ELSEVIER

Ultrasonics 39 (2001) 101–108

Ultrasonics

www.elsevier.nl/locate/ultras

Application of time delay spectrometry for rough surface characterization

P.C. Pedersen *, A. Grebe

Department of Electrical and Computer Engineering, Worcester Polytechnic Institute, Worcester, MA 01609, USA

Received 19 February 1999; received in revised form 16 June 2000; accepted 19 July 2000

Abstract

This paper describes the design and performance of an ultrasound measurement system, utilizing a swept frequency excitation signal, for analyzing the backscattered signal from planar rough surfaces. The implementation is in the form of a time delay spectrometry (TDS) system operating in reflection mode whose advantages are improved signal-to-noise ratio even with low peak power relative to conventional pulse-echo methods. Because of simultaneous transmission and reception, the TDS system requires two transducers. The TDS measurement system uses a swept frequency spectrum analyzer as the central analog processing unit. Both planar piston and focused transducers in the low MHz range were used for the measurements. Due to the statistical nature of rough surface backscatter, the mean of several statistically uncorrelated measurements is required to characterize the scattering behavior of a given rough surface. Backscatter data are obtained for a series of planar rough surfaces, in the form of scattering magnitude vs. frequency and vs. incident (=backscattered) angle. Analysis of the results reveals a good correlation between the root-mean-square (RMS) height and mean backscatter magnitude at 0° incident angle, and between the ratio of RMS height to correlation length and the difference in mean backscatter magnitude between 0° and 5°.

PACS: 43.35.Zc; 43.58.-e
Keywords: Time delay spectrometry; Rough surface; Remote sensing; RMS height; Linear sweep

1. Introduction

Instrumentation for assessing the parameters of a rough surface in a statistical sense have many applications, ranging from estimating the wave height on the ocean as a measure of wind speed, to analyzing condensation phenomena and assessing the smoothness of coated surfaces, to determining the roughness of machined surfaces for quality control in manufacturing processes. The most direct and quantitative measurement is profilometry which generates a deterministic record of the selected surface profile; profilometers may either be in the form of a contacting mechanical stylus or a laser beam. The alternative is remote sensing where the rough surface is irradiated or insonified with a suitable wave, and statistical parameters of the rough surface are extracted from properties of the backscattered waveform.

Profilometric measurements are based only on the roughness along the scan line(s) and can for a mechanical stylus only be obtained on solid, stationary surfaces; furthermore, the stylus may cause scratch marks on the surface. It should also be noted that the results obtained with profilometers can be erroneous unless it is known a priori that the roughness is either one-dimensional (1D) or independent of direction. Furthermore, many surfaces do not permit contact measurements and/or are not optically accessible, such as the inside of a pipe where the corrosion requires estimation; in such a case, measurement of the surface roughness by remote sensing must instead be used. Remote sensing has the additional advantage of basing the assessment on a surface area, rather than a surface line, thus requiring a smaller region to achieve statistically representative results. The information can be gathered much quicker with remote sensing which therefore permits real-time monitoring of surface roughness during a manufacturing process.

* Corresponding author. Tel.: +1-508-831-5641; fax: +1-508-831-5491.
E-mail address: pedersen@ee.wpi.edu (P.C. Pedersen).

0041-624X/01/$ - see front matter
PII: S0041-624X(00)00044-5

Optical techniques represent the most common approach for measuring surface roughness whether by profilometry or by statistical analysis of backscattered data, and such techniques have been widely described in the literature; a broad overview is given in Ref. [1], while Ref. [2] presents a quantitative analysis. When the roughness measurements need to be carried through an intervening non-transparent or optically disturbing medium, ultrasound methods become a suitable alternative and have been explored by several investigators. An early investigation was carried out by de Billy et al. [3] who studied the ultrasound backscattered energy from 1D periodic surfaces as a function of root-mean-square (RMS) roughness, frequency and angle of incidence. Blessing et al. [4–6] reported on wide area measurements (scatterometer) and scan line measurements (profilometer) on rough and sinusoidal surfaces, using ultrasound frequencies in the 10–50 MHz range, with good agreement between roughness and echo amplitude, as predicted by the coherent term of the scattered wave amplitude in the Kirchhoff model. When air transducers are employed, a much lower frequency must be used, due to the attenuation in air. Oh et al. [7] used focused ultrasound to determine the echo amplitude from periodic cusped surfaces.

