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REGULAR PAPER

Design, development and experimental study of novel configuration of reflectivity invariant retro reflective fiber optic sensor for measuring of surface roughness

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Abstract

This paper reports a novel retro reflective fiber optic surface roughness sensor. The sensor probe consists of four fibres out of which three are parallel and one is inclined at an angle of 5°. The reflector is placed at an optimised distance in order to get the maximum sensitivity for the surface roughness measurement. This configuration makes the sensor immune to variation in reflectivity of reflector. Mathematical modelling of this fiber optic displacement sensor is reported based on the ray tracing method. MS surfaces are sprayed with aluminum to get different surface roughness values, which are measured on the standard instrument. Experiments are performed for measuring surface roughness values for these surfaces. Experimental results show a good agreement with the simulation results. These results are also compared and validated with the standard instrument used to measure the surface roughness. Experimental validation of the invariance with reference to reflectivity of reflector is also done.

1 Introduction

Reflector surface is an inherent component of non contact type fiber optic displacement sensor. It is characterized by two important properties namely, reflectivity and surface roughness. The sensor response can be made independent of reflectivity of the surface, and sensor can be configured to measure the surface roughness only using the self referencing technique [Fukuo *et al.* 1999]. Different configurations of fiber optic displacement sensor are reported for measuring the surface roughness [George *et al.* 1995; Jianli & Sacharia, 1999; Yuan & Pan, 1993]. Even though a number of mechanical techniques are used to measure the roughness value of the surface, optical techniques are found to be the best method due to its non contact type and in-situ process measurement ability. Generally, optical detection of surface roughness is related to the amount of light scattered by the surface, which is related to specularordiffused reflection. Standardized surface parameters like average roughness value and rms roughness value can be estimated using optical techniques for different applications such as: measuring the roughness of metals, estimating the roughness of corroded metals, dimensional inspection of some complex curved surface components etc. Artificial neural networks (ANN) are also used to characterize the surface roughness [Zang *et al*. 1996].

In this paper, we propose a fiber optic sensor for measuring the surface roughness of the reflector. A novel configuration of self referenced reflective intensity modulated fiber optic sensor with a fixed distance from the reflector and an inclined receiving fiber is proposed. Mathematical modelling of the sensor structure is done using the ray tracing model developed in MATLAB [Supriya & Shaligram, 2011]. A sensor probe is fabricated and experimental results show a good agreement with the theoretical results. These results are also compared and validated with the standard instrument used to measure the surface roughness.

2 Theoretical model

Surfaces like mirror have high reflectivity and generally, for single ray incident on it there is single ray reflected. This is possible for perfectly specular surfaces, and reflection is specular reflection as per the laws of reflection. But in practical cases surfaces are not specular. They are having slight irregularies in the surface structure. Due to this for single incident ray there is possibly a number of reflected rays. This occurs due to irregularities of surface profile, which causes scattering effect. Beckmann-Spizzichino developed the reflectance model for reflection of light using physical optics, and Torrance Sparrow developed the model using geometrical optics [Lawrence *et al*. 1998]. Due to simplicity of the model, the Torrance Sparrow model is more popular for describing the mechanism of the specular reflection from the rough surfaces. Based on the geometrical optics, this model is valid only when the wavelength of light is much smaller than the root mean square surface roughness. The Torrance Sparrow model is expressed as:

$$f = \frac{F(\theta)G(\omega_i,\omega_r)D(\theta_r)}{4\cos(\theta_i)\cos(\theta_r)} \tag{1}$$

where, $F(\theta)$ is the Fresnel term,

$G(\omega_i, \omega_r)$ is the Geometrical attenuation due to shadowing and masking, $D(\theta_h)$ is the Distribution function of microfacets on the surface, θ_i is the source angleand θ_r is the viewer angle. In reality, surfaces are neither perfect polished reflectors nor perfectly rough surfaces. When light from the source is made incident on the surface whose roughness is to be measured, the random characteristics of the micro profile will make the light scatter at the incident point as shown in Figure 1 [Yong *et al*. 2000].

The received light intensity is also a function of the geometry and the fabrication parameters of the fiber i.e., *IR* (*a*, *NA*, α, *z*, σ) where, a the is radius of core, *NA* is the numerical aperture, α is the angle of inclination of the fiber, *z* is the distance and σ is related to average surface roughness *Ra*. θ' the is angle of specular reflectionwhich is expressed as:

$$I(\theta) = \frac{1}{\left(2\pi K \exp\left(-\frac{4\pi Ra\cos(\theta_0')^2}{\lambda}\right)\right)} \exp\left(-\frac{(\theta-\theta_0')^2}{2\pi K \exp\left(-\frac{4\pi Ra\cos(\theta_0')^2}{\lambda}\right)^2}\right) \tag{2}$$

