Influence of Surface Finish on Random Walk Co-efficient of Laser Based Optical Rotation Sensor

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Citation

Received: January 19, 2018; Accepted: February 26, 2018; Published: April 27, 2018

Abstract: Laser based optical rotation sensor is an inertial navigation grade sensor which works on the principle of Sagnac effect and detects the rotation of an object where it is mounted. The grade of rotation sensors are generally defined based on the coefficient of random walk and bias stability over a period of time. The factors that influence the coefficient of random walk are scale factor and lock-in threshold that in-turn dependents on the back scattering coupling coefficient, which arises from the surface quality of the optical components used in the sensor. In the present study, the glass material preferably fused silica has been processed for different roughness values (Ra) suitable to optical rotation sensor and its influence on random walk coefficient has been practically measured and presented. Roughness value is found to be dependent on the polishing condition.

Keywords: Inertial Navigation Sensor, Random Walk Coefficient, Lock-in, Surface Roughness, Scattering

1. Introduction

Inertial navigation grade sensor consists of a set of inertial sensors along with electronics. It does not rely on external measurements; instead it utilizes the inertial properties of sensors to provide self-contained, non-radiating, non-jammable and accurate determination of instantaneous navigation states. Inertial Measurement Unit (IMU) is assembled with three set of accelerometers and three optical rotation sensors in three orthogonal axes with a cluster of electronics and frame assembly. It provides information about altitude, force and angular rate measurement in a strap down system. When a navigation computer is added to an IMU, it becomes an Inertial Navigation System (INS), where a relationship between the orthogonal frames of the vehicle, the sensors and the navigation are continuously computed. Due to this, an onboard computational load, relative to gimbaled systems has considerably increased. Advancement in sensor and computer technology has increased the array of strap down INS and effected in reduction of size, power consumption and cost of the inertial systems. It measures two parameters like, inertial rotation and specific force, which is determined by laser based optical rotation sensor and accelerometers, respectively. By combining the inertial measurements along with the gravity model, determination of position, velocity and direction can be obtained. In the development of navigation grade sensor various operational technologies and fundamental operating principles have been utilized. They are classified as (i) Rotating Wheel Sensor (ii) Sagnac Effect Sensor and (iii) Coriolis Effect on a vibrating structure based Sensor. Sagnac effect sensor has basically a circular configuration of light beams and it is related to the propagation characteristics of a light wave within a rotating system [1-4].

1.1. Sagnac Effect and Principle of Operation

When two counter propagating light beams travel in a closed circular path in an inertial space, the time taken to travel for both the beams and to reach a particular point are same in the absence of an inertial rotation perpendicular to the plane of the circular path. The travel time t₀ is represented as
when the closed path is rotated at an angular rate Ω, the travel time for both the beams is not the same. This rotation rate induces a path length difference ∆L between the counter propagating beams in a closed optical path. This phenomenon is known as Sagnac effect. First order approximation for the difference in the travel time ∆t, due to path length difference is given by

$$\Delta t = \frac{4\pi R^2}{c^2} \frac{\Delta \phi}{\Omega} = \frac{4A}{\Delta L} \Omega$$  \hspace{1cm} (2)

where,

A – Area enclosed by the closed optical path (πR^2)
c – Velocity of light in the medium
Ω – Input angular rate about inertial space
R – Radius of the closed optical path

The corresponding optical path length difference is determined as ∆L = ∆txc. In practice, frequency measurement is utilized instead of time measurement. Hence for a beam of frequency f, the change in frequency between clockwise and counterclockwise beam is given by ∆f using Interferometry principle [1].

The important part of a laser based optical rotation sensor is to create a ring type laser resonator as depicted in Figure 1, which can easily detect the Sagnac phase difference with a condition that the optical path length L for the beam to return to itself as an integral number m of wavelength λ so that a relation L = mλ is achieved.

