A CHARGE-COUPLED DEVICE FOR SONAR BEAM FORMING

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ABSTRACT This paper describes a charge-coupled device (CCD) that has been specially developed for sonar beam forming.

The principle of operation that is employed here for beam forming reduces the number of interconnections to a minimum. It consists of sampling and multiplexing the signals from a large number of hydrophones, the samples then being fed into a delay line. The signal is non-destructively read out at different points along the delay line so that, at a given time, the delays required to form a particular beam are available. An instant later, the signals available at the same points permit forming another beam, and so on. The device that has been developed consists of a transversal filter having 512 stages, of which only 39 coefficients are non-null. It permits forming 32 beams from a circular array of 32 hydrophones, each beam using 12 hydrophones.

I. INTRODUCTION

In sonar systems, as a general rule, the signals from the hydrophones of the antenna are spatially processed. The operations involve the weighted sums of delay signals.

Systems primarily based on cabled circuits use a very large number of circuits and interconnections. Systems primarily based on software need a large computing capacity because of the number and high frequency of the signals that must be processed.

However, the delays and weightings required for beam forming can be performed by CCD delay lines [1]. Several techniques can be used. The first (Figure 1) is to use one delay line per hydrophone, the signals thus being processed in parallel. The operation is repeated as many times as there are beams. This method requires many interconnections because the processing system cannot be integrated into a single unit. Another way (Figure 2), only suitable for circular arrays, is to multiplex the signals from the hydrophones and to process them in a single CCD that is analogous to a transversal filter. The beams are formed successively by the same circuit, and are supplied multiplexed.

The interconnections are reduced to a minimum, but the length of the delay line and the clock frequency may exceed the technological possibilities. By interpolating the samples of signals in the same circuit, the last two parameters can be minimized without increasing the difficulties of realization.

The CCD described in this paper uses the second technique.

II. PRINCIPLE OF OPERATION OF CCD BEAM FORMING

The beam-forming method described is applicable to a large bandwidth sonar having a circular array of N hydrophones, M hydrophones being used for each beam.

To form a beam, the signals x_i (t) from the M hydrophones are added after having been delayed τ_i and weighted A_i so as to compensate for the delays due to the geometry of the array, and to ensure the required beam pattern response as a function of the angle of incidence of a plane wave :

$$y(t) = \sum_{i=1}^{M} A_i x_i(t)\,\delta(t-\tau_i).$$

The signals from the N hydrophones are sampled at a frequency F_e, and then sent multiplexed in series into a CCD delay line of L stages that has M taps corresponding to the delays τ_i. The taps are connected to an adder. At a time t, the output signal of the adder is a sample of a beam, and a time t + Δt it is a sample of the next beam. After a time NΔt, all N beams have been formed. The CCD must have a number of stages L, and a sampling frequency F = NFe, such that :

$$L = \tau_{max} \cdot FeN,$$

where τ_{max} is the maximum geometrical delay that is to be compensated.

The delays τ_i are composed of a whole number of sampling periods. If this quantification is not to alter the beam pattern, the following condition must be satisfied :

$$Fe >> 2F_{max},$$

where F_{max} is the upper limit of the frequency band. Because of this requirement, L can reach very high values, which are technologically difficult to realize, and where the transfer inefficiency, ϵ, would be prohibitive at the frequencies concerned.

To reduce L, Fe must be reduced, the signals then being delayed by fractions of sampling periods to obtain a suitable beam pattern.

This can be done by interpolating the signal samples in an FIR (Finite-duration Impulse Response) filter. This type of filter is easily realized on CCD registers by adding 2p taps around the theoretical delay τ_i (Figure 3). From the 2p samples of signal x_i (nT), one calculates (Figure 4) :

$$X \left[(n+a)\ Te \right] = \sum_{j=0}^{j=2p-1} I_{aj} \times \left[(n+p-j)Te \right]$$

where : $a<1$

and $Te = \frac{1}{F_e}$.