Whereas previous ultrasound-based techniques for assessing surface roughness have been based on pulse-echo measurements, a swept frequency measurement technique termed time delay spectrometry (TDS) is utilized in this paper. The TDS concept was initially developed for free field loudspeaker characterization in a reverberant environment [8], but has been applied to a number of measurement situations, such as biological tissue characterization [9], study of highly attenuative media [10], and characterization of hydrophones and ultrasound transducers [11,12]. In these applications TDS has been used in a transmission mode; however, for rough surface characterization a reflection mode TDS is required. Range discrimination is achievable by appropriate signal processing although the spatial resolution in the axial direction is lower than with pulse-echo techniques for the typical TDS operating parameters. Reflection mode TDS has seen only limited use; apart from unpublished studies of undersea sediments by Heyser, only one paper describes such a system [13].

The chief advantage of TDS over the conventional pulse-echo technique is an improved signal-to-noise ratio (SNR) since more signal energy can be generated over the duration of a long sweep than in a short pulse. Better SNR permits a wider frequency range to be used for the rough surface characterizations, for a given transducer, and gives a more accurate normalization of the measured data with the transducers' own bandwidth characteristics. Improved SNR is also an advantage if the rough surface measurements are to be carried out through a strongly attenuating medium. In contrast to the high intensity sound pulses and the associated likelihood of non-linear behavior produced by broadband transducers, TDS measurements utilize much lower peak intensities. The TDS technique requires two transducers because transmission and reception occur simultaneously, but that gives the added advantage of being able to measure the backscattered field as a function of reflected angle for different angles of the insonifying sound field.

2. Time delay spectrometry concept

Fig. 1 illustrates the TDS concept. The transmitting transducer is driven by a repetitive linear sweep signal from frequency f_1 to f_2, with a sweep duration, T_s. The sweep rate is $S = (f_2 - f_1)/T_s$. The resulting sound field insonifies the rough surface under the incident angle ϕ, and the backscattered signal from the rough surface is detected by the receiving transducer under a reflected angle equal to the incident angle and sent to a narrow-band tracking filter. The actual angle between the paths d_1 and d_2 is generally smaller than indicated in Fig. 1. The propagation delay along the path $(d_1 + d_2)$ is $t_d = (d_1 + d_2)/c$. The instantaneous frequency of the desired received signal lies below the instantaneous frequency of the excitation signal by (St_d) Hz. Undesired signals, such as signals reflected off the walls or the floor of the measurement tank, will have instantaneous frequencies which are further offset relative to the instantaneous frequency of the excitation signal, due to the larger propagation delay.

If the center frequency of the tracking filter is set to be (St_d) *below* the instantaneous frequency of the sweep signal and if the bandwidth of the tracking filter is appropriately narrow, the filter will suppress signals from the receiving transducer which are due to sound paths

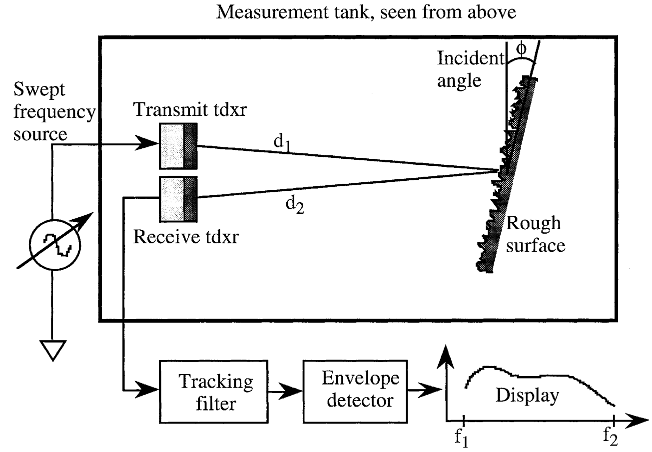


Fig. 1. Conceptual block diagram of the reflection TDS measurement system for measurement of rough surface scattering.

which are either shorter or longer than the path along path $(d_1 + d_2)$. In other words, a range resolution is achieved so that only signals received from the rough surface region will pass through the tracking filter. The tracking filter is followed by an envelope detector whose output is the magnitude of the backscattered signal from the rough surface as a function of frequency. The set-up allows the backscatter signal from the given rough surface to be determined as a function of frequency and incident angle, for different transducer types.

3. Experimental system

Fig. 2 shows the actual implementation of the reflection TDS measurement system where the HP 3585A swept frequency spectrum analyzer provides the linear sweep signal in the form of the tracking generator output and implements the tracking filter as the intermediate frequency (IF) filter. The HP 3585A spectrum analyzer allows the center frequency of the IF filter to be frequency offset relative to the instantaneous tracking generator frequency [12].