Hence the fundamental relationship to define the operation of a basic rotational sensor can be determined as

$$f_{cw} - f_{cw} = \Delta f = \frac{4A}{\Delta L} \Omega$$  \hspace{1cm} (3)

This frequency difference is termed as beat frequency and the optical path implies, sources of scale factor SF error which is termed as

$$SF = \frac{4A}{\Delta L}$$  \hspace{1cm} (4)

The unit of scale factor is determined in terms of radian/pulse or arc-sec/pulse. Basically a word count is used to determine the pulse, hence by measuring the number of fringes moving across the field of view for a fixed time, the angular rate can be determined by using the scale factor [1-2]. The theoretical analysis of optical rotation sensor deals with amplitude and frequencies of the counter propagating laser waves using helium-neon as an active medium in a gas laser. It leads to a characteristic condition on threshold operation, frequency synchronization at low rates describing the lock-in phenomenon, distorted waveforms with higher lock-in rates describing non-linearity in scale factor [5-7].

1.2. Lock-in

It is a unique error with a severe detrimental effect on the performance of the optical sensor. It originates when two beams travelling in opposite direction with same frequency synchronize to form a dead zone namely a lock-in zone. It is in that zone that the optical rotation sensor is not able to detect even a small rotation rate. This phenomenon is shown in the Figure 2 and the problem arises when the input rate to the optical rotation sensor approaches towards zero from either directions. If Ω, is the lock-in rate then the effective lock-in band is 2Ω. A typical lock-in rate in production of an optical rotation sensor varies between 36 to 360°/hour. At such a small rate, the frequency difference between the two beams becomes quite small and the defects such as backscatter from the components also causes the beams to be locked to each other [8-10].

$$\Omega_l \approx \frac{\text{Lock-in rate}}{2}$$

The lock-in zone which is generated in the optical rotation sensor is mathematically determined with respect to the back scattering coupling coefficient ‘γ’, and the phase difference ‘β’ between the back scattered beam and the beam with which coupling takes place. Hence the expression is given as
This back scattering phenomenon arises from the optical components and is due to the surface roughness of the mirrors or prisms that has been utilized in the sensor. Mathematical relation shows that, the lock-in rate is directly proportional to the random walk coefficient \( W_D \), hence for a minimum value of random walk coefficient, its lock-in value should be minimum, which in turn is related to the surface roughness [11-13]. If the surface finish is very smooth leading to lesser scattering points, then the lock-in value will be less, which is the prime requirement for the good performance of an optical rotation sensor. Hence, the relation between scale factor, lock-in and random walk coefficient is given by

\[
W_D = \frac{\Omega_0}{\sqrt{2\pi \Omega_D}} \sqrt{\frac{SF}{\pi \Phi}}
\]

where, \( \Omega_0 \) is the peak dither rate. In the above expression, \( \Omega_0 \) and \( \Omega_D \) are expressed in terms of degree/hour and scale factor \( SF \) is expressed in terms of arc sec/pulse or degree/pulse. It is understood that, the surface finish plays a vital role in determining the performance of the optical rotation sensor. In this paper, an influence of surface finish on random walk coefficient has been obtained by processing fused silica glass substrates, with a precise polishing technique and the substrates has been characterized for its roughness values using Veeco 3D-profiler.

### 2. Experimental Procedure

Glass samples were prepared using Fused Silica glass (Suprasil 311, 3D Heraeus, Germany). The big block of glass has been sliced into the desired sizes (shown in Figure 3(a-b)) and are processed using the deep conventional grinding techniques by lowering the average size of the abrasives ranging from 60 micron to 3 micron in 7 steps [14-16]. Considering the phenomenon of subsurface damage created during the grinding process using aluminium oxide powders, in each grinding step excess stock material was removed (approximately 10 times) of the previous abrasive size. Similarly, during polishing of glass samples various cerium oxide slurries (M/s Rhodes, Hastilite PO) and Colloidal Silica (from M/s Universal photonics, USA) have been procured, whose average particle size ranging from 1 micron to 70 nm were used by the conventional as well in submerged polishing technique. Metrological aspects such as surface profile of the components fabricated have been analyzed using 3D-profiler (M/s Veeco, and Model: NT1000) which works on the principle of phase shift Interferometry [13] and its corresponding images have been captured. During the polishing cycle, temperature of the clean room has been maintained at 24±0.5°C and relative humidity has been maintained at 55±5%. The pH values of the slurries were maintained from 5.5 to 9.9, so that it will have removal and reflow of material, accordingly. All the processes have been completed in class 100 clean room.

