XI. COGNITIVE INFORMATION PROCESSING*

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A. ARRAY TRANSDUCERS FOR MEDICAL USES OF ULTRASONICS†

1. Introduction

Ultrasonic systems of various types have been used in clinical practice for several years. Although with their aid the problem may be attacked in many different ways, with almost all of them an attempt is made either to take an internal measurement or to produce an image of soft tissue without the use of damaging radiation such as x rays or of internal probes. Essentially all systems depend on some form of reflection of the ultrasonic signal. In the early designs it was assumed that the reflecting surfaces were flat and perpendicular to the beam of ultrasonic energy. Such assumptions were unacceptable, of course, so many of the newer systems use a technique called "compound scanning" which is somewhat more tolerant to the curvature of the surfaces that are being examined. Compound scanning does not completely eliminate the problems caused by surfaces that were not perpendicular to the axis of the ultrasonic transducer because it tends to only display surfaces that are tilted up to a few degrees.

To overcome some of the limitations of previous systems, the approach described

*This work was supported principally by the National Institutes of Health (Grant 5 PO1 GM14940-05).

†This work was supported in part by the National Institutes of Health (Grant NS08571).

here makes use of an array of transducers that can not only be made tolerant to tilted surfaces, but can also detect the angle of the tilt.

2. Technique

Consider the system shown in Fig. XI-1. Here a large plane transducer is driven with a pulse to generate a plane wave. This wave is reflected off the target and is received by the spherical receiver. If the target is of nonzero length and is not spherical, the energy reflected from it will be concentrated onto some limited area of the receiver. We would then expect that it would be possible to determine the angle at which the target is tilted.

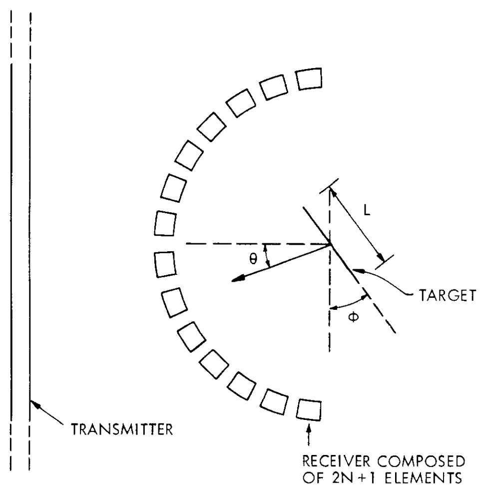

Fig. XI-1.
A plane transmitter is pulsed to produce a plane wave that is reflected off a target of length L, tilted by an angle ϕ. The reflected energy is measured at an angle θ by an element of a circular receiver.

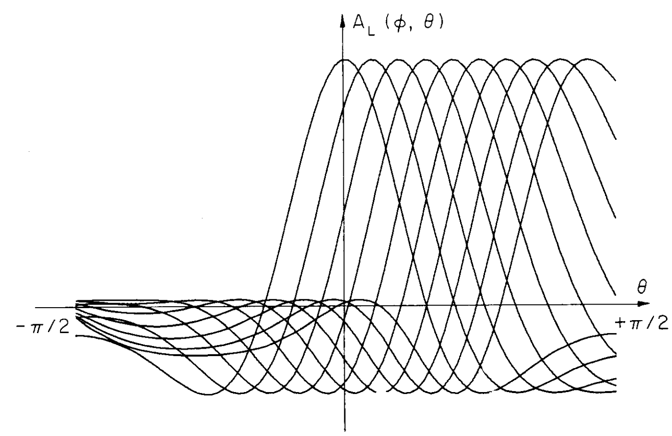

Fig. XI-2.
Reflected signal as a function of angle for targets tilted from 0 to $\pi/4$ and $L = \lambda$.

As a test of the potential of this method of angle detection, a hypothetical two-dimensional situation was numerically evaluated. The target was assumed to be flat and of finite but small length, leading to the reflection pattern indicated by Eq. 1. (See Fig. XI-2.) The receiver was assumed to be composed of a finite number of elements. Two tests were then made. In the first the correlation function was computed between the signal received from a rotated target and the signal from a target parallel to the transmitter, as indicated by Eq. 2. In the second test the autocorrelation function of the signal received from a tilted target was calculated by evaluating Eq. 3.

