An Experimental 2 MHz Synthetic Aperture Sonar System Intended for Medical Use

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Abstract—Conventional *B* scan used in medical ultrasonic diagnosis has a low lateral resolution and difficulty in detecting specular reflectors. Synthetic aperture sonar is a hybrid between holography and *B* scan and offers a higher lateral resolution as well as better detection of tilted specular reflectors. A system working at 2 MHz ($\lambda = 0.75$ mm) has been built. The system design is given and the important features of the electronic system as well as the optical processing are described. The system resolves two wires strung at a distance of 2 mm and is thus about one order of magnitude better than conventional *B* scan systems working at the same frequency.

INTRODUCTION

In medical ultrasonic diagnosis a method known as *B* scan is used; it is summarized in Fig. 1 [1, p. 151]. It uses a pulsed ultrasonic transducer which is scanned laterally and the echoes are displayed on an oscilloscope screen. The method gives a picture of a cross section through the body. The advantage of *B* scan is that it uses a simple linear scan which can be performed fast. The main disadvantage of the method is the low lateral resolution. As can be seen from Fig. 1 the coordinate labelled abscissa is made proportional to the lateral position of the ultrasonic transducer. Because of the relatively large diameter of the ultrasonic beam the point reflector in Fig. 1 remains in the beam during an appreciable length of time of the scan and the recording is "blurred" in the horizontal direction. At a frequency of 2 MHz, which is often used for scanning the abdomen or the female breast, the ultrasonic beam typically has a diameter of 1 to 2 cm. The longitudinal resolution depends on the pulse length and typically is 1 to 2 mm at the same frequency of 2 MHz, i.e., one order of magnitude better. A second problem of *B* scan is that many interfaces in the body reflect sound specularly. If such an interface is not perpendicular to the beam, the ultrasound will be reflected off at an angle and this interface will not be detected. The synthetic aperture sonar system, which will be described in this paper, gives better lateral resolution and improved detection of tilted specular reflectors.

We start with a heuristic description of the synthetic aperture sonar system. In analogy to optics and especially microscopy it is clear that a better lateral resolution is obtained, if the ultrasound beam is focused by means of a large aperture. Unfortunately the improved lateral resolution is only obtained over a very limited depth as can be seen from Fig. 2. Outside the depth of focus the beam has an even larger diameter than the beam commonly used in *B* scan and this approach has only found limited use [2].

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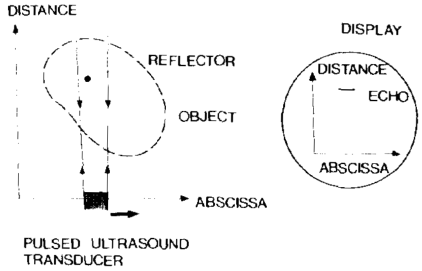


Fig. 1. Principles of *B* scan. Repetitively pulsed ultrasound transducer is translated. Received echoes are displayed on oscilloscope screen. On display, abscissa is made proportional to lateral position of transducer, distance coordinate is made proportional to echo delay and the intensity is made proportional to amplitude of echo.

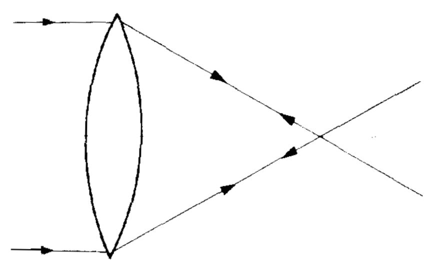


Fig. 2. Focusing beam by means of lens with large aperture increases lateral resolution, but only over small depth because of depth of focus. Outside depth of focus, beam has even larger diameter than beam commonly used in *B* scan.

