

Plastic optical fibre sensor for spine bending monitoring

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Abstract. This paper presents a study on the application of plastic optical fibre for spine bending monitoring based on an intensity modulation. The bending angle is measured as the angle between the emitting and receiving fibres is changed. The measured light attenuation is compared with a theoretical evaluation and the differences between these values are discussed. It was found that the light attenuation for the light intensity agreed well (margin of error < 15%) with the theoretical value for the range between 180° (representing no bend) and 200° and it was significantly increased for the bending angle beyond that value due to the effect of fibre gap increment which resulted in a less reliable experimental estimation.

1. Introduction

The importance of optical fibre in sensing applications has been highlighted by many researchers and these have been summarized in [1] according to the type of measurands. In general, the optical fibre type can be classified into glass optical fibre (silica) and plastic optical fibre (POF). These two types of fibre can be distinguished from several point of views such as fibre handling issues (connection, flexibility and technical precision level requirement), fibre optic parameters (signal loss, wavelength operating range, numerical aperture and bandwidth) and cost of handling (component cost, system cost and test equipment) which have been summarized in [2].

As compared to POF, glass fibre potentially offers a more sensitive and accurate measurement. However as the overall cost is more expensive, plastic optical fibre has been widely studied due to the overall use of low cost components such as LEDs, photodiode, multimode fibre and basic amplifier circuit for signal amplification. Furthermore, the strains encountered in this application are likely to be a few percent in magnitude in which glass optical fibres cannot endure and can easily break. Therefore the use of POF in this investigation represents a better solution. However, the intensity modulation technique employed in this investigation is dependent on many extraneous factors such as noise and drift of the LED and photodetector circuit, intensity fluctuation due to source temperature changes, external light source coupling and fibre bending effects. Such errors have been minimized using forms of referencing techniques such as balanced bridge, divided beams and two-wavelength referencing [3].

This paper presents the development of a simple and low cost optical fibre bending sensor based on intensity modulation for use in physiotherapy clinical environments. To define the minimum working range of the sensor, typical range of motions of human spine comprising of lumbar, cervical and thoracic are presented. The working range and the light attenuation characteristics of the sensor are presented and compared with the theoretical values. To understand the effects of fibre gap



(longitudinal displacement) and fibre tilt angle (bending angle) with respect to the light attenuation, both results of light attenuation (in dB) versus fibre gap (in mm) and bending angle (in degree) are initially presented. A brief overview of currently available optical-based sensors for monitoring human spine bending is also presented in orders to provide an up to date comparison between of those techniques and the one of this investigation.

2. Human spine monitoring

Spine monitoring activities have widely been conducted as a measure to differentiate between healthy and back-pain patients, apart from interviews and discussions approaches which are considerably difficult to provide meaningful data for further analysis [4]. As for the back-pain sufferers, the spinal examination is an understandably difficult task for them to undergo as this process would normally require some exaggerated activities of back movements such as flexion, extension, lateral bending and axial rotation.

Moreover, for most measuring techniques, the devices are placed directly on the skin surface at the back of the body which adds more distress to the patient condition. Besides that, for certain patients' condition it is necessary to continuously monitor the spine movement up to several hours in order to identify the actual cause of the back problems [5]. To reduce this discomfort experience, several non-invasive techniques have been widely studied to provide alternatives to physiotherapists in handling these tasks and to increase more comfort to respective patients.

2.1. Human spine range of motion and sensor working range

As stated above, human spine monitoring involves several parameters which are flexion angle, extension angle, lateral bending and axial rotation. Besides that, several other parameters can also be measured in the same area along the human spine such as point to point position, angular velocity and acceleration as well as range of motion. Range of motion of human spine is defined as the angle between the maximum bending between flexion and extension.

