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Forouzbakhsh, Farshid; Rezanejad Gatabi, Javad; Rezanejad Gatabi, Iman

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A new measurement method for ultrasonic surface roughness measurements

F. Forouzbakhsh a,*, J. Rezanejad Gatabi b, I. Rezanejad Gatabi c

a Electrical Engineering Department, Faculty of Engineering, University of Tehran, Campus No. 2, North Kargar Ave., Tehran 14516, Iran
b Electrical Engineering Department, Iran Univ. of Science and Tech. Narmak, Tehran, Iran
c Electrical Engineering Department, K. N. Toosi Univ. of Tech., Seyyed Khandan Bridge, Tehran, Iran

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A B S T R A C T
This study proposes the application of Doppler-based ultrasonic method to surface roughness measurements. The fabricated prototype measures the slope of the under-test surface at small holes to evaluate the roughing parameters and this makes for more precise measurement. The device comprises an ultrasonic transmitter emits sound pulses that travel across to the under-test surface. The reflected wave is separated into many weak sounds, a few of which are received by the receiver. The Doppler effect caused the frequency of the received wave to be shifted with respect to the surface roughness at the reflecting point. The relationship between the Doppler shift and the roughing slope is mathematically analyzed.

Compared to the transit-time based techniques, the dependency of the sensor on the sound speed in air is decreased by a factor of 2 and therefore a more precise measurement is achieved. The fabrication of a prototype device and experimental verification of the analytical results are reported.

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1. Introduction

All smooth surfaces possess some degree of roughness, even if only at the atomic level. For man-made surfaces, this roughness arises from the manufacturing process which may involve chemical deposition, grinding, polishing, etching or several other commonly used techniques. Correct function of the fabricated component often is critically dependent on its degree of roughness.

In the manufacturing industry, surface must be within certain limits of roughness. Therefore, measuring surface roughness is vital to quality control of machining workpiece, especially if it is non-contact method compared to the direct conventional method; which uses stylus type devices. In the direct contact method, measurements are obtained using a stylus drawn along the surface to be measured: the stylus motion perpendicular to the surface is registered. This registered profile is then used to calculate roughness parameters. This method requires interruption of the machine process, and the sharp diamond stylus may make micro-scratches on surfaces (i.e. destructive damaging effect).

Several attempts [1–6] have been reported of studying non-contact techniques for the assessment of surface roughness. Of these worth mentioning works, the study by Hilton [5], where he used two orthogonally polarized laser beams to produce two independent speckle patterns that are imaged and auto-correlated to deduce the roughness of the surface being illuminated. Roberts and Briggs [6], have used several techniques such as acoustic emission and incident X-ray scattering for the characterization of surface roughness and sub-surface damage. Bilgen and Rose [7], theoretically analyzed and discussed the problem of the signal noise of back scattering generated by rough surface using modeled techniques [8].

In this paper, we proposed an ultrasonic non-contact sensor which implements the Doppler effect instead of
the ultrasonic travel-time to describe the roughness parameters. Using the Doppler effect instead of the ultrasonic travel-time will result in a much lower dependency of the sensor on the sound velocity in air, which will provide a more precise measurement.

Imaging surface roughness using speckle grain pairs as discussed in [5] encounter problems when the surface is not a polarization maintaining surface. The condition that surfaces must maintain polarization of scattered light restricts the range of potential applications to those dealing with plastic or metallic surfaces. The unexpected dependence of normalized ACV with the speckle image brightness is another issue. Having no such problems, the proposed method would be superior to this technique.

2. Principle of operation

Fig. 1 illustrates the block diagram of the sensor. The under-test surface is moved at a constant velocity of \( V_x \) in the positive x-direction as illustrated in the figure. An oscillator generates an standard signal of frequency \( F_0 \) which is amplified and transmitted from a transmitter to the under-test surface in an inclined direction. The sonic wave is reflected diffusely on the surface where it is separated into many weak sounds, a few of which are received by the receiver. The Doppler effect causes the frequency to be shifted [9]. If \( F_d \) denotes the Doppler shift, the frequency of the received signal is \( F_0 + F_d \).

Since \( F_d \) is very smaller than \( F_0 \), its detection requires a high-precision circuitry which may be practically inapplicable. To overcome to this issue, the received signal is amplified and mixed with a signal of frequency \( F_0/F_0 \) (where \( F_1 < F_0 \)) in a mixer to create the beat frequency signals. The lower frequency beat is filtered through a low-pass filter and therefore the output of the low-pass filter has a frequency of \( (F_0 - F_1) + F_d \), where \( F_d \) is comparable with \( (F_0 - F_1) \).

The output of the low-pass filter is applied to a high-pass filter and then to a full-wave rectifier. Of its frequency response, the high-pass filter provides the amplitude of its output voltage proportional to its input frequency, \( (F_0 - F_1) + F_d \). The output of the high-pass filter will rectified in the rectifier stage to provide the output voltage, \( V_o \).

In this manner, the dc-component of the output voltage is proportional to the frequency \( (F_0 - F_1) + F_d \).

Any hole on the under-test surface causes the reflecting point of the surface, the point A, to be moved in y-direction at a velocity of \( V_y \). Thus the instantaneous velocity vector of the point A in xy-plane can be written as: \( \vec{V} = V_x + V_y \).

