Modeling of Fiber Optic Tilt Sensor using MATHEMATICA and Simulation Studies of its Application as Automobile Throttle Position Sensor

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Abstract— Fiber optic sensors offers advantages of non intrusivity, good spatial resolution, satisfactory dynamic behavior, accuracy and more favorable operating characteristics like reliability, access to measuring points otherwise inaccessible and possibility of reducing the size of the measuring probes.

This paper describes modeling of fiber optic tilt sensor to improve the range of measurement using two receiving fibers placed to the same side of the transmitting fiber are presented. A simulation program based on the geometry of sensor probe is developed to study of the application of sensor probe as throttle position sensor. Simulation studies shows that the measurement range of fiber optic tilt sensor increased when receiving fibers are placed to the same side of transmitting fiber.

Keywords*-Tilt Sensor, TPS*

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I INTRDUCTION

Fiber optic sensors offers advantages of optical instrumentation such as non intrusivity, good spatial resolution, satisfactory dynamic behavior, accuracy and more favorable operating characteristics like reliability, access to measuring points otherwise inaccessible and possibility of reducing the size of the measuring probes so that they are handy and easy to use[1]. Due to ruggedness and often contactless characteristics, optical systems are one of the most adopted, particularly when fast changes in displacement need to be measured [2]. Fiber-optic sensors provide geometric versatility and can be configured as “point” or “distributed” sensors [3].

One of the applications of fiber optic sensor is angular displacement measurement. Two methods are used for doing angular measurement namely interferometric and triangulation method. Interferometric methods are more precise over small ranges but these techniques have limitations for their integration in miniature mechanical systems [4]. Triangulation method is based on the light transmitted [5] or reflected [6] by a mirror. Fiber-optic sensors offer the possibility of reducing strongly the part of the sensor which interacts with the mechanical system. The interaction can take place by a direct contact with the fiber [7–9]. Two systems based on the fiber-optic bundle (or fiber-optic probe) [10, 11] demonstrate the possibility of non-contact measurement of two measurands. Concerning the angular displacement, in [10] the sensor reaches a middle range (±10◦) with a low precision (0.8º), while in [11] the sensor precision was 0.5 mrad (0.03º) over a short range of 20 mrad (1.15º). Khiat A et al demonstrated two configurations of fiber-optic sensor able to measure high-precision angular displacements with small size for easy integration in miniature mechanical systems. They used lens-free and GRIN micro-lens configuration for which the micro-lens is fixed on the tip of the probe. [12] Mingguang Shan et al demonstrated differential reflective fiber-optic angular displacement sensor, the sensor output is based on subtraction of two power signals from two receiving fibers placed on both sides of one emitting fiber. The linear angular range of the sensor is ± 6.1º [13]. S.S.Patil et al developed a generalized model for studying and analyzing any configuration and scenario of fiber optic sensor. It helps in analyzing manufacturing tolerances as well as effects of the geometrical parameters on performance of the sensor [14]. P.B. Buchade et al reported influence of geometrical offset between the transmitting and receiving fiber tips (h), lateral separation between the transmitting and receiving fibers (s), the angle between transmitting and receiving fibers and the angle of the reflector (θr), effect of angle between transmitting fiber and receiving fiber on the performance of fiber optic displacement sensor [15-16].

This paper presents modeling of fiber optic tilt sensor to improve the range of measurement using two receiving fibers placed to the same side of the transmitting fiber. A simulation program developed based on the geometry of sensor probe is developed to study the response of proposed sensor probe.

II THEROTICAL ANALYSIS

A conceptual diagram of the sensor that measures the tilting angle or linear distance traveled of an external mirror is shown Fig. 1. The sensor probe consists of one transmitting and two receiving fibers. A divergent light beam is emitted by transmitting fiber (TR) toward the external mirror. The beam is incident to the surface of tip of receiving fibers (RF) after reflection at the mirror. Tilting the mirror changes the shape of the reflected beam and linear displacement changes the size of the beam. The intensity of the light reaching two receiving fibers (RF-A, RF-B) set on side of the transmitting fiber thus changes in response to the tilt or linear displacement.[15].