There are many reference text that facilitate the understanding of the anatomy and basic terminology related to human spine, e.g. [6]. In order to define the sensor working range, it is necessary to find the bending angle limitation of the lumbar, cervical and thoracic spines in the intended directions of the spine movement. Typical range of motion of human spine can be found in [7] and presented in summary in table 1. However, the actual range of motion may depend on several other factors such as age, gender and spinal health condition.

Table 1. Typical range of motion of human spine [7].

Type of movement	Cervical	Thoracic/ Lumbar
Flexion	45°	75°
Extension	55°	30°
Lateral bending	40°	35°
Rotation	70°	30°

3. Review on current optical fibre sensor for spine bending monitoring

A wide range of sensors have previously been studied and tested on patients to monitor the spine bending movement with differing degrees of success. As all these research work have been conducted by different persons and under widely differing testing environments and subject groups, it is not possible to accurately compare each sensor's performance. The prime reason for providing this brief background is to identify the differences between each sensor type in terms of sensing mechanism, type of measurand and sensor installation requirement as compared to the sensor design presented here.

The first optical fibre sensor is designed using plastic optical fibre with abraded fibre side [8]. To measure the light attenuation at multiple points along the spine, the fibre was cut at several positions along the same side of the fibre using the technique proposed in [9] as shown in figure 1. This sensor was proven to be comfortably wearable and extensible in sensing length. Besides that, it is also possible to measure the direction of the bending throughout the measurement. If the abraded area is at the external side (convex) of the bending fibre, more light will escape the fibre, thus giving a higher attenuation and vice versa. On the other hand this sensor was sensitive to noise and fluctuation of the light source and detector as well as external light coupling effect at the abraded fibre areas.

The second sensor was realised using a positional optical fibre [10] to record the curvature of the spine during static flexion and extension position. It was designed using 8 paired optical fibre sensing loops periodically spaced at 6 cm along a flexible metal ribbon. Each sensor loop detected bend and twist along the substrate and converted the data into orthogonal orientation vectors. Then, the position of each sensor along the tape, relative to a base or reference point was tracked and recorded using the software developed by the ShapeTape™ supplier company (Measurand Inc). More description on the sensing mechanism for this type of sensor is presented in [11] and illustrated in figure 2. This optical fibre sensor was shown to have the ability to resolve spinal shape change across time at multiple spinal regions. However, as the measurement was based on sensor orientation with respect to the base sensor, the attachment process was difficult and time-consuming. Furthermore, it was not possible to measure any lateral bending as metal ribbon is stiff in sideways directions.

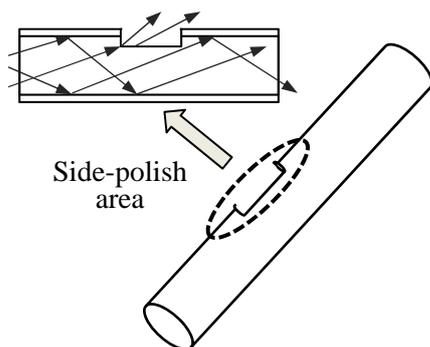


Figure 1. Side-polish optical fibre bending sensor

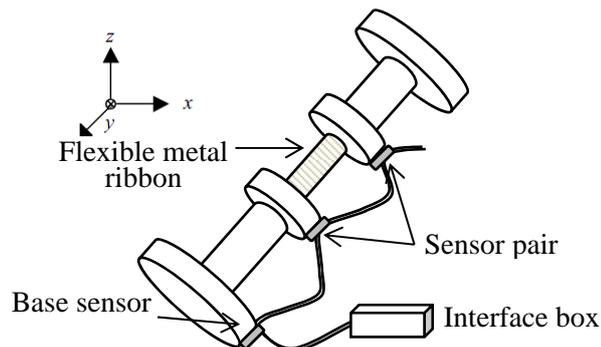


Figure 2. Positional optical fibre sensor

The next sensor was implemented using optical fibre goniometer (FOG) system [12]. The overall sensor comprised of a baseplate, a flexible rod, infrared LED source, a phototransistor and a modified 1 mm diameter optical fibre. The baseplate was placed on the sacrum level (S1) using adhesive tape. The fibre was inserted in a flexible rod and it was placed onto the lumbar spine by using two slider tubes. Similar to the previously considered positional optical fibre sensor, this FOG sensor was also not able to measure any movement in lateral directions.

