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An Intensity-Modulated Optical Fibre Displacement Sensor with Convex Reflector

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Abstract:
A novel intensity-modulated optical fibre displacement sensor with convex reflector technology is described. A common form of the intensity-modulated optical fibre sensor performs its measurement by making use of a pair of straight optical fibres with a plane reflector. The reflected optical signal intensity changes as a function of change in displacement. This paper describes an alternative sensing structure with a convex reflector instead of a plane reflector and demonstrates the derivations of geometric and Gaussian mathematical models. The blind region or non-sensitive region is minimized when the plane reflector is replaced by a convex reflector. Such type of optical sensor can be used where space required for the measurement is the major limitation. Since the intensity stabilization of light emitting diode (LED) is the prime necessity of intensity modulated optical fibre sensors, the instrumentation for intensity stability of LED is developed.

Keywords: Intensity modulated optical fibre sensor, displacement sensor, convex reflector, blind region

I. INTRODUCTION

Optical fibre sensor technology plays major role for advancements of technologies such as telecommunications, sensor and control. Optical fibre sensors offer several advantages over the conventional sensing devices such as small size, lightweight, potentially multiplexable immune to electromagnetic interferences (EMI), without electromagnetic susceptibility (EMS), high sensitivity, fast response time, and good accuracy [1], [2].

There are many different types of optical fibre sensors that have widely been used today. One of the most well known is that which exploits an intensity modulation scheme. Intensity-modulated optical fibre sensors have become popular not only for their accuracy, ruggedness, and contactless operation, but also because the detection schemes associated with them are very simple and low cost [3]-[5].

The simple form of intensity modulation mechanism consists of a pair of straight parallel optical fibres; one transmitting fibre projects the light on reflector and the other receiving fibre collects the reflected light from the reflector, which is moved in the direction parallel to the fibre axis due to the effect of a physical quantity. The physical quantity may be displacement, force, pressure, torque, sound or vibration. However, the problem with this mechanism is that it has large blind region or non-sensitive region [6], [7]. This leads to need large space for measurement.

This paper focuses on the design of intensity-modulated mechanism with a pair of straight parallel optical fibres with a convex reflector. The derivations of the geometric and Gaussian mathematical models are developed for describing the characteristics of sensing mechanism. The mathematical models show that the blind region or insensitive region is minimized when a plane reflector is replaced by a convex reflector. Hence the effective space required for the measurement is reduced. It is verified by performing experiments with plane and convex mirrors. The electronic circuit with feedback mechanism is designed. Also the LED fibre coupler with feedback PIN photodiode is developed.

The paper is organized as follows: Section I gives the introduction of intensity modulated optical fibre sensor. The mathematical model of the intensity modulated optical fibre sensor with convex reflector is derived in Section II. The experimentation is described in section III. The results are discussed with the conclusion in section IV which is followed by the references.

II. THEORETICAL ANALYSIS

A typical two-fibre refractive index sensor configuration is shown in Fig.1. It consists of a transmitting fibre (T), convex reflector (M), and a receiving fibre (R). An optical source (LED) and a photo-detector (PD) are connected by connectors to transmitting fibre (T) and receiving fibre (R) respectively, which are not shown in the figure. The fibre tips and concave reflector are separated by a distance h. The geometrical and Gaussian approaches will be presented for modelling of the

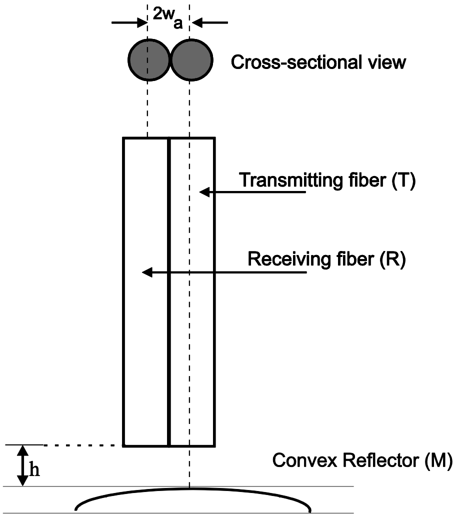

Fig. 1 The basic configuration of two fibre displacement sensor with convex reflector.sensor.

