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A NOVEL VARIABLE DELAY SYSTEM FOR ULTRASOUND BEAM STEERING/FOCUSING

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RESUME

Dans les systèmes échographiques d'imagerie ultrasonore utilisant une barrette de transducteurs piézoélectriques, le balayage et la focalisation électroniques du faisceau sont obtenus par l'introduction de lignes à retard dynamiques en série de chacun élément récepteur pour compenser les différences de retard des signaux échantillonés par la barrette en fonction de la position de la source réfléchissante.

La compétition entre les diverses lignes à retard analogiques et à données échantillonées est basée sur la considération de la largeur de bande nécessaire, de l'incrément de retard et du retard maximum, ainsi que de la complexité du contrôle de la variation des retards, de la distorsion du signal et de la dynamique.

Nous proposons ici une nouvelle technique de retard, suivant laquelle on introduit d'abord le déphasage de l'oscillation porteuse, et après on retarde indépendamment l'enveloppe de l'écho. Cette seconde opération est basée sur une nouvelle ligne à retard à données échantillonées capable à retarder l'enveloppe d'un signal radiofréquence sans modifier la phase de la porteuse. On montre que le nouveau système peut produire une variation continue des retards par un simple contrôle digital, et présente une négligeable distorsion autant que une large dynamique. Nous décrivons le principe de fonctionnement et les résultats expérimentaux de la nouvelle technique.

SUMMARY

In echographic ultrasound imaging systems using a phased-array transducer, beam steering/focusing is achieved electronically by variable time-delay networks inserted in series with each array element to compensate for the difference in arrival times of echo waveforms from different directions. Competition between various analog and discrete delay systems involves cost/performance considerations in terms of required bandwidth, delay increment and maximum delay, control complexity, signal distortion, dynamic range.

A novel processing technique is described that performs the required echo delay equalization first by properly phasing the echo carrier, and successively by independently delaying the echo envelope. This second operation is based on a new analog sampled-data delay line, capable of delaying the envelope of a r.f. signal without modifying the carrier phase.

The new system is demonstrated capable of providing continuously variable delay under simple digital control, while exhibiting low distortion and high dynamic range. Basic operation and experimental results of the new delay technique will be presented.

A novel variable delay system for ultrasound beam steering/focusing

I - Introduction

Ultrasound echo techniques for noninvasive diagnostic imaging have undergone a tremendous development in recent years, evolving from one-dimensional systems using a single piezoelectric element towards bidimensional equipments using arrays of elements, capable of providing tomographic images in real time. One of the major efforts has been directed towards the visualization of the dynamic activity of the heart. Even though various solutions have been proposed [1,2], the requirement of a high number of frames per heart cycle, coupled to anatomical constraints claiming for a hand-held easily manoeuvrable probe, have oriented towards the development of an electronic sector scanning system relying on a small array of piezoelectric transducers operated according to the phased-array principle [3,4]. In such a system the echo waveform from a point target is spatially sampled by the array elements, and signal contributions from contiguous elements suffer a mutual delay depending on the target angular position. The key operation of equalizing these delays so as to produce directionally selective interference of echo signals must be accomplished by means of a dynamically variable delay-line in series with each array element.

Analog lumped-constant and sampled-data delay systems as well as the digital approach have been used or investigated for this purpose [5]. Competition among different solutions depends on a number of requirements, including delay increment and maximum delay, bandwidth, signal distortion and markedly phase distortion, rapidity of delay variation and complexity of delay control, dynamic range, and, as a non ultimate factor, on the cost at which the desired performance can be achieved.

II - The new delay technique

A common feature of all the above delay techniques is that the delay-line bandwidth is dimensioned with reference to the maximum frequency of the echo signal, even though the signal energy is concentrated in a narrow band around the resonance frequency of the transducer. As the operation frequency for cardiological applications ranges from 1.5 to 3.5 MHz, analog sampled-data delay lines require a sampling rate as high as 5-10 MHz, in spite of the fact that the video signal bandwidth is generally less than 1 MHz.

