Metal roughness profile inspection using a micro-displacement fiber optic bundled sensor

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A system and method for roughness or surface profile inspection for a simple polished cylindrical metal using a micro-displacement fiber optic bundled sensor system is demonstrated. The system used a red laser, a probe, a photo-detector, along with an 8 bit ADC and a computerized data acquisition system. The bundled sensor probe consists of both a transmitting and a receiving fiber. This sensor system adopts an intensity modulation technique based on a target of reflecting surface or mirror. The transmitted light of the red laser emits from the transmitting probe impinges the target surface and partially reflected back to the receiving probe. The intensity of the reflected light is measured. The micro-displacement sensor system has high linearity areas in the range of 550 μm (150-700) μm and in the range of 900μm (1550-2450) μm. Its sensitivity was 0.15 μm. The sample has a roughness index of 23%. This method is practically suitable in conjunction with a micro-computed tomography system in order to determine the exact surface profile of the 3D tomography object being inspected prior to the image reconstruction.

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1. Introduction

An x-ray CT is a powerful method in developing an image of internal structure of an object being inspected, both in axial and lateral images. The x-ray CT has also great role in non-destructive evaluation of internal structure. However, due to the powerful energy of the x-ray, the radiation interaction on the surface of the object is unable to envisage significant information related to the surface of the object, specifically for material dimension less than 10 mm. During image reconstruction procedure, the CT system is unable to determine the exact surface. Under formal mathematical approach on the inversion or back-projection methods, it is assumed that the image reconstruction area is a circle [1-2]. In fact, a micro-x-ray computed tomography system has a shortage on determining exact surface profile of a tomography object profile.

A variety of optical sensors for micro-displacement measurements based on intensity modulation technique have been reported in recent years [3-5]. Fiber optic displacement sensor plays an important role in a broad range of industrial, military and medical applications [6]. Two particular potential advantages of fiber optic displacement sensors include the extremely accurate non-contact sensing and the possibility of its use for roughness or surface profile of a small composite material. The fiber-optic sensor is interesting due to their inherent simplicity, small size, mobility, wide frequency capability, extremely low displacement detection limit and ability to perform non-contacting measurement. These properties have led to a variety applications in mechanical and biological measurement, as well as communication system. In fact, they are also widely used in sensing applications because of their better signal coupling, large core radius, and high numerical aperture and great capability to receive the maximum reflected light from the target [7-8].

The common optical methods that are applicable to measure the surface roughness texture are interferometry, speckle, light scattering and focus [9-10]. Ellipsometry is another technique that has been used for surface characterization [11]. In this paper, a simple fiber-optic displacement sensor is proposed to be used for determining exact surface or external profile of the 3D object being inspected. The system is under-construction, developed in conjunction with a CT apparatus. The sensor is using a multimode plastic fiber as probe and a red He-Ne laser as transmitter. The sensor mechanism is based on intensity modulation technique, in which the reflected light of the laser from a reflecting surface or target is coupled back into the probe and the intensity of the reflected light relative to the transmitted light is used to determine the distance between the target and probe. Then, this sensing capability is used to determine a metal roughness profile of a small object in corporation with a micro-CT system.

2. Experimental setup

The basic schematic diagram of the experimental set-up is shown in Fig. 1. The sensor consists of a light source, a fiber optic probe and a photodiode detector based on

OPT-101 photodiode (Burr-Brown). The fiber probe is a bundle plastic fiber of 200 mm in length, which consists of one transmitting core of 1 mm in diameter and 16 receiving cores of 0.25 mm in diameter. In this normal displacement sensor, a mirror is used as a reflecting target and the intensity modulation technique is adopted. The beam from the laser light source travels through a transmitting core and then impinges to the mirror. Then, the reflected light from the surface of the mirror is transmitted back through the receiving cores, travels to the photo-detector. Forward and back displacement of mirror at normal direction will provide intensity variation on received light intensity. The bending losses are minimized by putting both fibers in close contact to form an equal radius of curvature.

