A Parallel Analog Fourier Transformer for Acoustic Underwater Holography and Sector Scanning Sonar by C.J.M.Wolff.[x]

1. INTRODUCTION

Well known techniques in underwater acoustic imaging are sonar, acoustical holography and imaging by means of an acoustic camera. The subject dealt with in this article concerns the two former techniques. Speaking in terms of sonar, a novel technique of realizing sector scanning will be discussed. However in terms of acoustical holography the technique should be refered to as Fourier transformation.

Several techniques of realizing a Fourier transform have been discussed in the literature. These are reconstruction of the image by means of optical interference (3)(4), or digital calculation by means of FFT (4)(5). Each of these techniques has its specific charcteristics, which may be disadvantageous in some particular situations. In marine applications the main disadvantage of optical reconstruction is the problem of time delay between making the hologram and reconstructing the image. The disadvantage of FFT is that in some applications it is not fast enough to process the available information without skipping part of it.

The "Within Pulse Scanning Sonar" or "Sector Scanning Sonars" apply electronic beam forming based on phase shifting of the incoming signals. Essentially this process is a Fourier transformation as well. One of the sector scanning techniques described in the literature is the modulation scanning technique by Voglis (1) (2). The instrumentation presented in this article is based upon this technique. Realization of a modulation scanner, however, is characterized by operation on the acoustic carrier frequency, a great number of tuned filters and trimmed phase shifting networks. In the novel technique, on the contrary, the acoustic carrier frequency is immediately eliminated, no phase shifting networks occur and the filters are only of the low pass type. It is our belief that these modifications make a sector scanner easier to manufacture. In the following the apparatus will be refered to as Parallel Analog Fourier Transformer or PAFT.

* Technisch Physische Dienst - TNO - TH, Delft, Holland.

2. PREPARATION OF THE HYDROPHONE SIGNALS BY QUADRATURE DETECTION

The signals received by the hydrophones in the array can be understood as both amplitude and phase modulated carriers.

$$h_n(t) = A_n(t) \,.\cos \{\omega_o t + \phi_n(t)\} \qquad \text{I}$$

In the case of a single CW source $A_n(t)$ and $\phi_n(t)$ reduce to constants A_n and ϕ_n. For ease of the discussion this situation will be assumed applicable and in practice the duration of the transmitted pulses will be chosen long enough to approach it.

Handbooks about acoustical holography show that the image can be reconstructed by Fourier transformation of the aperture function, described by the amplitudes and phase of the hydrophone signals. The carrier frequency only acts as a factor and therefore may be eliminated. This is being done by quadrature detection. In this manner the information of the hydrophone signals f_n is represented by the pair

$$\begin{aligned} Re(f_n) &= A_n \cos \phi_n \\ Im(f_n) &= A_n \sin \phi_n \end{aligned} \qquad \text{or } f_n = A_n e^{i\phi_n} \qquad \text{II}$$

3. THE PRINCIPLE OF THE ANALOG FOURIER TRANSFORMER

The Fourier transform of a function $f(x)$, defined on $(-x_o, x_o)$ is denoted by

$$b(\psi) = \int_{-x_o}^{x_o} f(x)e^{-ix\psi}dx \qquad \text{III}$$

If $f(x)$ has been sampled, as is the case with acoustic receiving arrays, the formula changes into

$$b(\psi) = \sum_{-N}^{+N} f_n e^{-in\psi} \qquad \text{IV}$$

where f_n denotes the complex value of the function $f(x)$ in the point number n, 2N+1 is the total number of points, and $b(\psi)$ represents the Fourier transform of f. In general the number of points may be both odd and even, but in order to simplify the discussion it is assumed to be odd.

In fig. 1 the transformation process is represented grafically, and essentially the Analog Fourier Transformer is only a realization of this scheme. It shows 2N auxiliary signals $e^{-in\psi}$, 2N complex multiplying blocks and one adding block.

