北海道大学工学部研究報告
第119号（昭和59年）

Bulletin of the Faculty of Engineering,
Hokkaido University, No. 119 (1984)

Ultrasound Holographic B-scan Imaging System Using Wideband Chirp Signal

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(Received September 30, 1983)

Abstract

Aiming at high resolution ultrasound imaging, a new holographic technique is proposed. This method is based on a combination of the holographic principle and B-scan imaging technique. In the conventional B-scan techniques, very short pulses of ultrasound must be used to obtain higher longitudinal resolution, however the average power of ultrasound decreases in proportion to the pulse width, so that the signal to noise ratio is aggravated. In the proposed system, we employ the pulse compression technique using wideband chirped ultrasound instead. After the longitudinal processing, a one dimensional holographic image reconstruction is performed to obtain lateral resolution. While the longitudinal and lateral pulse compression are based on different theories, the resulting algorithm is almost the same. The main calculation is Fourier transform and it can be calculated using the Fast Fourier Transform (FFT). In this paper, a computer simulation is presented to demonstrate the point spread function of this image reconstruction. Further, an experimental system based on this theory is presented and experimental results show the potentiality of this imaging method.

I. Introduction

The application of the ultrasound imaging technique is spreading in many fields such as nondestructive testing, medical diagnosis or underwater imaging. Especially The B-scan imaging which visualizes a two dimensional section of the specimen is the most widely used technique. In the conventional B-scan imaging system, the lateral resolution is limited by the aperture of the tranducers and the range resolution is limited by the pulse width of transmitted ultrasound. As for the range resolution, the use of short time pulse improves the resolution, however it causes a decrease of signal to noise ratio. Another possibility to improve the resolution is to employ the holographic technique. In this case, while the lateral resolution is greatly improved by a synthetic aperture, the range resolution is aggravated because the holography technique must use a coherent wave.

It has been also problem in the field of the microwave radar until the synthetic aperture radar (S. A. R.)[1] was developed. Since the success of S. A. R. is a result of combination of holography and pulse echo technique, it may be possible to employ the same technique in acoustical imaging.

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In this paper, we propose a new technique of B-scan imaging which makes it possible to obtain both a higher resolution and wereas in signal to noise ratio than the conventional imaging system. In the proposed method, a wideband chirped ultrasound is employed instead of impulse or coherent ultrasound. The range resolution is obtained by pulse compression using chirp signal. The difference from the conventional B-scan imaging system is that the phase information still remains after this processing and this makes it possible to oftain lateral resolution by the holographic image reconstruction. The calculations required in an image reconstruction are phase rotation (complex multiplication) and the Fourier transform, and it can be calculated effectively by a digital computer. In this paper we briefly describe the theory of image reconstruction and the realization of hardware system. Further, an experimental result demonstrating high resolution is shown.

II. Principle

Figure 1. shows the coordinate system of B-scan imaging system. In this figure, the center of imaging area is assumed as (0, z_0). The receiving and transmitting transducers are located on the straight line of z=0 and it is assumed that the location of them is the same for simplicity. The transmitter fires a burst of ultrasound at each sampling point. The waveform s(t) is given as follows,

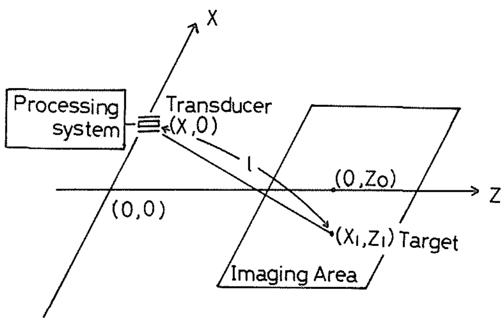

Fig. 1 Coordinate system for B-scan imaging system.

$$s(t)=\begin{cases}\exp(j\omega_0 t+j\frac{1}{2}ut) : -\frac{T}{2}<t<\frac{T}{2} \\ 0 \quad : \text{elsewhere}\end{cases} \tag{1}$$

