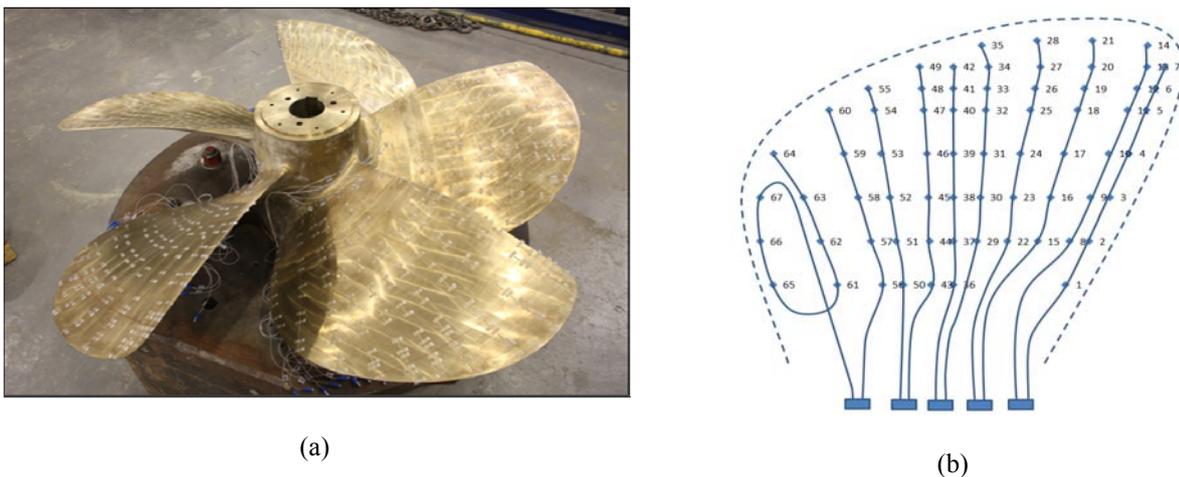


Figure 4 (a) a propeller with all the blades instrumented with a FBG-based sensor network; (b) layout of FBG sensors on each propeller blade

In order to verify the experimental results obtained, a comparison has been made between the experimental data obtained from the 335 FBGs and those obtained from the theoretical modelling using the finite element analysis of the structure. As a result, a very good agreement has been reached.

FIBRE OPTIC MOISTURE INGRESS SENSOR

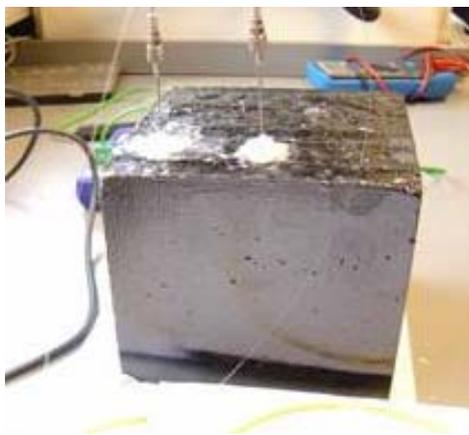
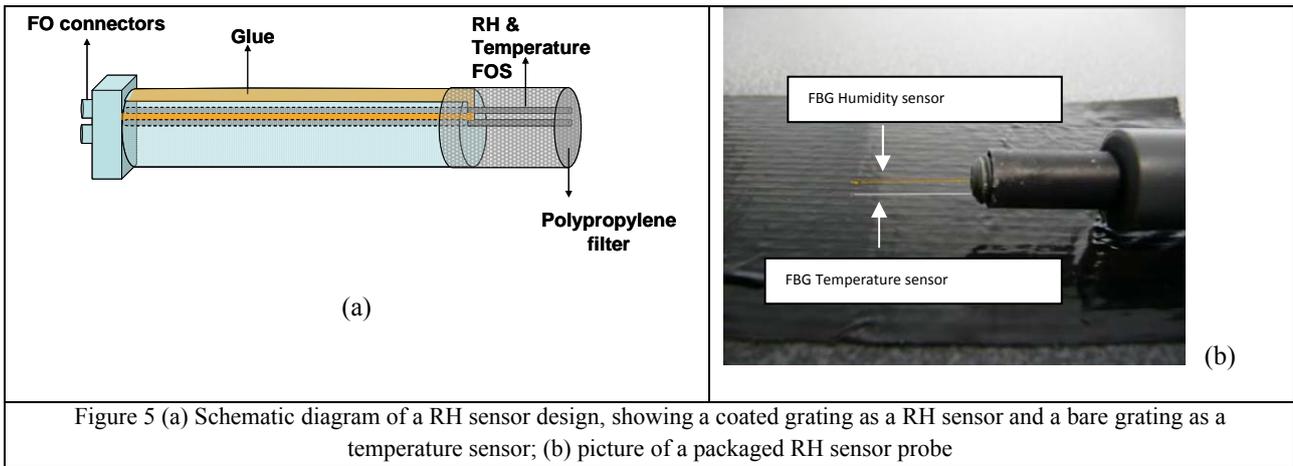
The fibre grating can be made to act as the basis of the Relative Humidity (RH) sensor principle and the humidity sensing concept used in this sensor exploits the strain effect induced in a FBG through the swelling of a thin layer of applied polymer coating. The swelling of the polymer coating, arising from the absorption of moisture, changes the

