ULTRASONIC REAL-TIME RECONSTRUCTION IMAGING

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Introduction

The results of the studies in the optical image reconstruction may not be directly generalized to the acoustical case. Two main features explain the need for further studies :

- first, specific problems appear since the ultrasonic devices dimensions may not be termed as extremely large with respect to the wavelength. So, for a given aperture, the phase rotation will be slower for the acoustical case than for the optical one.

- second, new particular abilities are given by ultrasonic waves, which allow original reconstruction schemes. The low velocity of acoustic waves leads to short wavelengths at frequencies easily generated using standard electronic equipment. It is then possible to launch pulsed ultrasonic wavetrains and to get echographic B scan images (Annexe 1). On an other hand, it is possible to use phase and amplitude sensitive receivers and so to bypass the holographic technics.

Two original schemes of image reconstruction using these specific properties, of the ultrasound will be described. The first one uses an acousto electronic lens mode with two transducers arrays, one for sampling the acoustic field reflected by the object and the other for reconstructing the image after an electronic inversion of the relative phases between the channels. In the second scheme, the reconstruction is performed optically after the transfert of acoustical informations onto a light beam via acousto-optic interaction.

These two devices have been conceived in order to allow the observation at a high image rate (up to 1000 per second) of the fast motion of the cardiac valves.

Theory

Wave propagation may be depicted by the Huyghens model of the decomposition of an arbitrary surface into elementary omnidirectionnal sources. The strength of these sources is proportionnal to their area and to the wave amplitude in their neighbourhood. The wave amplitude at some observation point P may then be computed by summing all the contributions from the elementary sources. When the phases (i.e. resulting from the summation of the relative phase of the sources and the phase lag introduced by the path between the sources and the observation point) of these terms are stationnary, constructive interference occurs and the resulting amplitude is high. In the opposite case, this amplitude remains very low. Starting from the propagation equation, Rayleigh and Sommerfeld (1, 2) have given a mathematical foundation to the Huyghens principle.

Assuming that the observation distance is much greater than the source dimensions, Fresnel has suggested a simplified description using the Fresnel's function:

$$\phi_1(P) = \frac{1}{j\lambda z_1} \exp\left(-\frac{j\,k|P|^2}{2z_1}\right) \tag{1}$$

The amplitude inside a plane P_1 is then expressed as a convolution integral in terms of that inside the plane P_o

$$U_1(P) = U_o(P) * \phi_1(P) \tag{2}$$

where P stands for the two coordinates in the plane, z_1 the distance between the two planes, k and λ respectively the wave vector modulus and the wavelength.

Owing to the following property of the Fresnel's function

$$\phi_1^* (P) * \phi_{2-1}(P) = \delta(P) \text{ if } z_{2-1} = z_1 \tag{3}$$

the information $|U_o(P)|$ may be deduced from $U_1(P)$ since :

$$U_2(P) = U_1^*(P) * {}_{2-1}(P) = U_o^*(P) * \phi_1^*(P) * \phi_{2-1}(P) = U_o^*(P) \tag{4}$$

That means physically that if we take the complex conjugate of the information of the shadow in a plane P_1 (i.e. if we invert the relative phase), the amplitude in the plane P_2 such as $z_{2-1} = z_1$ will be the same as in this one in plane P_o (i.e. in plane P_2 we obtain the image of the scattering power of the object set in plane P_o)

We get a further step in simplication (3) and developped a model taking advantage of the linearity of the exact formulas. This allows then to consider each point source in plane P_o as radiating individually. This model gives a first approximation of the results and allows an easy interpretation of the device behaviour.

By choosing source dimensions lower than the wavelength, the amplitude may be assumed uniform, so that only the phase variations are taken into account. Moreover in the B scan (see Annex 1) echographic mode, only a single variable has to be considered. At some distance d from the source, the relative phase varies along a line perpendicular to the mean direction (see fig. 1), according to the approximate quadratic law :

$$\phi(x) = -\frac{2\pi}{\lambda}\left[\sqrt{d^2 + x^2} - d\right] \simeq -\frac{\pi x^2}{\lambda d} \qquad (5)$$

which is valid in the paraxial approximation.