Where W_0 is the angular frequency of the center of chirp signal, u is the chirp rate and T is the pulse duration time. The frequency sweep range B is given by

$$B=uT \tag{2}$$

The reflected wave from the targets located at coordinate (x_1, z_1) can be written by

$$g(x, t)=\Gamma\exp\{j\omega_0(t-\frac{2l}{c})+j\frac{1}{2}u(t-\frac{2l}{c})\} \tag{3}$$

where

$$l=\sqrt{(x-x_1)^2+z_1^2}, \tag{4}$$

x in the lateral offset of trnsducers and Γ is a complex coefficient of target reflèction. Raw data are collected at many points along the line and these are stored in a memory device. The data are recorded as a space-time signal. Since the equation (3) has a carrier component which has no information of targets, it should be removed by the coherent detector using reference signal. The reference signal r_0 (t) is given by

$$r_0(t)=\exp(-j\omega_0 t). \tag{5}$$

The detected signal $g_1(t)$ becomes as follows,

$$g_1(x, t) = \Gamma \exp(-j\frac{4\pi l}{\lambda})\exp\{j\frac{u}{2}(t-\frac{2l}{c})^2\}. \tag{6}$$

where $\lambda = \dfrac{2\pi c}{\omega_0}$

Since the first exponential function of the right side of the equation (6) is independent of variable t, the information regarding the longitudinal direction is all contained in the second exponential function. At first, the pulse compression of the range direction must be done. The first step of this processing is multiplying a reference signal. This reference signal r_1 (t) is determined by the longitudinal distance between transducers and the center of imaging area. In the case of fig. 1, it becomes as follows,

$$r_1(t) = \exp\{-j\frac{u}{2}(t-\frac{2z_0}{c})^2\} \tag{7}$$

Multiplying (6) by (7), a new form of $g_2(x, t)$ is obtained :

$$g_2(x, t) = \Gamma \exp(-j\frac{4\pi l}{\lambda})\exp\{j-\frac{u}{c^2}(z_1^2-z_0^2)\}\exp\{-j\frac{2u}{c}(z_1-z_0)t\} \tag{8}$$

$g_2(x, t)$ contains variable t only in the last exponential function of right side and range information z_1-z_0 is expressed as the angular frequency of the function of t. The pulse compression of in a longitudinal direction is obtained as the result of spectral estimation of equation (8). The correspondence of z coordinate with angular frequency can be written by

$$z_1 = \frac{c\omega}{2u} + z_0. \tag{9}$$

Usually, FFT algorithm is used for this spectral estimation, however, another technique, in which the Maximum Entropy Method (M. E. M)[4] is used for the spectral estimator, is reported and its gives good resolution. Unfortunately, the M. E. M. estimates only the power spectrum, so that the phase information which is indispensable to the lateral processing disappeared. Further, since the M. E. M. requires more computing effort than FFT, it is almost impossible to construct a real time imaging system. From the facts described above, the use of FFT technique as the spectral estimator is reasonable. After the longitudinal compression, the information of targets is contained in each corresponding range bin. The next step of image reconstruction is lateral compression. The information contained in the range bin $z = z_1$ can be expressed by $g_{z1}(x)$:

$$g_{z1}(x) = \Gamma_1 \exp(-j\frac{4\pi l}{\lambda}) \tag{10}$$

Where Γ_1 represents the combination of constants which is meaningless in the lateral compression. Assuming that x is smaller than z_1 enouqh, (4) can be rewritten as follows,

$$l = z_1 + \frac{(x-x_1)^2}{2} \tag{11}$$

Substituting (11) into (10) :

$$g_{z1}(x) = \Gamma_1 \exp(-j\frac{4\pi z_1}{\lambda} - j\frac{2\pi(x-x_1)^2}{\lambda z_1}) \tag{12}$$

The equation (12) expresses the ordinary Fresnel transformed hologram. There are many techniques[2] which can be applied to the image reconstruction from (12). The most popular technique is to transfrom the Fresnel transformed hologram into a Fourier transformed hologram. This transform is given by

$$g_{z1}(x)=g_{z1}(x)P_{z1}(x) \tag{13}$$

Where $P_{z1}(x)$ is the propagation function of $z=z_1$ and it is written as

$$P_{z1}(x)=\exp(j\frac{2\pi x^2}{z_1}) \tag{14}$$

Equation (13) is rewritten as

$$g_{z1}(x)=\Gamma_1\exp(-j\frac{4\pi z_1}{\lambda}-j\frac{4\pi x_1^2}{\lambda z_1})\exp(j\frac{2\pi x_1}{\lambda z_1}x) \tag{15}$$

Since the first exponential function of the right side of (15) is independent of variable x, this factor can be assumed as constant. As a result, the lateral position x_1 is obtained from the spectral estimation of (15). The correspondence between x and spatial angular frequency ξ is given by

$$x_1=\frac{\lambda z_1}{2\pi}\xi \tag{16}$$

The pulse compression technique used in longitudinal and lateral direction are derived using different principles, however, the resulting algorithms are almost the same. This nature is very useful in the design of special purpose hardware of image reconstruction since the required calculation becomes simple repetition of 1-dimensional FFT.

