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Summary

The possibility is examined of converting analog into digital information by means of almost passive electrical devices. Special enphasis is put on the problem of pulse height analysis in view of the use for nuclear fast events. A 16-channels analyser is sketched for an example, and ex= perimental evidence of the possibility of resolution times of the order of 1 μsec is given.

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PROPOSAL FOR AN ANALOG TO DIGITAL ELECTRONIC CONVERTER, SUITED FOR APPLICATIONS IN PULSE AMPLITUDE ANALYSIS.-

The present preliminary report develops the basic idea of the possibility to convert an analogical information, like a pulse amplitude, into a corresponding digital information, by use of a passive network and of an electronic discriminator. The fundamental circuit is described in § 1.

Naturally following developments of this basic idea are taken into consideration in view of the possible designing of a pulse amplitude analyser, like the one described at § 2 and 3. For preliminary experimental tests of the basic network see § 4.-

§ 1 - Let us consider a delay line with a characteristic inpedence Z_o, length l, time delay τ per unit length, and characteristic attenuation length λ. Suppose then injecting a pulse at the extremity A of the line (Fig. 1) and suppose that the line is open at both terminals: the pulse is then reflected back and forth between the two terminals. At ter=

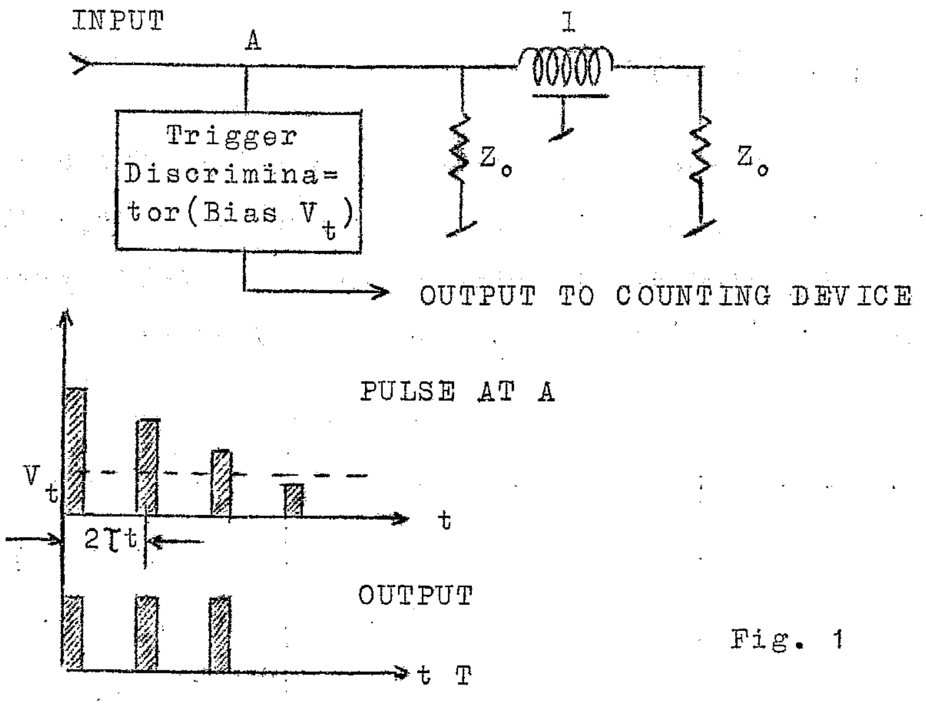


Fig. 1

minal A we observe the injected pulse at time $t_o=0$, the first reflected pulse at time $t= 2\ l\ \tau$, the second reflected pulse at time $t_2= 2\ 2l\ \tau\ = 4\ l\tau$, and so forth. Due to the attenuation in the line, a pulse of amplitude V_o injected in the cable, after having travelled a length l, is reduced to the amplitude

$$V\ (l) = V_o\ \exp(-\frac{l}{\lambda})$$

As a consequence of the attenuation, the successive pulses observed at terminal A have the following amplitudes:

$$V_o\ ;\quad V_o\ \exp(-\frac{2\ l}{\lambda})\ ;$$

$$V_o\ \exp(-\frac{4\ l}{\lambda})\ \ldots\ldots\ V_o\ \exp(-\frac{2\ n\ l}{\lambda})\ \ldots\ldots\ ;\quad \text{at times:}$$

$$t_o = 0\ ;\quad t = 2\ l\ \tau\ ;$$

$$t_2 = 4\ l\ \tau\ \ldots\ldots\ t_n = 2\ n\ l\ \tau\ \ldots\ldots$$

Now suppose that we inject the successive pulses observed at A in a discriminator triggered from pulses of amplitude greater than V_t. It will be triggered n times if the amplitude of the n-th reflected pulse is greater than V_t, that is to say:

$$V_o\ \exp(-\frac{2\ n\ l}{\lambda}) > V_t$$

In such a way a biunivocal correspondence is established between the number of trigger pulses, and the original amplitude V_o of the pulse injected in the device. In this simple case, the digital coding of the pulses will result as follows:

Nr.of trigger pulses	Amplitude of analysed pulses min.	max.
0	0	V_t
1	V_t	$V_t\ \exp(\frac{2\ l}{\lambda})$
2	$V_t\ \exp(\frac{2\ l}{\lambda})$	$V_t\ \exp(\frac{4\ l}{\lambda})$
...	....	....
n	$V_t\ \exp(\frac{2(n-1)l}{\lambda})$	$V_t\ \exp(\frac{2\ n\ l}{\lambda})$

If we let one channel of a pulse amplitude analyser correspond to each number of trigger pulses, we obtain the analysis of the amplitude of the incoming pulses in n channels, the width of wich is proportional to the bias V_t of the trigger discriminator and is exponentially increasing with the number of the channel, in such a way that the percent width is costant.

We are used to consider pulse amplitude analysers with channels having all the same width. The next paragraphs will show that, using the basic idea above described, it is easy to design an amplitude pulse analyser with the channels having the same width. Before starting to describe this apparatus, we shall consider the advantages of a pulse amplitude analysis in channels of exponentially increasing width; for this purpose we have drawn the diagrams of fig.2, which shows how an ideal spectrum featuring two peaks is supposed to be analysed by a constant width 16-channels analyser, and by a 16-channels analyser of the type described above (constant percent width analyser).

The istograms show that resolution of the two systems is comparable in the higher channels, being of course much better in the lower channels for the exponential type analyser. Furthemore it must be observed that, in the latter type of analysis, the relative uncertainity of amplitude derived from the finite width of each channel is constant for all the channels, that is from the lowest to the higher ones.

§ 2 - For a convenient comparision of the line coding system with the conventional pulse amplitude analysers, we shall describe a line coding device suitable for the analysis of the pulse amplitude in channels of constant width. Furthermore, we do consider that the speed of a simple device, like the one described in the foregoing paragraph, is limited by the speed at which a pulse counting system may work in a reliable way. For the moment being, we do not know any reliable counting system able to count pulses spaced less than 0,1 microsecond. If we are supposed to count the number of pluses coming out of the trigger discriminator, of the above described device, with a counter as fast as the one above, we are compelled to space pulses to at least 0,1 μs, and the analysis of a pulse in a 16-channels analyser requires 1,6 μs as a minimum.

In the system description of which follows below, the possible maximum speed of analysis is increased by the use of the counting devices only in the recording part of the apparatus, when the pulses are already sorted in the different channels, and the average counting rate is statistically lowered by the sorting operation.