The interpolation coefficients, I_{aj}, can be calculated in several different ways (Spline function, Lagrande polynomials, etc.).

The value of p depends on Fe/F_{max} and on constraints due to the beam pattern.

In this way, F_e/F_{max} and the number of stages, L, can be greatly reduced. The influence of ϵ is thus minimized

Because the sampled signals from the hydrophones are multiplexed in the delay line, the transfer inefficiency, ϵ, creates intermodulation between them, which results in a deviation of the beam axis and a change in the secondary lobes of the beam pattern.

Figure 5 shows the effect of interpolation at 5 kHz on the beam pattern of an array of 32 hydrophones, 12 hydrophones being used per beam, for F_e/F_{max} equal to 6 and 2.5.

Figure 6 shows the influence of ϵ on the beam pattern of the same array at 5 kHz.

This beam-forming circuit is thus similar to a transversal filter with Np taps. In addition, by modifying the tap weighting of the circuit, specific changes can be made to the basic beam pattern as a function of the frequency. This possibility is very interesting for large-bandwidth sonars.

III. DESCRIPTION

The device described below was designed for a circular antenna of 32 hydrophones, and was to give 32 beams, each beam using 12 hydrophones. The frequency F_e was chosen to be 6 F_{max} = 30 kHz. The CCD's clock frequency was thus to be 32 F_e = 960 kHz.

Interpolation of each delay was assured by 2p = 4 taps.

Because a maximum delay, τ_{max}, of 396 μs was required, the total number of stages was given by $L = \tau_{max}F + 3$ elements per interpolation = 380 + (3 x 32) = 476.

In actual fact, the CCD was realized with a total of 512 stages so that it could be used for other applications.

The beam-forming circuit is thus, practically speaking, a delay line with a large number of delay elements, which has several intermediate taps where the signal can be read non-destructively. To read and weight the signal with interpolation at the taps, a split-electrode design was used, so that the device has the structure of a CCD transversal filter.

The schematic diagram of this device is shown in Figure 7. An input stage permits biasing the signal samples so that they can be injected into the CCD. The samples are then delayed 512 times, and meet 39 taps where they are read out non-destructively because of the split electrode structure. Due to the large numbers of stages, a folded design was used, the arms of 128 stages being interconnected by diffusion zones [2]. A serial output permits checking the correct operation of the delay line. The split electrodes are connected to two charge-sensing circuits, which work by integrating the charge currents in low-value capacitors C− and C+.

After biasing, the voltages available at these capacitors control the injection into the two channels of a differential CCD stage [3]. The potential of floating electrode FG, which is proportional to the difference between the charges injected into the two channels, supplies the output signal after a sample-and-hold stage.

This device was made using N-channel technology with two levels of polycrystalline silicon, and TMOS depletion. Figure 8 is a photomicrograph of the circuit. The chip dimensions are 4.4 mm x 2.6 mm.

IV. EXPERIMENTAL RESULTS

Here we present the results of the first series of tests on the circuit. Three supply voltages and seven phase signals were required.

The impulse response (Figure 9) is a means of assessing its performance. The operating frequency is 1 MHz, and the output signal is available on the 500 ns-wide peaks of a square wave. Unit tap weightings are available at several points along the delay line, so the transfer efficiency is easily assessed.

For example, the 1st and 381st stages have unit tap weighting. So, the ratio of the signal amplitudes measured at these two points gives directly the transfer inefficiency (these are two transfers per stage) :

$$\epsilon = \frac{1}{2(N-P)} \ln \frac{An}{AP} ,$$

where P = 1 and N = 381.

The first batches of these devices were made using surface transfer technology, which gave measured values of ϵ that varied from 2.5×10^{-4} to 4×10^{-4}. These values are too high for beam-focusing applications, as they correspond to excessive deflection of the beam axis (Figure 6). For this reason, buried-channel technology was used to reduce ϵ to 10^{-4} or less.

