Rough surfaces characterization using a Time-Reversal Mirror

Philippe ROUX*, Julien de ROSNY*, Mathias FINK* and James H. ROSE+

*Laboratoire Ondes et Acoustique, ESPCI, Paris 5 (France) and +Department of Physics and Astronomy and Ames Laboratory, Iowa State University, Ames, Iowa.

Abstract: A new method is described for determining the rms height and autocorrelation function of rough surfaces using measurements made with an acoustic time-reversal mirror (TRM). First, the TRM insonifies the surface and the backscattered wave is recorded and time-reversed. Second, the TRM is displaced parallel to the surface and, at each displacement the previously-recorded time-reversed wave is rebroadcast. For zero displacement the time-reversed wave is matched to the surface and the original incident pulse is recovered. However, with increasing displacement the signal ceases to resemble the incident pulse. The decorrelation of the signal allows one to characterize the surface.

A schematic of the experiments is shown in Fig. (1). We immerse an otherwise flat roughened plate in a water bath and insonify it with a broad-band, phase-sensitive, linear acoustic array. The array is oriented with its axis normal to the average surface of the sample. The array elements are pulsed simultaneously and identically to produce a locally-plane wave that propagates to the surface and reflects. The resulting backscattered waves are recorded on each transducer (Figure 2). Next, the array is translated along its length parallel to the surface by a distance d.

The recorded reflected signals at each transducer element is time-reversed digitally. Next, the time-reversed signals are rebroadcast; that is, the electric signal received by the i’th element is time-reversed and then used to drive a signal-generator, which in turn pulses that element. The rebroadcast wave propagates to the surface interacts and reflects (Figures 3). Finally, the signal, \( S(\omega, d) \) is the summed response at frequency \( \omega \) of all the elements of the array in plane-wave reception. For randomly rough samples, we report estimates of the spatially-averaged signal, \( \text{Sig}(\omega, d) = S(\omega, d) \), which means that we mean \( S(\omega, d) \) over different places on the surface.

The linear transducer array consists of 128 elements excited at a central frequency of 3.5 MHz (the wavelength in water is equal to 0.42 mm). The sampling frequency is 20 MHz. The center-to-center spacing between two neighboring elements is 0.205 mm along the x-axis. Thus, the total aperture of the array is about 26 mm.

The method for determining the rms height \( h \), the correlation length \( L \), and the correlation function \( C(r) \) are described in references [1, 2]. For randomly rough surfaces, it is first assumed that the surface height distribution is representative of a Gaussian random process. Second, it is assumed that the spatial and ensemble averages are the same. Third, the phase-screen approximation is used to characterize the effects roughness on the reflected wave. That is, it is assumed that the rms height is small compared to the correlation length. No
such restriction is placed on the wavelength and the wavelength can be comparable to $h$. Finally, we assume that the effects of diffraction may be neglected. Under these assumptions, we find that

$$\text{Sig}(\omega, d) \propto e^{-4k^2h^2}e^{4k^2h^2C(d)}$$

(1)

The normalized autocorrelation function is then given by

$$C(d) = 1 - \frac{\ln[\text{Sig}(\omega, d)/\text{Sig}(\omega, 0)]}{\ln[\text{Sig}(\omega, \infty)/\text{Sig}(\omega, 0)]}$$

(2)

The rms height is given by

$$h = \frac{1}{2k} \sqrt{\ln[\text{Sig}(\omega, 0)/\text{Sig}(\omega, \infty)]}$$

(3)

Figure 3. Spatio-temporal representation of the field after time-reversal:
(a) $d=0$; (b) $d=0.25$ mm; (c) $d=0.5$ mm;

Figure 4 shows the signal $\text{Sig}(\omega, d)$ spatially averaged over 55 different places on the surface at four different frequencies. Equations (2) and (3) were then used to obtain estimates of the rms height and the normalized autocorrelation function. The TRM estimates for the autocorrelation function are in good agreement with independent measurements made with a mechanical profilometer (Figure 5).

Figure 4. Spatially-averaged signal $\text{Sig}(\omega, d)$ at four different frequencies

Figure 5. Normalized autocorrelation function obtained from the profilometer (full line) and the acoustic TRM (dashed line). The square points correspond to the standard deviation.