The principle of the tilt measurement is based on the sum of the optical powers received by the both receiving fibers. At the base position in Fig. 1, the intensities of the light detected by the receiving fiber RF-A will be larger than the receiving fiber RF-B. When the mirror tilts toward receiving fibers, the center axis of the light beam will move first toward RF-A then towards RF-B. At a point closer to the center axis, the intensity

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216 - 219

of the light beam is higher; resulting in the difference between the intensities measured by both receiving fibers.

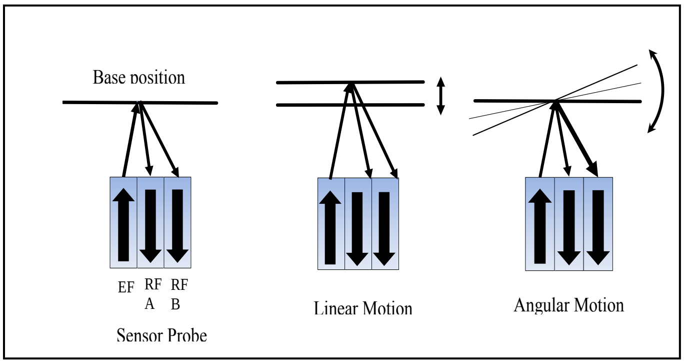

Figure 1 Conceptual geometry of sensor probe

The sensor output is represented sum of output signals of RF-A and RF-B

$$S_{rot} = PRB/PRA \quad (1)$$

To derive the relationship between the incident power into the detecting region of the fibers and the mirror position (Z, Ψ) the geometry of the sensor is shown in Fig 2.

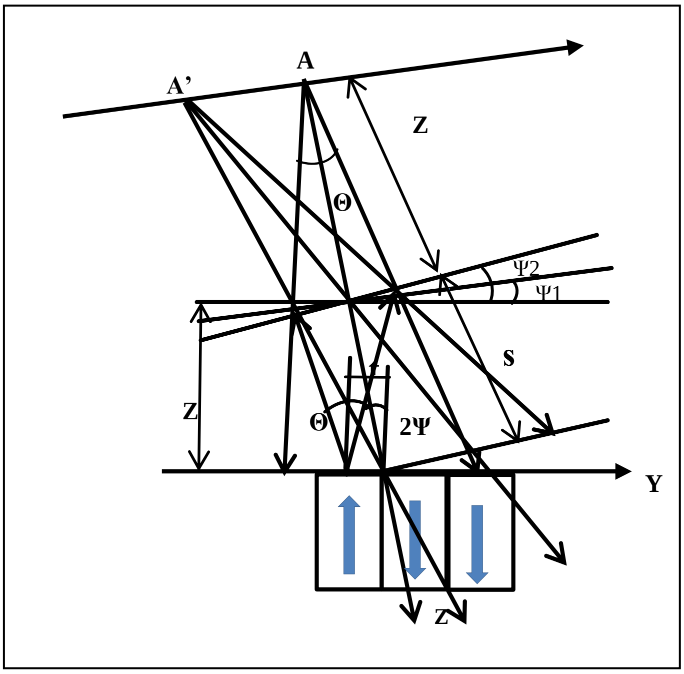

Figure 2 Configuration of tilt sensor

The transmitting and receiving fibers having core diameter **2a** are placed at distance **l** apart. The mirror is placed at a distance **'Z'** from the sensor probe and rotated at an angle **Ψ**. A divergent Gaussian beam is emitted by the transmitting fiber towards mirror. The reflected light intensity is received by two receiving fibers. Sagrario [17] presented a simplified mathematical model to characterize the performance of FBAS. Ishikawa [18] also presented a model for integrated angular displacement sensor, but it just uses the light diverging from a vertical cavity surface emitting laser. Similar to many others [14-16], it is assumed that the intensity distribution of the emitting light from transmitting fiber has a modified Gaussian profile,

$$I(x, y, z) = \frac{2P}{\pi w(z)^2} \exp \frac{-2(r^2)}{w(z)^2} \quad (2)$$

where r is the radial distance from the fiber center, P is the total power of the emitting light, and ω(Z) is the effective radius of the output optical field. If the beam diverges with the full-angular width of Θ, the beam half-width *w* varies according to

$$w(Z) = Z \tan(\Theta/2) \quad (3)$$

Provided *Z* is much larger than the beam waist
According to Snell's law, the transmitting fiber seen by the receiving fiber is the same as a virtual fiber at an image plane behind the mirror at the same distance Z as shown in Fig. 2
The intensity IR (x, y) of the light coupled into RF [18] can as be written

$$I(x, y) = \frac{2P\cos(2\Psi)}{\pi w(z)^2} \exp \frac{-2\left(x^2+y_R)^2\right)}{w(z)^2} \quad (4)$$