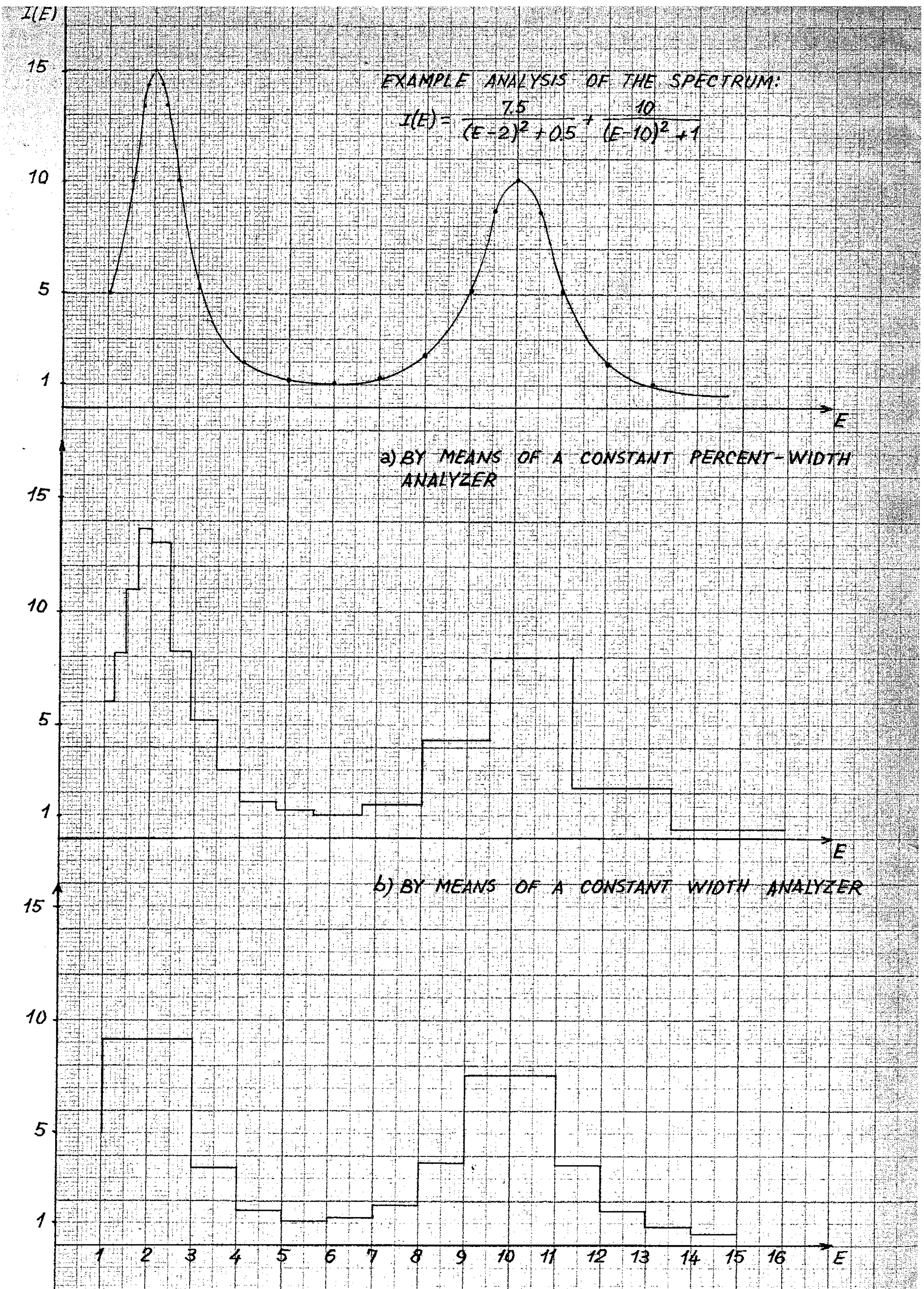
The present paragraph handels about the line coding system, and about a device which is triggered only by the last pulse of a series, which we shall call 'last pulse trigger (LPT) circuit'.

The block diagram of a 16 channel pulse analyser based on the line coding principle will be discussed in the next paragraph.