The spectrum analyzer is interfaced to a 486 personal computer via general purpose interface bus (GPIB), and the PC sets up the spectrum analyzer parameters, initializes the measurements, and transfers the data to the PC for data analysis with the commercial software package MATLAB [14]. This data is displayed as mean amplitude vs. frequency and incident angle, ϕ. In addition, the PC controls the transducer position via stepper motor commands.

As described in Refs. [12,13], the achievable resolution in the frequency domain, f_{res}, of the measured backscatter response from the rough surface is given as

$$f_{res} = 2.50\frac{S}{B} = 2.50\frac{f_2 - f_1}{T_s B}, \qquad (1)$$

where B is the resolution bandwidth of the IF filter of the spectrum analyzer. Note that Eq. (1) is experimentally determined for the HP 3585A spectrum analyzer [12] and that the factor 2.50 will likely be slightly different for other spectrum analyzers. The sweep range $(f_2 - f_1)$ is determined based on the a priori known useable bandwidth of the transducer pairs. For the measurements presented in this paper, $B = 100$ Hz is chosen; the lower bound for B for the HP 3585A spectrum analyzer is given as $B_{min} = 53/T_s$. When resolution bandwidth B, sweep range $(f_2 - f_1)$, and desired spectral resolution f_{res} are chosen, the sweep time T_s can be calculated, using Eq. (1). In this work, a sweep time was selected to achieve a f_{res} around 100 kHz which is considered fully adequate. An inverse relationship exists between tank size and f_{res} because a larger tank size permits a wider bandwidth of the IF filter without encountering interference from sound signals along different path lengths, and the wider IF bandwidth in turn gives a faster responding IF filter. Specifically, a tank of minimum length of 32 cm as well as minimum water height of 32 cm is required.

To obtain reliable results, the backscatter measurements must be repeated for several positions of the transducers relative to the rough surface; the repositioning of the transducers is carried out by stepper motors controlled by the PC.

The distance d_1 is specified so that the rough surface is located slightly beyond the near field–far field transition of the transmitting transducer at the highest frequency, f_2, in the linear sweep, in order to achieve good beam uniformity. Next, the −40 dB beam width is measured at the axial distance d_1 from the transducer, using the lowest frequency, f_1, in the sweep signal for a given transducer. To ensure that no edge diffraction takes place from the rough surface, the dimensions of the rough surface sample must then exceed the −40 dB beam width.

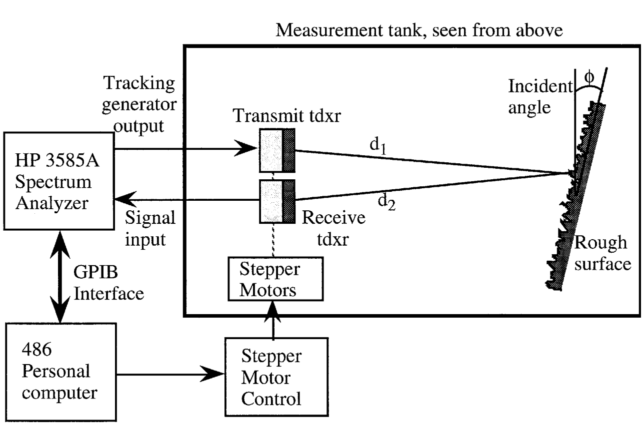


Fig. 2. Implementation of the reflection TDS measurement system based on the HP 3585A spectrum analyzer.

4. Rough surfaces, description and profilometric characterization

4.1. Statistical parameters for rough surfaces

Many types of random rough surfaces may be encountered in practical applications. Machined surfaces can often be described as having a 1D roughness, occurring in a specific direction, with a 2D low level roughness background. Other surfaces exhibit a definite 2D roughness where the surface may be either isotropic or anisotropic. Examples of anisotropic rough surfaces are biological tissue interfaces and wind-generated rough ocean surfaces. Condensation patterns on nonwetted surfaces or abrasives typically can be described as isotropic rough surfaces. Only 2D isotropic rough surfaces will be investigated in this paper.