On the assumption that air is stationary relative to the sensor, the Doppler shift \( F_d \) is given by:

\[
F_d = F_0 \frac{Cs + \vec{V} \cdot \vec{U}_k}{Cs + \vec{V} \cdot \vec{U}_T} - 1
\]

(1)

where \( C_s \) is the velocity of sound in air, \( \vec{U}_T \) is the unit vector of transmitted direction of the ultrasonic wave and \( \vec{U}_k \) is the unit vector of the direction of the received wave. From \( \vec{V} = V_x + V_y \), we will get:

\[
F_d = F_0 \frac{Cs + V_x \cos \beta + V_y \sin \beta}{Cs - V_x \cos \alpha - V_y \sin \beta} - 1
\]

(2)

where \( \alpha \) is the supplement of the angle between the transmitted direction of the ultrasonic and x-axis and \( \beta \) is the angle between the direction of the received wave and x-axis. Since \( V_x \), \( \alpha \) and \( \beta \) are known, measurement of \( F_d \) allows \( V_y \) to be evaluated through the following formula:

\[
V_y = \frac{F_d Cs - (F_0 + F_d) V_x \cos \beta - F_0 V_y \cos \beta}{(F_0 + F_d) \sin x + F_0 \sin \beta}.
\]

(3)

It allows the direction and the magnitude of the velocity vector \( \vec{V} \) to be calculated.

Calculating \( \vec{V} \) in any sampling time allows a profile representing the shape of the surface to be sketched. The roughing shape and peak-to-valley height can be achieved from the sketched profile and therefore the roughing parameters are mathematically calculated.

Eq. (2) implies that \( V_y \) is directly proportional to the sound velocity in air, \( C_s \), by a factor of \( m \) where \( V_y \propto mC_s \) and:

\[
m = \frac{F_d}{((F_0 + F_d) \sin x + F_0 \sin \beta)}.
\]

(4)

By choosing appropriate values for the angles \( \alpha \) and \( \beta \), it is possible to force the factor \( m \) to have a very small magnitude which will result in a much lower dependency of the sensor on the sound velocity in air related to the transit-time based sensors.

Fig. 2 illustrates the factor \( F_d/F_0 \) versus the slope of the surface at the point A \( (V_y/V_x) \) for various values of \( V_x \), where \( \alpha = 70 \) (deg) and \( \beta = 60 \) (deg).

This illustration implies that by increasing the factors \( V_x \) and \( F_0 \), the frequency shift \( F_d \) and therefore the sensitivity of the device is increased.

As a practical example, on the assumption that \( F_0 = 1 \) MHz and \( V_x = 0.1 \) (m/s), the frequency shift \( F_d \) is approximately 10 Hz when the slope of the surface is 1 (deg).
3. Experimental results

The primary experimental device comprises a circular plane rotating at a constant angular velocity of \( \omega \). The under-test object is mounted on the rotating plane which is placed near the transmitter–receiver pair. Fig. 3 illustrates photographs of the fabricated device.

The transmitter continuously emits sound pulses at the frequency of 100 kHz to the under-test object which are reflected by the surface. The reflected ultrasonic is received by the receiver to provide the output voltage. The dc-component of the output voltage is directly proportional to the received frequency. i.e., it is proportional to the roughing slope.

To verify the response of the sensor, we placed an approximately flat surface near the prototype at various angles representing different roughing slopes. The surface was moved at a velocity of 0.02 (m/s) and the dc-component of the output voltage was measured.

Fig. 4 illustrates the experimentally aided trace of the dc-component of output voltage versus the roughing slope. It indicates an approximate sensitivity of 18 (mV/deg) for the prototype at the illustrated slope range.

The output signal of the prototype is applied to an 8-bit analog to digital converter which is connected to the parallel port of the PC.

In each sample, the prototype provides its output voltage based on the slope of the reflecting point. It allows the slope of the under-test object to be determined at various test points. To sketch the complete profile of the surface, we consider it as a piecewise linear curve at which the slope of each line segment is equal to the slope of the under-test surface at corresponding test point. Based on this method, the implemented software can sketch the distance of the under-test surface from the transducers at each sampling time. We name it the “distance–time” profile of the surface. However, the complete profile of the surface can be achieved by transforming the horizontal axis of the distance–time profile from time to distance, that is by multiplying the horizontal axis by \( V_x \), where \( V_x \) is the tangent velocity vector of the under-test object at the reflecting point as introduced in Section 2.

Fig. 5 illustrates the experimentally aided distance–time profile of an object near a hole using 1 MHz frequency of ultrasonic. The angle of the hole’s side wall is different at the various points. Here the object surface has been moved with velocity at 25 mm/s. The hole length that has been scanned in the experiment is exact 4 mm.

As illustrated in this figures the dimension and shape of the holes can be determined through the distance–time profile.
4. Conclusions

We have proposed and demonstrated a Doppler-based ultrasonic surface roughness measurement. Implementing the Doppler effect instead of the ultrasonic transit-time to describe the roughing parameters will result in a lower dependency of the sensor on the sound speed in air which provides a more precise measurement in various environmental situations.

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