To evaluate the performance of the whole device, it was operated as a matched filter. A PROM was then programmed to generate the time-inverted impulse response, in three levels (0, +1, −1), of the CCD.

When fed into the CCD, this signal should give an output signal with a correlation peak whose amplitude with respect to the secondary lobes can be used to characterize the overall performance of the device. In addition, the amplitude of this peak is close to the maximum level for normal beam-focusing operation, so it can be used to estimate dynamic range.

Figure 20 shows this operating mode. The correlation peak amplitude is 7 dB above the first lateral lobe, instead of the theoretical value of 7.4 dB.

The dynamic range is estimated from the ratio between the maximum signal and the noise measured in an 8-kHz bandwidth. First results give a figure of better than 60 dB.

V. CONCLUSION

These first results prove the feasibility of forming sonar beams by using CCD's and applying the principle of multiplexed hydrophones with interpolation.

More complete results will be obtained when the device is used with a simulated sonar antenna.

REFERENCES

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[2] C.R. Hewes "A self contained 800 stage CCD transversal filter" in proceedings of international conference on the application of CCD San Diego, CA ; 29-31 Oct. 75.

[3] J.L. Berger, J.L. Coutures "A charge coupled differential stage" in proceedings of 4th European solid state circuits conference – Amsterdam 18-21 Sept. 78.