A 2D isotropic rough surface is described by statistical parameters which are assumed uniform over the surface and independent of direction. For the ultrasound measurements reported here the surface parameters of interest are: (i) the RMS height; (ii) the correlation length, λ_0, which is distance where the (normalized) autocorrelation function has decreased to $1/e$ of its initial value of unity; and the ratio RMS height/λ_0. The higher order moments and the shape of the correlation function can provide additional definitions of the rough surface. If $z(x)$ is the height profile along a line across the rough surface, the RMS height is given as follows, using the assumption of a stationary, ergodic profile with zero mean:

$$\text{RMS height} = \sigma = \left(\lim_{L\to\infty}\frac{1}{L}\int_0^L z^2(x)\,\mathrm{d}x\right)^{1/2}. \qquad (2)$$

Similarly, the autocorrelation function, $\rho(\xi)$, can be obtained directly from $z(x)$ or from the power spectrum of $z(x)$, denoted $G(\omega)$, as

$$\rho(\xi) = \frac{\lim_{L\to\infty}\frac{1}{L}\int_0^L z(x)z(x+\xi)\,\mathrm{d}x}{\sigma^2} = \int_{-\infty}^{\infty} G(\omega)\mathrm{e}^{\mathrm{j}\omega\xi}\,\mathrm{d}\omega$$

where

$$G(\omega) = \left|\frac{1}{2\pi}\int z(x)\mathrm{e}^{-\mathrm{j}\omega x}\,\mathrm{d}x\right|^2. \qquad (3)$$

4.2. Preparation and reference characterization of rough surfaces

The rough surfaces were produced by gluing sandpaper sheets onto glass plates and coating them with enamel spray for waterproofing. The dimensions of the rough surfaces are 13×9.5 cm^2. The grit values of the sandpaper range from 36 (very rough) to 150 (very smooth).

The actual values of the RMS height and λ_0 were obtained by measuring $z(x)$ with a laser profilometer [15] based on a triangulation principle. The laser profilometer has a vertical resolution of 12.5 μm, limited by noise, and a horizontal resolution of 25–30 μm, determined by the laser sensor. Four profiles of 4 cm length each were obtained for each rough surface and linked together to give a 6400 point data file. The data file was then processed according to Eq. (2) to give the RMS height and according to the Fourier transform expression in Eq. (3) to give the correlation function, $\rho(\xi)$, from which λ_0 was obtained. The actual shape of the correlation functions can either be approximated to a Gaussian function or to a triangular function.

The greater the RMS height is, the stronger is the diffuse scattering and the weaker is the backscattering at normal incidence. Conversely, the longer λ_0 is the smoother the surface will appear, and increasing λ_0 will make the diffuse scattering weaker and the backscattering at normal incidence stronger. Thus, the ratio of RMS height to λ_0 gives a measure of scattering diffusivity. In Table 1, the RMS values, the λ_0 values, and the RMS/λ_0 ratios are listed for the grit values of the sandpaper-based rough surfaces. Representative backscatter signal amplitude vs. frequency and angle of incidence will be presented for the surfaces marked with asterisks in Table 1; however, the roughness characterization results are based on all six rough surfaces.

Table 1
List of the statistical parameters of the rough surfaces[a]

Grit value	RMS height (mm)	Correlation length, λ_0 (mm)	RMS/λ_0
36*	0.191	0.315	0.606
50*	0.123	0.186	0.661
60	0.078	0.203	0.384
80*	0.055	0.151	0.364
120*	0.021	0.161	0.130
150	0.018	0.156	0.115

[a] Backscatter results vs. angle and frequency are shown later for the grit values marked by asterisks.

5. Data acquisition, processing and display

Backscatter measurements have been carried out as a function of frequency over the effective frequency range of the combined transmitting and receiving transducer, using the TDS measurement system as previously described. Both focused and unfocused transducers with different center frequencies were investigated. However, the representative results presented in this paper are limited to

- An unfocused, 2.25 MHz transducer pair, with diameter 0.375 in. The transducers in this set have a useable bandwidth from 1 to 5 MHz. The center-to-center distance between the transmitting and receiving transducer is 1.10 cm. The rough surface is placed 21 cm from the transducers which is in the far field for the whole frequency range. The axes of the transducers are adjusted so that they intersect at 21 cm. It has been verified that edge diffraction effects from the rough surface are negligible over the whole frequency range.
- An annular array transducer with eight rings, operated so that the inner four rings function as the transmitting transducer with diameter 1.25 cm and the outer four rings as the receiving transducer, shaped as a ring with outer diameter of 2.5 cm. The focal length is 8 cm. The annular array transducer has a useable bandwidth from 1 to 7 MHz. The rough sur-