The static displacement of the mirror is achieved by mounting it on a motorized translation stage that is controlled by a personal computer. The distance between the fiber optic probe and the mirror can be varied in successive steps of 50 µm. The laser source emits the red light of peak wavelength 632.8 nm and the maximum output power is approximately 1 mW. The light is launched into the transmitting core (TF) and the reflected light (RF) intensity is directed to the a photo-detector sensor. The light intensity is converted into voltage analog signal in the detector, and it is subsequently converted into a digital signal using an 8 bits of an analog to digital converter (ADC) system. The digital signal is fed into a Data Acquisition System (DAS) controlled by a PC. The intensity signal variation received by the detector is converted to the voltage variation and measured against the corresponding change in micrometer translation stage. The results of sensitivity will be used to calibrate the surface difference of a 3D object profile.

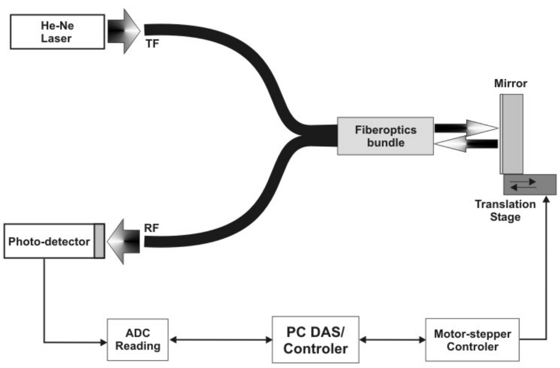


Fig.1. The schematic diagram of micro-displacement sensor using fiber optic bundle multimode.

The schematic diagram of the experimental set-up for determining a metal roughness profile is shown in Fig. 2. The cylindrical metal that is used in this experiment is made of a polished bronze and has a diameter of 30 mm. The cylinder was rotated by motor-stepper with a rotation step of 7.2^o so that 50 data points were obtained for a complete full rotation. Each step of rotation covered angular distance of 188.5 um. The light source is sent into the transmitting core and the reflected light intensity from the metal surface is caught by the receiving core and traveled to the photo-detector, and then treated similar to the system described in Fig. 1. The reflected intensity received by the photo-detector is measured. This voltage measurement corresponds to the closest surface of the cylinder relative to the distance of the fiber optic bundle, whereas the closest surface is a function of the angular orientation of the cylinder.

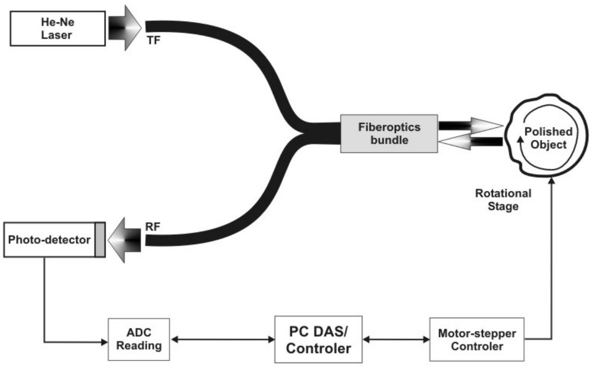


Fig. 2. The schematic diagram of fiber optic bundled displacement sensor for surface inspection.

3. Results and discussion

On the early experiment, the sensitivity on distance discrimination from reflected surface to the optical bundled is measured. This was accomplished by examining the linearity between the micro-translation of the flat mirror as a function of the number of rotational step of the stepper motor. Fig. 3 shows the linearity of the step-number to the mirror displacement is more than 99%. This curve is used for calibrating the displacement sensor. As it can be seen in Fig. 3, each step of the stepper-motor is corresponded to a displacement of (9.9 ± 0.1) µm.