As per the reflectance models, the received light is a combination of specular reflection (B) and diffused reflection (A) considering guassian

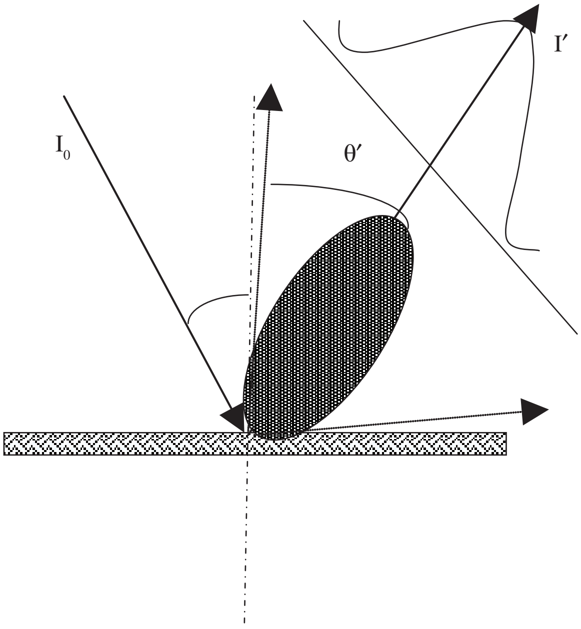

Figure 1. Intensity distribution on the rough surface.

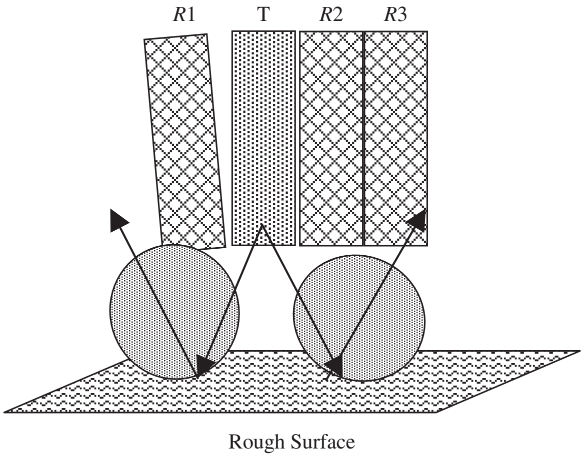

Figure 2. Geometry of the sensor.

distribution of microfacets. Total received intensity is expressed as:

$$IR(\theta)_{total} = B + \frac{AIR(a, NA, \sigma, Z)}{\cos(\theta 1)} \exp\left(\frac{\theta^2}{\sigma^2}\right) \quad (3)$$

Elliptical shape in the figure indicates the distribution of diffused light intensity after reflection from the rough surface. The intensity profile is Gaussian as indicated in the equation. The dashed line indicates the normal to the plane of surface, and dotted line indicates end limits of the diffused reflection intensity distribution function. In order to have a direct relationship between the sensor output and the surface roughness *R*a, the dependence of sensor output on geometrical parameters should be nullified. The sensor structure is as shown in Figure 2 where, fiber *R*1 is inclined at an angle of 5°. Final expression for the sensor output will depend only on the surface roughness σ, and is expressed as:

$$IR(final) = \frac{IR1(\theta,\sigma) - IR3(\theta,\sigma)}{IR2(\theta,\sigma) - IR3(\theta,\sigma)} \quad (4)$$

3 Sensor structure

The sensor structure is an extension of the self referenced fiber optic displacement sensor. Generally, the self referenced fiber optic displacement sensor consists of two receiving fibers (*R*1 and *R*2) arranged on either side of the transmitting fiber (T) with a reflector at a distance. This arrangement is useful in making the sensor output immune to variations in reflectivity of the reflector and fluctuations in light source intensity. As discussed in previous section, specific arrangement of four fibers as shown in Figure 2 is useful in making the sensor output proportional to the surface roughness. Sensor consists of four optical fibers having the following parameters, viz., core radius (a)=0.418 mm, cladding thickness (cd)=0.612, fd=2.2 mm, NA=0.47.

Out of the four fibers, one fiber is the transmitting fiber in, which light is launched using the High Bright RED LED. There are two receiving fibers arranged on either side of the transmitting fiber. A photo detector L14G3 is used to detect the received light intensity after reflection from the surface. An asymmetry in the sensor structure is introduced by inclining the fourth fiber at an angle of 5°. Light received is detected by the photodetector. Distance between the surface and the fiber sensor end face is kept constant.

4 Experimental setup

Figure 3 shows the experimental setup for measuring the surface roughness of the surface using the fiber optic sensor. The developed sensor is placed on the surface whose roughness is to be calculated. LED driver circuit is used to drive LED with a constant intensity, and phototransistor L14G3 is used for detection of the reflected light intensity received by the three receiving fibers.