Suppose that we have to sort pulses into 4 equally wide channels:

- Pulses of amplitudes between V_t and $2V_t$ will be sorted in Channel Nr. 1
- Pulses of amplitudes between $2V_t$ and $3V_t$ will be sorted in Channel Nr. 2
- Pulses of amplitudes between $3V_t$ and $4V_t$ will be sorted in Channel Nr. 3
- Pulses of amplitudes above $4V_t$ will be sorted in Channel Nr. 4

We can inject the pulses in a four access delay line e.g. through diodes, and by attenuators which together with the lines characteristic attenuation attenuate the pulses amplitude by the factors shown in Fig.3 a).



I(E)
EXAMPLE ANALYSIS OF THE SPECTRUM:
I(E) = 7.5 / ((E-2)^2 + 0.5) + 10 / ((E-10)^2 + 1)
15
10
5
1
E
a) BY MEANS OF A CONSTANT PERCENT-WIDTH ANALYZER
b) BY MEANS OF A CONSTANT WIDTH ANALYZER
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

FIG. 2

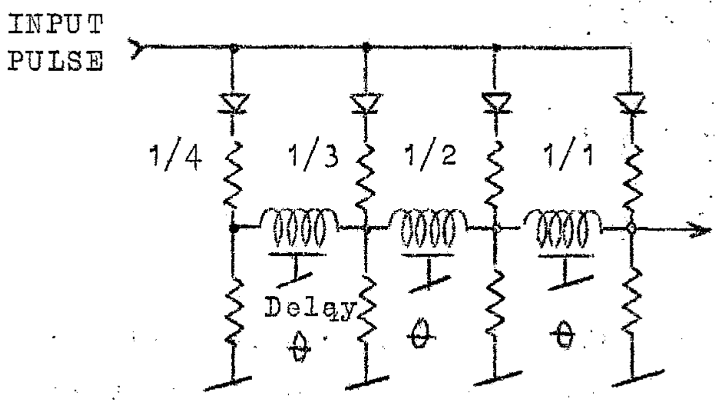


Fig. 3 a)

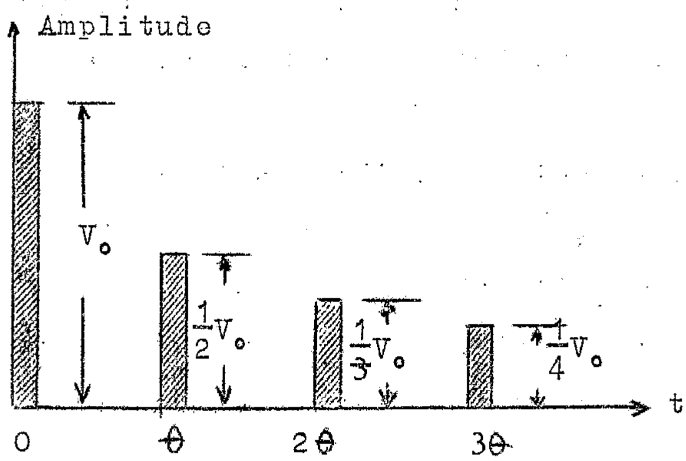


Fig. 3 b)

We shall have thus at the output four pulses, as shown in Fig. 3 b), of which the first is of full amplitude V_o at time t = 0, the second of amplitude $V_o/2$ at time $t = \theta$, the third of amplitude $V_o/3$ at time $t = 2\,\theta$ and the last of amplitude $V_o/4$ at time $t = 3\,\theta$. These pulses may be injected in a trigger discriminator, biassed at V_t; it is easy to show that the number of the pulses of the trigger sorts the amplitude of the incoming pulses according to the precedent table. In fact, the amplitude V_o of a pulse can be written as follows:

$$V_o = (k + \varepsilon)\, V_t$$

where k = 0, 1, 2, ...; $0 < \varepsilon < 1$.