4. Sensor configuration implementation

Several aspects have been considered before a suitable configuration is proposed for the development of spine bending sensor using plastic optical fibre such as the overall size of the sensor, interface medium between the sensor and the human body surface as well as approach to reduce the effect of external disturbances. For the initial experimental setup of this study, the type of fibre used was Mitsubishi Rayon GHV4001 (multimode plastic optical fibre (PMMA) with a core diameter of 1 mm, numerical aperture at 0.5, step index profile), a green LED source (IF-E93) with peak wavelength at 530 nm which was ideally mapping to the lowest attenuation window of PMMA fibre [13] and a stabilized RiFOCs detector. A few millimetres of fibre gap was allowed to give a smooth bending angle movement between the emitting fibre and receiving fibre.

In this section, two separate configurations of the OFS of this investigation are considered:-

4.1. Fibre longitudinal displacement loss

Both input and output fibres end were polished with a flat end tip. The emitting fibre was attached on a static stage while the other fibre was placed on the micrometer positioning stage (moveable part) using an adhesive tape. The receiving fibre was moved in a longitudinal direction and the change of the output intensity of the detector was measured at every 0.25 mm movement. The relationship between the light intensity loss and the distances between fibres is presented in [14] as shown below:-

$$\alpha = -10 \log \left(1 - \frac{2 \cdot s \cdot NA}{3 \cdot d \cdot n_0} \right) \quad (1)$$

Where s is the distance between the fibre gap, NA is the numerical aperture of the fibre, d is the diameter of the fibre core and n_0 is the refractive index of the medium in between those fibres (in this case, air).

4.2. Fibre tilt angle loss

This type of configuration is based on the changes of the light intensity as the angle between the emitting fibre axis and the receiving fibre axis is increased. Both end tips of the emitting and receiving fibres were polished with flat surface and placed into V-pin crimp simplex connector (HFBR-4501Z). Clear silicon soft rubber tubing with inner diameter of 4 mm and outer diameter of 6 mm was used to firmly hold both fibres (with an initial gap of 1.5 mm) in their positions as shown in figure 3. The sensor was then placed on top of a custom-made bending rig to allow a better sensor movement. An 8 inch spinal goniometer was placed next to the bending rig for measuring the bending angle. The light intensity in the form of voltage output was measured for each 5° of bending angle between 130° and 230° . The maximum initial voltage value was measured at the output for a straight fibre (180°) and the light intensity was found to be linearly dependent on the fibre axis changes between 180° and 220° and between 180° and 140° .

In general, the light attenuation that is caused by the changes of the angle between the fibre axes can be presented in an equation [15]:

$$\alpha = -10 \log \left(\cos \theta \left\{ \frac{1}{2} - \frac{p}{\pi} \sqrt{1-p^2} - \frac{\arcsin p}{\pi} + q \left[\frac{r}{\pi} \sqrt{1-r^2} + \frac{\arcsin r}{\pi} + \frac{1}{2} \right] \right\} \right) \quad (2)$$

Where

$$p = \frac{\cos \theta_c (1 - \cos \theta)}{\sin \theta_c \sin \theta}, \quad q = \frac{\cos^3 \theta_c}{(\cos^2 \theta_c - \sin^2 \theta)^{3/2}}, \quad r = \frac{\cos^2 \theta_c (1 - \cos \theta) - \sin^2 \theta}{\sin \theta_c \cos \theta_c \sin \theta}$$

Where θ is the angle between fibre axes and θ_c ($\theta_c = \arcsin [NA/n_0]$) is the acceptance angle for the fibre, which is depending on the fibre numerical aperture. For the type of fibre used in this measurement, the acceptance angle, θ_{max} is 30° , which limits the light attenuation calculation using the above equation up to an angle of fibre axes of 59° .