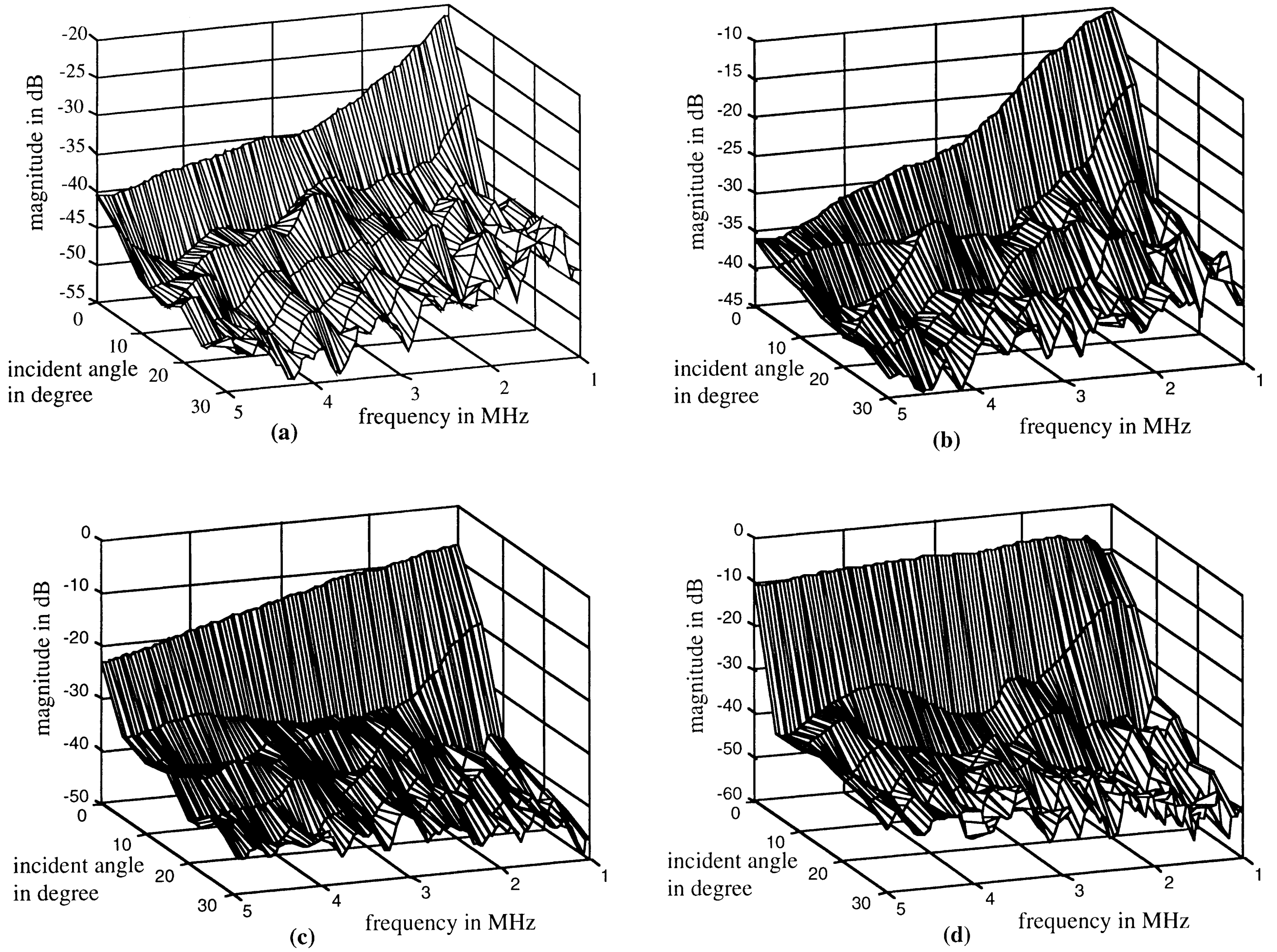


Fig. 3. Backscatter signal amplitude for rough surfaces with grit values 36 (a), 50 (b), 80 (c), and 120 (d), as described in Table 1, using a pair of unfocused 2.25 MHz transducers with 0.375 in. diameter. Range of incident angles span from 0° to 30°.

face is placed 18 cm from the transducers which is well beyond the focal point. It has been verified that edge diffraction effects from the rough surface are negligible over the whole frequency range.

The measurements were carried out for a set of incident angles: 0°, 5°, 10°, 15°, 20°, 25°, and 30°. All the backscatter results have been normalized by the transducer pair's combined frequency response. For the planar piston transducers, this was obtained by using one transducer as transmitter and the other as receiver, separated by $(d_1 + d_2)$, and carefully aligning the transducers for maximum response. For the annular array transducer, the frequency response was measured by placing a planar reflector at normal incidence 18 cm in front of the annular array.