The depth of focus problem is solved in ultrasonic holography where the operation of recording the sound and of focusing are performed separately [3]. Focusing is done optically. This is possible, if the amplitude as well as the phase of the sound field are suitably recorded. The main disadvantage of ultrasonic holography is that the sound field has to be recorded over a plane. This is considerably more difficult to do than the simple linear scan used in *B* scan. Other problems of ultrasonic holography are the interference of out of focus images with the focused image during reconstruction and the distortions due to the fact that the wavelength of the light used in reconstruction is several orders of magnitude smaller than the wavelength of the sound used in the recording step.

The synthetic aperture sonar system to be described is a hybrid between traditional *B* scan and holography and combines the advantages of both systems. In the distance coordinate, where *B* scan works well, the synthetic aperture sonar system works like *B* scan, whereas in the abscissa coordinate,

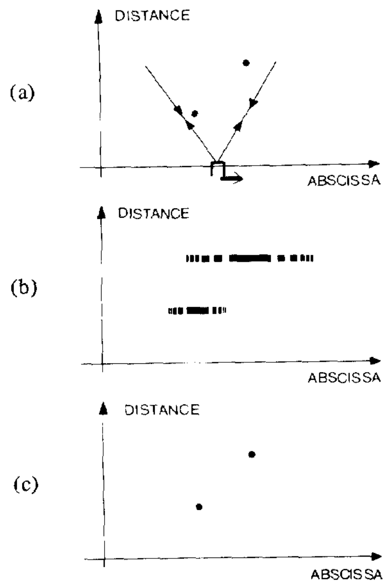


Fig. 3. Synthetic aperture sonar. (a) Recording arrangement. (b) First record. (c) Processed image.

where there is a problem, it works like a holographic system. The *B* scan is transformed into a synthetic aperture sonar system by making the following three modifications.

1) Instead of using envelope detection, which discards phase information, one uses a phase-sensitive detection method. The echoes are multiplied with a continuous wave reference signal which is coherent with the emitted pulse. Phase information is thus preserved.

2) A beam of wide angular divergence is used. This may seem paradoxical at first, but it is necessary in order to observe a given object over a large range of abscissa coordinate. This means that the echoes of an object are recorded over a large aperture. This is necessary to obtain good lateral resolution as observed earlier.

3) The record thus obtained is processed to give the desired image. This is analogous to the reconstruction step in holography. The processing can be performed optically and will be described in Section IV.

Let us now look at an idealized recording of two point objects. As shown in Fig. 3(a) the objects are scanned with an ultrasound beam which has a wide angular divergence in the plane given by the abscissa and distance coordinates. In the direction perpendicular to the paper the beam is made as "thin" as possible in order to obtain a well defined cross section. As shown in Fig. 3(b) the recordings are well confined and separated from one another in the distance coordinate. They occupy a considerable range in the abscissa coordinate where the two recordings overlap, because the lateral separation of the two objects is smaller than the extent of the ultrasonic beam. The recording is alternately light and dark because sometimes the echo is in phase and sometimes out of phase with the reference signal. The phase variation is slow when the object is in the center of the beam and becomes more rapid when the object is at the edge of the beam. A mathematical analysis shows that the records of point objects thus obtained are one-dimensional Fresnel zone plates. (Whereas in holography a point object is recorded as a two-dimensional Fresnel zone plate.) The processing step consists in focusing these zone plates in the abscissa coordinate whereas no processing is needed in the distance coordinate. The processed image is shown in Fig. 3(c).

There is one remaining problem. The zone plates shown in Fig. 3(b) have two focal points, one real and one virtual. The effect of this is an undesirable background in the processed image. In order to circumvent this problem the zone plate is modulated on a spatial carrier frequency. This means that we record the off-axis part of a zone plate and not the on-axis part. (This is analogous to the off-axis reference beam method in optical holography, see e.g. [4]). The modulation onto a carrier frequency is achieved by changing the phase of the reference signal by a certain amount between successive pulses.

The synthetic aperture sonar system just described is the ultrasound analog of the synthetic aperture radar systems, see [5, 6, 7]. Previous work on synthetic aperture sonar is reported in [10, 11] and was brought to the attention of the authors by a reviewer.