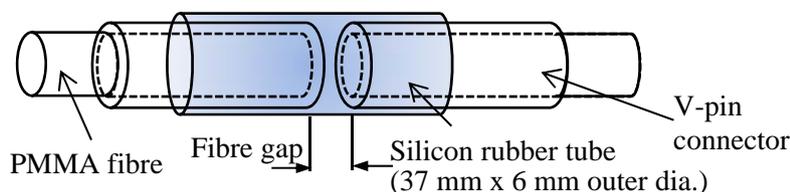


Figure 3. Proposed spine bending sensor

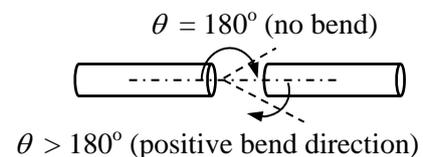


Figure 4. Fibre tilt angle

5. Results and discussion

To accurately define the light attenuation characteristic of the fibre bending angle, both fibre tilt angle and fibre gap (displacement) were measured separately. The measurements of light intensity versus fibre gap and fibre tilt angle are presented in figure 5 and figure 6, respectively.

From figure 5, the intensity of the light is in linear relationship with the fibre gap at three different slope degrees. The maximum slope ramp is between 0 mm and 2.75 mm, while the minimum slope is between 5.5 mm and 10 mm. For simplicity output intensity estimation, a suitable linear analysis can be found for each fibre-gaps sub-group separately using a regular linear equation approach.

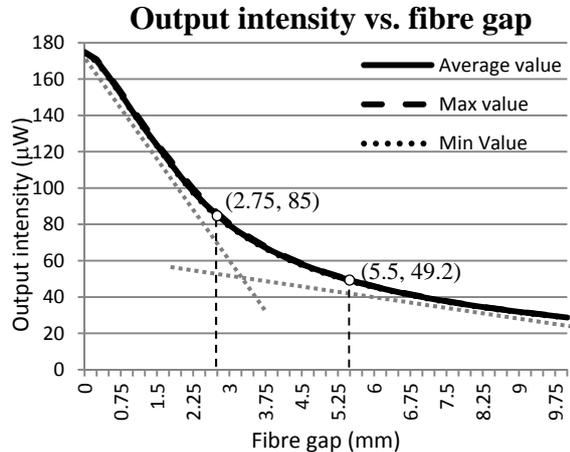


Figure 5. Light intensity (μW) vs. fibre gap (mm)

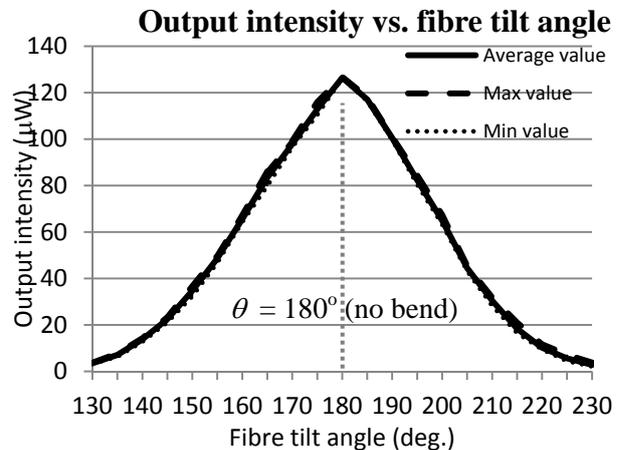


Figure 6. Light intensity (μW) vs. fibre tilt angle (degree)

