A NOVEL CCD FOR FAST TIME DELAY WITHIN-PULSE SECTOR SCANNING SONARS

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Introduction

A Time-Delay-and-Integrate CCD (TDI) is a multi-input device which inserts time delays between all pairs of adjacent input signals and progressively sums them to give a single output. If the inputs are fed from a linear array of equally spaced transducers the TDI can thus provide a time delay taper which gives coherent summation of the transducer outputs for a wavefront which is incident on the array at some angle θ_p which is other than 0°. The delays can be varied by a change in the clocking frequency and in this way the direction of the beam, θ_p, may be changed. It will be shown however that beam distortions arise with a conventional TDI when the beam is scanned at the high speeds required by a typical within-pulse sector scanning sonar. It is then shown that a new CCD structure named a non-uniform TDI (or NUTDI) can avoid these beam distortions. In this way a new and inexpensive technique is available for the beam scanning signal processor required for a within-pulse sector scanning sonar.

Conventional TDI Scanning Beam Distortions

Fig. 1 is a schematic of a conventional TDI. It contains an equal number of delay stages, α, between adjacent inputs and the actual delay between inputs, τ_p, is the product of α and the clock period τ. Fig. 2 shows how the device gives cophasal summation for a wavefront incident on an array at an angle θ_p if the time delay between the elements in the water, τ_ω, equals the time delay τ_p between the TDI inputs.

A beam is thus formed and, by varying the clock frequency, the value of θ_p will change and the beam is scanned. However a problem occurs when the beam is scanned at the very fast rate of one sector per pulse duration. It now becomes necessary for the clock periods to change significantly from one period to the next. When this happens, different time delays τ_1, τ_2, τ_3 etc are introduced between the various pairs of adjacent taps as shown in Fig.3. The effect is that cophasal summation occurs for an incident wavefront which is curved rather than linear. The differences in time between the curved wavefront and the linear wavefront are proportional to the distances BB',CC', DD', EE' etc as shown in Fig. 3 and will be referred to as scanning time errors.

In order to ease the interpretation of the final display, it is desirable that the beam should scan at a constant speed across the sector and it follows that the clock period should change linearly with time (Fig. 4) i.e. $\tau=\tau_1+\alpha t$ when r is a constant. For this law the scanning time errors are analysed in detail in Ref. 2.

A very informative way of monitoring the scanning time errors is to display the resulting distortions when the scanning beam pattern is computed. The computer plots presented in this paper are for the following sonar specifications:- 32 channel 500 KHz sonar with a 1° beam swept over a 30° sector. To scan over a sector centred on the boresight, the TDI is preceded by an oppositely-oriented Time Wedge Device (Fig. 5) which is a set of parallel serial-in/serial-out CCD delay lines with an incrementally varying number of delay stages and clocked at a constant period to provide a fixed electronic pre-deflection. Other simulation parameters are given in Fig. 5.

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The beam distortions observed are (a) a reduced and shifted peak response, (b) high side-lobes and (c) poor nulls. In Fig. 6 graphs G1, G2 and G3 demonstrate the effect of increasing scanning rate. The different extents of beam distortions for different target bearings are shown by G2 and G4. From such simulation studies, it can be concluded that severe beam distortions limit the maximum scanning rate to around 800 Hz, which has also been confirmed experimentally. This falls far short of the objective of 8 kHz presently employed in typical high resolution within-pulse sector scanning sonars using conventional scanning techniques

Fast Scanning with NUTDI Device

A conventional TDI is fabricated with an equal number of delay stages between neighbouring inputs and with all the inputs sampled simultaneously on the same phase. For a 3 phase CCD, every delay stage consists of three electrodes each clocked on a different phase. The key features of the new device structure are as follows

a) to have a non-uniform variation in the number of delay stages between adjacent inputs

b) to permit fractional numbers of delay stages between adjacent inputs by exploiting the 3 phase clocking and entering the device on different phase electrodes when advantageous.

The non-uniform variation in the number of delay stages between adjacent inputs effectively compensates for the scanning time errors imposed by the rapidly changing period. To a good approximation the scanning time errors are cancelled and cophasal summation occurs for a phase incident wavefront in spite of the high scanning rate.