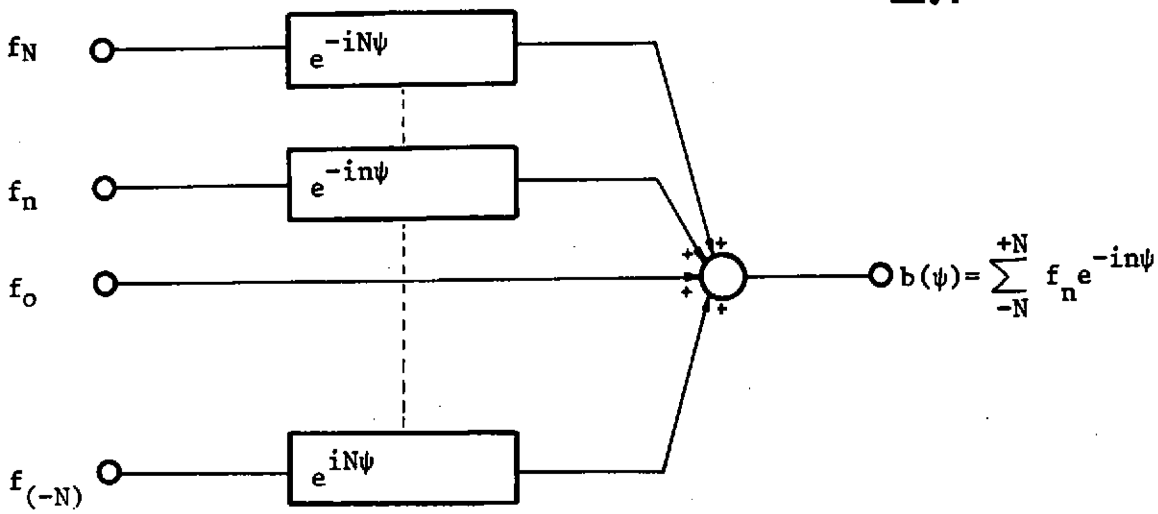

fig. 1 Schematic of the Fourier transformation process.

Multiplication of the complex signal $Ae^{i\phi}$ with the complex auxiliary function $e^{-i\psi}$ can be realized according to the definition, using four multipliers:

$$Ae^{i\phi}.e^{-i\psi} = A\cos\phi.\cos\psi + A\sin\phi.\sin\psi - iA\cos\phi.\sin\psi + iA\sin\phi.\cos\psi \qquad V$$

Fig.2 shows the schematic of such a complex multiplication.

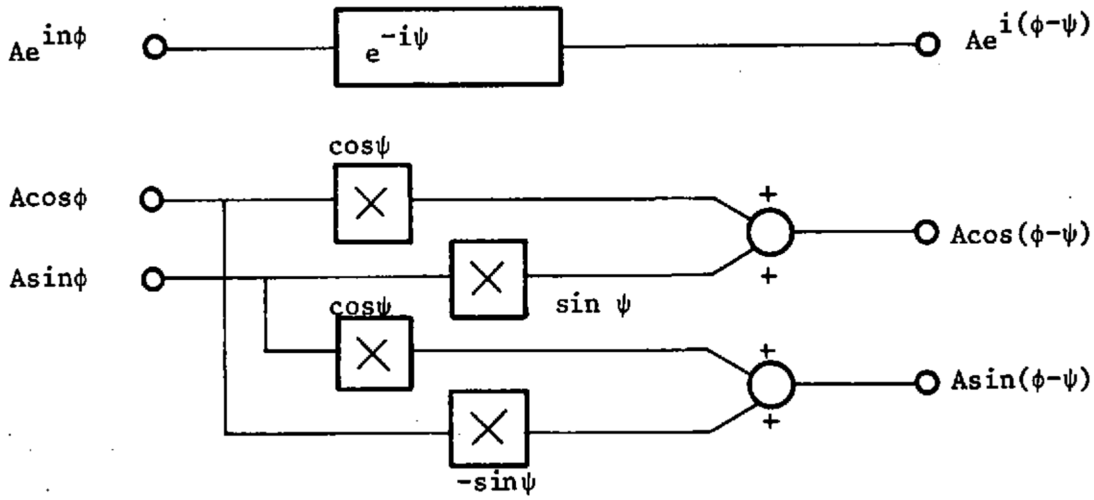

fig. 2 Addition of an auxiliary phase ψ to a complex variable.