The mathematical models with plane reflector are reported [8],[9]. This paper focuses on the mathematical model of optical fibre sensor with convex reflector.

Following assumptions are being considered for the mathematical model:

1. The transmitting fiber and receiving fiber have perfectly circular cross-sections with area S_a and radius w_a.
2. Both the fibers are straight parallel, with no space left between them and having the same numerical aperture NA.
3. The transmitting fiber is placed on the focal axis of the convex reflector CX.
4. The light intensity cone formed, as the light leaves the transmitting fiber, is perfectly symmetrical with divergence angle θ_a. The vertex O of the cone is located at a distance z_a from the fiber tip inside the fiber.

The mathematical model can be developed by considering the ray diagram of sensor configuration as shown in Fig. 2. The transmitting fibre is perfectly placed on the focal axis CX on the convex reflector M. The transmitting fibre emits light cone beginning at O, with divergence angle θ_a is given by the equation

$$\theta_a = \sin^{-1}\left(\frac{NA}{n_0}\right) \quad (1)$$

where NA is the numerical aperture and n_0 is the refractive index of the medium present in between the fibre tips and the convex reflector.

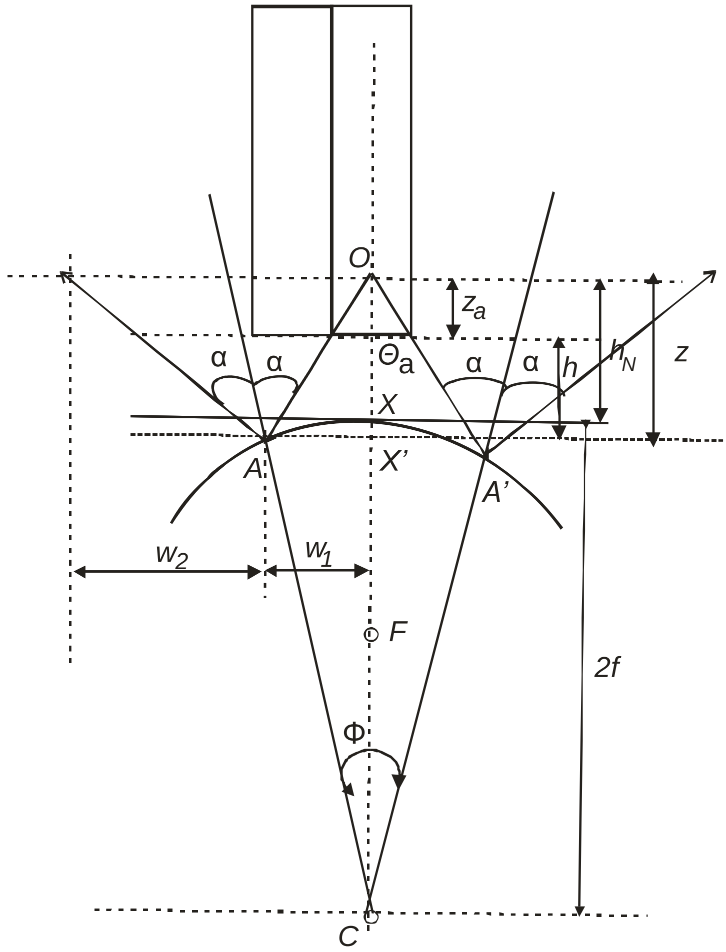

Fig. 2 Geometry of the light intensity modulation mechanism using a pair of optical fibres with a convex reflector.

In order to evaluate the amount of light collected by the receiving fibre, it is necessary to derive the circular cross sectional area of the reflected cone in the plane of the receiving tip.