It is also noted from figure 6 both positive and negative directions of the fibre axes angle are relatively linear between 180° and 215° and between 140° and 180° . When the bending angle is increased beyond that angles ($\theta < 140^\circ$ and $\theta > 215^\circ$) less light loss is measured. Fibre optic position with respect to the bending angle is illustrated in figure 4 where 180° represents no bending. The difference between the theory and measurement values for the fibre gap in figure 7 is significantly increased as the distance is increased which is understandable because the equation was initially derived for splicing loss estimation of fibre gap of less than 1 mm assuming uniform mode distribution [14]. The light attenuation characteristic for the applied tilt angle is shown in figure 8 and summarized in table 2. The differences are significant for $\theta > 200^\circ$ due to fibre gap increment caused by tilt angle.

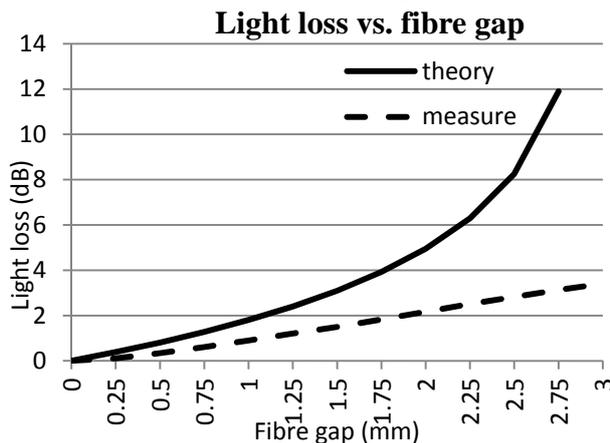


Figure 7. Light loss (dB) vs. fibre gap (mm)

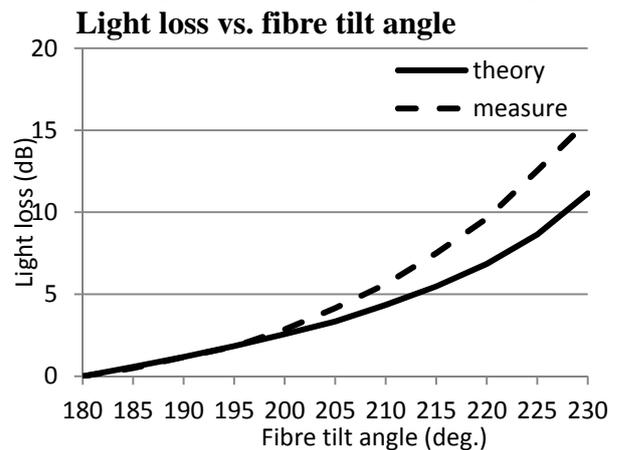


Figure 8. Light loss (dB) vs. fibre tilt angle (mm)

Table 2. Light loss comparison between theory and measurement for different tilt angle

Tilt Angle, θ ($^\circ$)	180	185	190	195	200	205	210	215	220	225	230
Measurement (dB)	0.00	0.49	1.16	1.81	2.85	4.15	5.61	7.50	9.61	12.53	15.55
Theory (dB)	0.00	0.57	1.18	1.84	2.57	3.34	4.35	5.47	6.85	8.64	11.15
Difference	0.00	-0.08	-0.02	-0.03	0.28	0.81	1.26	2.03	2.76	3.89	4.40
Margin of error (%)	0.01	14.0	1.7	1.6	10.9	24.3	29.0	37.1	40.3	45.0	49.5

6. Conclusion

Plastic optical fibre sensor based on intensity modulation for measurement of bend angles in the spines of human physiotherapy patients has been presented and discussed. The measurements of light intensity with respect to fibre gap and fibre tilt angle were compared with theoretical values. The light intensity decreases with the increase in the gap between emitting and receiving fibres as well as increases in bending angle between them. As the fibre gap increases sharply when the fibre was bent at a greater angle, it was found that the measurement values departed from the theoretical ones, but this was due to a higher degree of non-linearity in the measured intensity with the increasing angle. However a signal was still detected in this range.

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