In order to calculate $b(\psi)$ for all values of ψ, ψ is chosen linearly increasing with time: $\psi = \alpha t$. And consequently the result of the transformation process becomes periodic with a repetition frequency $\alpha/2\pi$. The auxiliary functions become $e^{in\alpha t}$ or $\cos(n\alpha t)$ and $\sin(n\alpha t)$, which can be generated easily for all n.

Applying the schematic of fig. 2 for all signals it would be possible in principle, to realize a Parallel Fourier transformer. It is however rather discouraging to see that for transforming say 81 points 320 analog multipliers and 40 synchronous frequencies would be required. But it appears to be possible to reduce the numbers of multipliers and auxiliary frequencies drastically. In general the number of multipliers can be halved. The number of frequencies can be shown to be proportional to the log of the number of points (2N+1). If 2N+1 is equal to 81, four frequencies will be sufficient. In his articles about Modulation Scanning, Voglis (2) indicates how the reduction can be realized. We shall apply now the same techniques.

First, the four multipliers of fig. 2 can be used to perform two multiplications at the same time. And for transforming three complex numbers the same number of multipliers can be used, as can be shown by inspection:

$$b_3(\alpha t) = \sum_{-1}^{+1} (R_n + iI_n).e^{-in\alpha t} = (R_1 + R_{-1}).\cos\alpha t + (I_1 - I_{-1}).\sin\alpha t + $$
$$+ R_o + i(-R_1 + R_{-1}).\sin\alpha t + i(I_1 + I_{-1}).\cos\alpha t + iI_o \qquad \text{VI}$$

The corresponding scheme is shown in fig.3. Similar combinations could be made of 2, 4, 5 points etc.

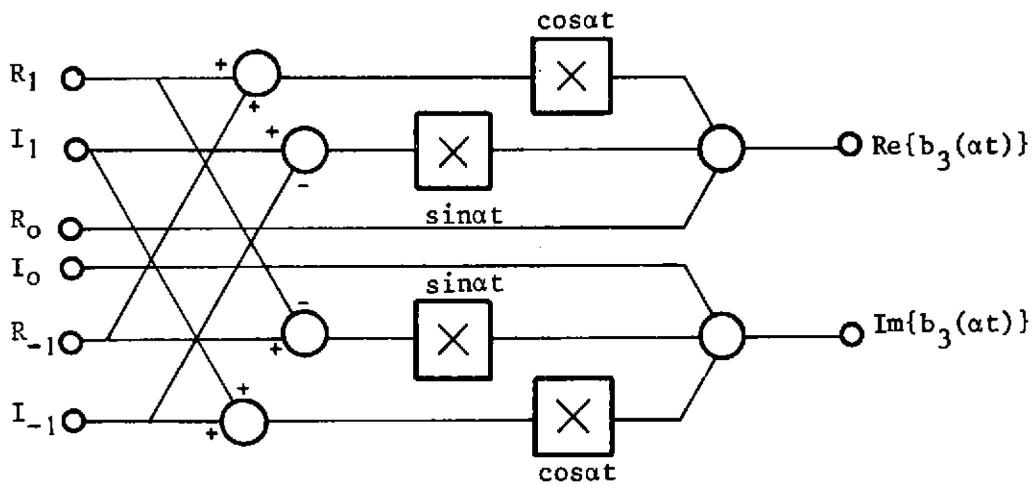

fig.3 The basic Fourier transformation unit.