At point A, on convex reflector, CA is the normal to the concave reflector. The incident ray OA gets reflected at point A, making an angle of reflection α to the normal CA. CA is the radius of curvature i.e. two times the focal length f of the convex mirror. Considering the triangle OAC, the angle α can be calculated by using the sine rule.

$$\alpha = \sin^{-1}\left(\frac{(2f - h_N)}{2f}\sin\theta_a\right) \tag{2}$$

Also, from triangle OAC,

$$\frac{\varphi}{2} = \alpha - \theta_a \tag{3}$$

In triangle $X'AC$,

$$\cos\frac{\varphi}{2} = \frac{X'C}{AC} = \frac{X'C}{2f} \tag{4}$$

$$X'C = 2f\cos\frac{\varphi}{2} \tag{5}$$

And

$$XX' = 2f - X'C \tag{6}$$

$$XX' = 2f\left(1 - \cos\frac{\varphi}{2}\right) \tag{7}$$

From fig.2

$$z = h_N + XX' \tag{8}$$

$$z = h_N + 2f\left(1 - \cos\frac{\varphi}{2}\right) \tag{9}$$

A. *The Geometrical Approach*

For the geometrical approach, the assumption is, the light intensity I (or irradiance) remains constant for all points inside the circular cross section of the cone and the intensity is zero outside the cone, i.e.

$$I = \begin{cases} \frac{P_E}{\pi w^2}, & \textit{inside the cone} \\ 0, & \textit{outside the cone} \end{cases} \tag{10}$$

where, P_E is the optical power emitted by the transmitting fibre and w is the radius of the circular cross section of the reflected cone for the current value of h. From fig. 2, $w = w_1 + w_1$.

Also $w_1 = z\tan\theta_a$ and $w_2 = (z - z_a)\tan(2\alpha - \theta_a)$

$$w = z[\tan\theta_a + \tan(2\alpha - \theta_a) - z_a\tan(2\alpha - \theta_a)] \tag{11}$$

Substituting the z from (9) in above equation,

$$w = \left[h_N + 2f\left(1 - \cos\frac{\varphi}{2}\right)\right] [\tan\theta_a + \tan(2\alpha - \theta_a) - z_a\tan(2\alpha - \theta_a)] \tag{12}$$

The above (12) shows that the radius of the circular cross section of the cone at fibre tip depends on the distance h and refractive index n_0 of the medium present in between the fibre tips and the convex mirror, i.e.,

$$w = f(h, n_0) \tag{13}$$

The optical power collected at receiver fibre tip is obtained by evaluating the overlapping area S of two circles: 1) the circle of radius w corresponding to the light cone and 2) the circle of radius w_a corresponding to the collecting area of the receiving fibre [8]-[10]. Radiometric analysis to calculate coupled power at receiving fibre by integrating transmitting area and receiving area is reported [11].

The optical power P collected by the receiving fibre is obtained by multiplying the illuminated area S_A by the light intensity in (10), i.e.

$$P = P_E\frac{S_A}{\pi w^2} \tag{14}$$

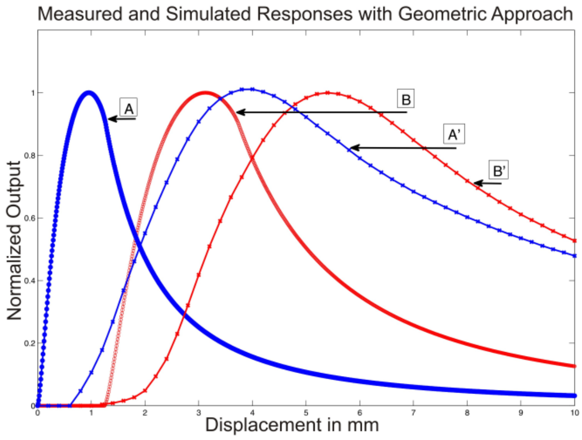

Fig. 3 Simulated responses with geometrical approach and measured output responses of optical fibre sensor obtained with plane and convex reflectors for air (RI=1). A- Simulated response with geometrical approach for convex reflector, B- Simulated response with geometrical approach for plane reflector, A'- Measured response for convex reflector, B'-Measured response for plane reflector.

B. *The Gaussian Beam Approach*

The Gaussian beam approach is more realistic than the geometric approach. Considering the light leaving the transmitting fibre, not a ray cone, but a paraxial wave beam with Gaussian profile [8]. The irradiance of emitted light does not remain constant over beam cross sections (as in geometric approach) [12], but decreases radially, according to

$$I = \frac{2P_E}{\pi w^2} exp\left(-\frac{2r^2}{w^2}\right) \tag{15}$$

where r is the radial coordinate and w is the radius as in (12).