The dependence of the sampling rate from the signal carrier frequency is a consequence of the fact that delay lines must provide both the equalization of the phase shift of the echo carrier, like in electromagnetic phased-arrays, and the equalization of the echo envelope time-shift. If phase equalization was independently accomplished by other means, the bandwidth of the delay line required to process the echo envelope would depend merely on the video bandwidth and no longer on the carrier frequency. A significant bandwidth reduction could therefore be achieved provided that the echo delay equalization is performed in two steps: first, the carrier phase shift is compensated for, and then, independently, a delay line is used to introduce the envelope time-shift. The drawback of this processing procedure is that, once phase compensation is performed, synchronous demodulation of the signal in two quadrature channels would be required in order to preserve the phase information. Two delay lines would therefore be needed, one for each video quadrature component, prior to recovering the original signal format. Bandwidth reduction would be therefore exchanged with a major complexity of the processing architecture.

The new analog sampled-data delay system described in the following section offers the unique capability of delaying the envelope of a r.f. signal without modifying the carrier phase. Based on this property, the processing configuration shown in Fig.1 has been devised.

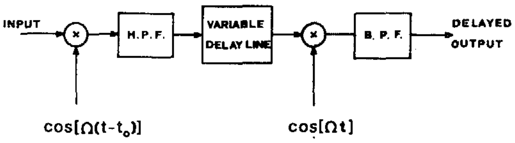

Fig. 1 - Principle of the new delay technique

Let the echo to be delayed by t_0 be described by

$$s(t) = a(t) \cos (\Omega t + \phi)$$

where $a(t)$ is the envelope, $\Omega/2\pi$ the carrier frequency and ϕ a constant phase angle.

A phase-controlled coherent reference oscillator generates the waveform

$$\cos \Omega (t - t_0) \quad ,$$

which is mixed with the echo, producing

$$\frac{1}{2} a(t) \cos (2\Omega t - \Omega t_0 + \phi) + + \frac{1}{2} a(t) \cos(\phi + \Omega t_0)$$

The low-frequency component is removed by high-pass filtering. Only the envelope of the selected component is processed by the delay line, thus yielding the output

$$g(t) = a(t - t_0) \cos (2\Omega t - \Omega t_0 + \phi)$$

which is a replica of the input signal delayed by t_0, apart from an inessential change of carrier frequency. The final frequency conversion shown in Fig.1 recovers the original frequency, if required.

III - The new delay line

The key element of the above technique is a new continuously variable delay-line, based on the principle of temporarily storing analog samples in a dynamic memory, to be picked-up at a later time, thus generating a delay between read-in and read-out. Its operation and basic configuration have been described elsewhere [5], and will be briefly recalled here.

Sampling and temporary storage of the input signal is performed using a tapped-delay-line (TDL)accessed in parallel through an analog multiplexer (Fig. 2). Let T_c be the multiplexer clock period, and $T_p = T_c/2$ the intertap delay. The analog gates of the multiplexer are sequentially switched from 1 to N at the clock period T_c, but each gate is enabled for a time interval $T_c/2$ only. The input waveform is therefore sampled at time interval T_c, and natural samples of width $T_c/2$ are launched from the individual taps.

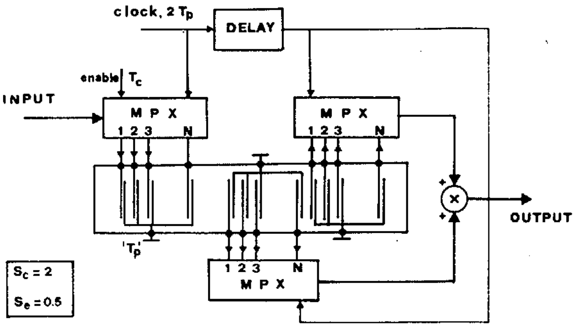

Fig.2 - Schematic diagram of the new analog sampled-data delay line

However, as the dead time $T_c/2$ between contiguous samples is compensated by the intertap propagation time $T_p = T_c/2$, samples appear contiguously propagating along the delay line. A signal time-block of length NT_c is therefore transferred in the delay line under the form of a sequence of N contiguous samples of length $NT_c/2 = N\ T_p$.

This read-in structure thus operates like a parallel-in serial-out analog dynamic memory, the storage time depending on the overall length of the delay line.