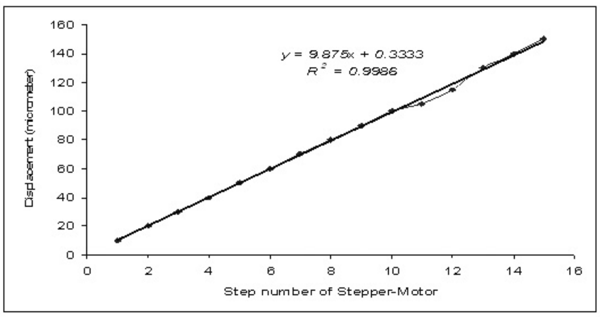


Fig. 3. Displacement vs. step number of stepper motor.

Fig. 4 shows the variation of the output voltage as a function of the displacement of the mirror from the fiber optic probe. The curve provides a maximum with a steep front slope and back slope. Both slopes indicate that the reflected light intensity versus distance of the mirror from fiber optic probe follows an almost inverse square law principle. The signal is very low at distance close to zero because the light cone unable to reach the receiving cores. When the displacement is increased, the size of the reflected cone of light at the plane of fiber increases, the receiving cores starts overlapping and output voltage produced. Further increase in the displacement leads to larger overlapping, and increases the output voltage. However, after reaching the maximum, the output voltage starts decreasing for larger displacements. This is due to large increase in the size of the light cone, while the power density decreases as the size of the cone of light increases. The maximum output voltage is 107 mV that is corresponds to the distance of 1.150 μm between the mirror and the fiber-optic probe.

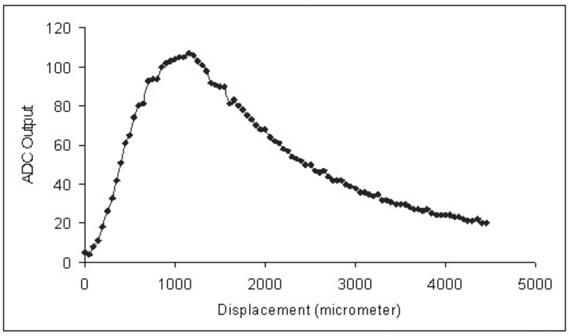


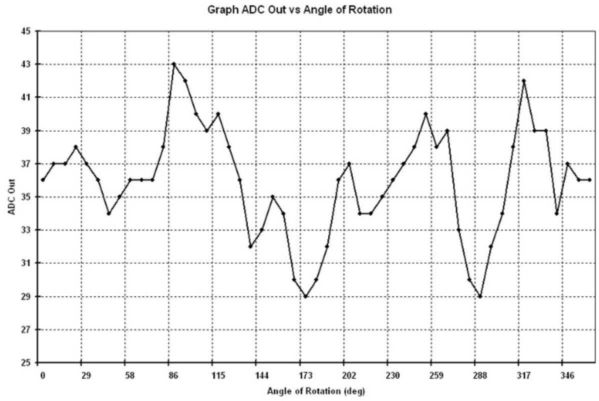
Fig. 4. ADC output vs. flat mirror displacement.

The experimental slope curves show a good linearity as shown in Fig. 4 with a certain regions exhibits linearity of more than 99%. For the front slopes, the high linearity areas are obtained at a displacement of 550 μm (150 -700 μm). On the other hand, the back slopes show a high linearity in the range of 900μm (1550-2450μm). The sensitivity and linearity of both the front and back slopes of Fig. 5 are summarized in Table 1. The sensitivity is positive on the front slope and negative on the back slope. The sensitivity of the front slope is used as a calibration of the surface differences that is 0.15 μm per ADC Output.

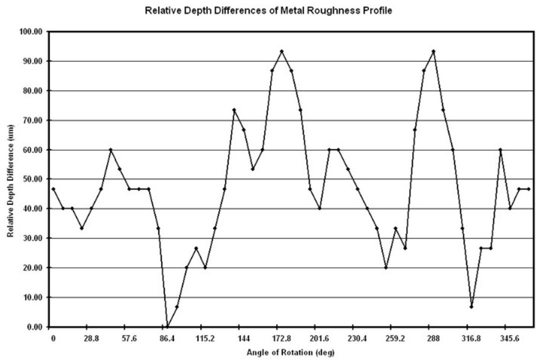
Table 1. The performance of the fiber optic bundled displacement sensor.

