Large Stroke Fiber Optic Displacement Sensor Using Self Referencing Technique

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Abstract: Fiber optic displacement sensors are widely used in industry. These sensors however, have a limited linear operating range. A typical sensor constructed with 1 mm core diameter fibers has linear operating range of about 2-3 mm. Moreover, output of these sensors depends on the source intensity, reflector properties and fiber losses. Self referenced configurations of fiber optic displacement sensors are generally used to make the sensor immune to variation in source intensity or reflectivity of reflector etc. This paper reports a new fiber optic displacement sensor configuration which is similar to the self referencing arrangement and has wider operating range. During the experimentation with different arrangements of this type of sensor configuration, it is observed that different asymmetries have effect on the sensor performance parameters viz. sensitivity and linear operating range. Simulations are also carried out for these different configurations using the reported mathematical model. It is revealed from the theoretical analysis that a combination of asymmetries viz. different core radii of two receiving fibers and unequal horizontal offset leads to improvement in the sensor performance while maintaining the immunity advantage. A sensor probe is fabricated having transmitting fibers with 0.488 mm radius and two receiving fibers with 0.488mm and 0.75mm radius placed at distance of 0mm and 5mm respectively from the transmitting fiber is fabricated with movable mirror at a distance. The whole assembly is enclosed to get rid of stray light. Experiments are carried out using the developed sensor probe and proper signal conditioning circuit. Linearity of the Fiber optic displacement sensor is experimentally confirmed over the distance of 20mm. Thus it is said to have large stroke of 20mm and can act as a substitute for commercial transducer like LVDT.

***Inex terms*: self referenced fiber configuration, large stroke measurement, fiber optic sensor**

I. INTRODUCTION:

The fiber optic sensors (FOSs), with the characteristics of immunity to electromagnetic interference, noncontact sensing method and easy integration, have attracted the attention of many researchers over the past decades. Fiber-optic displacement sensors will play an increasingly larger role in a broad range of industrial, military, and medical applications. The accuracy of the fiber-optic displacement sensor based on single-mode fiber as a sensing probe is very high, but its detection range is limited to a few millimeters due to large divergence angle of the output beam. Several studies measuring the linear displacements have been done, particularly those based on optical sensors. Perhaps, the most known methods are the interferometer methods, such as Michelson, which is in wide use. This kind of interferometer reaches nanometer resolution and a long-range measurement, but after interpolation. The SIOS Me_technik GmbH Company developed an interferometer based on Michelson technique, which has a resolution of 0.1nm and a 5m range. By using the Fabry–Perot interferometer a resolution of 50pmrms can be reached but for a small measurement range. In the study], the speckle interferometer technique is used and 1 nm of resolution on a 100 µmrange is obtained. For two-d imension measurement, a second interferometer is necessary, which makes the device bigger. In an interferometer based on the optical configuration and heterodyne interferometry was developed, a resolution about 0.5nm within 250µm displacement can be achieved. The optical encoder allows also the measurement of the linear displacements. For example, the Olympus society [8,9] developed amicro-encoder with a VCSEL laser. This sensor has a resolution of 100nm after interpolation. By using a double-head reading, a resolution of 2 nm is reached [10]. The study shown in [11] describes a double pass surface encoder, composed of a 2D sinusoidal grid and an optical sensor, a resolution higher than 5 nm was achieved. Another study used CMOS technology to develop an encoder that has a resolution of 125nm without interpolation [12]. The use of this measurement technique requires another device for the second measurement axis and in the majority of the cases the interpolation is necessary to reach a nanometer resolution. A direct measurement method in two-dimension based on inductive encoder was developed in [13] and a resolution of 10_m was obtained. Other techniques are used for the measurement of linear displacements. In the study [14], three VCSEL lasers and three photodiodes are used to measure the displacements of a mirror in two dimensions. Resolutions of 20nm and 40nm on 0.4mm and 1.8mm range are reached, respectively. Team [15] developed a micro-optical probe sensor (MOPS), which includes diode laser source, optical probe generation system and photo-detector. This sensor achieved a resolution measured of 0.4_m and the accuracy of 0.8_m. Two-dimensional capacitive sensor was developed in [16], the principle used the capacitance of parallel plate electrodes which depends on their mutual area of overlap, a resolution of approximately 1.2_m has been achieved and is limited by the electronics used. Fiber optic sensors are also used, 0.5nm resolution on a 30_m range is measured [17] by the use of one emission and one reception fiber, but the measurement is realized only in one dimension. Study [18] used microfabrication techniques to reduce the size of the optical sensor. The performances are given as follows: resolution of 9 nm and 100nm for a range of 10_m and 80_m, respectively. Team [19] proposes a fiber optic sensor that consists of one emission fiber with amicro-lens and eight reception fibers. Experiments in two dimensions were realized and the result gives an accuracy of 15_m for 1mm range. Another study [20] has used a fiber optic sensor based on intensity modulation technique to measure small distances. A very good linearity was shown over a range of 0.05–0.35mm with sensitivity of 168.8mV/mm and over a range of 1.05–2.20mm with sensitivity of 29.8mV/mm. As a summary, some of the sensors use interpolation to reach good limit of resolution, others have too big size when two dimensional measurements is needed and most of the sensors have small measurement range when nanometer limit of resolution is required. The fiber optic sensor which measures displacements in one dimension on a long-range is described in [21]. It is based on two fiber optic probes and a reflecting light silicon grating, used together the long-range linear measurements are obtained. The fiber collimator is one of the important passive devices, which has been widely used to improve the coupling efficiency in the field of optical communication, such as the optical switch, attenuators, isolators and the multiplexer/demultiplexer, etc. Compared with the normal single-mode fiber, the divergence angle of the collimator is much smaller, which makes it applicable to longdistance measurement such as the liquid level measurement. Some previous researches focused on a graded index-lens collimator to measure the displacement but in a small-distance range.7, 8A simple long-distance fiber collimator-based displacement sensor. The fiber bundle configurations are also used to improve the linear operating range. Hemispherical configuration of fiber optic sensor found to be optimized configuration for getting the linear operating range of the order of 10 mm. But it requires specific arrangement of fibers and output of the sensor is affected by improper coupling, stray light effects etc. Another configuration of fiber bundle with asymmetric core radii for transmitting and receiving fibers are also useful in improving the linear operating range of the order of 0.8 mm.