Where

$$z = y \sin(2\Psi) + d \cos(2\Psi) + d \quad (5)$$

$$y_R = y \cos(2\Psi) - d \sin(2\Psi) \quad (6)$$

By integrating I(x, y) on the area of detecting regions of receiving fibers the intensity at RFs is estimated. The area of the detecting region of RF-A 'A_1' and RF-B 'A_2' is defined as

$$A_1 = \{(x, y) | (x^2+(y-l)^2 \leq r^2\} \quad \textbf{(7)}$$

$$A_2 = \{(x, y) | (x^2+(y-2l)^2 \leq r^2\} \quad (8)$$

Where 'l' is the distance between centers of two neighboring fibers. The optical power received by the RFs is calculated using following equations:

$$\mathbf{P_{RFA}} = \int I(x,y)\, A_1\, dA \quad (9)$$

$$\mathbf{P_{RFB}} = \int I(x,y)\, A_2\, dA \quad (10)$$

III AUTOMOBILE THROTTLE POSITION SENSOR

The TPS or throttle position sensor feeds the ECM with throttle opening and rate of change. The angle of the throttle opening is instrumental in calculating fuel delivery and ignition timing. Newer engines even have control of the valve timing, for which the TPS value is also used. The position of the throttle valve is very important.

The TPS is a three wire sensor that measures the throttle plate opening as well as its rate of change. The assembly of TPS with throttle body is shown in Fig. 3.This sensor is a variable resistor, also called a potentiometer that is directly linked to the throttle plate shaft. The TPS outputs a voltage directly proportional to the throttle opening. As the accelerator is depressed the throttle plate opens and the TPS voltage increases

The main advantages of potentiometers include their ease of implementation, low price, analog output, no signal

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216 - 219

processing needed and ease to add additional channels to increase reliability. However, the potentiometers also have several drawbacks- high wear & failure rates, nonlinearities occurring later in lifecycle, no digital coding possible, bad signal-to-noise ratio, and redundant channels are worn out in parallel.

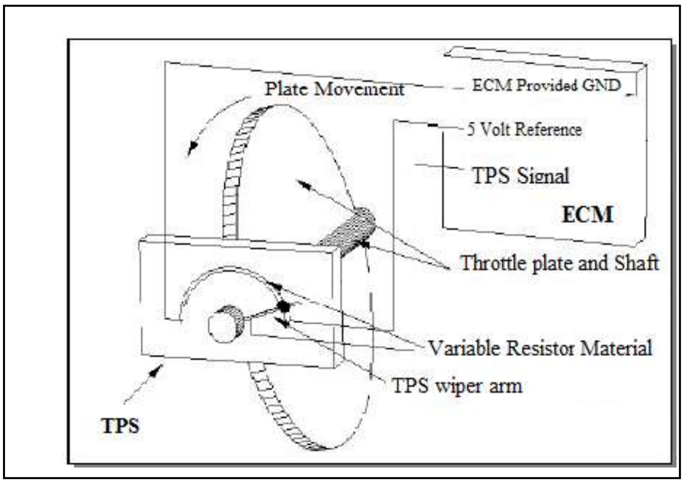

Figure 3. Assembly of TPS with throttle body

The drawbacks of potentiometers became an issue for the throttle position sensor application, the main reason being the increased safety and reliability requirements. The harsh environmental conditions for throttle position sensors include high temperatures, vibrations and shocks and exposure to various liquids and gases, which can all lead to early failure of potentiometers. Normal wear is another problem: Potentiometers typically allow about 5 to 10 mio full cycles, but as the throttle is mostly used in a small angle range (up to ca. 30°), the abrasion is biggest in this limited range. Before failing, nonlinear behavior can be observed due to wear of the resistive tracks and material build-up on the wipers, and unfortunately the worst effect is exactly in the driving range in which the sensor is used most. Finally, being a passive device, neither wire breakages and overvoltage nor internal defects can be detected and communicated to the ECU by the potentiometric sensors. To sum up, potentiometers are a suitable solution for systems where low cost is key and reliability and safety can be traded off. Since the throttle position sensor is a safety relevant application, most new sensors are based on contactless principles nowadays.