III. Resolution

In this method, an image is obtained as a result of the Fourier transform. This means that the theoretical resolution is calculated from the resolution of spectral estimation. The basic relationship between spectral resolution $\Delta\omega$ and time aperture T is given by

$$\Delta\omega=\frac{2\pi}{T} \tag{17}$$

In this case, T is the pulse duration time. The following equation is obtained by substituting (17) into (9),

$$\Delta z=\frac{c\pi}{B} \tag{18}$$

This equation expresses that the resolution is limited by the frequency sweep range of the chirp signal.

The lateral resolution is also limited by the aperture of Fourier transform. Since the aperture is the lateral length of scanning area, there is no limitation if the beam width of transducers is wide enough. However, Another limitation arises from the pulse compression of longitudinal direction. Because the trace of compressed pulse is mapped on a hyperbolic curve, compressed pulse exists over some range bins when the size of range bin z becomes small. This situation is illustrated in Figure 2. Using the size of range bin of equation (18), the maximum available aperture is given as the solution of following equations,

$$\Delta z = \sqrt{L^2 + z_1^2} - z_1 \qquad (19)$$

Solving (18) for L, we obtain the maximum available aperture as follows,

$$L = \sqrt{\Delta z (2z_1 + \Delta z)} \qquad (20)$$

Using the condition of $z_1 \gg \Delta z$ and substituting (18) into (20) we obtain

$$L = \sqrt{\frac{2c\pi z_1}{B}} \qquad (21)$$

When the aperture along the x axis is limited to L, the resolution of the spatial frequency domain is given as follows,

$$\Delta \xi = \frac{2\pi}{L} \qquad (22)$$

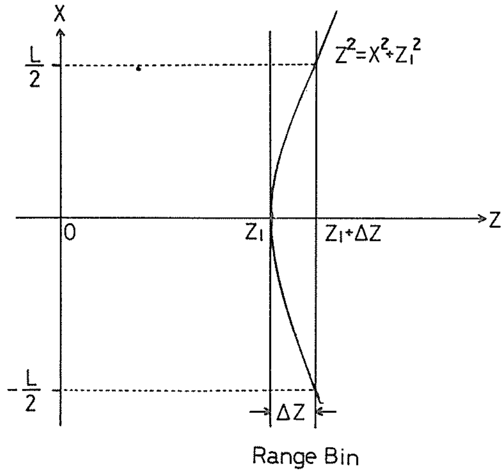

Fig. 2 The maximum lateral apperture after longitudinal Pulse compression.

Substiuting (21) and (22) into (16), the lateral resolution is given by

$$\Delta x = \sqrt{\frac{B\lambda^2 z_1}{2c\pi}} \qquad (23)$$

Equation (23) gives the maximum available resolution, and it corresponds to the beam width of a single transducer of diameter L. However, the aperture size is sometimes restricted by other factors such as the beam angle of the transducers or physical limitation of scanning width.

The quality of reconstructed image can be demonstrated by the computer simulation. Fiqure 3 shows an example of simulated data of $g_2(x, t)$ when the target is a point like object located at (x_1, z_1) and Table 1 lists the parameters which are used in this simulation. In this example, only the real part of $g_2(x, t)$ is plotted. Using equation (18), (21) and the parameters listed on Table 1, the theoretical resolution limit is given by

$$\Delta z = 0.625 \text{ mm} \qquad (24)$$

$$\Delta x = 4.75 \text{ mm} \qquad (25)$$

Table 1. List of parameters used in simulation

Item	Symbol	Value	Unit
Carrier frequency	ω_o	37.7 (6.00	X10^6 rad/sec MHz)
Wave length	λ	0.25	mm
Chirp rate	u	1.76	$\times 10^9$ rad/sec^2
Pulse duration time	T	683	$\times 10^{-6}$ sec
Sweep range	B	7.54 (1.20	$\times 10^6$ red/sec MHz)
Sampling frequency	f_s	3.0	MHz
Sampling interval (x axis)	x_s	0.5	mm
Scanning width	L	64	mm
Distance to target	z_1	452	mm