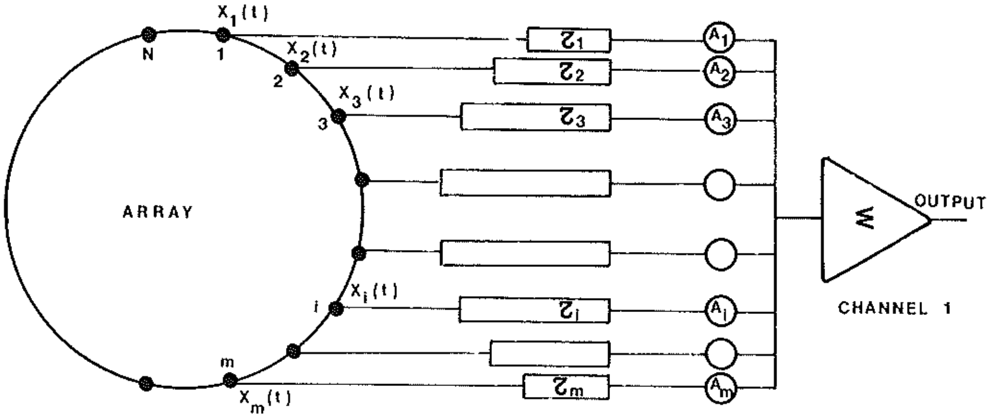


FIG.1 PARALLEL BEAMFORMING

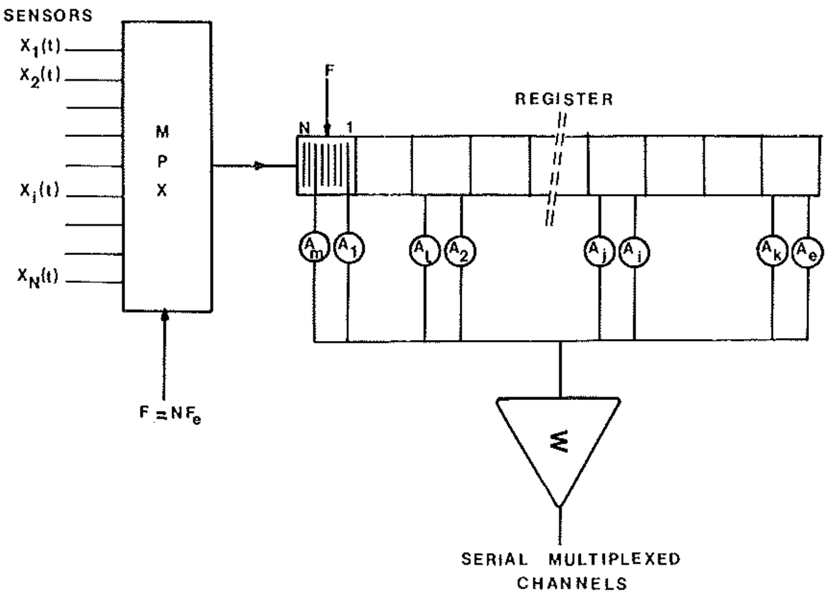
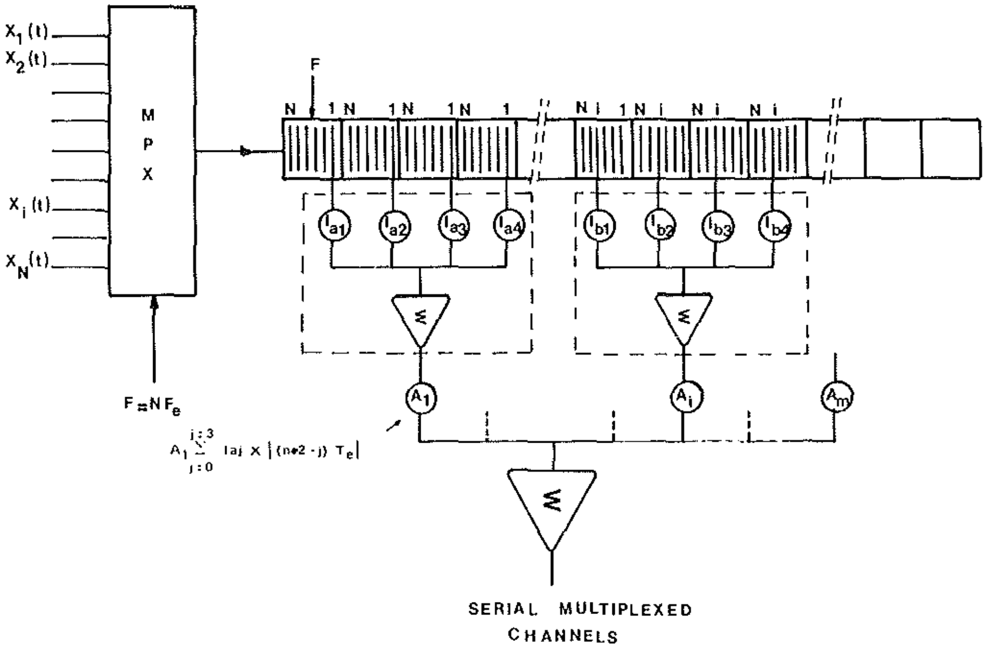
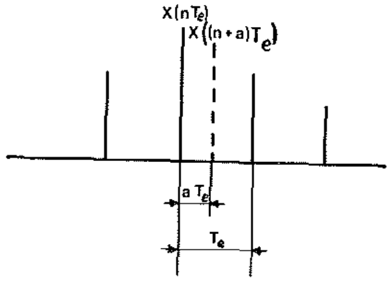


FIG. 2 MULTIPLEXED BEAMFORMING



$$A_1 \sum_{j=0}^{j=3} I_{aj}\, X\left|(n+2-j)\,T_e\right|$$

FIG.3 MULTIPLEXED BEAMFORMING WITH INTERPOLATION



$$X\left|(n+a)\,T_e\right| = \sum_{j=0}^{j=2p-1} I_{aj}\, X\left|(n+p-j)\,T_e\right|$$

