Physiological bending sensor based on tilt angle loss measurement using dual optical fibre

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Abstract—This paper presents the development of an extrinsic optical fibre sensor for continuous measurement of the human spine bending movement based on intensity modulation technique. Using the investigated sensor configuration, the bending angle was measurable in both flexion and extension direction with a maximum range of motion of 18° and -10°, respectively. From the output drift assessment of the sensor, bending accuracy of up to 0.5° was achievable, thus making it suitable for clinical environment application. A divided-beam referencing technique was also implemented in the sensor configuration to compensate for the input power fluctuation and temperature variation.

Keywords—bending assessment; divided-beam referencing; intensity modulation; optical fibre sensor

I. INTRODUCTION

In the application of the human spine system, various types of devices have been implemented to measure the bending movement of the human spine, as an effort to understand the problem source associated to back pain [1]. In general, most of these sensors can be categorized into three main groups, based on their method of operation. These groups include of the hand-held, non-contact and skin-mounted device types.

Hand-held devices are usually made of simple apparatus, manually operated by well-trained person, but practically not suitable for continuous measurement. Besides that, the accuracy of the measurement results is significantly dependent on the individual operator. Some good examples of this kind of device are flexible ruler, two-arm goniometer, inclinometer, pen pointer [2], and spinal wheel [3].

In the case of non-contact device type, the sensors are normally consists of a pair of source and detector. The source is typically mounted on the human skin and while the respective detector is securely placed nearby, within the working range of the device. This kind of sensor type includes of CCD camera system [4], rasterstereography [5] and video fluoroscopy [6]. However, this type of sensors requires a special room to operate effectively and a complex hardware and software integration for continuous measurement purpose, thus leading to high implementation cost of the overall system.

For the skin-mounted type, it is more suitable for continuous measurement of the spine bending movement, with several other associated advantages such as minimum human supervision requirement, non-invasive device, moderate cost, give no restriction to patient movement, can be made portable and does not require a special room to operate. Most commonly studied skin-mounted devices are strain gauge [7], ultrasonic sensor [8], electromagnetic sensor [9], inertial sensor [10], and motion analysis system [11].

However, the aforementioned device examples are more likely susceptible to electrical and magnetic interference as well as bulky in size, which may cause discomfort to the user. Alternatively, bending sensor based on optical fibre is more suitable in clinical environment application (e.g. in MRI surrounding) due to its inherited advantages. Besides its immunity to electromagnetic interference, the optical fibre is also relatively small in size, low weight, and has a better safety in terms of free from ground loops, electrical sparks, and dangerous high voltage problems. This guarantees that the sensor is free from fire hazard or electrical shock risk to patients since there are no electrical connections to the body.

In this paper, an extrinsic sensor using plastic optical fibre aimed for continuous measurement of the human spine bending movement application is presented. The magnitude and direction of the bending movement were measured from fibre tilt angle loss assessment between the source fibre and the two receiving output fibres. An additional fibre was also added into the sensor configuration, acting as a reference for the sensor output signal by means of a divided beam referencing method. The proposed sensor configuration has a maximum range of motion of 18° in flexion and -10° in extension directions, with a bending accuracy of up to 0.5°.

II. THEORETICAL ESTIMATION

A. Fibre tilt angle loss

Light attenuation of the transmitted signal due to angular misalignment between two identical fibres is approximately equal to:

\[ a = 10 \cdot \log(\frac{\theta_{max}^2 \cdot \pi}{\theta_{max}^2 \cdot \pi - 2 \cdot \theta_{max}}) \] (1)

Where; \( \theta_{max} \) is the acceptance angle of the fibre, and \( \epsilon \) is the tilt angle between the two fibres. From (1) and supported with our previous experimental investigation [12], it was found that smaller bending angles (0° – 5°) the light attenuation with respect to the bending angle was relatively 4 to 6 times smaller...
than the larger bending range (5° – 20°). As a result, it was difficult to measure the bending movement accurately between 0° – 5°, even at a very minimum output drift.

B. Fibre lateral offset loss

As this sensor configuration involves lateral misalignment between the input fibre and two sensor fibres (i.e. flexion and extension fibres), this offset loss was estimated using the following equation:

$$\alpha = 10 \cdot \log \left( \frac{d^2 - \pi/4}{d^2 - \pi/4 - d^2 x^2} \right)$$  \hspace{1cm} (2)

Where: \(d\) is the diameter of the fibre core, and \(x\) is the lateral distance the two fibres offset. Using (2), the loss is around 4dB, assuming the input fibre is centrally positioned between the two side-by-side output fibres end tips and the gap between the input and output fibres is kept as minimum as possible as shown in Fig. 2.

C. Gap between fibre end tip and reflector

This estimation was highlighted to determine a suitable gap between the fibre end tip and the mylar film (reflector) so that sufficient light can be coupled back into the reference fibre via the reflector while a part of it was transmitted into the sensor fibres (via the middle fibre). As presented by Faria [13], the light intensity received at the reference fibre is:

$$P_r(x) = \frac{2}{\xi^2} e^{-\xi^2/2}$$  \hspace{1cm} (3)

Where: \(\xi = 1 + 2x / z_o\), \(x\) is the gap between the fibre end tip and the reflector and \(z_o\) is the cone vertex distance from the fibre end tips (i.e. \(z_o \approx 1.75 \text{ mm for PMMA fibre [14]}\)). It was also shown [12] that for this particular type of optical fibre, the collected power at the receiving fibre achieved its maximum value at \(\xi = \sqrt{8}\), giving a gap value, \(x = 1.6\) mm.