The new device is known as a non-uniform TDI or NUTDI. Other approaches for overcoming the beam distortions present with a conventional TDI have been investigated but they have not proved successful.

It is possible to calculate the number of delay stages, X_n, from the nth input tap to the device output which gives perfect correction of the scanning time errors. In general this number will not be an integer. Analysis shows the number to be given by the formula

$$X_n = \frac{\log \left[\frac{\gamma}{\gamma - \alpha r(n-1)} \right]}{\log \gamma} \qquad (1)$$

where α is now the minimum number of delay stages between any two taps. This result is valid only for a linear period clock. It will be noted that the values of X_n are independent of the scan angle θ_p. This fact is of considerable importance as it signifies that the new device corrects the beam distortions at all angles throughout the scanned sector. This important feature occurs only with a linear period clock.

Using the simulation parameters given in Fig. 5, Fig. 7 shows the values of X_n for three cases- a uniform TDI, an ideal NUTDI as predicted from Eq. 2, and a NUTDI in which X_n has been approximated to the nearest integer. If it is chosen to exploit the option of entering the device on any one of three phases, the value of X_n may be approximated to the nearest one third and this gives rise to a fourth set of values as shown.

Computed beam patterns are shown in Fig.6. Graph G5 applies when X_n is approximated to the nearest integer and is for $\theta = 0^o$ and 8 kHz scanning rate.

The relatively large side lobes are caused by quantization time errors due to approximating X_n to the nearest integer. Since the quantization errors are proportional to the instantaneous clock period, the beam pattern deteriorates towards that part of the sector corresponding to the large clock periods. Graph G6 shows the improvement obtained when X_n is approximated to the nearest 1/3. A still further improvement is shown in graphs G7 and G8 which apply to $\theta = 0^o$ and $\theta = 10^o$ respectively. In these, residual quantization time errors are removed by introducing small fixed compensating phase shifts on the 32 inputs. Because the analysis shows the exact value of X_n to be independent of θ_p the quality of the beam pattern remains the same for all target bearings. The effect of applying Dolph-Chebyshev amplitude shading to the inputs is shown in Fig. 8.

At the start of each scan, a number of clock periods equal to the total number of delay stages in the device must elapse before the first sample from the first input emerges at the output. During this 'build-up' time, the output samples are not fully constituted from valid inputs, a fraction of which are from the previous scan. The 'build-up' time can be observed on the computer plots and is an inherent feature of time delay scanning.

Device Fabrication and Performance

Both the NUTDI (Fig. 9) and the Time Wedge device (Fig. 10) are fabricated using three phase polysilicon n-channel technology. Phase-referred "fill-and-spill" inputs[3] are used in both devices. Charge detection is by means of a floating diffusion with reset and output buffer transistors as well as on-chip sample-and-hold gates. The NUTDI has 32 input taps which are non-uniformly distributed as detailed in Fig. 7. The use of phase-referred inputs enables any one of the three clock phases to sample each input tap and thus provides a convenient means of obtaining "fractional delays". It is designed for a through gain of 2 (i.e. 1 volt input signals on all inputs give 2 volts output swing) and a maximum clock frequency of 5 MHz. Preliminary results using a linear period clock sweeping from 0.2µs to 1.3µs in a scan period of 125µs demonstrate fast scanning without any undue beam distortions. The Time Wedge device consists of 32 separate serial-in/serial-out delay lines fabricated on the same chip and with a common clock drive. The number of delay stages in the parallel delay lines varies from 2 to 64 in uniform increments of two. The Wedge has performance characteristics similar to the NUTDI.

Conclusion

It has been demonstrated that though conventional TDI devices can be used for beamforming purposes, they are not suitable for fast beam scanning applications. A new non-uniform TDI (NUTDI) device structure, specially configured for fast scanning, is described. Work is currently proceeding to incorporate the NUTDI and the Time Wedge device in a prototype within-pulse sector scanning sonar. It is envisaged that the present work will be extended to two-dimensional scanning using an NxN transducer matrix array where the significant system simplicity and compactness resulting from the use of such devices will be particularly advantageous.