The power collected by the receiving fibre is calculated by

$$P = \frac{2P_E}{\zeta^2} exp\left(-\frac{8}{\zeta^2}\right) \tag{16}$$

where $\zeta = z/z_a = 1 + 2\,h/z_a = 1 + h_N$

The simulated responses of (14) for geometrical approach and (16) for Gaussian approach are presented in fig.3 and fig.4 respectively. The plots show the normalised collected optical power $P_N = P/P_{max}$ versus the displacement for plane reflector as well as for concave reflector of the focal length 10 cm for a medium having refractive index 1. The results for a plane reflector are referred from the paper of José Brandão Faria et al [8]. The blind region is minimised in the optical fibre sensor with a convex reflector.

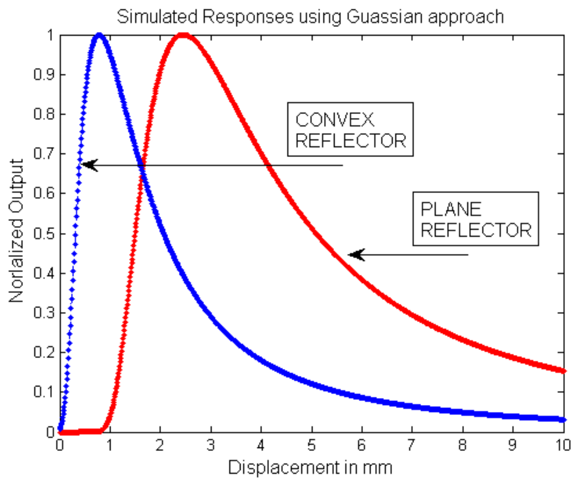

Fig. 4 Simulated output responses of optical fibre sensor obtained by Gaussian approach for plane reflector and convex reflector for refractive index = 1. The blind region of the sensor having convex reflector is zero, while plane reflector has a blind region.

C. *Sensitivity Analysis*

The sensor sensitivity S can be obtained by evaluating the derivative of P_N with respect to h_N, i.e. $\partial P_N/\partial h_N$. By using (16) the sensitivity function is expressed as,

$$S = \frac{2\partial P_N}{\partial \zeta} = \frac{4}{\zeta}\left(\frac{8}{\zeta^2} - 1\right) P_N \quad (17)$$

The Fig. 5 shows the sensitivity curves for plane reflector and convex reflector. These show the variations of the sensitivity corresponding to change in displacement. The optical fibre sensor with plane reflector has zero sensitivity or dead zone at the beginning, while the optical sensor with convex reflector doesn't have dead zone.

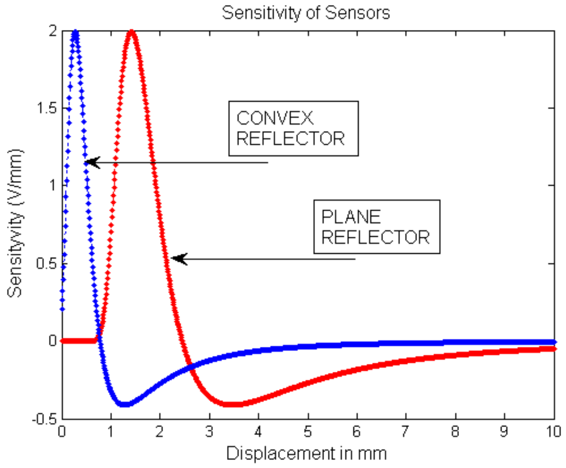

Fig. 5 The plot of sensor sensitivity versus displacement. The dead zone or blind region is absent in optical fibre sensor with convex reflector.

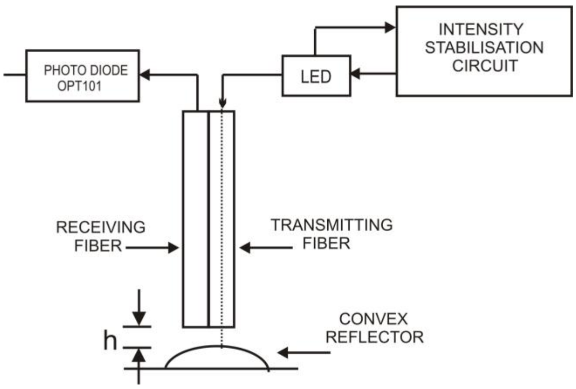

Fig. 6 The experimental setup of intensity modulated optical fibre sensor with LED stabilisation circuit for the comparison of plane reflector and convex reflector.