II. SYSTEM DATA

The system works at a frequency of 2 MHz corresponding to a wavelength of 0.75 mm in water. This frequency is commonly used for scanning the abdomen or the female breast. The system was designed for a useful depth of 20 cm and a lateral width of 30 cm. In order to avoid artifacts due to multiple reflections between transducer and object surface, the object is separated from the transducer by a minimum distance equal to the useful depth, i.e., 20 cm [1, p. 94]. The minimum range therefore is $R_{min} = 20$ cm and the maximum range $R_{max} = 40$ cm.

The resolution was fixed at 1.5 mm at a range of 20 cm. This resolution was considered sufficient and one minimizes a problem called "range curvature" in the synthetic aperture radar field. Range curvature means that the records in Fig. 3(b) are not strictly parallel to the abscissa but are slightly curved upwards, because the distance to the transducer becomes larger when the reflector is at the edge of the beam. At the resolution mentioned this change in distance is equal to the width of the record in the distance coordinate. This resolution leads to a pulse length of 2 μs.

The required resolution also determines the aperture angle of the ultrasonic beam. The lateral resolution is given by the relative aperture of the zone plates depicted in Fig. 3(b). From [7] it is known that the focal length of these zone plates is half the distance to the object if they are reconstructed at original size and with radiation of the wavelength that was used for recording. The distance δ between the maximum and the first zero in the diffraction pattern of a rectangular aperture is equal to the wavelength divided by the relative aperture

$$\delta = \frac{\lambda R}{2D} \tag{1}$$

where λ is the wavelength, R is the distance to the object and D is the length of the zone plate. We, therefore, obtain for

$\beta/2$, the half-angle of the aperture

$$\tan \beta/2 = D/2R \cong \lambda/4\delta. \qquad (2)$$

With the values of $\lambda = 0.75$ mm and $\delta = 1.5$ mm we obtain $\beta = 14.4° \approx 15°$. The ultrasonic beam was formed by placing a convex cylindrical Plexiglas lens of 2 cm radius of curvature in front of a plane transducer available commercially and used in medical diagnosis (NM 2/20 N from Kretztechnik, Austria).

The pulse repetition frequency was fixed at 1000 pulses/s. The interval between pulses is then considerably longer than it takes a pulse to travel to the most distant object and back again and reverberation problems are avoided.

As was mentioned in Section I, the zone plates are modulated onto a spatial carrier frequency. We will now compute the necessary carrier frequency which depends on the highest spatial frequency occurring in the zone plates of Fig. 3(b). The highest spatial carrier frequency occurs at the edge of the zone plate and is equal to the reciprocal of the distance ϵ the transducer travels for producing a path change of one wavelength. We, therefore, have

$$2\{\sqrt{R^2 + (D/2 + \epsilon)^2} - \sqrt{R^2 + D^2/4}\} = \lambda. \qquad (3)$$

The factor 2 stems from the fact that the pulse travels to the object forth and back again. Recognizing that $\epsilon \ll R, D$ we can expand the roots and obtain

$$\epsilon = \frac{\lambda\sqrt{R^2 + D^2/4}}{D} \approx \frac{\lambda R}{D} = 2\delta \qquad (4)$$

where we have used (1). Therefore, we obtain for the highest spatial frequency $f_{s\max}$

$$f_{s\max} = \frac{1}{\epsilon} = \frac{1}{2\delta}. \qquad (5)$$

In the Fourier transform domain the spectrum of the zone plate extends from $-f_{s\max}$ to $+f_{s\max}$ see Fig. 4(a). The purpose of modulating onto a carrier frequency is to have the spectrum occupy positive frequencies only. This can be accomplished by choosing the carrier frequency f_c as $f_{s\max}$, see Fig. 4(b). There is one additional consideration, however. Any (undesirable) nonlinearity in the recording process will give rise to sum and difference frequency terms, of which many will fall in the band shown in Fig. 4(b). For a carrier frequency $f_c = 3f_{s\max}$ all sum and difference frequency terms fall outside the useful spectrum as can be seen from Fig. 4(c). Therefore,

$$f_c = 3f_{s\max} = \frac{3}{2\delta} \qquad (6)$$

from (5). Inserting $\delta = 1.5$ mm, we obtain $f_c = 1$ cycle/mm. This then gives a maximum spatial frequency on the record of $4f_{s\max}$ or 1.33 cycles/mm.