References

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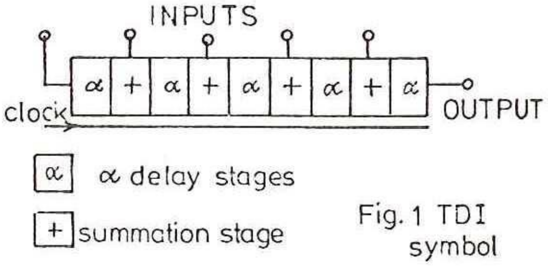


Fig. 1 TDI symbol

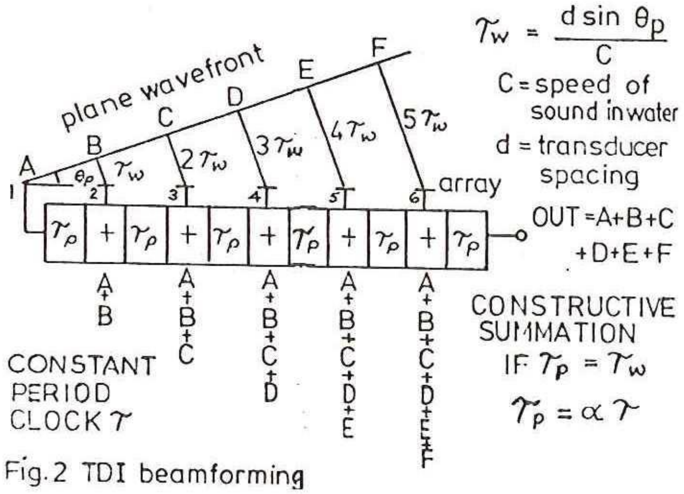


Fig. 2 TDI beamforming

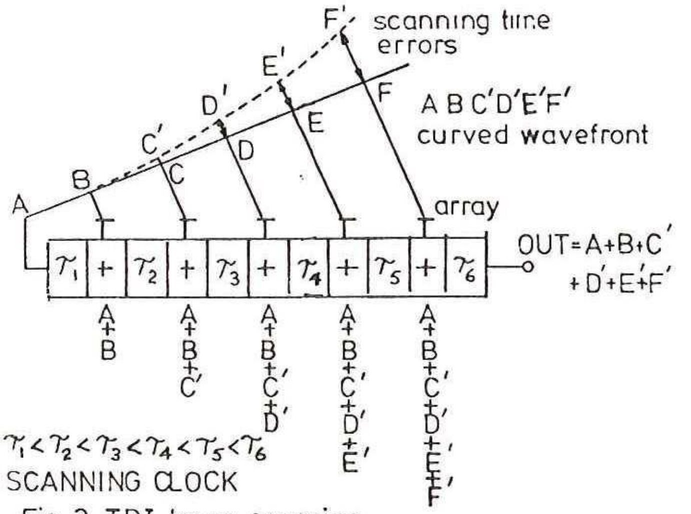


Fig. 3 TDI beam scanning

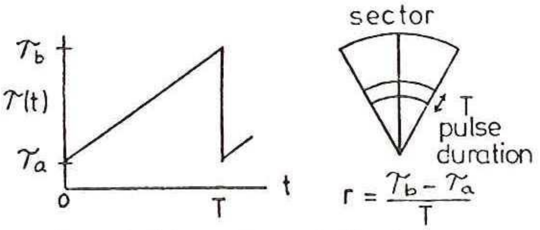


Fig. 4 Linear Period Clock

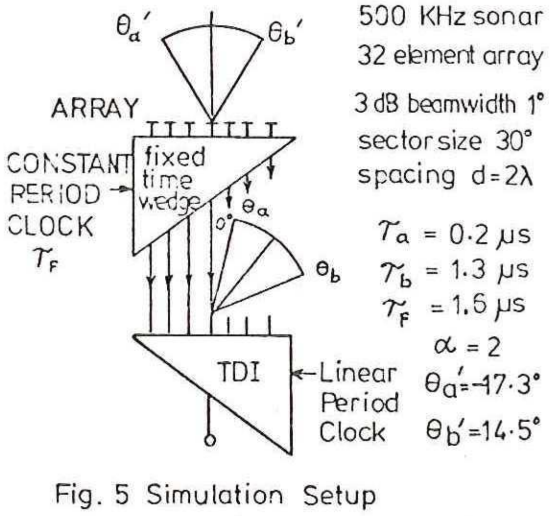
