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Original Research Article

Surface profile construction using two-dimensional optical fiber array

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ABSTRACT
The new method described in this research uses a two-dimensional arrangement of optical fibres to reconstruct a picture of surfaces with fine details about its roughness. The suggested approach is based on differential scatterometry and angle-resolved electromagnetic wave scattering from a surface. The sensor head is made up of a two-dimensional array of optical fibres, with the central fibre serving as the launcher of power onto the test surface and the remaining fibres in the array serving as receivers of the surface-reflected light beam. The surface roughness parameter is the three-dimensional tilt of each individual pixel. Since this approach is straightforward and based on intensity modulation, it is not necessary to illuminate the surface with strictly monochromatic light. The range of tilt angles that can be measured using this technique is between 10^{-1} and 10^{-4} radians. The fiber's location within the array that receives the largest amount of reflected intensity from individual pixels is used in an algorithm that has been developed to reconstruct the 3D surface profile. The surface image produced by this method contains data on the surface height of the pixels relative to a smooth reference surface in the range of 10^{-2} to 10^{+2} microns, in addition to tilt angle information. This approach is computer controlled and has the potential to be used for online or in-process quality control for producing smooth surfaces of high quality.

1. Introduction

In today's computer-integrated industries, it is crucial to assess the surface roughness of a smooth machined surface while the operation is ongoing. To estimate surface topology, numerous techniques have been proposed. Unfortunately, the majority of methods include restrictions or limitations on the types of test surfaces, operating conditions, and quantifiable ranges of roughness. Consequently, despite the scientific community's access to a wealth of knowledge on surface roughness assessment techniques, the need to advance current theory and systems is still evident. For many applications, it's crucial to detect surface micro-irregularities and identify surface properties.

Industrial applications employ optical methods to measure surface finish more frequently because they are quicker, more precise, and more dependable. Its expanding use is primarily driven by the fact that these techniques are both nondestructive and intrinsically capable of area averaging, in addition to speed and accuracy. The light scattering method constitutes one among the most intriguing possibilities for through-line/in-process surfaces characterization [1, 6], which has been employed among other optical methods [1-6] to quantify surface finish.

While many scientists now regard slope to be the parameter to define surface finish, most prior approaches adopted deviation of height over the mean surface as the roughness parameter. This work proposes a high speed and automatic technique to build surface profile with minute details of surface roughness. In order to achieve this, a sensor is created that satisfies the following requirements: (i) it must be highly accurate, non-contact, and non-destructive; (ii) in order to be utilised in computer-assisted production, it needs to be competent to continually measure various grades of surface roughness at high speed, it would be tiny, versatile, and it must be lightweight. The same sensor may be used to calculate the acceleration, velocity and displacement of an object continuously linearly moving as well as the frequency of an object that is vibrating.

2. Theory

To determine the roughness of a surface under test, a straightforward fibre optic sensor system using a manageable amount of optical components is provided. To define roughness, various factors must be considered. The slope of the surface at various locations is taken into account as the roughness parameter in the current technique. The following presumptions have been made in order to theoretically analyse:

(i) A continuous distribution of tiny elementary regions (microelements or pixels) with various tilts and orientations can be used to describe the surface.

(ii) Whereas the inclination and orientations of distinct tiny components are unrelated to each other, the position and orientation of every elementary's vertices are connected with the coordinates of the elemental areas around it.

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(iii) Any substance being tested can be used to normalise the surface's reflectance.

(iv) To prevent the shadowing effect, the tilt and orientation angles are sufficiently minimal.

Every fundamental surface area's dimension and orientations may be described in terms of the orientations which the perpendicular to that microelement encounters with every one of the three axes of the a cartesian system of coordinates.

The alternate approach for defining tilt and alignment that is recommended in this paper can be used to further easily recreate the surface description. The turning of the XY plane with respect to the X-axis (α) preceding a rotation of the identical plane about the Y-axis (β), or the other way around, might be considered as a twofold revolving of the facet with respect to its location for an entirely smooth plane for each positioning of a pixel in three dimensions. The approach is appropriate for the smooth machined surfaces under investigation as well as for slight pixel tilt and orientation.

The measurement item in the current approach reflects the emitted light, which is then picked up by a network of optical fibres terminating in optoelectronic converters. In addition to the slant and alignment of the image, the distance between the sensors and the pixel affects the quantified brightness of light that is reflected.