A similar structure, operated in a reciprocal manner, is used to read-out the samples sequence. The taps of the read-out structure are sequentially scanned by the multiplexer along the propagation direction, so that samples of width $T_c/2$ of the propagating sequence are outputted at time interval T_c, thus recovering the original time-base format. An interpolating filter recovers the continuous waveform. It can be demonstrated that the delay of the start time of the read-out clock with respect to initiation of read-in determines a corresponding delay between the input and output signals. Continuous delay variation is achieved simply by controlling the difference in application time between the read-in and read-out clock.

Processing of waveforms of indefinite duration is accomplished by repetitively operating the read-in multiplexer. The input waveform is so subdivided into adjacent time blocks of length $N\ T_c$, which are propagated as blocks of samples of length $N\ T_c/2$, separated by a dead time of the same length. In order to recover the original format, the read-out structure is composed of two adjacent N-tap sections, each controlled by a multiplexer, simultaneously and repetitively scanned from 1 to N, and the outputs from the two sections are summed. The maximum delay achievable by this configuration is $(N-1)\ T_p$.

It must be emphasized that the intertap spacing T_p has no relationship with the delay increment, as in conventional discrete analog delay lines based on electronic selection of taps: T_p is required to be half the sampling period T_c, and thus depends only on the input signal bandwidth. A further condition on T_p is established when the signal to be processed modulates a carrier of frequency f_s: the carrier is not affected by the sampling process provided that T_p is made an integral multiple of the carrier period $1/f_s$. The carrier phase is so preserved, as required by the delay system described above.

Surface-acoustic-wave (SAW) devices [6] offer an attractive means for implementing the tapped structure required by the new delay system. The maximum delay needed for ultrasound beam steering, which is in the range 6-10 μsec, is achieved by a compact, low-cost piezoelectric substrate. Tapping is easily implemented by interdigital transducers, offering a high degree of accuracy, high reliability and good reproducibility. SAW devices are inherently bandpass filters with centre frequencies typically above 10 MHz. The difference in operation frequency range has been so far generally considered a drawback to their use in ultrasound phased-array imaging systems. However, the frequency conversion needed to allow ultrasound echoes to be processed in a SAW device does not add any complication to the above system, as a mixing stage is anyhow required to introduce echo phasing. SAW interdigital transducers exhibit extremely low amplitude and phase distortion, moderate insertion loss for the required bandwidth, and high dynamic range.

IV - Experimental results

The scheme of the experimental set-up is represented in Fig.3. It consists of a frequency conversion unit, the delay line, and a logic control unit. The system is designed to process echo pulses of 1.75 MHz carrier frequency and 800 KHz bandwidth.

The frequency conversion unit performs the double function of introducing the phase compensation corresponding to the desired delay and of converting the input pulse frequency to the SAW TDL 17.5 MHz operation frequency.

The above parameters were chosen so as to control the whole system starting from a 28 MHz master clock. Synchronous division by 16 of the master clock, under control of the counting starting time, produces a 1.75 MHz waveform with phase programmable in increments of $2\pi/16$, corresponding to increments of 40 nsec of the carrier delay. Mixing of this phase-controlled reference waveform with a 14 MHz oscillation, generated from the master clock by division by 2, followed by proper band-pass filtering, provides a 15.75 MHz oscillation with the required phase-shift. This is applied to a double balanced mixer, where beating with the input pulse takes place. Subsequent band-pass filtering centered at 17.5 MHz selects the upper sideband for processing in the SAW-based delay line.