This paper proposes a novel configuration of fiber optic sensor for measuring the larger stroke of distance. It uses arrangement of three fibers, one transmitting fiber and two receiving fibers having asymmetric dimensions and placements. The output of the sensor is taken as the ratio of the outputs of the two receiving fibers. This technique is similar to self referencing configurations generally used for making the fiber optic sensor immune to variations in source intensity and reflectivity of the reflector. The next section describes the mathematical modeling of this fiber optic sensor. The succeeding sections describe basic principle, development of sensor prototype, actual experimental setup and results and discussion.

II. MATHEMATICAL MODELING OF THE FIBER OPTIC SENSOR

A theoretical model of the sensor can be established by first considering the two fiber model, with one transmitting fiber and one receiving fiber. The intensity of the light emitted by from the transmitting fiber is described with a Gaussian distribution, as shown in equation (1). The light intensity decays exponentially as it moves radially away from the centre of the light circle.

$$I(r,z)=\frac{2P_E}{\pi w^2(z)}\exp\left(-\frac{2r^2}{w^2(z)}\right) \quad \text{------(1)}$$

Where r is the radial co-ordinate, z is the longitudinal co-ordinate from the light origin, w(z) is the beam radius which is also a function of z and

$$w(z)=w_0\sqrt{1+\left(\frac{z}{z_R}\right)^2} \quad \text{------(2)}$$

The waist radius w_0 and Rayleigh range z_R are the important parameters in the Gaussian beam function.