The scanning velocity was chosen as 10 cm/s. This velocity can be handled without undue mechanical problems and is well within the limit imposed by the sampling theorem.

The required carrier frequency is obtained by choosing a reference signal which is offset by 100 Hz from the emitter signal. This offset at the scanning speed of 10 cm/s gives the required frequency of 1 cycle/mm. The system data are summarized in Table I.

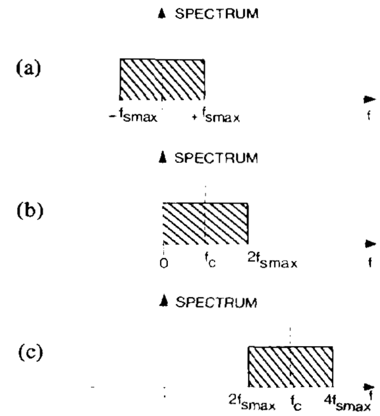


Fig. 4. Spectrum of first record. (a) With zero carrier frequency f_c. (b) With $f_c = f_{s\max}$. (c) With $f_c = 3f_{s\max}$.

TABLE I
SYSTEM DATA

Frequency of operation	2 MHz
Minimum range R_{min}	20 cm
Maximum range R_{max}	40 cm
Lateral scan width	30 cm
Resolution δ	1.5 mm
Pulse length τ	2 µs
Acoustical beam aperture angle	15°
Pulse repetition frequency	1000 pulses/s
Scan velocity	10 cm/s
Spatial carrier frequency	1 cycle/mm
Temporal carrier frequency	100 Hz

III. ELECTRONIC SYSTEM

Fig. 5 shows a block diagram of the electronic system, which we will now describe. The control unit controls the different functions and timing of the whole system. It also generates crystal stabilized signals of 2 MHz and 100 Hz. The 2 MHz signal is used for driving the power amplifier and together with the 100 Hz signal serves as input to the reference generator.

The switchable power amplifier drives the ultrasonic transducer during emission. It can deliver an electrical power of more than 50 W into an impedance of 50Ω. During reception of the echoes this amplifier is switched off and its output impedance becomes very high. During reception the transducer is, therefore, not loaded by the power amplifier.

The reference generator produces the 2.0001 MHz reference signal which is multiplied with the received echo signal. As was mentioned, the 100 Hz offset from the emission frequency leads to the spatial carrier frequency in the synthetic aperture sonar record. This unit will now be described in more detail. Fig. 6 shows a block diagram of this oscillator. The output signal of a voltage controlled crystal oscillator (VCO) is mixed with the 2 MHz signal from the control unit. The frequency of the signal at the mixer output is equal to the difference

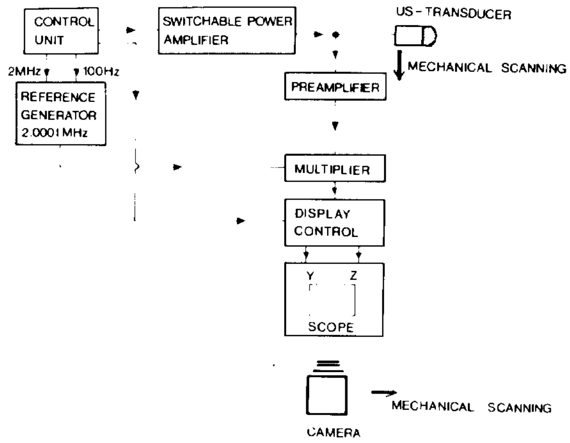


Fig. 5. Block diagram of electronic system.