When performing measurements on different regions of a given rough surface at a given incident angle, the backscattered signal amplitude vs. frequency is a Gaussian distributed random variable with a given mean and standard deviation. To make the result converge to a representative backscatter function, the average of several independent measurements must be determined. As the output from the spectrum analyzer is in dB, the results of the individual measurements must first be exponentiated, then averaged, and finally converted back to dB. Fifty independent measurements were used, by moving the transducer pairs in steps of 1.8 mm along given lines on the rough surface, with a 0.65 mm separation between lines.

Examples of the backscatter amplitude vs. frequency and incident angle, obtained with a pair of planar piston transducers, is shown in Fig. 3. The results for the four rough surfaces, marked with asterisks in Table 1, are shown in (a)–(d) in the figure. A well-behaved backscatter pattern is observed for the normal incident angle, and to a lesser degree for incident angles of 5° and 10°.

6. Data analysis

Several types of backscatter parameters can be derived from the amplitude vs. frequency and angle of the received and normalized sweep signals, such as the amplitude plots shown in Fig. 3. The most relevant of these parameters are: (i) Mean of the backscatter magnitude, measured at normal incidence; (ii) Difference between the mean backscatter magnitude at 0° and at 5°; (iii) Maximum slope, in dB/MHz, of the backscatter magnitude, measured at normal incidence; and (iv) Frequency location of maximum slope, in MHz, of the backscatter magnitude, measured at normal incidence. We have analyzed the relationships between these four backscatter parameters and two of the statistical parameters for the rough surfaces: the RMS height and the diffuse scattering parameter, RMS height/λ_0 as shown in Fig. 4. All of the combinations of backscatter parameters and rough surface parameters exhibit a definite correlation. Figs. 5 and 6 show two of these relationships, evaluated for the 2.25 MHz planar piston transducers and for the broadband annular array transducer

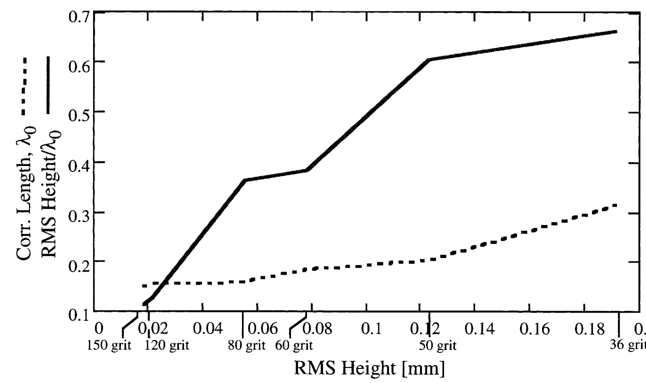
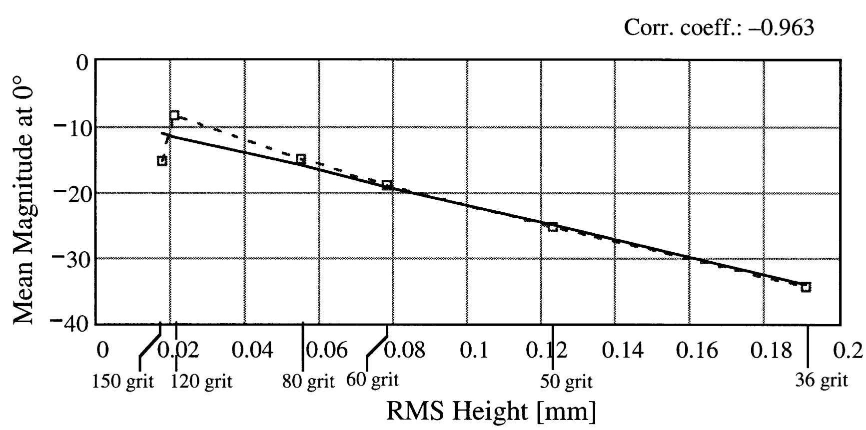
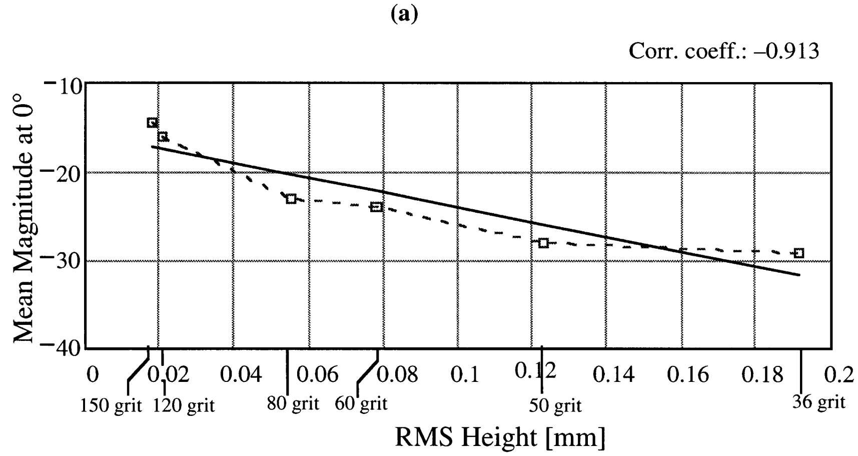