The amount of diffraction produced by a slanted facet, in accordance with scalar diffraction principle, is comparable to that produced by a flat stripe with a comparable cross-sectional area that propagate in the direction that is predicted by geometrically based optics concepts. The region of finite slope results in diffracted wave amplitude components that are laterally moved by a quantity as a percentage of the facet inclination at the transformation plane. The measurement is done carefully to separate the diffraction from the rest of the thing being tested.

It should be mentioned that the current approach suggests a constraint that the ratio of the wavelength of light to the pixel size and periodicity is fundamentally large. Since the information gained by the present method has no bearing of the qualities of the illumination, the investigation may be carried out with a strong illumination attached to the fibre. Due to the tilt and orientation of the lighted pixel, it is possible to determine the slope of the pixel by just pinpointing the location of the profile's maximum intensity that is reflected. Given that the level of sensitivity of the light emanating from an optical fibre is roughly Gaussian distributed, the extended brightness distribution of an entirely flat surface will appear to be identical to if it had been illuminated by a perpendicularly positioned optical fibre powered by an intense light laser. Whenever the illuminated surface is tilted, the distribution of intensity ceases to become symmetrical and turns non-Gaussian, causing the maximum value of the intensity profiler to migrate horizontally with regard to the pixel slant.

As $\hat{i}$ and $\hat{j}$ stand for the unit vectors along X and Y directions, respectively, and $V = x\hat{i} + y\hat{j}$ are the location vectors in the Cartesian coordinate system, if the intensity profile's peak is mirrored, is found there, then α and β may be inferred via following equations as follows:

$$\alpha = \frac{1}{2}\tan^{-1}\left(\frac{x}{h}\right) \text{ and } \beta = \frac{1}{2}\tan^{-1}\left(\frac{y}{h}\right).$$

As a result, the direction of tilt and slant of the pixel relative to the scanning surface is provided by the position vector displaying the highest value of the luminous profile of the light that is reflected.

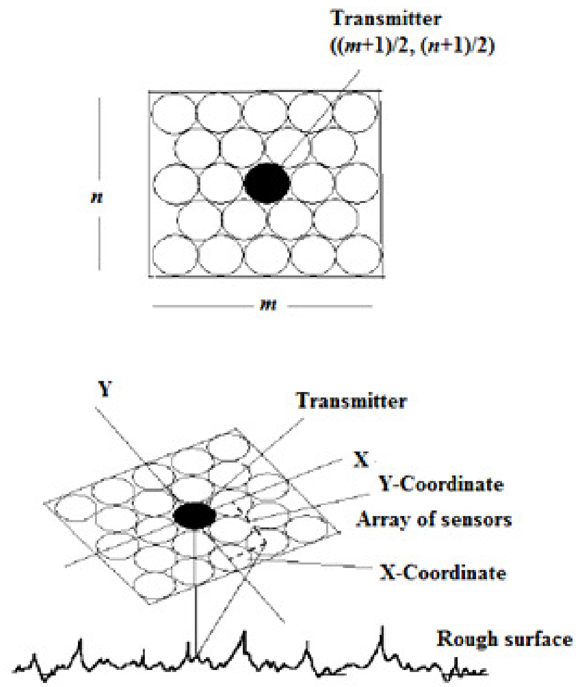

Figure 1: Surface image reconstruction.

Using the tilt and orientation of distinct pixels that make up an entire surface, an image of a surface may be created. The position of the fibre receiving the greatest intensity of reflected light has been used in the suggested method to determine the tilt and orientation.

The following presumptions have been made in order to estimate the degrees of inclination and direction of the individual pixels: (i) the transmitter is in the middle (0, 0); (ii) all optical fibres function as individual sensors; (iii) the central row's number of sensors is odd (m); (iv) the total number of rows is odd (n); and (v) the sensors in odd rows are odd (m).

The row's transmitter's position is determined by

$$pos = \frac{(m+1)}{2},$$

where, pos = position of the transmitter, and m = number of optical fibers in an odd row.