The light power collected by the receiving fiber can be evaluated by using the integral as shown in equation(3)

$$P(z)=\int_{Sr} I(r,z)dSr \quad \text{------(3)}$$

However, the exact integration is tedious and impossible. Therefore, assumptions and approximations were used to solve the integration. For points situated in the far-field, z>> zR the following relations with the divergence angle can be obtained.

$$\theta_a=\tan\theta_a=\frac{w(z)}{z}=\frac{w_0}{z_r}=\frac{\lambda}{\pi w_0} \quad \text{------(4)}$$

Figure 1 shows the geometry of fiber optic sensor consisting of three optical fibers, one transmitting and two receiving fibers. The configuraiton is specifically used to make the sensor immune to variations in source light intensity and reflectivity of reflector due to aging. The sensor output is self referenced by taking the ratio of the outputs of receiving fiber 2 and receiving fiber 1. The transmitting fiber and receiving fiber 1 has same core radii w_a1 . Receiving fiber 1 is placed at a distance S1 from transmitting fiber. Receiving fiber 2 has core radii w_a2 ($w_a2 > w_a1$) compared to receiving fiber 1 and is placed at a distance S2 (S2>S1) from the transmitting fiber.

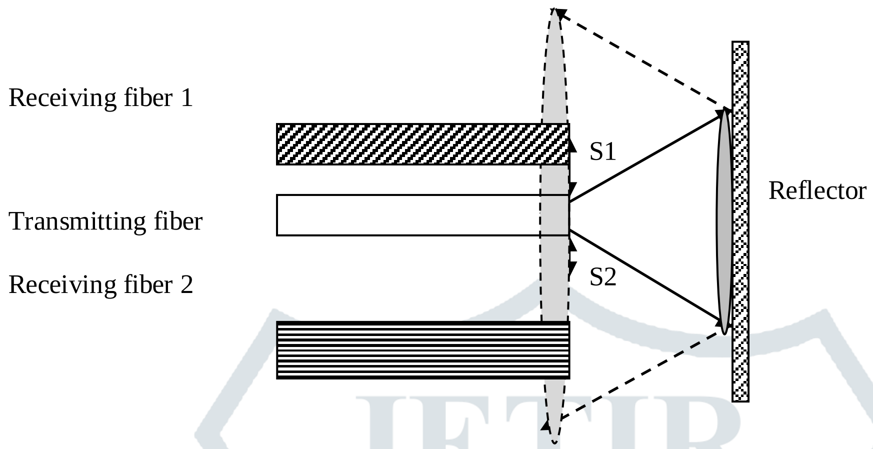

Figure 1: Geometry of Fiber optic Sensor

Figure 2 shows cross sectional view of the sensor geometry for fixed distance between the fiber end faces and reflector. It shows how the receiving fiber 1 and receiving fiber 2 has overlap with the reflected cone of light.

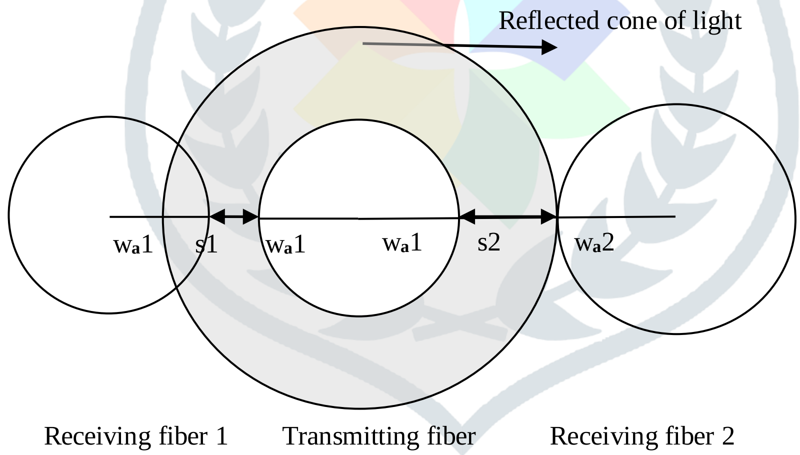

Figure 2 Cross sectional view of the fiber sensor geometry

Let radii of transmitting fiber, receiving fiber 1 and receiving fiber 2 be wa1 and wa2. From the equation(3) power collected by receiving fiber 1(R1) is given by

$$P_{R1}(r,z) = \frac{2P_E}{\pi w^2(z)} \exp(\frac{-2r^2}{w^2(z)}) \times \pi wa1^2 \quad \text{--(5)}$$