In this preliminary experiment a SAW TDL

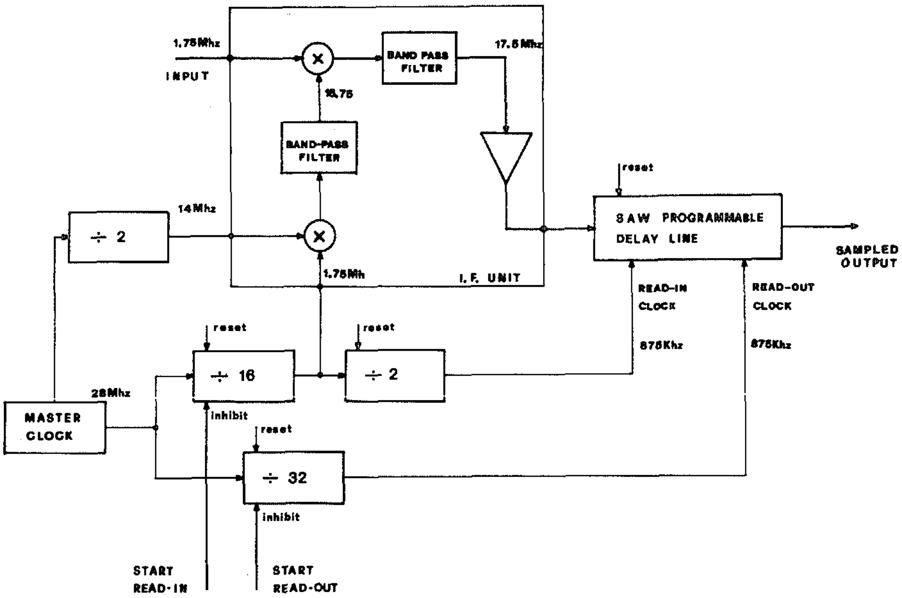

Fig.3 - Block diagram of the delay system

with N = 8 was used. The device was fabricated on a YZ $LiNbO_3$ substrate by sputtering a 3000 Å thick Al film and etching the interdigital transducers using standard lithographic techniques. Each tap consists of a 4 periodic sections interdigital structure at 17.5 MHz synchronous frequency, implemented by 9 25µ-width "split" fingers. The measured insertion loss resulted 18 dB. The intertap delay was 0.57 µsec, corresponding to ten synchronous wavelengths spacing. The TDL tap-to-tap frequency response is shown in Fig. 4 (top).

Digitally controlled analog multiplexers performed the required tap switching. As the individual taps are operated one at a time, it was possible to keep not activated taps at a low impedance, represented by a directly biased diode, so as to minimize electroacoustic regeneration and multiplexer cross--talk and feedthrough, which, otherwise, would severely degrade the SAW TDL response. The high r.f. insulation obtained is illustrated in Fig.4 (bottom), where the tap-to-tap impulse response is shown at an expanded vertical scale. Undesired spurious levels due to cross-talk and feedthrough appear as small spikes at the left of the main pulse, and are compared with the -40 dB triple-transit echo, appearing at the right delayed by 17 µsec. Mass-loading spurious pulses can also be observed.

The two clock waveforms at 875 KHz, controlling respectively the read-in and read-out section, are derived from the master clock by division by 32. At the beginning of each processing cycle, a start high level enables the read-out clock; a similar high level, shifted by the desired delay with respect to the read-out initiation, enables the read-in clock.

In Fig. 5 the envelope delay capability of the SAW sampled-data delay-line is demonstrated. An input video pulse appears progressively delayed in increments of 200 nsec, about one third of the intertap delay.

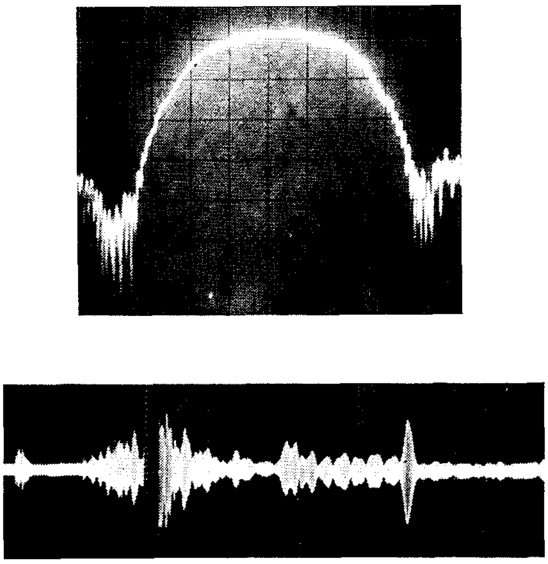

Fig.4 - Top: SAW TDL tap to tap frequency response
Centre frequency: 17 MHz. Horiz.scale:1 MHz/div.
Vert.scale: 10 dB/div.
Bottom: Details of the tap to tap impulse response showing spurious signals structure.
Horiz.scale: 2 µsec/div.
Vert. scale: 10 mV/div.