The minus sign means that the lateral rays have a phase lag with respect to the central one. If after sampling (whose step will be assumed lower than an half wavelength) we reemitt these signals with the same phase distribution, the reconstructed field will be equivalent to the one sampled and the corresponding beam will seem issuing from a virtual point source (fig. 1).

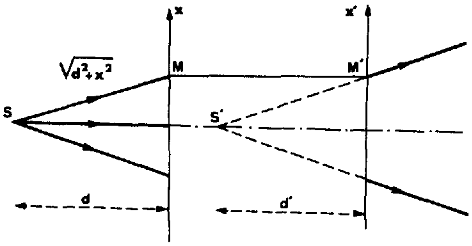

Fig. 1 : Direct connection between M and M' giving a virtual image S'

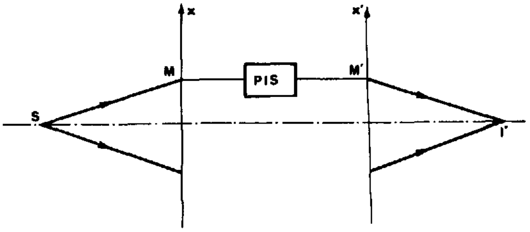

Fig. 2 : Phase inversion system (SIP) between M and M' giving a real image I'

But now if we inverted the sign of the phase distribution, the generated beam will converge toward a real image point I' (fig. 2). The relative phase lag introduced by the path M'I' is given by :

$$\phi(x') = -\frac{2\pi}{\lambda'}\left(\sqrt{d'^2 + x'^2} - d'\right) \simeq -\frac{\pi x'^2}{\lambda' d'} \qquad (6)$$

So that taking into account the relative phase of the source point M', the resulting phase of the ray issuing from M' at point I' equals :

$$\phi(M', I') = \frac{\pi x^2}{\lambda d} - \frac{\pi x'^2}{\lambda' d'} \qquad (7)$$

This phase appears stationnary versus M' if :

$$\frac{x^2}{\lambda d} = \frac{x'^2}{\lambda' d'} \qquad (8)$$

where x' represents the ordinate of the reemitting point connected to the receiving point of ordinate x and d' the distance of the real image I' to the reemitting away.

This result constitutes in fact the base of the holographic technics and we describe in the following two experimental methods performing in real time this mathematical transformation known as a Fresnel transform.

Acousto-electronic lens (4, 5)

The reflected acoustic field may be sampled by a piezoelectric transducer array and converted into an electrical form, so that the phase inversion process may be performed electronically. Several techniques are available to do so, the very first being to use electronic delays by analogy with a simple lens. However, for B. Scan echography, the distance from the object is continuously varying so that a very fast zoom effect is needed in order to keep the object well in focus. The relative phase inversion will then be performed using the non linear response of diodes in a ring modulator giving so the product of two sinusoïdal functions. Let us consider two input signals, a reference one A cos Ωt and an other one B cos $(\omega t + \phi)$. The output signal appears as :

$$AB \cos \Omega t \cos(\omega t+\phi)=\frac{AB}{2} \cos\left[(\Omega+\omega)t+\phi\right]+\frac{AB}{2} \cos\left[(\Omega-\omega)t-\phi\right] \qquad (9)$$

By electrical filtering we keep only the second part whose amplitude is proportionnal to B. The sign of its relative phase is inverted with respect to the input one if the reference pulsation Ω is higher than the information signal one ω. The generated wave focuses according to eq.8 at the distance d' :

$$d' = \frac{\lambda}{\lambda'} \left(\frac{a'}{a}\right)^2 d \qquad (9)$$

where a'/a stands for the period ratio of the reemetting and the receiving array. The focused signal is picked up by a third array lying in the convergence zone. By varying the reemitting wavelength λ' the distance d' may be kept constant when d is varied, so that the fast zoom effect is performed simply by changing the reference signal frequency.