From the figure, substitue r=2wa1+s1 in the equation(5)

$$P_{R1}(r,z) = \frac{2P_E w^2 a1}{w^2(z)} \exp(\frac{-2(2wa1+s1)^2}{w^2(z)}) \quad \text{--(6)}$$

Similarly for receiving fiber 2(R2)

$$P_{R2}(r,z) = \frac{2P_E w^2 a2}{w^2(z)} \exp\left(\frac{-2(2wa2+s2)^2}{w^2(z)}\right) \quad \text{---(7)}$$

The self referenced output of the sensor is considered as the ratio of the outputs of receiving fiber 2 to receiving fiber 1 as given by

$$P_{TOTAL} = \frac{P_{R2}}{P_{R1}} = 2\left(\frac{wa2}{wa1}\right)^2 \exp\left(-\frac{(wa2+s2)^2+(wa1+s1)^2}{w^2(z)}\right) \quad \text{---(8)}$$

III. SENSOR STRUCTURE

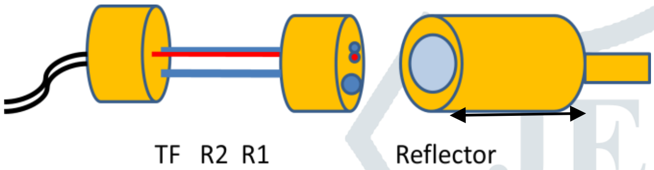

Figure 3 Large stroke fiber optic displacement sensor structure Figure 4 photograph of developed sensor

Figure 3 shows the actual structure of the sensor with large stroke of measurement. The sensor consists of one transmitting fiber with fiber diameter as 1mm and two receiving fibers with diameters of 1mm and 1.5 mm placed at distance of 1mm and 7mm from the transmitting fiber respectively. A mirror is attached to the long spindle which moves the reflector in linear fashion over the distance of 100mm. It is fabricated in backelite and enclosed in the pipe structure to avoid the effects of stray light on the sensor output. Light is launched into the transmitting fiber using the RED LED. Two photo detectors coupled to the receiving fibers are used to detect the light reflected from the mirror. Figure 4 shows photograph of developed sensor.

IV. EXPERIMENTAL SETUP

4.1 Simulation experiments

Using equation (8) the simulations are carried out using the mathematical model [] based on ray tracing approach in MATLAB. The fiber parameters used for simulation are as follows: Transmitting fiber : fiber diameter=1mm, NA=0.47
Receiving fiber 1: fiber diameter=1mm, NA=0.47, Receiving fiber 2:fiber diameter=1.5mm, NA=0.47, Interfiber spacing between transmitting fiber and receiving fiber 1=1mm , Interfiber spacing between transmitting fiber and receiving fiber 2=5mm, The final sensor output is ratio of the output voltages obtained by two receiving fibers and is plotted as function of distance Z varying from 0 mm to 25 mm.

4.2 Physical experiment

Figure 5 shows experimental setup for testing the larger stroke fiber optic displacement sensor.