III. EXPERIMENTAL

A. Experimental Setup

The experimental setup of intensity modulated optical sensor with LED intensity stabilisation circuit is shown in Fig. 6.

To verify the mathematical model of the sensing mechanism that employs a convex reflector (Fig. 1), a set of experiments was conducted with a pair of polymethylmetacrilate (PMMA) optical fibres, which have a core diameter of 1 mm, a core refractive index of 1.47, an *NA* of 0.50. The fibres, which are 70 cm long, were held in place with a stationary support. The reflector was fixed on a backlash-free 3-axis translational mechanism, with 3 micrometer screw-gauges, enabling movements over a vertical range of 0-15 mm far from the fibre tips, having resolution 0.01 mm (Fig. 7). A high intensity red LED (peak wavelength

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620 nm) and photodiode (OPT101), which operated in a photoconductive mode, were directly coupled to the transmitting and receiving fibres respectively. The red LED was driven by the LED stabilisation circuit, which is described subsequently. The transmitting fibre was aligned on the focal axis of the convex reflector with the help of an integrated device having laser-diode and a monitor photodiode (opnext-HL6340MC). The convex mirror having a focal length of 10 cm and diameter 50 mm is used. The experiments were carried out for plane reflector as well as for convex reflector at 25^0C temperature.

B. LED Intensity stabilisation

When light emitting diodes (LEDs) are used as light sources in sensor applications, their thermal stability which is temperature and time dependant becomes important. This requirement becomes even more stringent as the time period of observations increases [13]. Various techniques, such as intensity referencing and phase sensitive detection for temperature and intensity stabilization are reported [13]-[15].

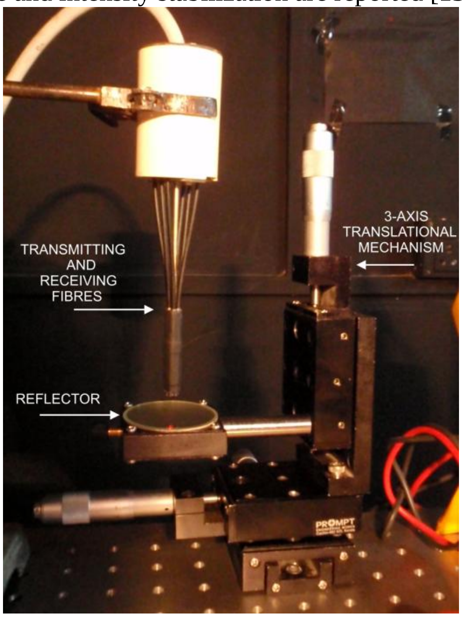

Fig. 7 Optical setup for the experiment with backlash free 3-axis translational mechanism.

The Fig. 8 shows circuit diagram of LED driver circuit with LED-Fibre connector. An intensity stabilized LED driver is designed by using LM723, which has in built temperature compensated zener diode for reference set intensity, error amplifier and current booster with short circuit protection. The intensity of the source LED is stabilized by using a BPW34, PIN photodiode, in feedback loop. LM723 is used in low voltage regulator mode. The voltage set-point is derived by using voltage divider network. The same network is biased by internal temperature compensated zener diode. The facility is provided for changing different coloured LEDs. The intensity of each source LED is set by sensing there light intensity output detected by photodiode BPW34. The intensity set-point is derived from internally temperature compensated zener diode (for 0^0 C to 70^0 C).

The LED-Fibre coupler with intensity referencing facility is developed. The mechanical assembly is shown in Fig. 9. The photograph is shown in Fig. 10. The light emitted by the LED is split by the beam splitter (80:20). The 80% light is used for the sensing purpose, while 20% light is utilised for referencing. The circuit and the LED-Fibre coupler are tested from 10^0C to 70^0C temperature. The intensity of the LED was appreciably stable.