Fig. 4. Relationship between the rough surface parameters, RMS height, correlation length, λ_0, and the diffuse scattering parameter, RMS height/λ_0. (– – –) RMS height vs. correlation length, λ_0; (—): RMS height vs. RMS height/λ_0. The specific rough surfaces are indicated by their grit values.

- Mean of the backscatter magnitude, measured at normal incidence vs. RMS height.
- Difference between the mean backscatter magnitude at 0° and at 5° vs. RMS height/λ_0.

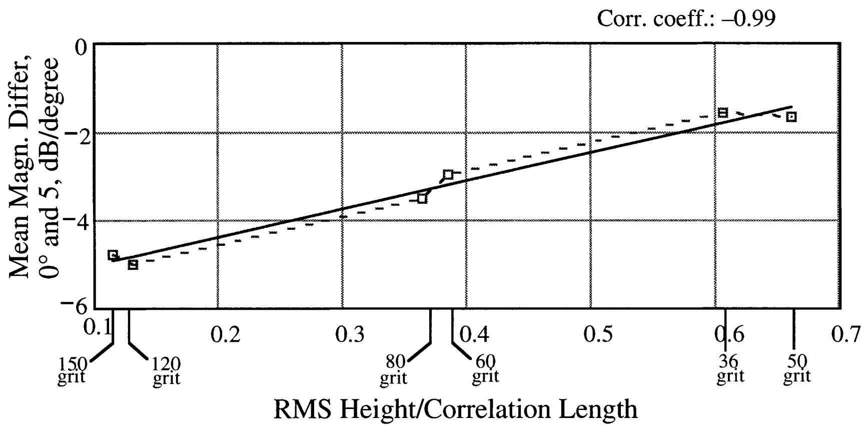


(a)

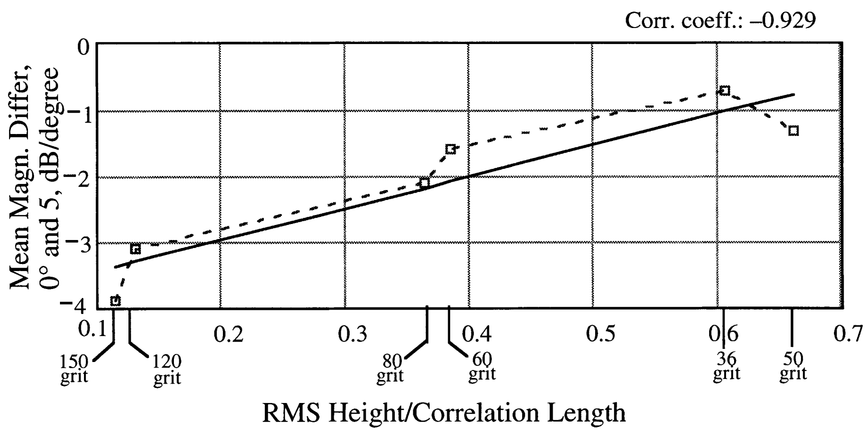


(b)

Fig. 5. Relationship (– – –) between RMS height and the mean magnitude of the backscattered signal, measured at normal incidence. The rough surface corresponding to a given data point is indicated by its grit value. The linear regression through the data points is shown as the solid line, with the correlation coefficient shown above the plot. (a) Data for the pair of 2.25 MHz planar piston transducers; (b) data for the annular array transducer.



(a)



(b)

Fig. 6. Relationship (– – –) between RMS height/correlation length, λ_0 and the difference between the mean backscatter magnitude at 0° and at 5°. The rough surface corresponding to a given data point is indicated by its grit value. The linear regression through the data points is shown as the solid line, with the correlation coefficient shown above the plot. (a) data for the pair of 2.25 MHz planar piston transducers; (b) data for the annular array transducer.