A comparison between the theoretical and experimental values is presented in Fig. 1. From these results, the output intensity reached a maximum value at a gap of 1.6 mm in both theoretical and actual measurements, thus this was applied in the sensor configuration.

D. Overall output ratio value (with reference signal)

The output intensity of the optical fibre bending sensor applied in this investigation, \(I_S\) was obtained from the manipulation of three fibre outputs as follow:

$$I_S = \frac{I_A r^2}{I_A r^2 + 1}$$  \hspace{1cm} (4)

Where: \(I_A\) is the light intensity at fibre A (flexion), \(I_B\) is the light intensity at fibre B (extension), and \(I_R\) is the reference output signal. By using this output arrangement to measure the bending angle, the poor sensitivity problem for small bending angles was effectively overcome.

III. SENSOR CONFIGURATION

The bending sensor in this investigation consists of a duplex step index PMMA fibre (EH 4002, Mitsubishi Rayon), a green LED (IF-E93, Industrial Fiber Optics Inc.), three photodiodes (SFH 250V, Avago Technologies), and three modified PTFE rods. A small size of mylar film with a centered 1 mm diameter hole was attached at the surface of the PTFE rod opposite to the source and reference fibre end tips.

As shown in Fig. 3, a divided-beam referencing technique was applied to provide a reference signal so that any common mode error which is likely to arise from the fluctuations of the input power and surrounding temperature can be rejected.

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**Figure 1.** Theoretical and experimental comparison

**Figure 2.** Optical fibre bending sensor probe

**Figure 3.** Block diagram of the bending sensor
At the position where the transmitted signal was reflected into the reference fibre, the two PTFE rods were fixed together using a solid connector so that the gap between these rods was maintained at all time during bending movement. At the next point where the light modulation took place, the PTFE rods were attached together using a 5 mm diameter silicon rubber tube. In terms of the PTFE rod design, one end of this PTFE rod was tapered so that a small portion of this rod can fit into the hole of the second rod (i.e. rod with the sensor fibres inside). This shape was adapted to help the two separate rods in maintaining their alignment after bending movement.

IV. MEASUREMENT RESULTS

During the experimental investigation, the optical fibre sensor probe was securely mounted on a self-made bending apparatus to allow the sensor to move consistently and to avoid cross sensitivity with any likely lateral movement, before the flexion-extension bending assessment was performed. The angle of the sensor is measured and cross-checked against a conventional goniometer (Prestige Medical) whose accuracy is limited to 1°. Therefore, all measurement value in this investigation was limited to this value.

A. Bending Assessment

The first measurement result presented here is the light attenuation of the sensor output with respect to angular bending in flexion and extension directions. The sensor was placed in a straight position at the beginning of the test for a 1 min period. Later, the bending angle was extended in the flexion direction for an additional 1.0° for the next 1 min and so on until a maximum bending was achieved. After this was completed, the sensor was returned to a straight position, before the same process was repeated in the opposite direction (extension).

From the bending assessment of the sensor shown in Fig. 4 and Fig. 5, it was found that the sensitivity of the sensor was relatively linear throughout the bending increment. The only issue was that, the output intensity level was slightly fluctuated at higher bending angles. This result was expected because at a larger fibre tilt angle misalignment, it was difficult to maintain the tilting position of the PTFE rods, due to the nature of the silicon rubber tube.

The sensitivity of the output voltage between each additional fibre bending angle was presented in Table I for better illustration of the sensor sensitivity.

<table>
<thead>
<tr>
<th>Bending angle</th>
<th>Normalized output voltage</th>
<th>Sensitivity$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10</td>
<td>-0.88</td>
<td>0.082/1°</td>
</tr>
<tr>
<td>-5</td>
<td>-0.47</td>
<td>0.092/1°</td>
</tr>
<tr>
<td>0</td>
<td>0.01</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>0.41</td>
<td>0.084/1°</td>
</tr>
<tr>
<td>10</td>
<td>0.84</td>
<td>0.086/1°</td>
</tr>
<tr>
<td>15</td>
<td>1.25</td>
<td>0.082/1°</td>
</tr>
<tr>
<td>18</td>
<td>1.40</td>
<td>0.050/1°</td>
</tr>
</tbody>
</table>

$^b$ Sensitivity between each 5° bending angle.

B. Output Drift

The output voltage drift test was conducted for 2 hours during a straight position of the fibre at a room temperature of 20°C ($\pm$ 5°C). As shown in Fig. 6, the output voltage was drifted to +0.003 from its initial zero value during this 2 hour assessment. It was presumed that, this drift was caused by the warm up process of the light source. At a later period, this output intensity remained consistent at the same output level.

C. Repeatability Assessment

The repeatability test was conducted to study the ability of the silicon tube to hold the fibre holders together during the bending and to maintain the same level of sensor output voltage after each repetitive bending movement. As shown in Fig. 7, the normalized output ratio was dropped from 0.41 V to -0.47 V as the sensor was bent from 5° to -5° and the same level of output ratio was reproduced after at least five times bending repetitions.
From the experimental results presented in this paper, some important properties of the sensor are summarized in Table II. The achieved working range and resolution of the sensor are compared to the typical range of motion of the human spine based on previous studies on human spine motion conducted by recognized physiotherapists [15]. The summary of the range of motion of the segmental of the human spine is presented in Table III. By referring to this set of data, it was presumed that the extrinsic optical fibre bending sensor in this investigation is capable to provide a continuous measurement of the human spine bending movement.

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