IV SIMULATION RESULTS AND DISCUSSION

From the geometry of the sensor for it can be seen that the distance of the reflector form the sensor probe defines the measurement range. For studying the sensor performance, range of the front slope region of the linear displacement curve is considered. The range of front slope of the linear displacement sensor is given by Z_{min} and Z_{max}. For tilted sample [19] Z_{min} and Z_{max} are related to tilt angle(θ) as

$$Z_{min} = (d-2a) / T(\theta_M, \Psi) \text{ and } Z_{max} = d / T(\theta_M, \Psi) \quad (11)$$

where θ_M is maximum angle of rays which can be received by receiving fibers and is determined by magnitude and orientation of tilt angle. When Ψ is positive $\theta_M = (\theta_N - 2\theta)$ and when Ψ is negative, $\theta_M = \theta_N$.

The tilt function $T(\theta_M, \Psi)$ is given as

$$T(\theta_M, \Psi) = (\tan\theta_M + \tan(\theta_M + 2\Psi)/(1 - \tan\theta_M * \tan\Psi) \quad (12)$$

When Ψ=0 the tilt function reduces to 2 tan θ_N . The emitted light falls on to the mirror having spot diameter w = Z tan θ_N. The spot size of the reflected beam on the plane of receiving fiber is $w' = 2w = 2Z \tan\theta_N$. The distance is optimized for illumination over the diameter of RF-A for Ψ**=0°** [19]. The distance (**Z**) between sensor probe and the mirror is calculated using equation

$$Z = \frac{3a+4tcl}{2\,Tan(\Theta)} \quad (13)$$

Based on above analysis a simulation program is developed or fiber with core diameter 980 micron and fiber diameter of 1 mm having NA= 0.42, Z=1.63 mm. The simulation result of sensor for above fiber parameters are shown in Fig 4. While performing simulation initially sensor geometry assumed with two receiving fibers to either side of transmitting fiber. The simulation output for such sensor geometry is as shown in Fig 4. It can be seen that the simulation program generates linear output having range of 10°.

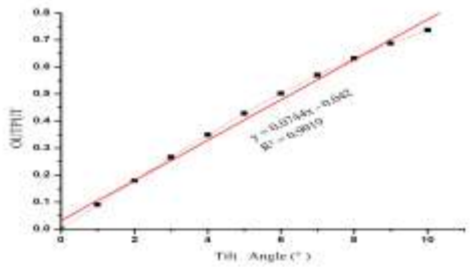

Figure 4a Simulation response of tilt sensor (transmitting fiber at center)

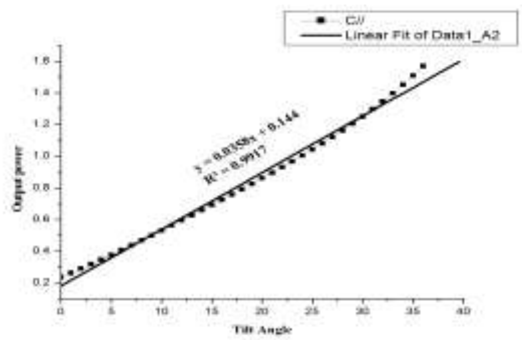

Figure 4b Simulation response of tilt sensor (receiving fibers to the side of transmitting fiber)

For application of throttle position sensor the working range required is of 40° hence to improve the sensor response for larger range, sensor probe geometry as shown in Fig 1 is considered. The output of simulation program is shown in Fig 5.It is seen that the operating range of the sensor for suggested geometry is increased up to 35°

V CONCLUSION

The modeling and simulation studies of fiber optic tilt sensor are presented using two sensor probe geometries: receiving fiber to either side of transmitting fiber and to the same side of the transmitting fiber. Simulation studies shows that the measurement range of fiber optic tilt sensor increased when receiving fibers are placed to the same side of transmitting fiber. Attempts for further improvement are being made

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