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Ultrasound pulse-echo measurements on rough surfaces with linear array transducers

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Abstract. The echo from planar surfaces with *rms* roughness, R_q , in the range from 0–155 μm was measured with a clinical linear array transducer at different angles of incidence at 6 MHz and 12 MHz. The echo-pulse from the surfaces was isolated with an equal sized window and the power of the echo-pulse was calculated. The power of the echo from the smooth surface ($R_q = 0$) is highly angle-dependent due to a high degree of specular reflection. Within the angular range considered here, -10° to 10° , the variation spans a range of 18 dB at both 6 MHz and 12 MHz. When roughness increases, the angle-dependence decreases, as the echo process gradually changes from pure reflection to being predominantly governed by backscattering. The power of the echoes from the two roughest surfaces ($R_q = 115 \mu\text{m}$ and $155 \mu\text{m}$) are largely independent of angle at both 6 MHz and 12 MHz with a variation of 2 dB in the angular range from -10° to 10° . The least rough surfaces ($R_q = 32 \mu\text{m}$ and $89 \mu\text{m}$) have responses in between with a higher degree of angle-dependence at 6 MHz than at 12 MHz.

Keywords: Ultrasound, linear array transducer, surface roughness, oblique interface

PACS: 43.35

INTRODUCTION

Medical diagnostic ultrasound imaging is one of the most often used imaging modalities at hospitals nowadays. Despite being easy, quick, portable and safe, ultrasound imaging suffers from a number of artefacts. One of these effects is that the images are angle-dependent due to the angle-dependence of the echoes received from interfaces larger than the wavelength of the ultrasound energy emitted.

We have previously studied the influence of roughness, angle and range between transducer and interface as well as transducer type on the echo signal from planar interfaces for a number of different single-element transducers [1]. This past investigation showed strong angle-dependence for smooth interfaces and gradually lower angle-dependence as roughness increased.

In the present study, the same effects as in [1] have been studied quantitatively for a linear array transducer on a commercially available ultrasound scanner at two different frequencies. The results are presented and discussed with comparison to a similar study [2].

MATERIALS AND METHODS

Phantoms

Measurements were performed on five rectangular rubber phantoms [1] with surface area of 10 cm by 10 cm and a thickness of 1 cm. The phantoms were made of Biresin® (type U1402, Sika Chemie GMBH, Stuttgart, Germany), which has properties (speed of sound $c = 1450 \text{ m/s}$ and density $\rho = 1.06 \cdot 10^3 \text{ kg/m}^3$ at 20°C) resembling those of human soft tissue. During the moulding of the phantoms, sandpaper was used to give the front surfaces of the phantoms different root-mean-square (*rms*) roughness in the range from 0 μm to 155 μm . Table 1 states the roughness of the surfaces in μm and in wavelengths of the signal at 6 MHz and 12 MHz.

TABLE 1. Roughnesses of surfaces in μm [1] and relative to λ

Sandpaper grid value	Smooth	P150	P100	P60	P40
R_q (μm)	0	32	89	115	155
R_q/λ (at 6 MHz)	0	0.12	0.35	0.45	0.60
R_q/λ (at 12 MHz)	0	0.25	0.69	0.90	1.21

Measurement Procedure

Measurements were accomplished in a scanning tank filled with demineralised degassed water. The phantoms were one at a time placed at one end of the tank in a device that allowed rotation over the vertical and horizontal axes. The ultrasound transducer (type 8811, BK Medical ApS, Denmark) connected to the ultrasound scanner (Pro-Focus, BK Medical ApS, Denmark) was placed facing the phantoms with the transducer elements in a horizontal line. The movement of the transducer was performed by an XYZ translation system (Dyrbæk A/S, Denmark). A sketch and a photo of the measurement setup is shown in Fig. 1.

The rotation over the horizontal axis was locked at the position of maximum energy of the received echo-pulse, allowing only rotation over the vertical axis. In order to reach the best alignment between surface and transducer, normal incidence was checked by moving the transducer to different locations along the vertical axis and observing the same position of the interface line represented on the screen of the scanner. During the measurements, the transducer was placed facing the phantom with the acoustic axis of the two middle elements normal to the vertical rotation axis.

With the assistance of the CFU Grabber application - a research interface developed at DTU (CFU, Center for Fast Ultrasound) - 11 measurements, separated 7.5 mm, were recorded across each surface for each angle. Specifically measurements were performed with the phantoms angled from -10° to 10° in steps of one degree over the vertical axis. The distance between phantom and transducer was 3 cm with the transmit focus distance also set to 3 cm. The measurements were performed at 6 MHz and 12 MHz with a sampling frequency, f_s , of 40 MHz and 48 MHz, respectively.

Signal Processing

An example of a measurement taken at a single position along the y -axis is shown in Fig. 2(a). The echo-pulse from the surface is isolated from the rest by first applying a window that excludes the interface between the transducer and water and scanlines influenced by edge effects. This is illustrated by the solid white line in Fig. 2(a). Afterwards the final isolation is done by finding the maximum of the envelope of the echo-pulse and then start the window 60 elements before this and end it 60 elements after. This corresponds to a window of 9λ at 6 MHz and 15λ at 12 MHz.