Such a pulse gives rise in the above described device to four pulses of following amplitudes:

1 th $\qquad (k + \varepsilon) V_t$

2^{th} $\quad (\frac{k}{2} + \frac{\varepsilon}{2})\, V_t$

3^{th} $\quad (\frac{k}{3} + \frac{\varepsilon}{3})\, V_t$

4^{th} $\quad (\frac{k}{4} + \frac{\varepsilon}{4})\, V_t$

Of these four pulses, only k have a greater amplitude than V_t, so that the discriminator is triggered only k times.

(An analysis in four channels is taken into consideration, but of course a larger number of channels can be taken into consideration).

We are now introducing the 'last pulse trigger' (LPT) circuit', which is supposed to give rise to a trigger pulse which should coincide with the last of the k-pulses coming out from the trigger discriminator. There are many ways to design one such circuit, but we shall discuss here the most simple of them.

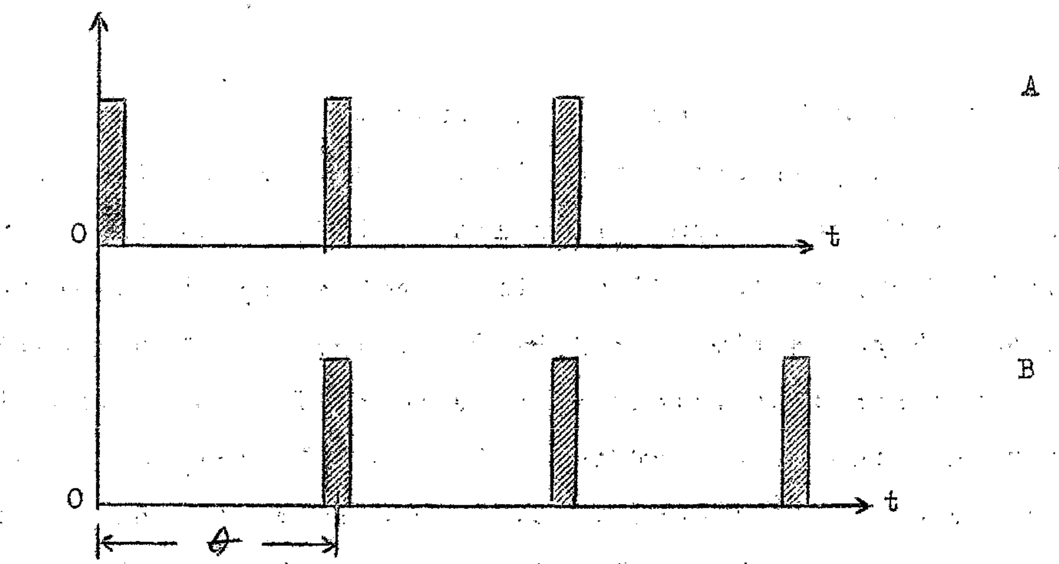


Fig. 4

Looking at Fig.4, we see that the three pulses shown in A are delayed in B by an interval of time θ, corresponding to the interval of time between two successive pulses. If series B pulses is injected in to the coincidence input of an anti - coincidence circuit, and series A into the anti - coincidence input, the only pulse to be allowed going through the circuit will be pulse 3, which is the last of the series. A LPT circuit may be done as shown in the block diagram of Fig.5; of course the output pulse of the anti - coincidence cir= cuit is delayed by θ in respect of the last pulse of the series injected in the input. In a general way, if the trigger discriminator gives rise to k pulses, spaced by time intervals θ, the output pulse from the LPT circuit starts at time k θ. Channel number k is thus coded as a time k θ.