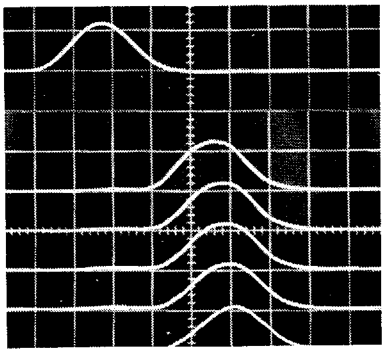

Fig.5 - Envelope delay experiments. The input video pulse (top) is delayed in increments of 200 nsec. Horiz.scale: 2 μsec/div.

The performance of the complete delay system is illustrated in Fig.6.

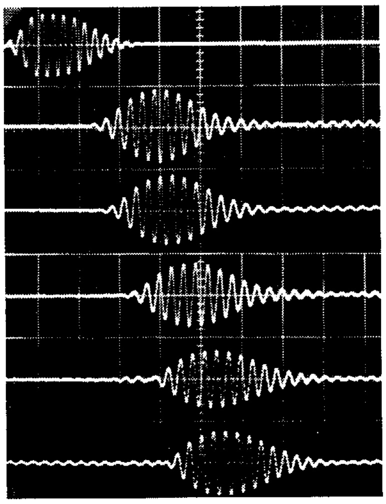

Fig.6 - Delayed replicas of an input r.f. pulse (top). Horiz.scale: 2 μsec/div.

The input waveform is a 1.75 MHz pulse simulating an echo return. The fine delay increment achievable is illustrated in Fig.7, where details of pulses delayed in steps of 80 nsec are shown.

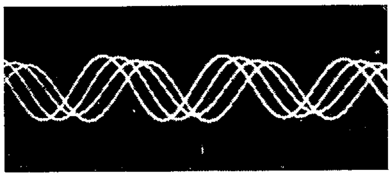

Fig.7 - Details of r.f. pulses delayed in steps of 80 nsec. Horiz.scale: 200 nsec/div.

The system dynamic range of about 40 dB is demonstrated in Fig. 8.

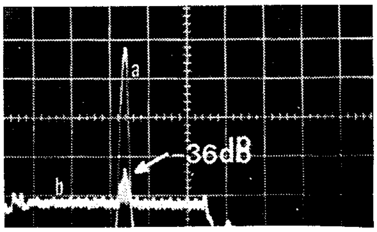

Fig.8 - Dynamic range of the delay system.
a-detected pulse envelope, vert.scale 200 mV/div.
b-the same with input pulse reduced of 36 dB, 5 mV/div.
Horiz.scale: 20 μsec/div.

Conclusions

A new analog sampled-data delay line with application to electronic beam steering in ultrasound phased-array imaging systems has been described. It is based or multiplexing samples of the input waveform among the taps of a tapped delay line, and in picking up the propagating acoustic samples at a later time via a read-out multiplexer-controlled tapping structure.

The system is capable of providing continuously variable delay of the signal envelope under simple digital control, while preserving the original carrier information.

Based on this property, an alternative approach to delay equalization of echoes from a phased-array has been proposed, consisting of two steps: first, the desired carrier phasing is introduced by mixing the echo with a phase-controlled coherent reference oscillator and selecting the upper frequency sideband; then, echo envelope delay is provided via the new analog sampled-data delay line.

An experimental realization of this processing configuration has been described, using a SAW device to implement the tapping structure. Experimental results on pulses at 1.75 MHz demonstrate that extremely fine trimming of the delay can be achieved, with good pulse fidelity preservation and a dynamic range of about 40 dB.

Independent control of carrier and envelope delay offers a new degree of flexibility. For instance, as an accurate echo phasing is the critical requirement for directionally selective interference of echoes, a phase increment more fine than envelope delay increment could be used. Moreover, phase equalization along the different channels of the array to compensate for nonuniformity of the array elements response could be simply introduced.

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