$$A_L(\phi,\theta) = k \frac{\sin\left[\frac{\pi L}{\lambda}(\sin\phi + \sin(\phi-\theta)\right]}{\sin\phi + \sin(\phi-\theta)}, \tag{1}$$

where L is the length of the target, K includes all effects of attenuation and target absorption, ϕ is the angle at which the target is tilted, and θ is the angle of the received signal. λ is the wavelength

$$\psi_{c_L}(\phi,\theta) = \left| \frac{1}{E_{c_L}} \sum_{n=-N}^{n=N} A_L\left(0, \frac{n\pi}{2N}\right) A_L\left(\phi, \theta + \frac{n\pi}{2N} + 2\phi\right) \right|^2$$

$$E_{c_L} = \sqrt{\left| \sum_{n=-N}^{n=N} A_L^2\left(0, \frac{n\pi}{2N}\right) \sum_{n=-N}^{n=N} A_L^2\left(\phi, \theta + \frac{n\pi}{2N} + 2\phi\right) \right|} \tag{2}$$

$$\psi_{A_L}(\phi,\theta) = \left| \frac{1}{E_{A_L}} \sum_{n=-N}^{n=N} A_L\left(\phi, \frac{n\pi}{2N}\right) A_L\left(\phi, \theta + \frac{n\pi}{2N}\right) \right|^2$$

$$E_{A_L} = \sqrt{\left| \sum_{n=-N}^{n=N} A_L^2\left(\phi, \frac{n\pi}{2N}\right) \sum_{n=-N}^{n=N} A_L^2\left(\phi, \theta + \frac{n\pi}{2N}\right) \right|} \tag{3}$$

As can be seen in Figs. XI-3 and XI-4, the 3-dB point corresponds to a 15° rotation of the received signal or a tilt of 7.5° of the target. Thus there would appear to be no fundamental limitation at this level which would lead to the downfall of the entire system.

To carry the evaluation a step further, and a little closer to reality, the receiver was flattened out and focused. This was done in two dimensions as shown in Fig. XI-5. In such an implementation, the same transducer would be used for both transmitter and receiver. In transmit mode, all elements would be excited in parallel with a short duration pulse. In receive mode, a delay would be introduced in the output of each receiver element to equalize the total delay between the processor and the target. Effectively this means that the array produces a plane wave on transmit and is focused to some point during receive.

The received signal is then correlated by multiplying the received and delayed signals by the numerical value of the signal that would be received from a tilted target. The resulting signals are then summed and sampled at the time corresponding

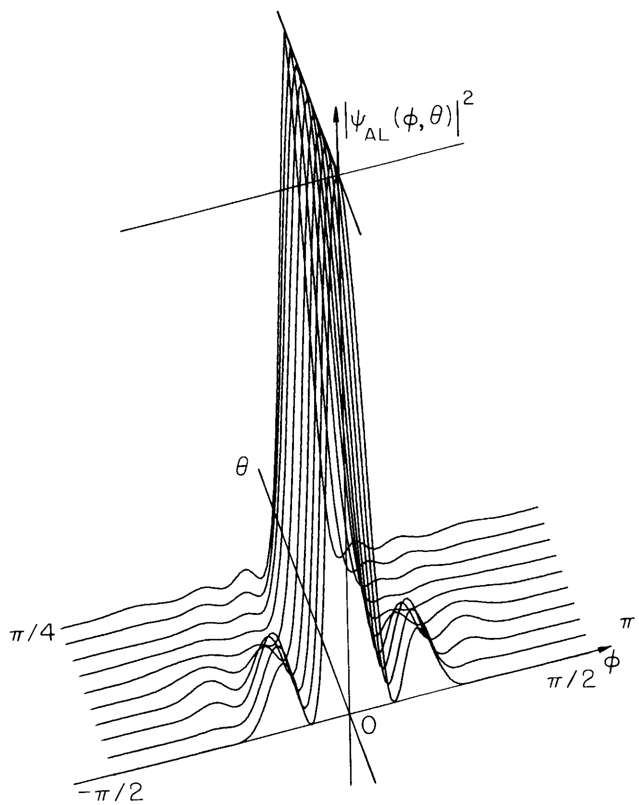

Fig. XI-3. Sensitivity function for the configuration shown in Fig. XI-1 using Eq. 3.