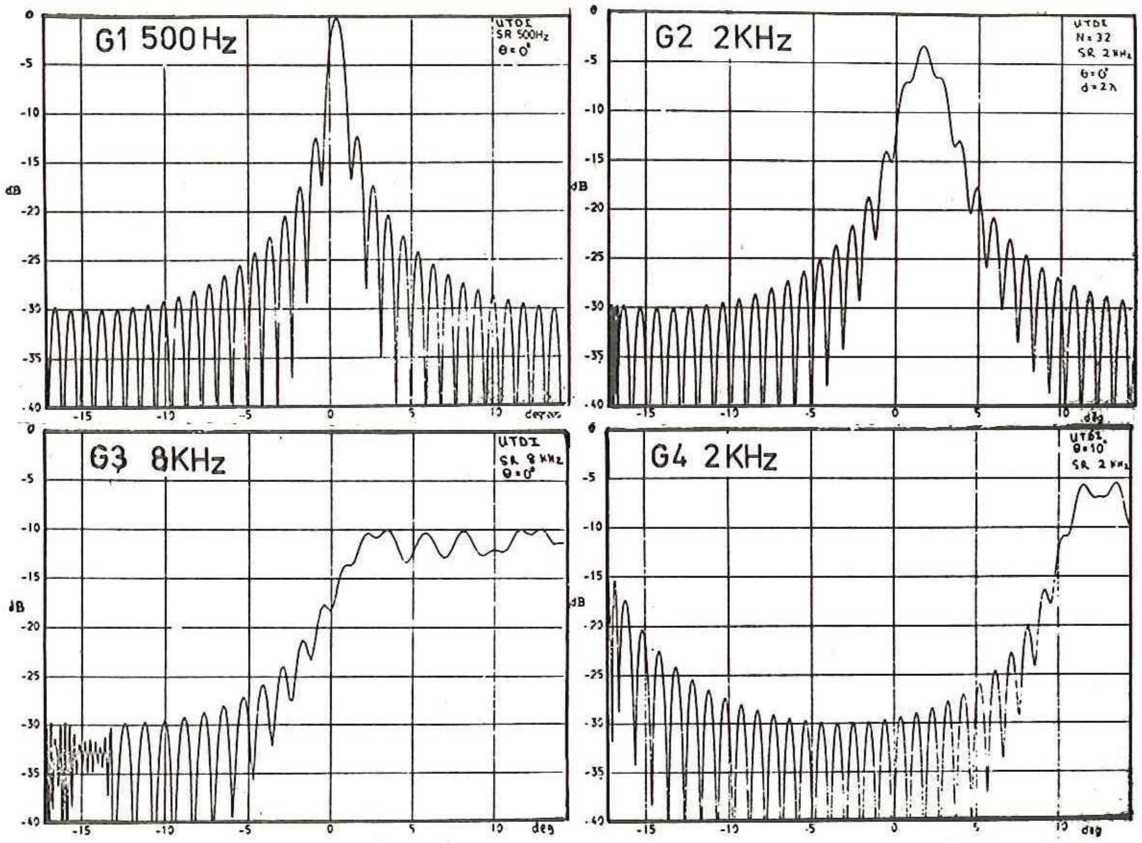


Fig. 5 Simulation Setup



↑ TDI G1, G2, G3 : Effect of increasing scanning rate : 500 Hz, 2 KHz, 8 KHz
G2, G4 : Different extents of distortions for different target bearings
G5 to G8 : NUTDI at a scanning rate of 8 KHz
↓ NUTDI G5 : common input phase G6 : individual input phase
G7 : with phase compensation θ=0° G8 : target bearing at ≃ 10°