FIG. 4 INTERPOLATION METHOD

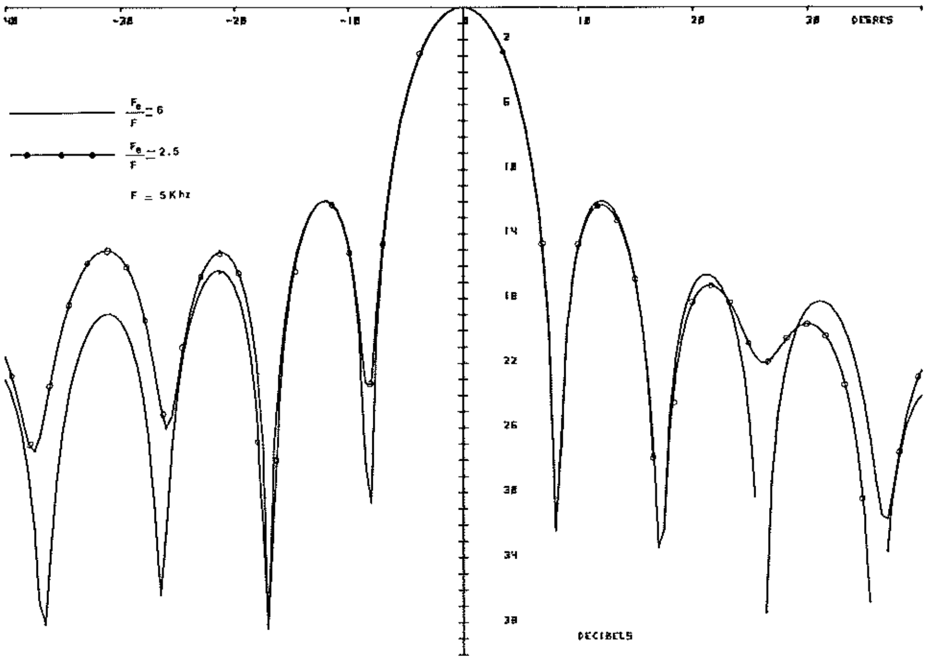


FIG.5 BEHAVIOUR OF BEAM PATTERN WITH SAMPLING FREQUENCY

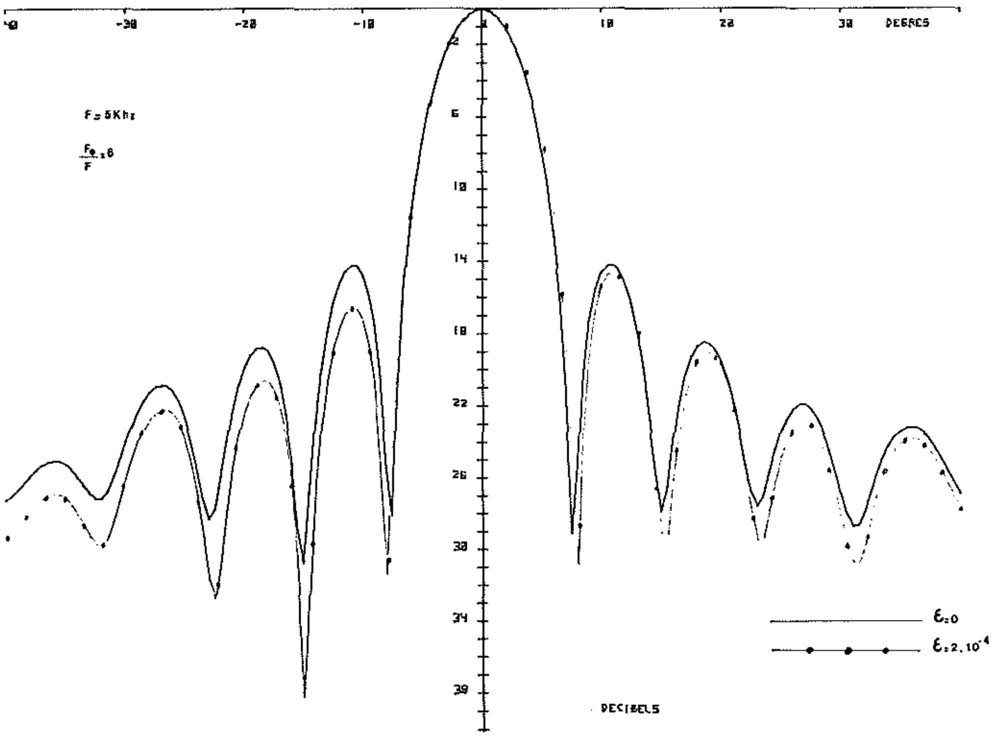


FIG 6 BEHAVIOUR OF BEAM PATTERN WITH TRANSFER EFFIENCY ε