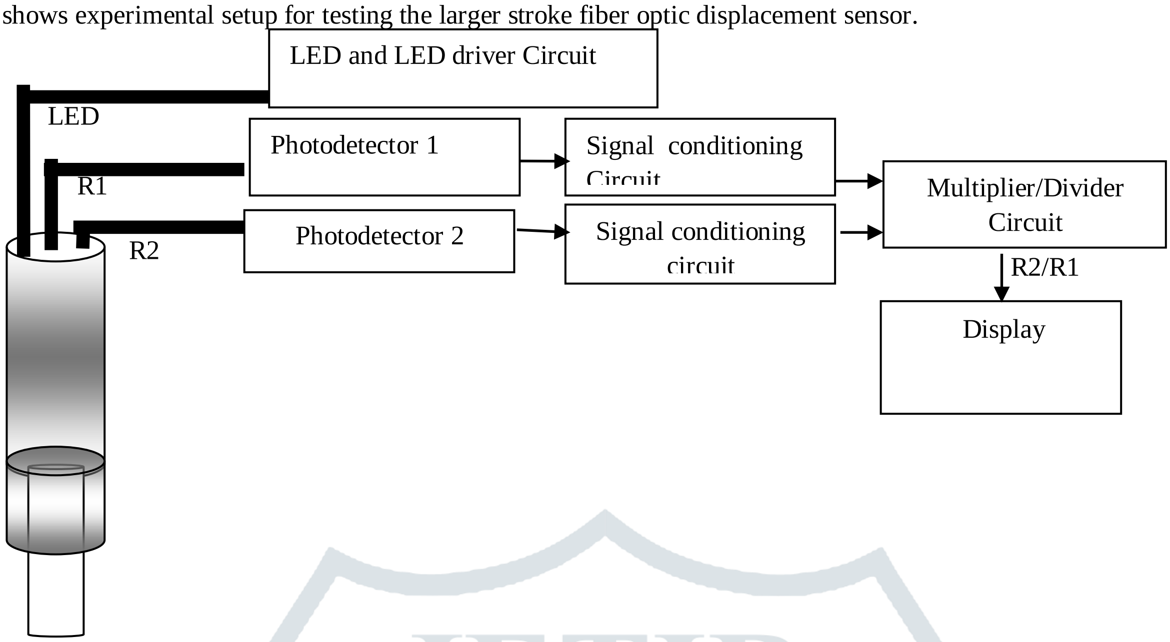

Figure 5 Experimental setup

Light is launched into the transmitting fiber using the RED LED. A cone of light is reflected by the reflector/mirror and is collected by receiving fiber 1 and receiving fiber 2. The two fibers are coupled to the identical photo detector

Experiment is carried out by varying the distance from 0 mm to 25 mm and sensor output is recorded as the ratio of the receiving fiber outputs R2/R1.

V. RESULTS AND DISCUSSION

The simulated sensor response and experimental results are as shown in the Figure 6. The ratiometric sensor response is analyzed by taking differential of the These are found to be in good agreement. The sensor response is then differentiated and analyzed to calculate sensitivity, linear operating range with specific % linearity. It is observed that for larger operating range sensitivity decreases with increase in non linearity of the response curve. Table 1 shows the exact figures obtained after analysis.

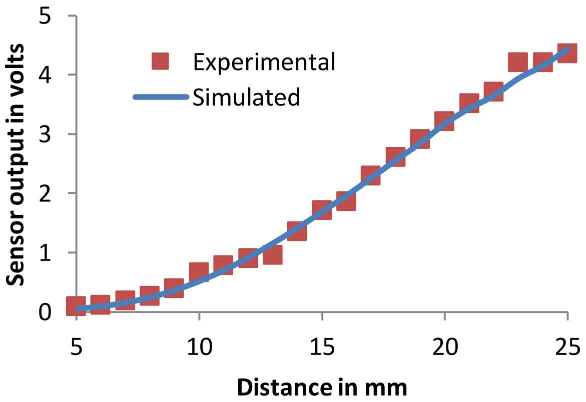

Figure 6 Simulated and experimental results

Sr. No.	Sensitivity	Linear operating range in mm	% linearity
1.	100%	3	0.01%
2.	90%	6.6	0.6%
3.	80%	10	1%
4.	70%	15	5%
5.	50%	20	6%

Table 1. Sensor performance parameters

It is concluded from the table that as operating range increases sensitivity decreases. The non linearity in the sensor output increases for larger operating range. This analysis is useful in optimizing the sensor performance parameters as per the user requirement. It is observed that the linear operating range of 20 mm is obtained with 6% non linearity. Thus this type of sensor useful for measuring larger distances and can be replacement for commercially available Linear Variable Differential Transformer (LVDT)

VI. CONCLUSION

Larger stroke fiber optic displacement sensor is designed, fabricated and tested for the measurement range of 25 mm with 6% linearity. The self referenced configuration used with one transmitting fiber and two receiving fibers having different fiber diameters. The sensor geometry has asymmetric placement of receiving fibers with reference to position of transmitting fiber. The simulated and experimental results are matching.

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