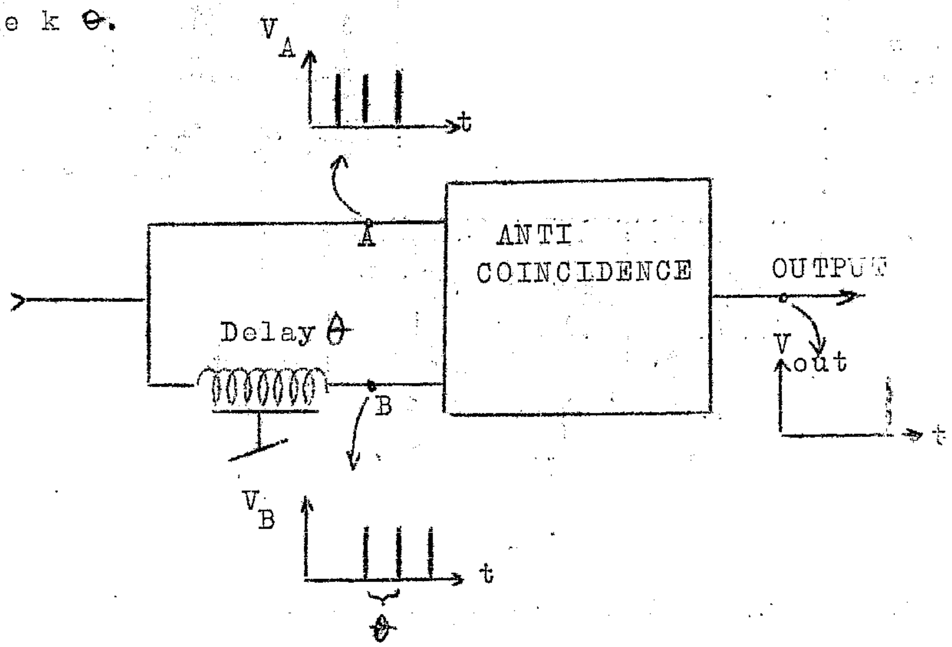


Fig. 5

§ 3 - We shall consider now block diagram of Fig. 6.

Aim of the circuit is to introduce a pulse in the channel output wire which corresponds to the k value of the analysed pulse. This operation is being performed by decoding the information contained in the interval of time between the 'zero time' and k θ time of the start of the pulse coming out from LTP circuit. We might suppose, for instance, that is k = 3; the LTP circuit pulse starts at time 3 θ and is injected, with various delays, into the four coincidence circuits. Coincidence circuit Nr.3 will be the only one to receive the pulse at the time: (3 + 1) θ = 4 θ. A pulse formed in the 'zero time trigger'