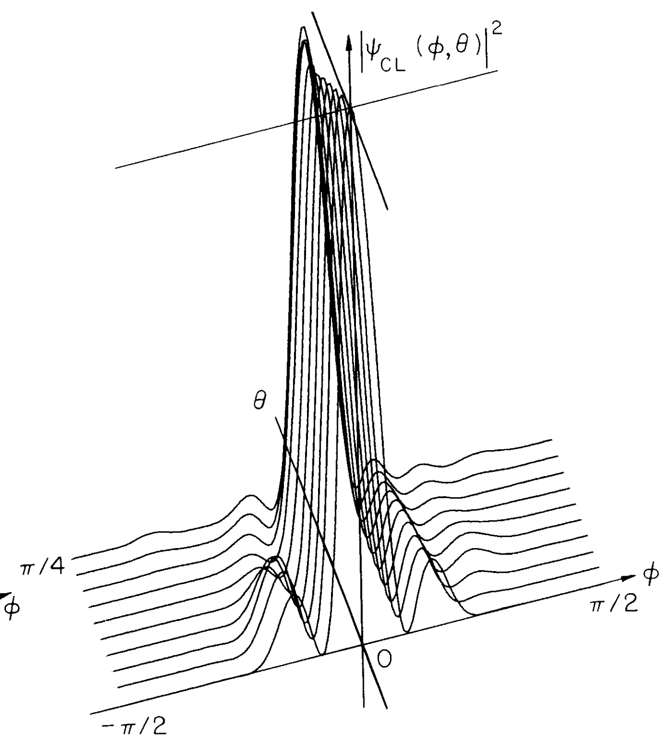

Fig. XI-4. Sensitivity function for the configuration shown in Fig. XI-1 using Eq. 2.

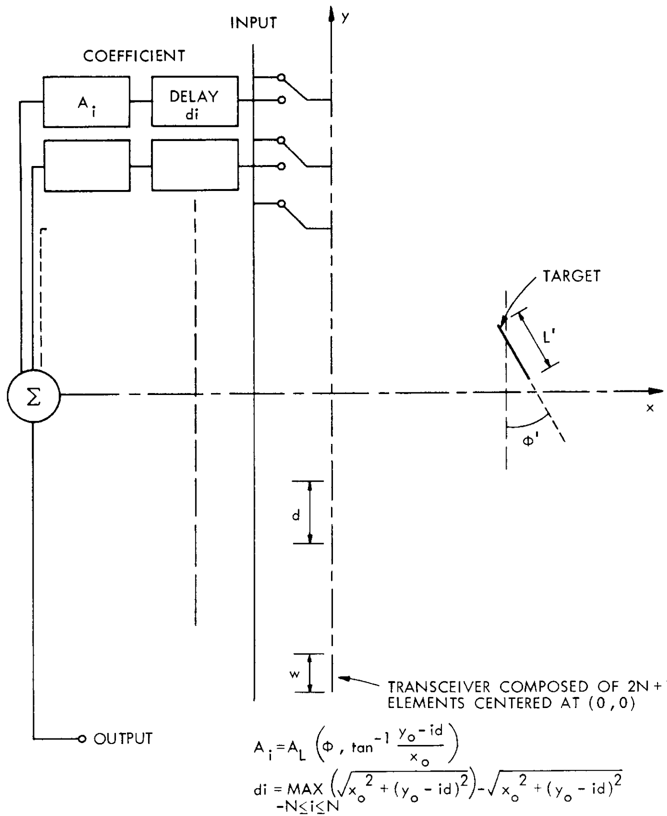

Fig. XI-5. An array of elements is driven in parallel during transmit. During receive, the array is focused by the use of electrical delays and is made sensitive to a target at a specific angle (ϕ).

to the complete system time delay. The time sampling is done to improve the distance resolution. This entire process is represented by Eq. 4.

$$R_{\phi,\phi',L,L',x_o,y_o}(t,x,y) = \sum_{i=-N}^{i=N} A_L(\phi,\theta_i)\, r_{L',i,x,y,\phi}\left(t + \frac{\sqrt{x_o^2 + (y_o - id)^2} - x_o}{c}\right)$$

$$r_{L',i,x,y,\phi}(t) = \frac{\sin\left(\frac{W}{2}\sin\phi\right)}{\sin\phi}\, A_{L'}\left(\phi, \tan^{-1}\frac{y - id}{x}\right) h\left(t - \frac{\sqrt{x_o^2 + (y - id)^2}}{c}\right)$$