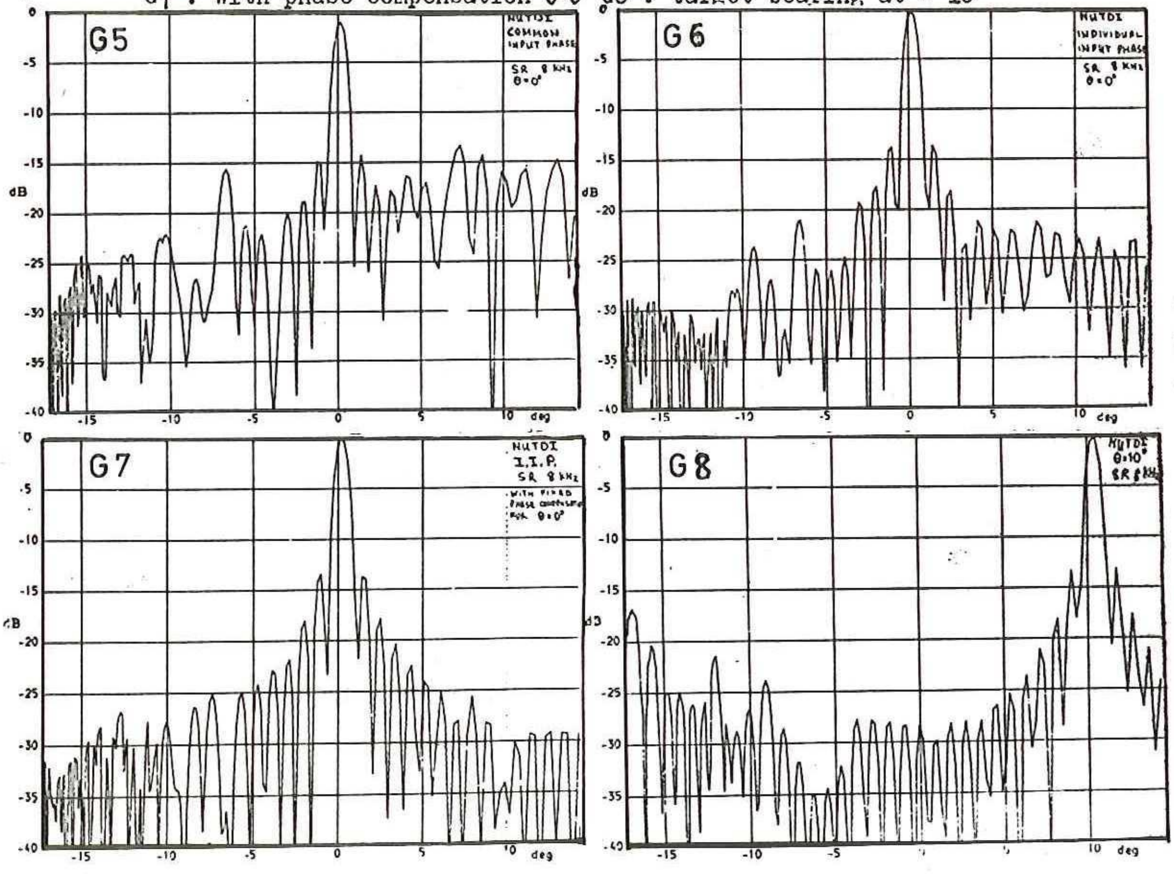
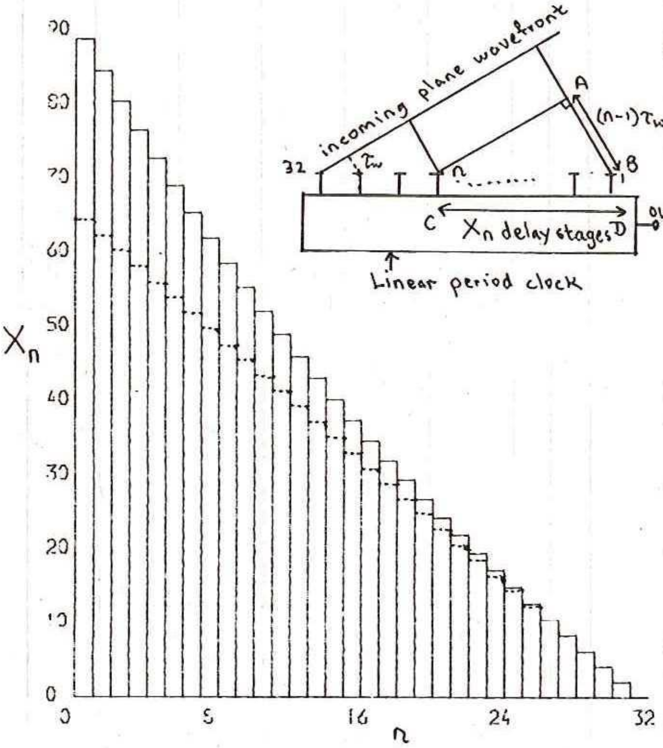