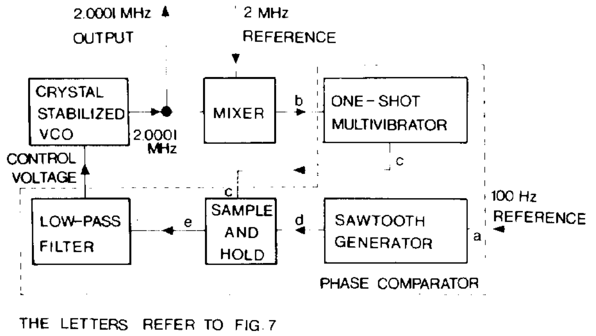


Fig. 6. Block diagram of reference generator.

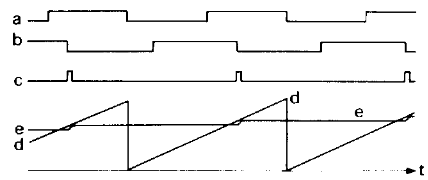


Fig. 7. Waveforms in reference generator. (a) 100 Hz square wave. (b) Mixer output shaped by Schmitt trigger. (c) Sampling pulse. (d) Sawtooth voltage triggered by (a). (e) Sample and hold output voltage.

between the frequency of the VCO and 2 MHz (i.e., 100-Hz nominal). This output difference signal is shaped by a Schmitt trigger to a square wave shown in Fig. 7(b). We now compare the phase of this difference frequency signal with the phase of the 100 Hz signal delivered by the control unit. This comparison is done by a phase comparator; the output voltage of this phase comparator then controls the exact frequency of the VCO. The frequency of the VCO is thus locked to 2.0001 MHz and its frequency stability is determined by the crystal oscillator of the control unit. The phase comparator has to give a very clean output voltage which has little delay. To satisfy these two requirements we have chosen the following principle [8]. The 100 Hz reference signal (Fig. 7(a)) triggers a sawtooth generator (Fig. 7(d)). Each time the mixer output voltage goes from 1 to 0 a one shot multivibrator produces a 30-μs pulse (Fig. 7(c)) which controls a sample and hold circuit such that the value of the sawtooth voltage is sampled at this instant. This voltage is low-pass filtered and applied to the control voltage input of the voltage controlled oscillator. The frequency regulating element of this VCO is a varactor in series with the crystal.

We now return to the description of block diagram Fig. 5. In response to the reflected ultrasonic energy the transducer produces signals with an amplitude between a few microvolts and about 10 mV. These signals are amplified by the preamplifier. The preamplifier is protected from the high voltage (80 V_{peak}) applied to the transducer during emission by a capacitor connected in series with two antiparallel diodes. This circuit restricts the maximum input voltage to a value lower than 0.7 V_{peak}. During emission the diodes conduct and the input capacitor of the preamplifier is connected in parallel with the transducer acting as an additional capacitive load. During reception the limiting diodes do not conduct, the input impedance of the preamplifier and the sensitivity of the transducer are high.

The multiplier demodulates the echo signal by multiplying it with the 2.0001 MHz reference signal. Note that the phase of the signal is preserved in this process. The demodulated signal is low-pass filtered in order to remove the sum frequency component and the bandwidth of the multiplier is 0.6 MHz. The multiplier is built around a double-balanced modulator integrated circuit SG 3402 (Silicon General).

The display control unit adds a bias voltage to the output of the multiplier which is then displayed as intensity on the oscilloscope. Outside the interval of interest the signal is blanked. This unit also produces the sawtooth voltage required for the vertical deflection of the beam. In the horizontal direction the beam is not deflected but the camera is translated, as will be discussed in the next section.