Secondly, in order to reduce the number of auxiliary frequencies, the sets of three can be combined in a similar way. This results in the scheme presented in fig. 4 where 9 complex figures are Fourier transformed in two stages. The auxiliary frequency of the second stage is three times the basic repetition frequency: $3\alpha t$. In a similar way 27 points can be transformed in three stages, 81 points in four, etc.

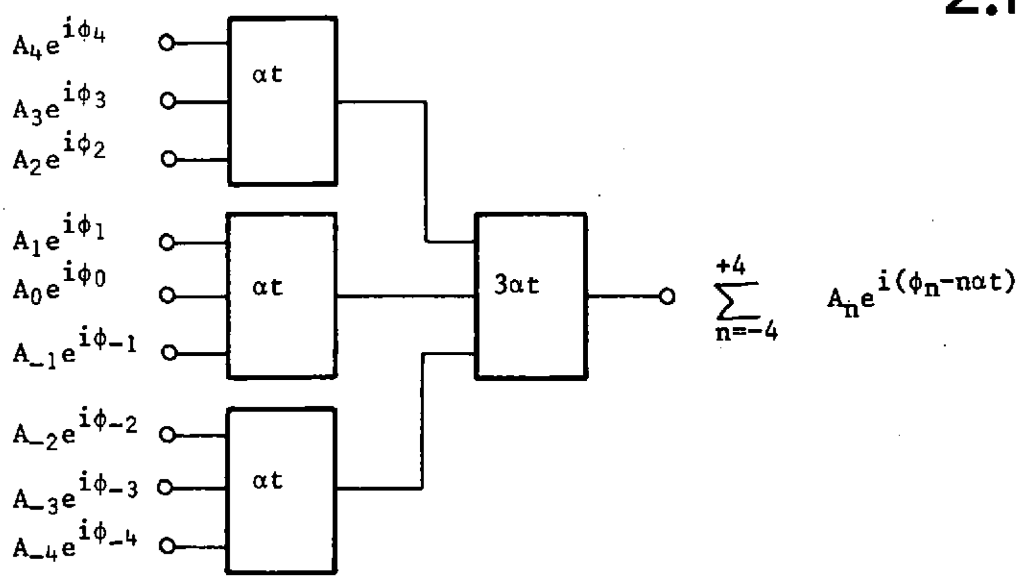

fig. 4 combination of four basic units to one larger one.

4. REALIZATION OF A 27 POINTS TRANSFORMER

At our Institute a 27 points Analog Fourier Transformer consisting of three stages has been built. The repetition frequency of the transformation is 30 kHz, and consequently the bandwidth of the output signal is 30 x 27 = 810 kHz theoretically. In practice both real and imaginary outputs have a bandwidth of 0 to 405 kHz. In order to save components, the 27 quadrature detectors can be combined with the first transformation stages according to schemes of fig. 8a or fig. 8b. We prefered to use the circuit of fig. 8a, because it is realiazable using multipliers in the switching mode, while the circuit of fig. 8b requires full multipliers.

It should be noted that the output of the Fourier transformer is a complex function and therefore it consists of a real and imaginary part. Before displaying the signals by intensity modulation of a CRT, the two complex outputs have to be combined. In fact one should calculate the modulus of the complex output signal. But for the purpose of making images we approximated the modulus of the vector by simply summing the moduli of both components:

$$\sqrt{R^2 + I^2} \simeq |R| + |I| \qquad \text{VII}$$

The subsequent error varies between 0 and 40% or ± 20% as can be seen in fig. 5.