Bragg wavelength of the FBG, where this can be calibrated to give a direct indication of the humidity level. Thus the shift in the Bragg wavelength in equation (2) for the polymer-coated FBG can be modified as follows.

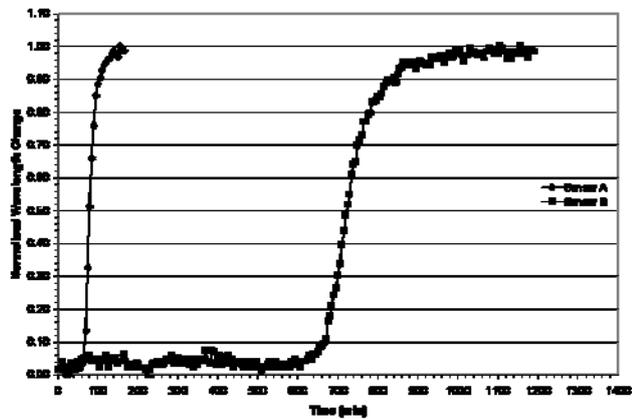
$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - P_e)\alpha_{RH} \cdot \Delta RH + [(1 - P_e)\alpha + \xi]\Delta T \quad (3)$$

where α_{RH} and α_T are the moisture expansion coefficient and the thermal expansion coefficient of the coated FBG.

Achieving temperature compensation is important as such grating-based devices are temperature sensitive and thus a second ‘temperature-only’ grating element is used to create the complete sensor system. To do so, a bare FBG is also included in the sensor design. Figure 5 (a) and (b) shows respectively the schematic diagram and a picture of the humidity sensor probe design, in which both grating elements can be seen – a bare FBG without coating is used for temperature measurement and for temperature compensation of the coated humidity sensor.



(a)



(b)

Figure 6 (a) A concrete samples of water/cement ratio of 0.7; (b) RH response of the optical sensors

In order to investigate moisture migration in structures, samples with different concrete characteristics were prepared and a bitumen layer was coated on the surface of the sample cubes, except for the one face which allowed moisture to

permeate. As shown in Figure 6(a), samples with a water-to-cement (w/c) ratio of 0.7 had sensors positioned at 25 mm and 75 mm away from the uncoated face. Figure 6(b) shows typical results illustrating, as expected, the longer time for the moisture ingress to be detected at sensor B, this being manifested as a change in the characteristic wavelength of the sensor. The time difference of the water to reach sensors A and B is a function of both the mix type and the sensor position for the moisture ingress propagating through the sample. Thus by creating samples with varying concrete mix proportions, the data recorded on moisture ingress could give a clear and quantitative indication of the permeability to water in different samples with different porosity values.

FIBRE OPTIC ACOUSTIC SENSOR

Similar to FBG-based vibration sensor discussed above, a FBG can also be modified to be an acoustic sensor by modifying the design of the FBG interrogator. Figure 7 illustrates the layout of a sample metal plate instrumented with both the FBG-based acoustic sensor and a PZT sensor, coupled with their corresponding interrogation systems. The signal detected by the photodiode is cross-compared with the signal detected by the PZT sensor, placed adjacent to the FBG on the same metal plate.