IV. RESULTS AND CONCLUSION

The Fig. 3 shows the comparison of the simulated responses of the sensors for plane as well as for convex reflector for air (RI=1) obtained from the mathematical representation by the geometrical approach. The blind region

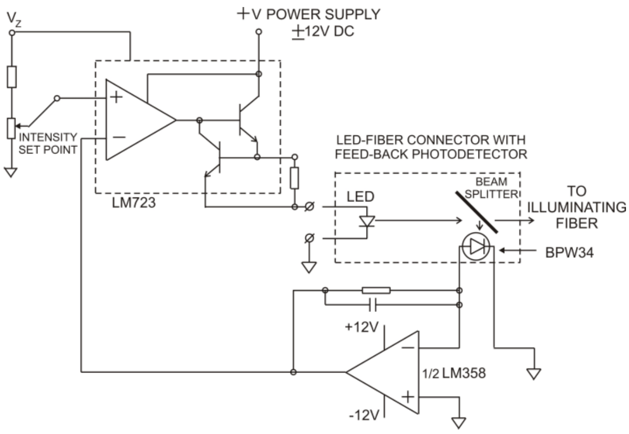

Fig. 8 LED stabilisation circuit with LED-Fibre connector with feed-back PIN photodiode BPW34.

of the sensor, having convex reflector is zero, while the sensor with plane reflector is having blind region.

The Fig. 3 also shows the measured responses for plane and convex reflectors. The measured responses are almost unmodelled effects such as nonlinear characteristics of the radiant light beam [8], distance between two fibre tips (since the fibre cores were separated by their claddings and the plastic coatings) and the possible small mechanical misalignment between the transmitting fibre and the focal axis of the convex mirror create significant amount of errors. The major problem with this configuration is to place transmitting fibre on the focal axis of the convex reflector. These result in relatively large modelling errors in simulated normalized output responses.

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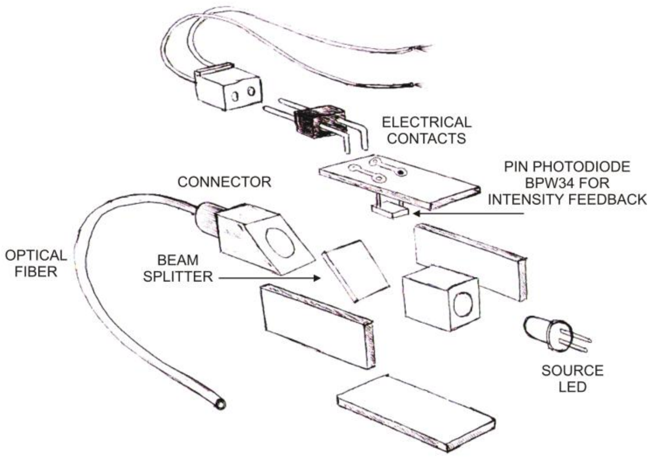

Fig.9 The mechanical assembly LED-Fibre coupler with feedback PIN photodiode BPW34.

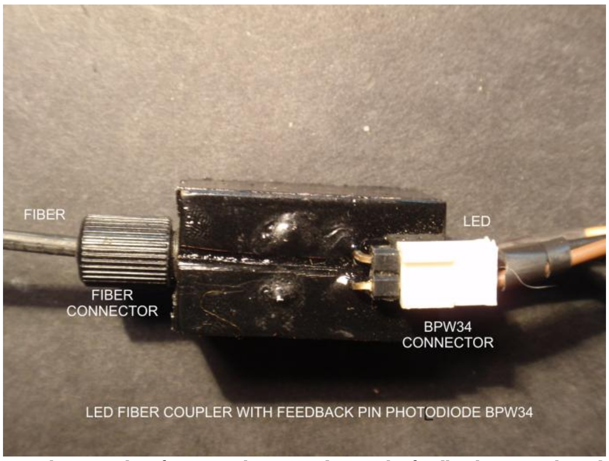

Fig.10 Photograph of LED-Fibre coupler with feedback PIN photodiode BPW34.

The mathematical models of intensity-modulated optical fibre sensor with convex reflector is developed and verified experimentally. The study shows that the blind region of the fibre optic sensor can be minimized by using convex reflector. Such type of sensor can be used, where the space required for the measurement is the major limitation.

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