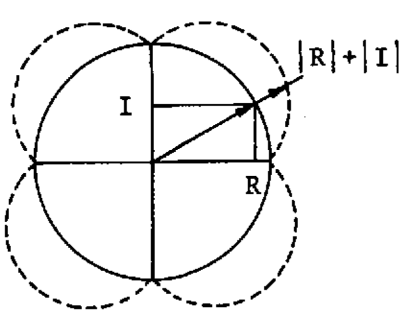

fig.5 Approximation of $\sqrt{R^2+I^2}$ by $|R|+|I|$

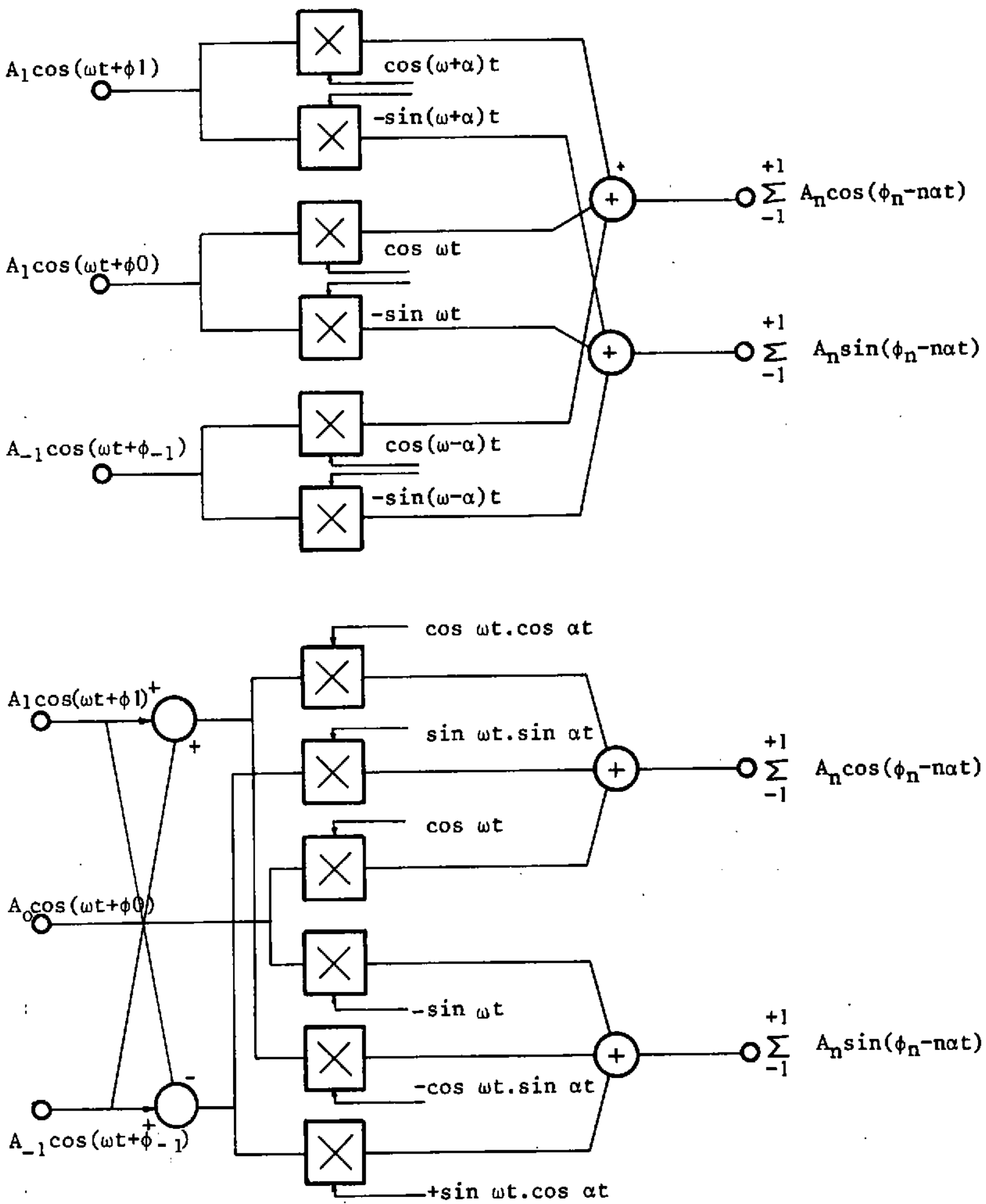

fig.8 Two methods of combining the quadrature detection and the first Fourier transformation stage.

a) Top: method with switching multipliers

b) Bottom: method with full multipliers.