IV. OPTICAL RECORDING AND PROCESSING

A Tektronix oscilloscope 602 was used for displaying the signals because of its good resolution. The resolution of this scope is more than adequate in the distance coordinate. The resolution requirement in the abscissa coordinate is much higher because of the spatial carrier frequency. In section 2 we computed the maximum spatial frequency as 1.33 cycles/mm. Since the scanning distance is 30 cm we have to display a maximum of 400 spatial cycles. This exceeds the resolution of the oscilloscope. Therefore, the beam was not deflected in the azimuth coordinate, but the recording camera, a 35 mm Nikon-F, was translated mechanically. In order to reduce the lateral beam size, the line represented by the vertically deflected spot on the oscilloscope was focused by means of a glass rod into a slit of 0.1-mm width. Kodak High Contrast Copy Film was used for recording. It was developed in Kodak D-19 for 6 min.

We now turn to the design of the optical processor. The processor has to transform the record of Fig. 3(b) into the images of Fig. 3(c). The processing is different in the distance coordinate where a straight imaging operation is required and the abscissa coordinate where one reconstructs a hologram, i.e., the focal points of the zone plates lie outside the plane of the drawing. An anamorphic optical system which includes cylindrical lenses is thus required. A further complication arises, because the focal lengths of the zone plates shown in Fig. 3(b) are not constant but vary with the distance

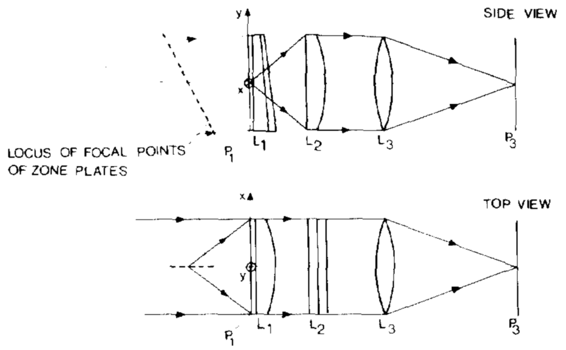


Fig. 8. Two views of optical processor.

coordinate at which they occur. This is compensated for by a cylindrical lens whose focal length is proportional to height.

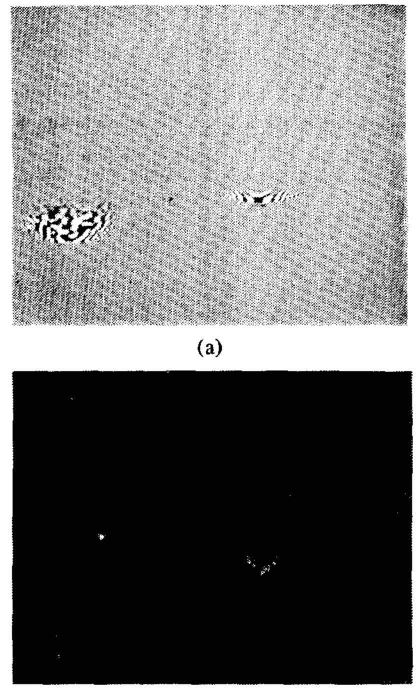
The principles of the processor are described in [5, 6] and our processor was built along those lines. Fig. 8 shows two views of the processor. Collimated laser light is incident on the synthetic aperture sonar record in plane P_1, where there is also a cylindrical lens L_1 whose focal length varies with height y. It has been shown in [5, 6] that a pie-shaped section of a lens known as axicon can be used for this purpose. The surface of the axicon is a cone. The focal points of the axicon are made to coincide with the focal points of the zone plates. To the right of the axicon we, therefore, have a wave with no curvature in the x direction. The wave then passes through a conventional cylindrical lens L_2 whose focal point is in plane P_1 of the record. To the right of L_2 we now have a plane wave. This plane wave is focused by spherical lens L_3 into plane P_3. Thus our goal of processing the one-dimensional zone plate into a point is achieved.