Output of the photo detector is properly buffered and the ratio of differences in the intensity of three fibers is calculated using multiplier divider circuit. The final output is direct display of the surface roughness of the surface under consideration.

In order to use the sensor for detection of the surface roughness, different samples having varying surface roughness were fabricated.

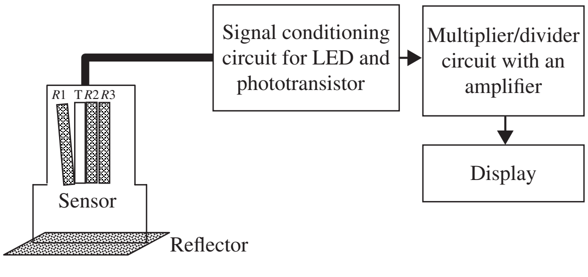

Figure 3. Experimental Setup.

Sand blasting technique was used to prepare the surfaces of different surface roughness. Aluminum metal sheets were used for preparation of the surfaces. Actual surface roughness is calculated by using the standard instrument used for measuring Ra (average surface roughness) of the sample.

5 Results and discussion

Intensity of light reflected from the surface depends on the texture of the surface and the distance between the surface and light source. For smooth surface, the amount of light entering the receiving fiber *R*2 is more compared to *R*1 and *R*3 because of less scattering of light. Hence, output of the sensor is low indicating a small roughness value. As the roughness of the surface increases, the amount of light entering *R*3 and *R*1 increases, while that in *R*2 decreases because of the scattering effect. Amount of light entering *R*1 is more compared to *R*3 because *R*1 is inclined so that it can capture more diffused light compared to straight fiber R3. Combined received signal voltage increases with an increase in the roughness of the surface. The developed sensor was tested on sample surfaces having different surface roughness. The Surface roughness sensor is placed on the sample, and the roughness is calculated for that sample as per the equation (4).

Simulation experiments are carried out using the ray trace model [Supriya & Shaligram, 2011]. It uses one transmitting fiber and three other receiving fibers, which are arranged as per the geometry shown in Figure 3. Out of the three receiving fibers two are parallel to the transmitting fiber, while the third one is inclined at an angle of 5 degree. Simulation experiments are carried out considering the following parameters for simulation: a. Radius of each optical fiber: 0.488 mm, b. NA: 0.47, c. length of optical fiber: 30 mm and d. cladding thickness: 0.612.

Using the equation (4) the received intensity was calculated and the results were plotted for four different types of surfaces specially fabricated for different surface roughness.

The actual values of surface roughness Ra in micrometer for the sample surfaces are measured on the standard instrument Surftest MITUTUYO-SJ-210P, a portable surface roughness tester. It has a stylus, which scans the surface over the length of 10 mm. Table 1 below shows actual values of Ra measured on this instrument for the samples 1 to 4.

Table 1. Ra values measured on standard instrument Surftest MITUTUYO-SJ-210P.

Sample number	Ra in µm
1	6.554
2	7.686
3	9.234
4	10.47

Comparison of the simulated values, experimental values and standard data is done by normalizing data. Ra values and sensor output were normalized for the type of surface then both were plotted on the same graph as shown in Figure 4.

Figure 4 shows comparison of the results and they were found to be following similar trend. Type of the surface from samples 1 to 4 corresponds to an increase in the value of the roughness in micrometer. Slight differences in the values is because of the distance between the surface and the sensor head. The developed sensor was made to scan the entire surface by proper mechanical arrangement, and then by taking the average of the output voltages of the sensor one can get Ra value for that surface.

6 Conclusion

The developed surface roughness sensor is a non contact type fiber optic based sensor having all the advantages of using optical technology for sensing. The sensor is useful in measuring the surface roughness irrespective of the type of the metal whose roughness is to be measured. Addition of asymmetry in the geometry is useful in making

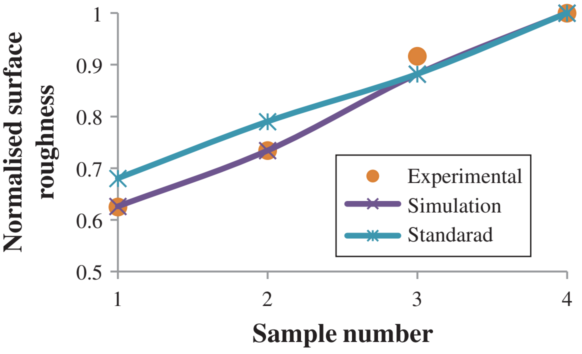

Figure 4. Comparison with the standard values.

the sensor output independent of the reflectivity of the surface, and the variation in the source intensity is due to aging or degradation.

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