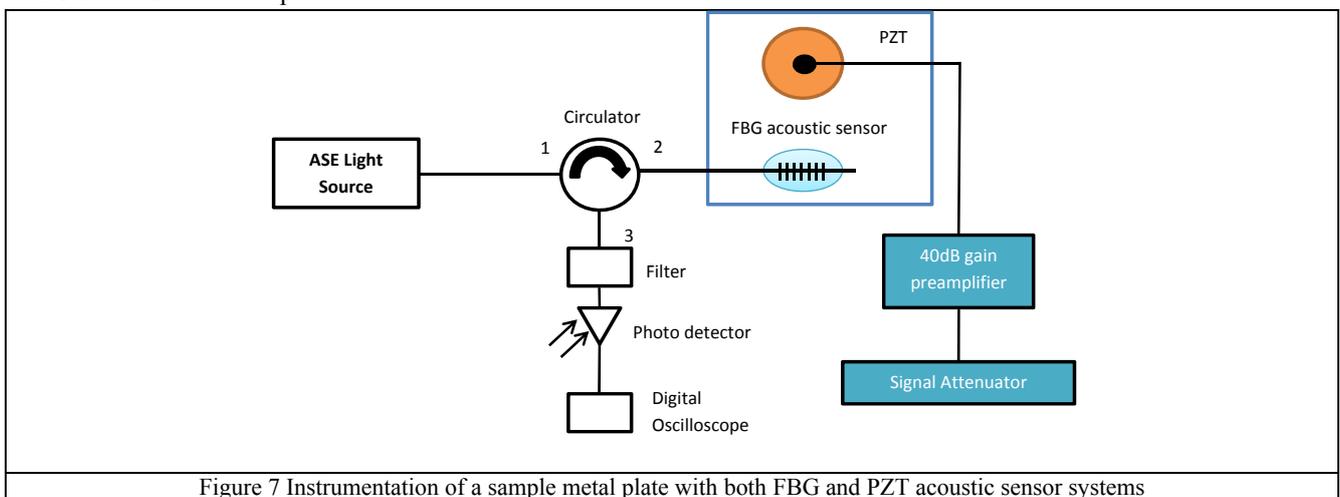


Figure 7 Instrumentation of a sample metal plate with both FBG and PZT acoustic sensor systems

Figure 8 shows the raw data collected by both the PZT and FBG acoustic sensors when a sonotrode operates at a fixed frequency of 19.5kHz and is positioned 1mm above the metal plate, for a time frame of 5s in a water tank in order to simulate a cavitation process. After the conversion of the signals from the time-domain to frequency-domain, it is noticeable from Figure 8 that the same frequency element of 19.5kHz, which matches with the excitation frequency, has been captured by both sensors. Compared to PZT sensor, FBG sensor has shown some additional second harmonic signals which require further investigation.

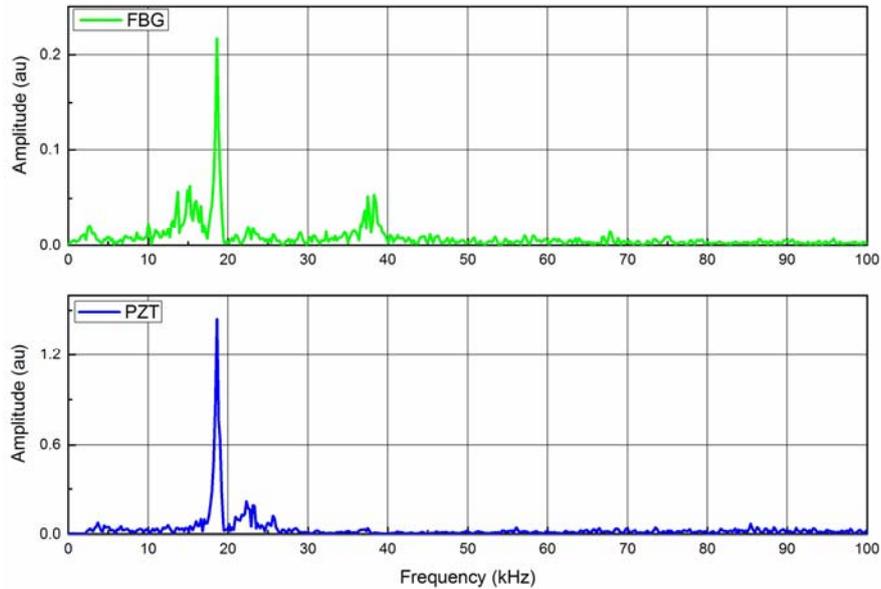


Figure 8 Frequency response comparison between FBG based acoustic sensor and PZT based acoustic sensor

SUMMARY

A suite of optical fibre sensor systems has been developed and evaluated, showing promise for wide industrial applications. These sensors have been designed to provide real-time measurement of a suite of key parameters that would help engineers to diagnose the properties of a variety of structures and materials and thus to understand better their performance and characteristics. Research is still 'on-going' both to expand the portfolio of novel sensors and instrumentation incorporating optical fibres and to widen the functionalities and scope of optical fibres from static to dynamic domain.

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