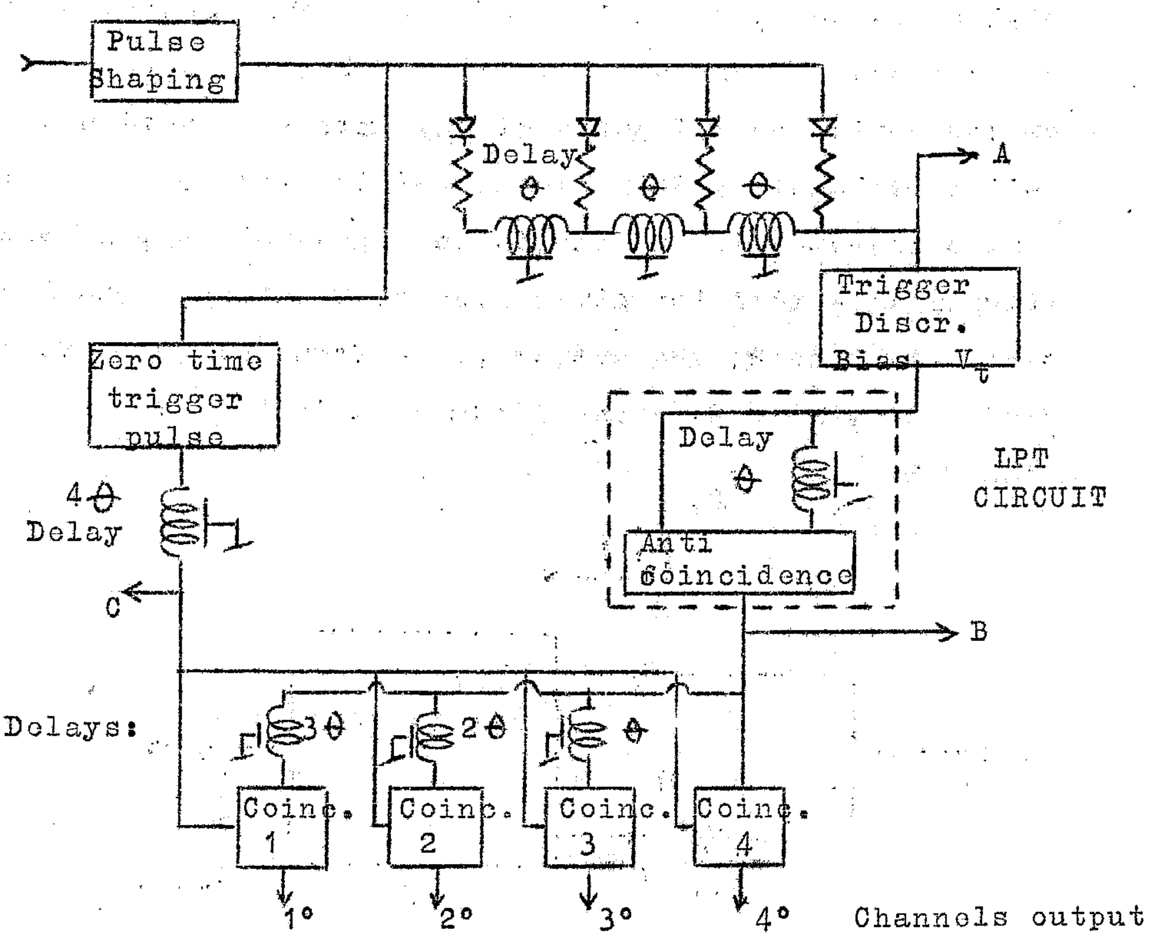


Fig. 6

and delayed by 4 θ, is injected in the four coincidence circuits. Coincidence circuit Nr.3 receives the two input pulses at the same time, being the only one which fires; a pulse is generated in the 3th channel output wire.

As already said, coding is here considered in four chan= nels as an example of delay line coding system; circuits are naturally suitable for coding pulse amplitudes in much more channels. Aiming at keeping the possible speed of operations at a maximum level and at improving the reliability of the de= vice, a system of amplitude analysis was studied, which uses a two-steps coding system.

Let us consider again the amplitude of a pulse:

$$V_o = (k + \varepsilon) V_t$$

By means of the above described device, the value of k has been analysed. We shall now try to analyse in a similar way the value of ε. In this way coding of the input pulse results by means of a pair of digits, k and ε, each one ranging from 1 to 4. Of course, this is equivalent to an analysis of the amplitude in a 16 channel analyser.

Following the schema of fig.6 amplitudes of the pulses coming out from the coding delay line and attenuator, as observed at point A, are:

$$(k+\varepsilon)V_t\,, \quad \left(\frac{k+\varepsilon}{2}\right)V_t\,, \quad \left(\frac{k+\varepsilon}{3}\right)V_t\,,$$

$$\left(\frac{k+\varepsilon}{4}\right)V_t\,;$$

These pulses are injected into the device shown at Fig. 7 whith the purpose of giving at the output D a pulse of amplitude proportional to εV_t. This pulse can be coded and analysed again by means of a device similar to that sketched in Fig. 6.