The axicon had a diameter of 50 mm and a cone angle of 170° and was bought from Special Optics, Cedar Grove, N.J. Assuming a refractive index of 1.5 we have a focal length of 23 cm at a distance of 1 cm from the center and of 46 cm at a distance of 2 cm from the center. As suggested in [6] only a small vertical strip of the image is processed at any one time. In order to obtain the full image the synthetic aperture sonar record as well as the slit are translated and the processed image is recorded on Polaroid film. This has the advantages that only the central region of the pie-shaped axicon section is used and that the distortion of the image (distance dependent magnification) pointed out in [6] is avoided.

V. EXPERIMENTS

The experiments were performed in a water tank lined with natural rubber. The whole recording setup including the water tank was put on antivibration mounts. This greatly reduced the extreme sensitivity of the signal to building vibrations, although strong building vibrations still influenced the signal somewhat. The acoustic transducer was mounted on a very sturdy arm to minimize its vibrations.

The theory developed in [9] shows that the amplitude transmission of the synthetic aperture sonar record should be proportional to the amplitude of the received echo. Basically this is so because the optical processor is linear in amplitude. Attention was therefore paid to working in the linear region



(a)

(b)

Fig. 9. (a) Synthetic aperture sonar record of two synthetic rubber balls of 30 mm and 1 mm diameter. Zero spatial carrier frequency. (b) Reconstruction of record of (a) but with carrier frequency of 1 cycle/mm [left and right interchanged with respect to (a)].

of the electronic system, the brightness of the oscilloscope screen and the photographic film.

A variety of objects was used for testing the system, such as synthetic rubber balls and metal pins. As an illustration Fig. 9(a) shows the record of two rubber balls of 30 mm and 1 mm diameter, recorded with zero carrier frequency. The small rubber sphere approximates a point object and its record on the right of Fig. 9(a) should be compared with the schematic drawing of Fig. 3(b). Fig. 9(b) shows the reconstruction of the two rubber balls. A spatial carrier frequency of 1 cycle/mm was used. Note that only the front of the large rubber ball was insonified. Most of the tests were done with two wire grids mounted at a distance of 7 cm from each other. Each grid has a number of groups of three copper wires strung at different distances. The diameter of the copper wires was 0.3 mm. Fig. 10 shows the reconstruction of this object. (This now is a cross section through the object.) Going from left to right in the top grid and from right to left in the bottom grid the wires are strung at a distance of 1 cm, 5 mm, 4 mm, 3 mm, 2 mm, 1.5 mm, and 1 mm. It is seen that in the top grid wires spaced 2 mm apart can be resolved, whereas in the bottom grid only a spacing of 3 mm can be resolved. These experimental values for resolution are close to the values expected theoretically and are about one order of magnitude better than those of a conventional B scan working at the same frequency.

One problem that is evident from Fig. 9(b) and Fig. 10 is the "speckle problem" well known in holography. (Speckle is the granularity in the image of a diffusely reflecting surface when its illumination is spatially coherent.) It is not yet clear how much of an impediment speckle would be in a medical

Fig. 10. Processed image of two wire grids.

diagnosis system, but probably speckle will have to be reduced.

The system described demonstrates that synthetic aperture sonar is indeed a system which gives a significantly higher lateral resolution than conventional *B* scan. In medical applications one will encounter the following problems.

1) The system is not real time but a processing step is needed before the image is obtained. Possible solutions are either a rapid film development and fixing or processing the record by computer instead of optically.

2) The resolution perpendicular to the plane of the scan (plane of drawing Fig. 3) is the same as in conventional *B* scan. At a distance of 28 cm the width of the beam (half intensity points) in this direction was measured as 1 cm.

3) Object motion of more than about 0.1 mm leads to phase changes during recording and a loss of resolution in the reconstructed image. It should, however, be borne in mind that the recording of one point only takes between 0.5 s and 1 s depending on distance and that this time could be further reduced by building a more rapid scan.

4) Speckle as discussed earlier.

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