Fig. 6 computer simulation results



UTDI (---)	NUTDI (—) XN	INT (XN)	IXN	FXN
62	88.94	89	89	0
60	84.58	85	84	2
58	80.48	80	80	1
56	76.52	77	76	2
54	72.69	73	72	2
52	68.99	69	69	0
50	65.40	65	65	1
48	61.92	62	62	0
46	58.55	59	58	2
44	55.27	55	55	1
42	52.08	52	52	0
40	48.98	49	49	0
38	45.96	46	46	0
36	43.02	43	43	0
34	40.15	40	40	0
32	37.36	37	37	1
30	34.63	35	34	2
28	31.96	32	32	0
26	29.36	29	29	1
24	26.81	27	26	2
22	24.32	24	24	1
20	21.88	22	22	0
18	19.50	19	19	1
16	17.16	17	17	0
14	14.87	15	15	0
12	12.62	13	12	2
10	10.42	10	10	1
8	8.26	8	8	1
6	6.14	6	6	0
4	4.05	4	4	0
2	2.01	2	2	0
0	0.00	0	0	0

Fig. 7 Device Structures : X_n vs. n for TDI and NUTDI devices

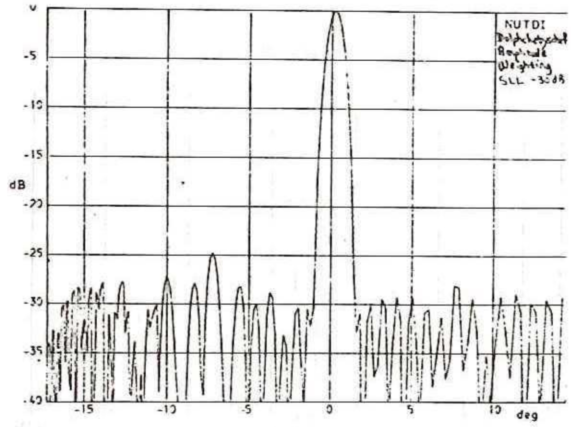


Fig. 8 With Dolphchebyschef amplitude weightings

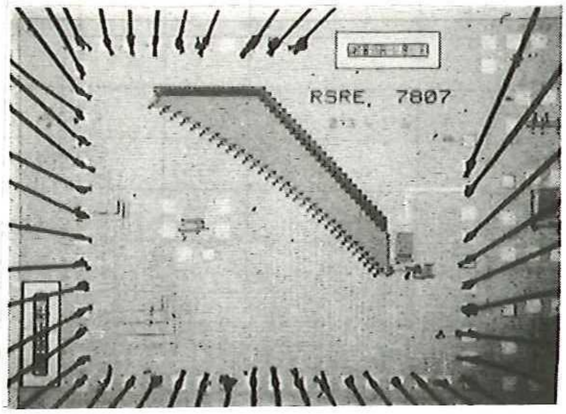


Fig. 9 NUTDI Device

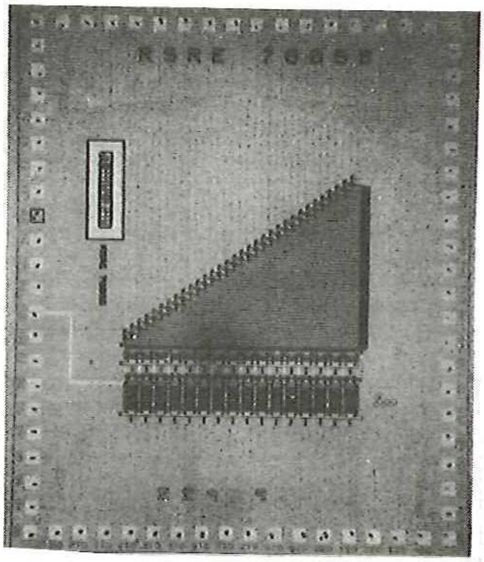


Fig. 10 Time Wedge Device