5. RESULTS

The 27 point Fourier transformer has been tested at several temperatures. It could be expected that the balance of the multipliers is sensitive to changes in temperature. This is important since the zero frequency as well as the auxiliary frequencies are in the output band. Between 0 - $40^{o}C$ environmental temperature drift resulted in 1.5 mV unwanted signal at the output but no distrortion could be noted. The output "noise" level is also of the order of 1.5 mV.

The dynamic range of the output of the Fourier transformer appeared to be 60 dB and because of variable gain in the first stage mixers the input dynamic range is greater : 74 dB.

The 27 points Analog Fourier Transformer requires 70 multipliers. So the technique still could be expensive if it was not possible to use simple multipliers. In fact rather cheap modulators have been applied. The 54 modulators in the first stage were common mixers (Signetics N5596) and the 16 multipliers in the second and third stages were little more expensive ones (SGS-L025).

Some final remarks

- No coils or transformers are applied in the Analòg Fourier Transformer. Only integrated circuits and active low pass filters are used. So in principle the technique can be realized in modern production methods.

- The processing of the received signals is independent of the used acoustic frequency.

- Integration time can be as long as the duration of the acoustic pulse provided. Integration is performed before the first transformation stage. Or in the scheme of fig.8 the integration is performed as low pass filtering in the first stage.

- The main disadvantage of the PAFT is that the auxiliary frequencies are in the output band. This requires ahigh degree of balance of the multipliers and compensation of leak through.

- Using the circuits of fig.2 showing how to realize electrically controlled phase shifting, it is possible to perform variable focussing as well. This could be achieved in the cheapest way if in the last stage of the transformation, the centre signal is fed through one phase shifting circuit like fig.2.

like fig. 2. In that case the minimum image forming range is decreased approximately by a factor 3.

- Also 2-dimensional images can be formed using the same analog transformation technique. For example a 9 x 9 element square hydrophone and a 81 point transformer will be sufficient to realize a TV-like image. Probably in that case a larger array is prefered and the image repetition frequency could be lowered to some 50 in lieu of 10.000 Hz.

6. LITERATURE

1. G.M. Voglis - A General Treatment of Modulation Scanning as Applied to Acoustic Linear Arrays - Part 1 and Part 2. Ultrasonics vol.9 (july and october 1971).

2. G.M. Voglis - Design Features of Advanced Scanning Sonars Based on Modulation Scanning - Part 1 and Part 2. Ultrasonics Vol.10 (january and may 1972).

3. R. Diehl - Holographic Processing of Acoustic Data Obtained by a Linnear Array. Signal Processing, A Nato advanced Study Institute, edited by Griffiths, Stocklin and Van Schooneveld, Academic Press(1973)

4. A.F. Metherell (Editor) - Acoustical Holography vol.3 p.191-286. Plenum Press 1971.

5. P.S. Green(Editor)- Acoustical Holography -vol.5. Plenum Press 1974.

6. P.N. Keating - Comparison of processing requirements in phased array Sonar and Acoustical Holography. JASA vol. 54 nr.3, 1973.

7. D.J. Creasy, J.R. Dunn - A High Resolution Within - Pulse Sector Scanned sonar with Electronically Variable Focussing. IERE-Conference on Instrumentation in Oceanology Bangor, september 1975.

8. M.L. Holley, R.B. Mitson, A.R. Pratt - Developments in sector scanning sonar - idem.

Ackownledgement:

I should like to thank all the people of our Institute who helped to realize the prototype of this Fourier Transformer. In particular Mr.J. Delcour for stimulating the project and Mr. M. Joon and Mr. J. Jansen for the construction of the apparatus.