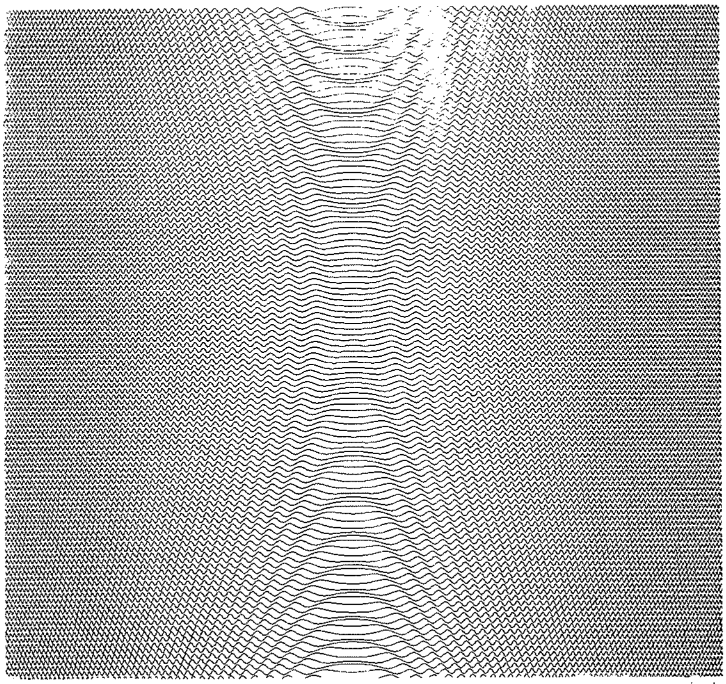

Fig. 3 A part of simulated $g_1(x,t)$. (real part)

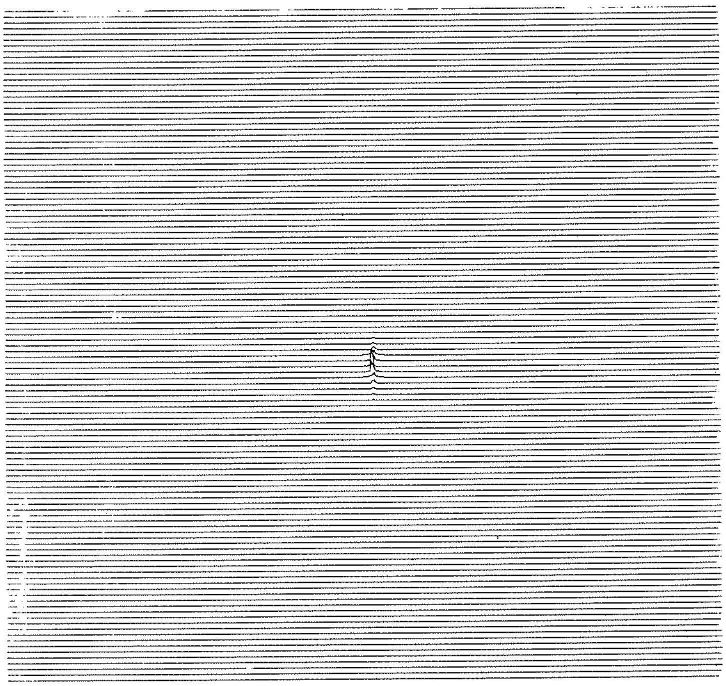

Fig. 4 Point spread function (P. S. F) of the system.

As for the lateral resolution, since the scanning width is greater than L of equation (21), it does not affect the resolution. A reconstructed image is shown in Figure 4. This example displayed the intensity of reconstructed image and it can be regarded as the point spread function of this imaging system. This simulation demonstrates that this method has potentiality of a high resolution ultrasound imaging system.

IV. System realization

The imaging system based on this theory consists of three subsystems which are transmitter, receiver and control subsystems.

The transmitter subsystem generates the chirped ultrasound and amplifiers it to obtain sufficient ultrasound energy. Further, the reference signal that is required in the coherent detection of the receiver is also generated in this subsystem. For the lateral image reconstruction, each of transmitted pulses must be the same in the level of phase, so that it is impossible to employ simple voltage controlled oscillator (V. C. O.) as a chirp signal generator. In our system, we designed a digital-analogue hybrid chirp signal generator. When we can utilize a complex carrier and baseband chirp signal, the chirp signal of central frequency ω_0 can be written as follows,

$$c_f(t)=R_e\ \{f_c(t)*c_h(t)\} \tag{24}$$

where

$$f_c(t)=\exp(j\omega_0 t) \tag{25}$$

$$c_h(t)=\exp\ (j\frac{u}{2}t^2) \tag{26}$$

These complex signals are usually generated by using phase shift network, however, such a technique is not suitable for the case of $c_h(t)$ since it has a wide spectral distribution from DC, so that it is difficult to make a phase shift network. To generate a complex chirp signal, we employ digital wave memory which stores the complex wave form. However, In the case of a carrier signal, since it has only one frequency component of fc, the digital delay line can be used instead of phase shift network. The block diagram of designed chirp signal generator is illustrated in figure 5.