Parameter	Value
Sensitivity (front slope):	0.149μm^{-1}
Linearity range (front slope):	550μm (150-700μm)
Sensitivity (back slope):	0.0416 μm^{-1}
Linearity range (back slope):	900μm (1550-2450μm)
Linearity (front and back slope):	> 99%
Dynamic range	4.450mm

In the experiment, we determined a metal roughness profile using measured the reflected intensity from a metal surface. Fig. 5 (a) shows ADC output versus rotation of a metal. The change of intensity from ADC output shows a different surface roughness levels. Such ADC output variation corresponds to the relative depth difference of the surface roughness as described in Fig. 5 (b).



(a)



(b)

Fig.5 (a). ADC output vs. rotation of metal surface. Fig.5 (b). Relative depth difference vs. rotation of metal surface.

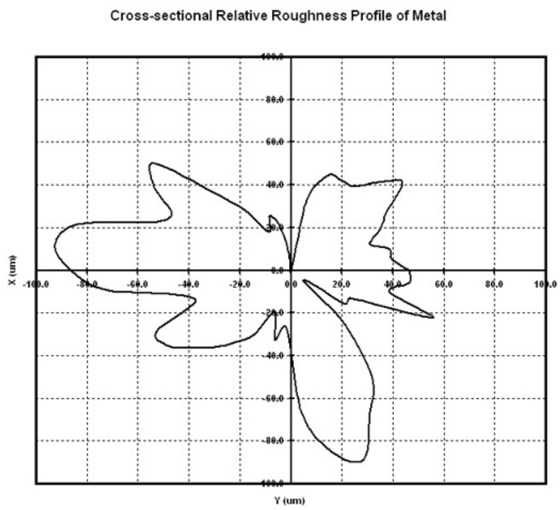


Fig. 6. Relative depth difference vs. rotation of metal surface.

Fig. 6 is a presentation of the relative depth difference relative to the rotation of the metal surface. The graph showed that the metal has a mean of 47 μm with a standard deviation of the mean of 21 μm. The maximum difference is 93 μm, so that it has an index of roughness of about 23%.

The circular profile of a metal surface of the polished bronze is shown in Fig.7. It is observed that the polished bronze is not perfectly circular. This is due to a polished bronze have a roughness level. The experimental results indicated the capability of implementation of the displacement sensor for the roughness sensor as a quantitative guidance for the manufacture design. This method can be implemented for determine the external profile of a tomography object, so that that external profile can be used as the image boundary prior to image reconstruction procedure.

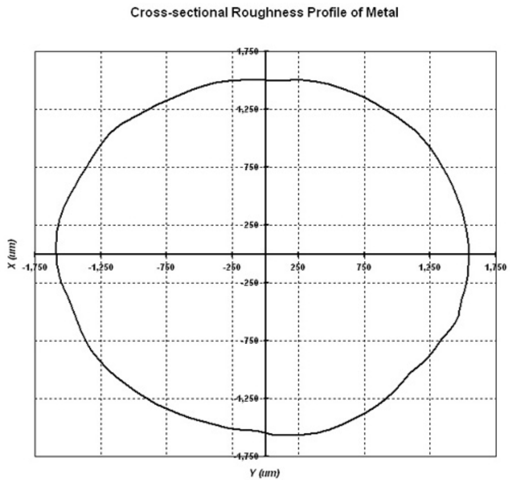


Fig.7. A metal roughness profile.

4. Conclusions

A roughness profile of a polished metal is able to be estimated using a micro-displacement sensor with a multimode bundled fiber. The roughness can be expressed in fluctuation of a reflected intensity of the light from the surface. The roughness profile along with its index of roughness can be used as a preliminary information on CT image reconstruction procedure, so that the maximum and the minimum diameter, as well as the estimated error of the diameter of the object outline can be determined.

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