The results show near-linear relationships, with the greatest deviation occurring at the highest and at the lowest grit value, maybe because the chosen frequency range is not optimal for these roughness values. Specifically, correlation coefficients of −0.963 and −0.913 are obtained for mean backscatter magnitude vs. RMS height for the 2.25 MHz planar piston transducers and for the broadband annular array transducer, respectively. The corresponding correlation coefficients for mean backscatter magnitude difference vs. RMS height/λ_0 are −0.99 and −0.929. It should be noted that the rough surface parameters, RMS height, correlation length, λ_0, and the diffuse scattering parameter, RMS height/λ_0 are related, as shown in Fig. 4. Therefore, when a backscatter parameter is correlated with a given rough surface parameter, such as RMS height, it will also be correlated to some degree with the other rough surface parameters.

In order to quantify the utility of this technique for assessing surface roughness parameters and to statistically determine the agreement between backscatter data and actual roughness values, further experimental studies with a larger set of rough surfaces need to be performed, possibly supported by modeling results.

7. Discussion and conclusions

An ultrasound method for characterizing rough, planar surfaces has been presented, based on linear sweep excitation, in the form of a TDS system, rather than pulse excitation. The rough surfaces were created from sandpapers of varying grit value, mounted on glass plates. When the average magnitude of the backscattered signal is measured on a given rough surface, reproducible results were achieved between surfaces with the same roughness statistics. The small displacement of the transducer pair relative to the rough surface between each backscatter measurement may have yielded backscatter data that were not completely independent, and using a larger step size would have allowed a more rapid convergence and thus fewer measurements.

The result indicate a strong agreement between selected backscatter and surface roughness parameters. The backscattered signal beyond 10° exhibits mainly random fluctuations, so an improved measurement accuracy may be achieved for the angular range from 0° to 10°. The transducers were driven directly by the tracking generator output of the spectrum analyzer which has a maximum output of 0 dBm/50 Ω, or 0.223 V_{RMS}. That ultrasound backscatter measurements can be carried out at such a low excitation level is evidence of the sensitivity of the TDS technique; nonetheless, a better SNR could have been achieved with some power amplification of the excitation signal.

References

[1] J.C. Stover, Optical Scattering: Measurement and Analysis, SPIE Optical Engineering Press, Bellingham, Washington, USA, 1995.

[2] K. Allardyce, N. George, Diffraction analysis of rough reflective surfaces, Appl. Opt. 26 (1987) 2364–2375.

[3] M. de Billy, F. Cohen-Tenoudji, et al., The possibility of assigning a signature to rough surfaces using ultrasound backscattering diagrams, IEEE Trans. UFFC 23 (1976) 356–363.

[4] G.V. Blessing, D.G. Eitzen, Ultrasonic sensor for measuring surface roughness, SPIE Vol. 1009 Surface Measurement and Characterization (1988) 281–289.

[5] G.V. Blessing, D.G. Eitzen, et al., Surface micrometrology using ultrasound, IEEE 1990 Ultrason. Symp., 1990, pp. 1047–1052.

[6] G.V. Blessing, J.A. Slotwinski, et al., Ultrasonic measurement of surface roughness, Appl. Opt. 32 (1993) 3433–3437.

[7] S.J. Oh, Y.C. Shin, E.S. Furgason, Surface roughness evaluation via ultrasonic scanning, IEEE Trans. UFFC 41 (1994) 863–871.

[8] R.C. Heyser, Acoustical measurement by time delay spectrometry, J. Aud. Engng. Soc. 15 (1967) 370–382.

[9] R.C. Heyser, D.H. LeCroisette, A new ultrasonic imaging system using time delay spectrometry, Ultrasound. Med. Biol. 1 (1974) 119–131.

[10] P.M. Gammell, Time and frequency domain measurements of materials with high ultrasonic attenuation using time delay spectrometry, Rev. of Progress in Quantitative Nondestructive Evaluation, vol. 5, Plenum Press, New York, 1986, pp. 759–765.

[11] P.A. Lewin, Calibration and performance evaluation of miniature ultrasonic hydrophones using time delay spectrometry, Proc. IEEE Ultrasonic Symp., 1981, pp. 660–664.

[12] P.C. Pedersen, P.A. Lewin, L. Bjørnø, Application of time-delay spectrometry for calibration of ultrasonic transducers, IEEE Trans. UFFC 35 (1988) 185–205.

[13] P.M. Gammell, Single transducer swept frequency ultrasonic reflection measurements, Ultrasonics 17 (1979) 183–186.

[14] D. Hanselman, B. Littlefield, Mastering Matlab 5. A Comprehesive Tutorial and Reference. Upper Saddle River, New Jersey, USA, Prentice Hall, 1998.

[15] W.A. Johnsen, Design and Analysis of Device to Acquire Detailed Topographic Information from Pavement Surfaces, M.S. Thesis, Dept. of Manufac. Engng., Worcester Polytechnic Institute, 1995.