The purpose of receiver subsystem is data collection of returned ultrasound. This part consists of a pre-amplifier, coherent detector and digital wave memory. The block diagram

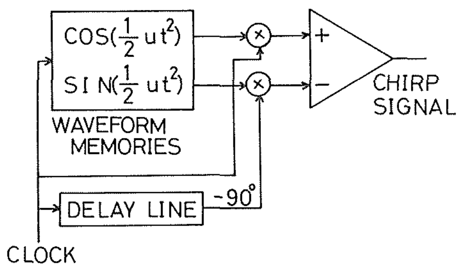

Fig. 5 Schematic diagram of digital-analogue hybrid chirp signal generator.

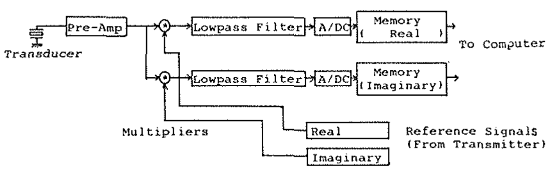

Fig. 6 The blook diagram of receiver subsystem.

is illustrated in figure 6. The returned ultrasound is converted into an electric signal by the transducer and the result of coherent detection is stored in wave form memory. The required reference signal in the detection is supplied from transmitter subsystem. The collected data are read by a computer after the completion of 1 line data collection. The imaging area regarding the range direction is determined by the range gate. The gate signal is generated by the timer circuit triggered at the same time as the firing of ultrasound.

The controller subsystem controls the time sequence of data collection including the firing timing, range gate delay time, scanner control and data storing in the disk system. Since this subsystem is constructed using a micro-computer system, the system configuration is flexible. Further, it is possible to calculate certain parts or the whole of the image reconstruction processing.

The whole system is illustrated in figure 7. The image is reconstructed by a large computer system or micro computer system and the resulting image is displayed on CRT. The required calculation time to reconstruct an image depends on its size. In the case of our experimental system, the size of a collected data is 2048 × 128 points of complex numbers and the amount of calculation is almost equal to the same size of a 2-dimensional Fourier transform. Usually, the image is reconstructed by a large computer system, however, recent progress of micro-computers will make it possible to build a real time imaging system based on such a super micro processor.

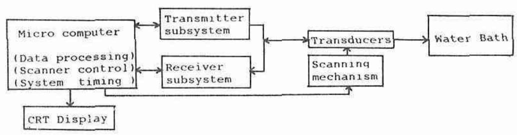

Fig. 7 System configuration of the imaging system.

V. Experiment

In this section, we show some demostration of our imaging system. Figure 8 shows the object which is used as the target. This object consists of nine tin plated wires with diameters of 3mm and eight of which are placed along the circle in 5cm radius and the remainder is placed 3cm behind this circle. The parameters used in this experiment are the same as in Table 1. Figure 9 shows an example of collected data or $g_2(x, t)$ and figure 10 shows the reconstructed image. The resulting image shows that this method has good resolution both in the lateral direction and the range direction.

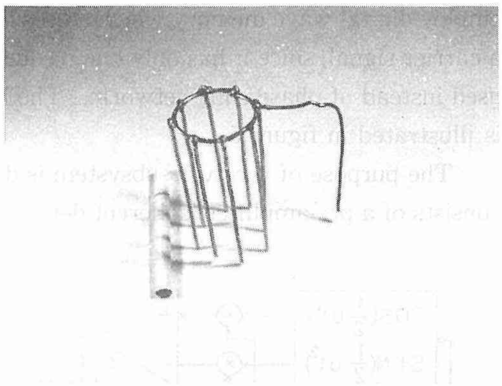

Fig. 8 A resolution test object.