The validity of this approach has been verified using a 10 channels device. The reemitted field is visualized using Schlieren's method which gives an optical image of the acoustic field distribution (fig. 3) where the converging effect appears clearly.

The system described here is an analogical computer for the Fresnel transform which is more simpler and faster than digital computers for this purpose. A sector scan apparatus which uses the same principle is now under study. Other applications may also be devised like in radioastronomy for example.

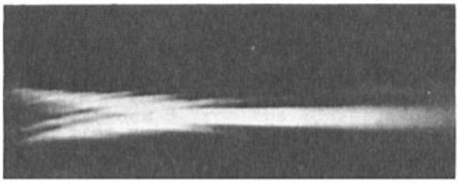

Fig. 3 : Reconstructed acoustical field distribution

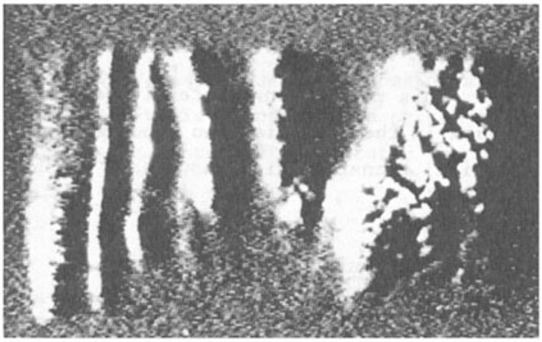

Fig. 4 : Image of the heart

Acousto-optic processing (6, 7)

Another technique is to put the useful informations onto a light beam. The acousto-optic interaction may be viewed as a nonlinear interaction phenomenon involving a reference optical signal A cos Ωt and an acoustical signal B cos $(\omega t + \phi)$. This gives diffracted optical beams such as :

$$\alpha AB \cos\left[(\Omega + \omega)t + \phi\right] \text{ for the plus one order}$$
$$\alpha AB \cos\left[(\Omega - \omega)t - \phi\right] \text{ for the minus one order}$$

where α is an efficiency factor characterizing the interaction medium.

A spatial filter allows to select either the plus one order corresponding to a virtual optical image or the minus one order giving a real optical image or the insonifying object. Cylindrical optical lens are used to form the image on a screen. A galvanometric mirror converts the temporal modulation of the light beam spatial modulation in order to restitute the second set behind this galvanometric mirror compensate for the distance variation of the successive lines in order to keep the whole image well in focus.

A complete imaging apparatus using the acousto-optic interaction principle has been built for medical applications, more specifically in the cardiologie area and an image given by this prototype is shown on fig. 4.

Conclusion

In this paper we have described two new imaging devices using the specificities given by the low frequencies used in ultrasonics. The analogic technics allow real time reconstruction schemes and in the ultrasound imaging area classical holographic technics may easily be bypassed. The two devices described appear as analogical Fresnel transform devices whose applications may be extended to other domains as the radioastronomy area. Experimental results confirm the theoretical predictions and images of in vivo structures as the heart have been obtained.

References

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Annexe 1 B scan echographic mode

The so termed B scan echographic mode charaterizes the imaging technics commonly used in sonar and radar devices. The image is formed in the reflection mode using a short pulsed wave. The time delay (t_i) needed by the pulse to propagate from the source to the reflecting object and back to the receiver allows to separate the successive lines set at different distances (d_i).

This gives one dimension of the image. The second dimension may be obtained either by a mechanical displacement of the source and the receiver (as in the radar device) or by an electronical commutation of transducers in an array structure or by a real time, one line scheme, reconstruction device. In this last case the reconstruction scheme has to take into account the distance variation of the successive lines by using a fast zoom effect.