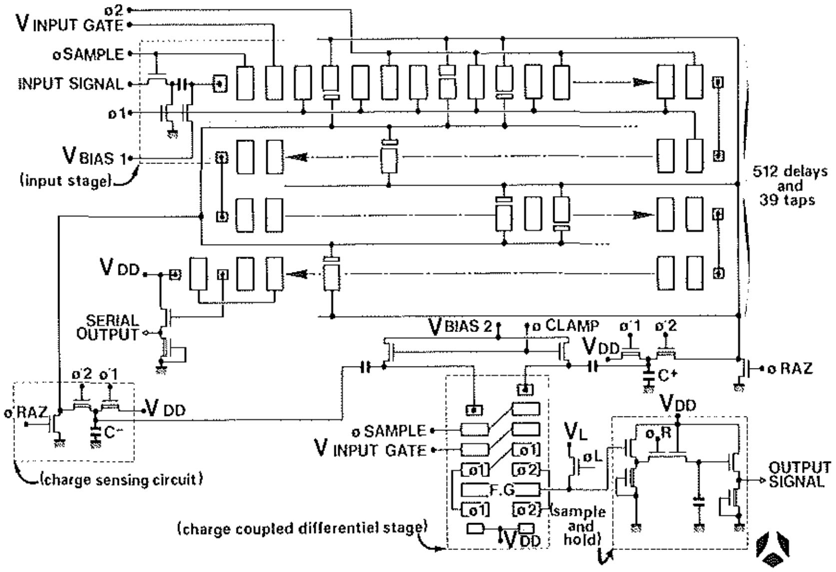


fig.7 DESIGN OF CCD FOR SONAR BEAM FORMING THOMSON-CSF

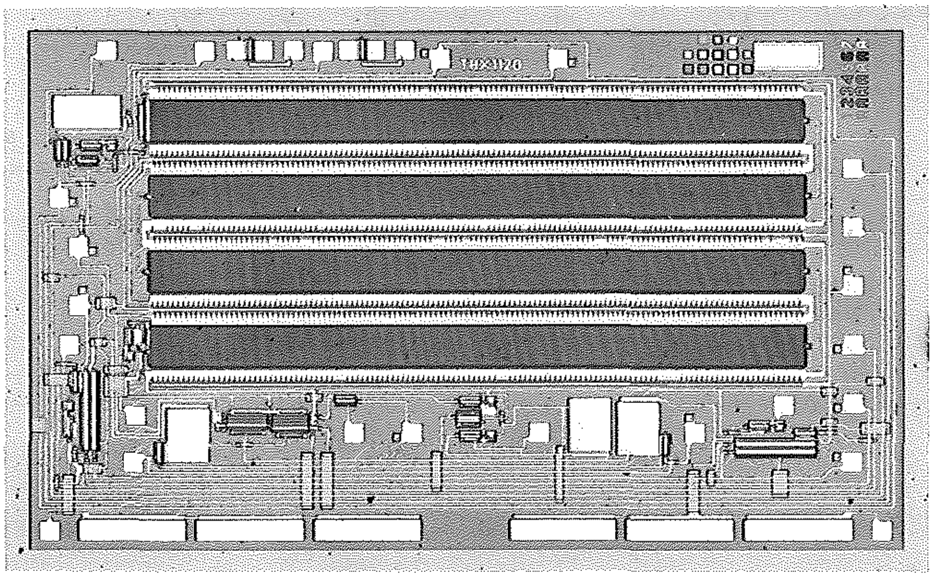


fig. 8 : PHOTOMICROGRAPH OF CCD FOR SONAR BEAM FORMING