### 3. Results and Discussion

Optical components were lapped and polished with respect to the dimensional accuracies, of the order of 1 to 2 microns and angular accuracies of the order of less than 5 arc-sec. The flatness of the order of \( \lambda/20 \) has been fabricated, and assembled according to the final requirement of optical rotation sensor. Optical components with various roughness values ranging from 7Å to 1.6 Å have been generated and its corresponding lock-in threshold and random walk coefficient values are mentioned in the Table 1. Various roughness ranging from 6.9 Å to 1.6 Å are shown in Figures 4-7. The effect of grinding media material is clearly seen from the results of surface roughness.
Table 1. Roughness, Lock-in and Random Walk Coefficient values.

<table>
<thead>
<tr>
<th>Roughness $R_a(\AA)$</th>
<th>Lock-in Threshold $\Omega_L (\text{deg/ hr})$</th>
<th>Calculated Value using Allan Variation of Random Walk Coefficient $W_d (\text{deg/} \sqrt{\text{hr}})$</th>
<th>Theoretical Value of Random Walk Coefficient $W_d (\text{deg/} \sqrt{\text{hr}})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.9</td>
<td>800</td>
<td>0.018</td>
<td>0.011</td>
</tr>
<tr>
<td>3.8</td>
<td>450</td>
<td>0.010</td>
<td>0.009</td>
</tr>
<tr>
<td>2.5</td>
<td>300</td>
<td>0.007</td>
<td>0.006</td>
</tr>
<tr>
<td>1.6</td>
<td>180</td>
<td>0.004</td>
<td>0.003</td>
</tr>
</tbody>
</table>

Figure 4. Average rough measurement with masked condition (average particle size 1 micron).

Figure 5. Average rough measurement without masked condition (average particle size 0.9 micron).
Initially, the surface roughness of the bare sample is very high and reduced to 6.9Å°. Further improvement in the grinding methodology and grinding media material is found to have a major effect on the surface roughness. There is a
significant decrease in surface roughness with the improved methodology. Based on the Lock-in threshold data, the Random walk has been evaluated and correlated with the theoretical values. Figure 8 shows the theoretical and measured random walk coefficient values. There is a good agreement between theoretical and measured values. Initially, the measured random walk co-efficient is found to be higher and a linear decreasing trend in the value is observed with increasing parameter. The measured values follow the similar trend to the theoretical values.

![Figure 8. Comparative data of theoretical and measured random walk coefficient.](image)

Figure 9(a-b) shows the variation in random walk coefficient with respect to roughness for the theoretical and measured values. At lower roughness value, the random walk coefficient is also lower. With the increase in the surface roughness, random walk coefficient also increased and followed a linear increasing trend. The main factor that influences the random walk coefficient is the grinding material. In the present study, deep conventional grinding technique is used by lowering the average size of the abrasives ranging from 60 micron to 3 micron in 7 steps [14-16]. Considering the phenomenon of subsurface damage created during the grinding process using aluminium oxide powders, in each grinding step excess stock material was removed (approximately 10 times) of the previous abrasive size. Similarly, during polishing of glass samples various grinding material such as cerium oxide slurries and colloidal silica, whose average particle size ranging from 1 micron to 70 nm were used by the conventional as well in submerged polishing technique. The methodology applied in this study has resulted into a significant improvement in the surface roughness, which guide to the higher values of random walk coefficient.
The trend of random walk coefficient with respect to surface finish shows that the coefficient of angular random walk may further be improved by achieving the surfaces of better finish. This trend shows that there is a need to identify conventional / non conventional polishing techniques for super finishing of optical surfaces [8, 17-18]. Hence the surface finish of optical components plays a major role in determining the grade of optical rotation sensor.

4. Conclusion

In this study, glass substrates of fused silica with different surface finish, using various abrasives like aluminium oxide, zirconium oxide and cerium oxide have been prepared using conventional and submerged polishing techniques. The optics so produced have been assembled one after the other to form the optical rotation sensor for evaluating the lock-in threshold using the precise rate tables. Based on the lock-in threshold data, the random walk has been evaluated and correlated with the theoretical values. The trend of random walk coefficient with respect to surface finish shows that the coefficient of angular random walk may further be improved by achieving the surfaces of better finish. This trend shows that there is a need to identify conventional/non-conventional polishing techniques for super finishing of optical surfaces. Hence, the surface finish of optical components plays a major role in determining the grade of optical rotation sensor.

References