VI. Summary

Poor resolution is a problem in conventional B-scan imaging especially in the lateral direction. A special feature of holography is its good lateral resolution. By combining the

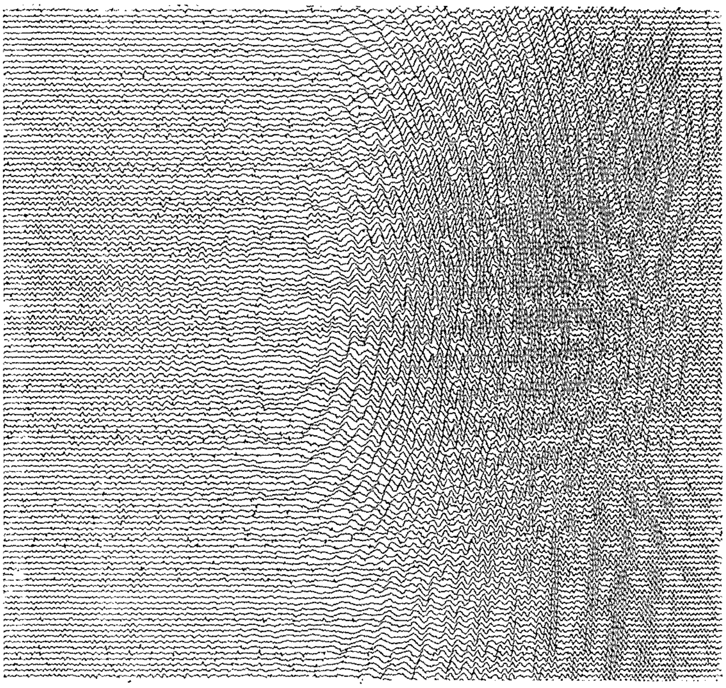

Fig. 9 A recorded data from the test object.

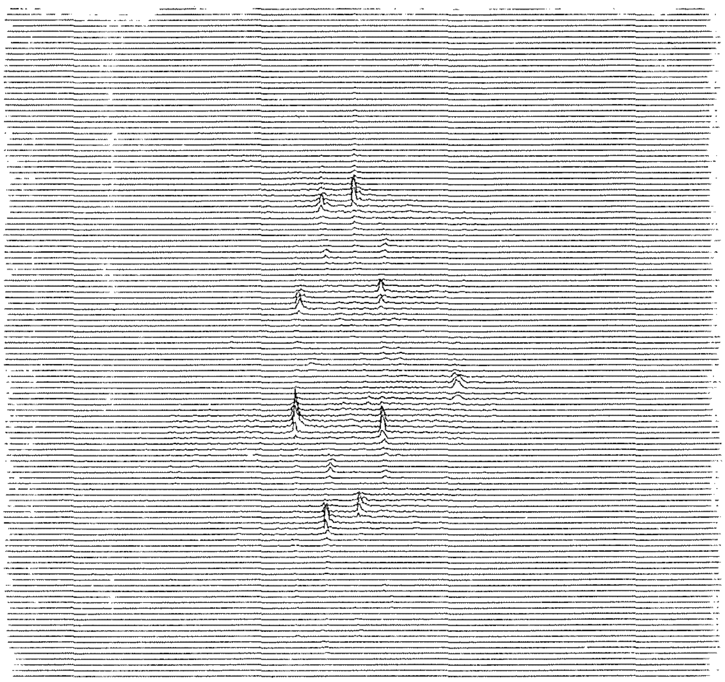

Fig. 10 A reconstructed image from the data of figure 9.

conventional B-scan technique with holographic imaging, it is possible to achieve good resolution in any direction all over the range.

The main problem of the proposed method is the phase incoherence of ultrasound. In the simulation and experiment, it is assumed that the targets are stable during data collection, however, if the targets are moving objects such as live human bodies, the irregular phases occur and this causes the degradation of the reconstructed image. To avoid this disadvantage, rapid data collection is necessary. In our experimental system, since the data are collected using a mechanical scanner, more than 10 minutes is required. During this period, the targets cannot move over half of the wavelength. This restriction is quite serious especially in the application to medical diagnosis in which a live human body is the object. An approach to solve this problem is the use of the array transducer system. Using the array system, whole data are collected by an ultrasound burst, so that this restriction will be greatly relaxed. Another problem is the computation time to reconstruct an image. When a Z80 based microcomputer system is used in the reconstruction, the processing time will exceed 2 hours. For the real time imaging system, sophisticated digital signal processing system is required.

ACKNOWLEDGEMENTS

The authors with to thank Professor Odazima for his advice regarding the ultrasound transducer and Dr. Ohohigasi for his kind co-operation in offering the use of ultrasound transducers. We also thank our colleagues for their helpful discussions and their technical advice not to mention their unstinted cooperation and goodewill.

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