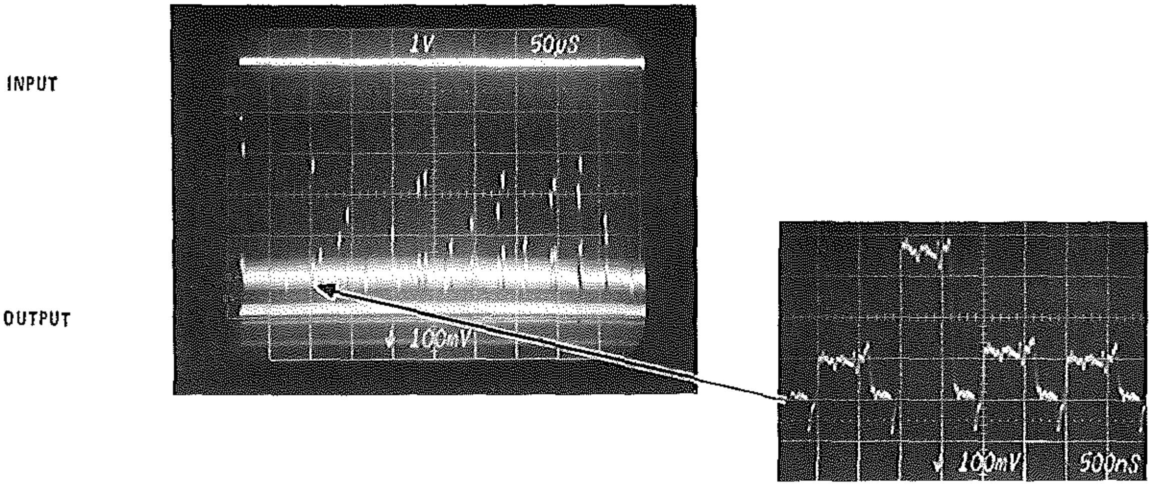


fig. 9 : IMPULSE RESPONSE OF CCD FOR SONAR BEAM FORMING

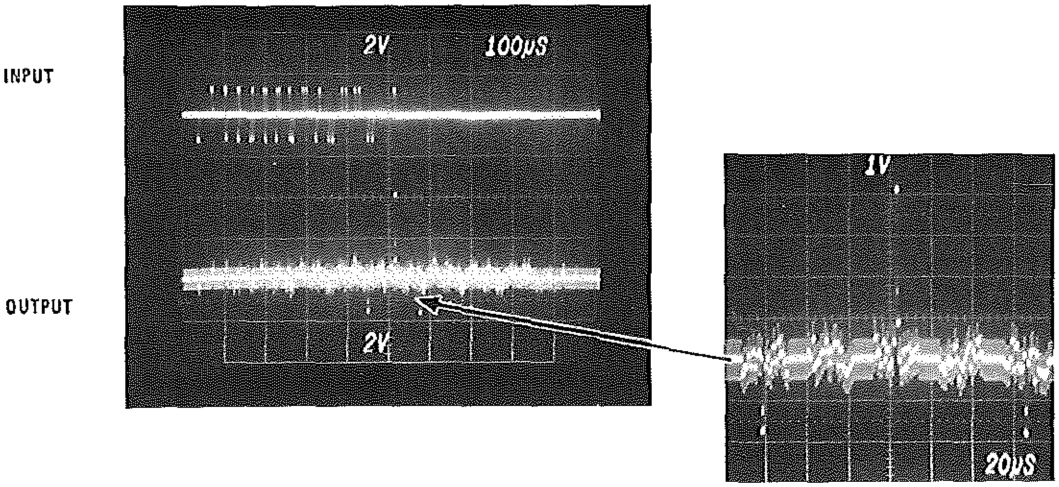


fig. 10 : AUTOCORRELATED RESPONSE TO A THREE LEVELS
ADAPTATED INPUT