Assume that L is the sensor number in that row getting the maximum intensity, Q is the row number containing the sensor receiving the maximum intensity, and R is cladding radius. If optical fiber's coordinates (x, y) are those that receive the greatest amount of reflected light, then the coordinates (x, y) may be roughly described as follows:

Calculation of the X coordinate:

If the sensor is on the left side of the transmitter:

For even numbered rows: $x = -R[2(pos - L) - 1]$

For odd numbered rows: $x = -2R(pos - L)$

If the sensor is on the right side of the transmitter:

For even numbered rows: $x = R[2(L - pos) - 1]$

For odd numbered rows: $x = 2R(L - pos)$

Calculation of the Y coordinate:

If the senor lies above the transmitter: $y = \sqrt{3}R(Q - row)$

If the senor lies below the transmitter: $y = \sqrt{3}R(row - Q)$

Let's assume that the projection of elementary pixels on the perfect smooth surface is a square with side "*a*" and that the surface is a continuous arrangement of (*MN*) microelement count in *N* columns and *M* rows. One corner of the entire surface was chosen as a starting point of the Cartesian coordinates system in order to rebuild a surface image.

The positions for the pixels' corners along X-axis are given by $\left[aq, 0, a\sum_{k=1}^{q}\tan(\alpha_{1,k})\right]$.

The corner coordinates for each pixel along Y-axis are given by $\left[0, ap, a\sum_{j=1}^{p}\tan(\beta_{j,1})\right]$.

And the coordinates of all other corners are given by $\left[aq, ap, a\sum_{j=1}^{p}\sum_{k=1}^{q}(\tan\alpha_{j,k} + \tan\beta_{j,k})\right]$.

In this case, *p* and *q* each have a range of 0 to *M* and 0 to *N* possible values.

3. Experimental setup

Studies of the surface topology of a mirror with excellent reflectivity that has a collection of optical fibres arranged in a Rhombus-shaped pattern have been conducted. Multimode optical fibres with a graded index have been employed. This fibre has a 125-micron cladding diameter, a 50-micron core diameter, a numerical aperture of 0.2, a transmission loss of 2.5 dB/km, and a bandwidth of 1000 MHz-km. It is composed of silica glass.

The illuminating source is non-monochromatic radiation in visible regime of electromagnetic spectrum having an optical power of 750 mW, and the detector is an n-p-n photo-transistor inside an TO-20 type hermetically evacuated container.

4. Results and discussion

It has been discovered that the proposed fibre optic sensor head can calculate surface slope between 10^{-1} and 10^{-4} radians. In the range of 10^{-2} to 10^{+2} microns, it can also measure the height variation from a reference smooth surface. Tested with certain sample tilt and orientation values, the algorithm was discovered to produce the surface profile with fine tilt and orientation details as well as height variation, as shown in Figure 2.

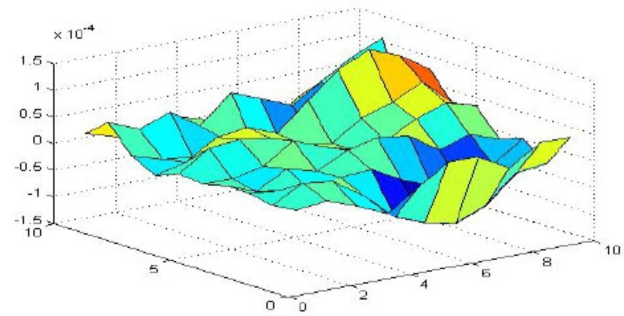

Figure 2: The surface profile with minute details of tilt and orientation as well as height.

5. Conclusions

The analysis of the intensity and direction of the reflected light from the surface has led to the proposal of a revolutionary high speed technique to generate surface images. An optical fibre array sensor that uses the central fibre to illuminate the surface and the other fibres in the array as receivers has been built based on the findings of simulations.

By identifying the receiving fibre in the array that gets the largest amount of reflected intensity and assuming that the surface is a continuous distribution of elementary pixels, it is possible to determine the orientation and tilt of the elementary pixels that make up the entire surface.

The setup utilised to accomplish this method is fairly straightforward and can produce slope measurement accuracy in the region of 10^{-1} to 10^{-4} radians, which is a respectable level. In the range of 10^{-2} to 10^{+2} microns, it can also measure the height variation from a reference smooth surface. By identifying the fibre in the array that is capturing the most reflected power and using that information to rebuild the surface image, an algorithm has been developed to determine the orientation and tilt of each individual pixel.

This method may be used to examine the surface profiles of fragile materials and is simple to apply under computer control. This sensor should have several uses in the robotics industry as well as for online and in-process quality control.

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