$$\theta_i = \tan^{-1}\frac{y_o - id}{x_o}, \qquad (4)$$

where

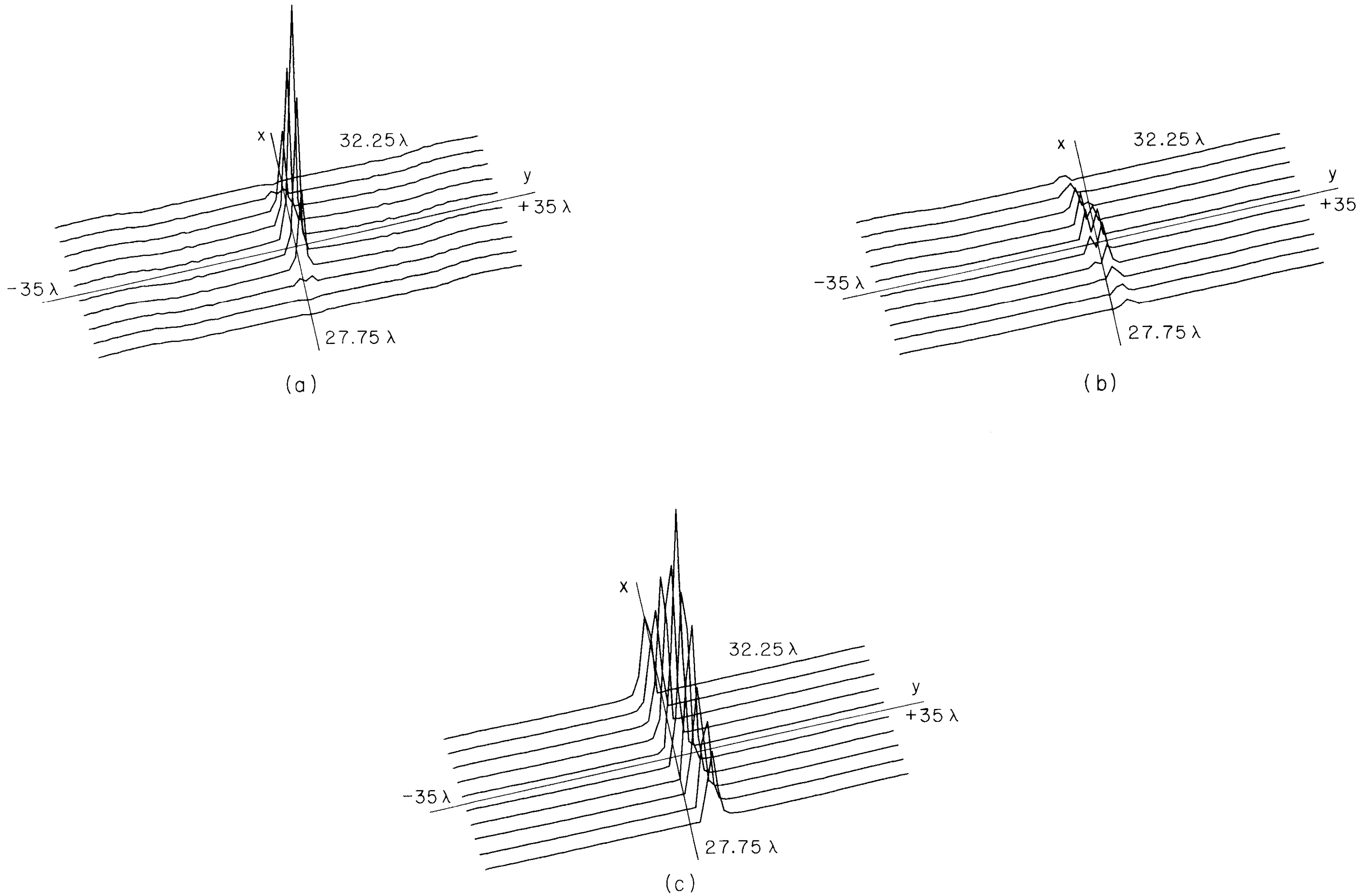

Fig. XI-6. Sensitivity functions for the arrays shown in Fig. XI-5. (a) Both target and receiver angles zero. (b) Only target tilted $\pi/6$. (c) Both target and receiver tilted at $\pi/6$. For $L = L' = 4\lambda$,

$$n = 50,\ w = \lambda,\ d = \lambda,\ h(t) = \begin{cases} \left(1 - \left|\frac{tc}{3\lambda}\right|\right) & \text{if } |t| < \frac{3\lambda}{c} \\ 0 & \text{otherwise.} \end{cases}$$

ϕ is the angle of target tilt that is being tested

ϕ' is the actual angle at which the target is tilted

L is the assumed length of the target

L' is the actual length of the target

x_o and y_o are the x and y coordinates of the focal point of the array

$r_{L',i,x,y,\phi}(t)$ is the waveform received from a target at location x, y of length L' and tilted ϕ. The waveform is received at the i^{th} element of the array

c is the velocity of sound

W is the width of each receiver element

d is the distance between elements.

Equation 1 was used as the directional function and a triangular waveform was used as the system timpulse response. Figure XI-6 then shows the results of evaluating Eqs. 4. Figures XI-6a and XI-6c shows the system response when the actual target angle and the assumed angle are the same. When the angles are different as in Fig. XI-6b, the response is greatly reduced, as can be seen.

3. Conclusion

The system that has been described here appears to be capable not only of detecting a target that is tilted with respect to the transmitter of an ultrasonic imaging system but can even measure the angle at which the target is tilted. This capability should allow the creation of an even more powerful system that could integrate all of the echoes from a large curved target into a display that would show all parts of the target rather than only those which are nearly parallel to the ultrasonic transducer.

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