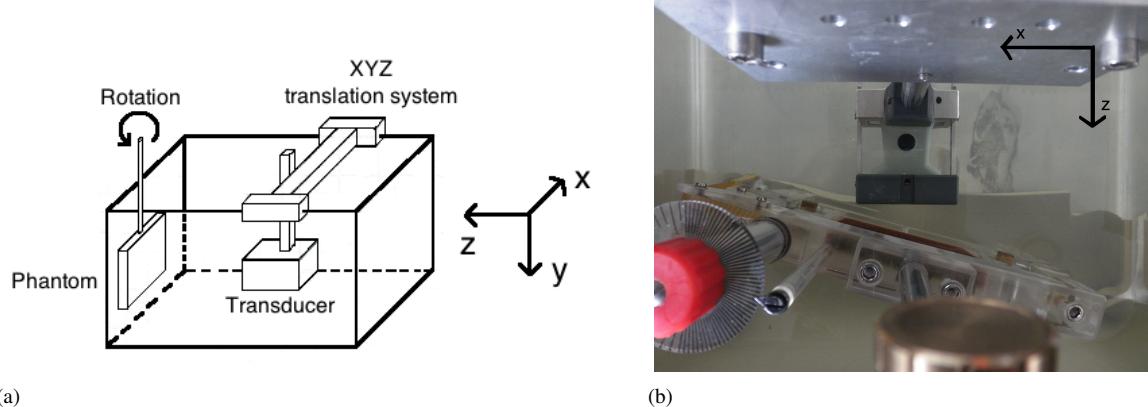
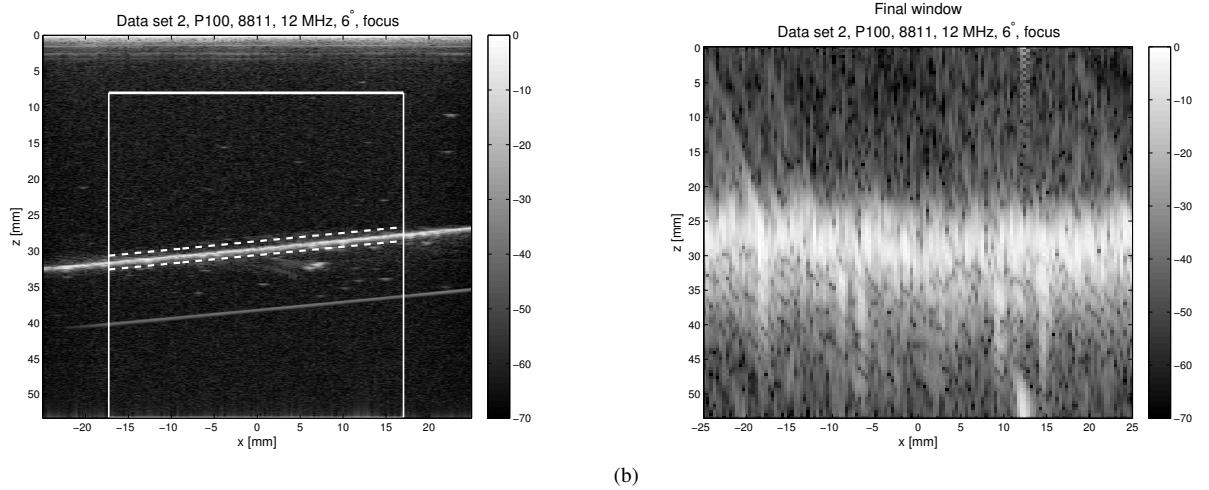


FIGURE 1. (a) Sketch of measurement setup (b) Measurement setup seen from above. Transducer placed in the middle of the image with angled phantom below.



(a)

(b)

FIGURE 2. (a) Envelope of received beam-formed signals from rough surface with $R_q = 89 \mu\text{m}$ at 6° and 12 MHz. The first window is marked by the solid white box and the second window is marked by the white dotted box (b) Final isolated echo-pulse compensated for the angle. Both images are shown in dB relative to the highest level of the envelope of the given measurement.

The window is illustrated by the dashed line in Fig. 2(a). The isolated echo-pulse compensated for the angle is also shown in Fig. 2(b).

The power from the echo was calculated by:

$$P_{g_{r,x_n,y_m}(t)} = \frac{1}{T_W} \int_1^{T_W} (|g_{r,x_n,y_m}(t)|)^2 dt \quad (1)$$

where $g_{r,x_n,y_m}(t)$ is the isolated echo-pulse of the n 'th scanline in the m 'th measurement along the y -axis, and T_W represents the length of the applied window.

The power is then averaged over the number of scanlines in each measurement, N , and the number of measurements along the y -axis, M , giving the mean power of an entire surface at a given angle. The power is then normalized with respect to the smooth surface ($R_q = 0$) at 0° .

RESULTS

The normalized power for the five phantoms measured at 3 cm are shown in Fig. 3. The power of the smooth surface is highly angle-dependent at both 6 MHz and 12 MHz. The level drops from 0 dB at 0° to around -17 dB at $\pm 10^\circ$ and the -3 dB bandwidth at 6 MHz is $\sim 6.5^\circ$ and at 12 MHz $\sim 4^\circ$. At angles close to 0° the level at 6 MHz is more steady than at 12 MHz. The responses from the rough surfaces are less angle-dependent. At 6 MHz only the two least rough surfaces ($R_q = 32 \mu\text{m}$ and $R_q = 89 \mu\text{m}$) show some angle-dependence with a drop in level for the least rough surface from around -2 dB at 0° to -7 dB at $\pm 10^\circ$. At 12 MHz the levels of the responses from the rough surfaces show virtually no angle-dependence.

DISCUSSION

The most important factor in interpreting these measurements is the roughness measured in wavelengths. The roughness measured in wavelengths increases with a factor of two, when the frequency increases from 6 MHz to 12 MHz, rendering most of the surfaces quite rough ($R_q \geq 0.5\lambda$) at 12 MHz. When the roughness is small compared to the wavelength, as is the case for the least rough surfaces at 6 MHz, the response is a combination of reflection and scattering which gives rise to an angle-dependent response. When the roughness is more than about half a wavelength, the response is primarily caused by back scattering and little angle-dependence is observed.

When the surface is smooth, only reflection phenomena takes place. When considering the power of the received

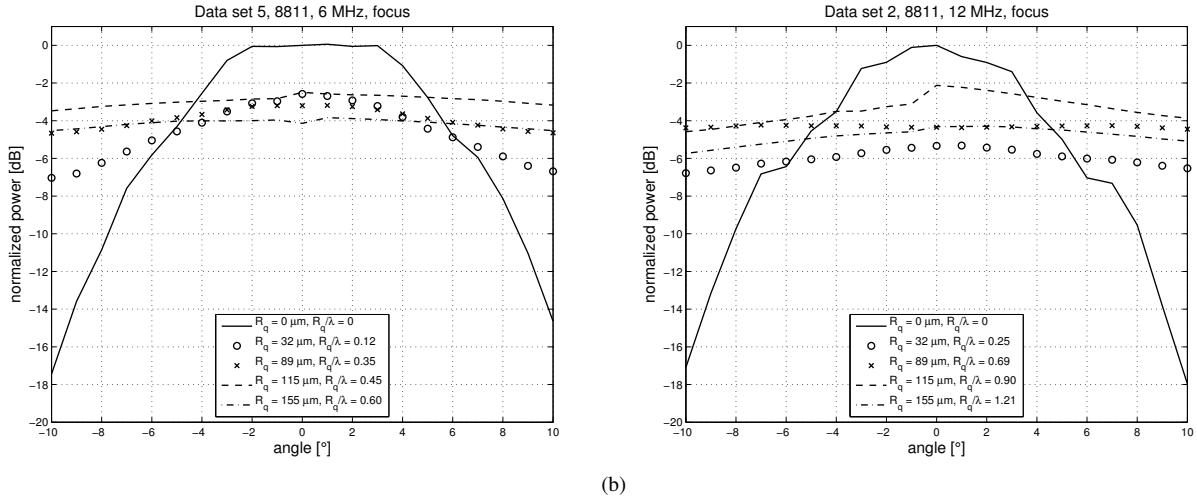


FIGURE 3. Power as a function of angle at (a) 6 MHz and (b) 12 MHz

signals for the smooth surface, a more pronounced plateau at small angles are found at 6 MHz than at 12 MHz. This is consistent with the fact that phase-cancellations at the transducer surface becomes more pronounced as the frequency increases [3].

Comparing to the measurements in [1], where measurements are done with a single-element focused transducer, it can be observed that the angle-dependence is much less when linear array transducers are used. The level of the response from the smooth surface [1] was in the range from 0 to -40 dB for angles of $\pm 7^\circ$, whereas in the present measurements the level is in the range from 0 to -7 dB in the same angular range.

Sukamana and Ihara [2] measured the reflection from surfaces of different roughness using air-coupled single element transducers. They find that the dependence on angle decreases when the roughness increases, as was also found in the present study. Further, they find that the amplitude of the received signal decreases with roughness when the echo-pulse is measured at an angle where the echo-pulse has a large specular component. On the other hand, the amplitude increases with increased roughness when measuring at an angle where the scattering part dominates the echo-pulse. This tendency can also be seen in Fig. 3(a).

CONCLUSIONS

The echo-pulse from surfaces of different roughness has been measured at an angular range of -10° to 10° using linear array transducers. Measurements from the smooth surface show a high degree of angle-dependence with a span of 18 dB in the angular range. Surfaces with a roughness smaller than the wavelength also show some angle-dependence, whereas surfaces with roughness comparable to or larger than the wavelength show virtually no angle-dependence with a span of only 2 dB in the angular range. Measurements with linear array transducers are less dependent on the angle than measurements with single-element focused transducers.

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