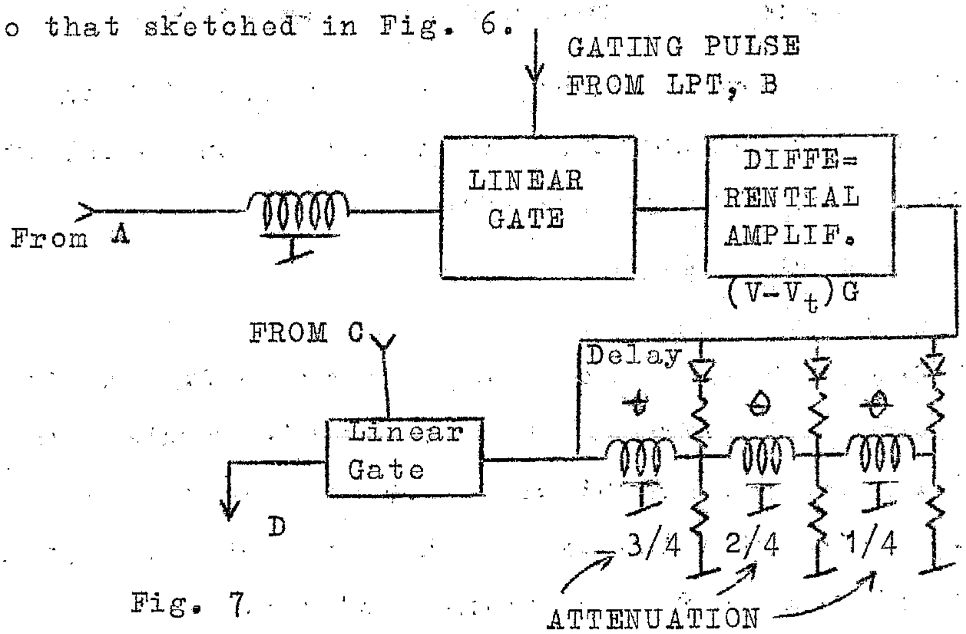


Fig. 7

The circuits of Fig. 7 are working as explained below : the four pulses coming from point A are delayed by θ and presented at the input of a linear gate. A gating pulse coming from the LPT circuit opens the gate at time k θ (point B of Fig.6). We have thus, at the output of the linear gate, only one pulse at time k θ, that is the pulse of amplitude:

$$\left(\frac{k+\varepsilon}{k}\right)V_t = V_t + \frac{\varepsilon}{k}\,V_t$$

The differential amplifier, which follows the linear gate, performs the operations of substracting an amplitude V_t and multiplies the result by a fixed gain G. From the differential amplifier, through the cathode follower, a pulse of amplitude

$$\frac{\mathcal{E}}{k} V_t G$$

is injected into the coding delay line and attenuator.

Purpose of this part of the device is to remove the factor 1/k, wich carries an already analyzed information from the amplitude of this pulse. In fact, at the output of the delay line, there are four pulses of amplitude:

$$\frac{\mathcal{E}}{k} V_t G \; ; \; \frac{\mathcal{E}}{k}\frac{3}{4} V_t G \; ; \; \frac{\mathcal{E}}{k}\frac{2}{4} V_t G \; ; \; \frac{\mathcal{E}}{k}\frac{1}{4} V_t G$$

at the following times:

$$k\,\theta \; ; \quad k\,\theta + \theta \; ; \quad k\,\theta + 2\,\theta \; ; \quad k\,\theta + 3\,\theta \, .$$

If we suppose, for instance, that the value of k was k=3, the only pulse starting at time 4 θ, is the second pulse wich starts at time 4 θ, with an amplitude

$$\frac{\mathcal{E}}{3} \; \frac{3}{4} V_t \; G$$

This pulse, but for the constant factor G/4, has the desired amplitude $\mathcal{E} V_t$. For the selection of this pulse among the four others which come out of the line, a linear gate is being used, opening of which takes place by means of a gating pulse coming at time 4 θ from point C of Fig. 6.

The pulse of amplitude

$$\mathcal{E}\, V_t \frac{G}{4}$$

may be now analysed in four channels, for instance, by means of an identical device to the one indicated in Fig. 6. As a final result, the pulse amplitude is coded by the two numbers k and $\mathcal{E}$, represented by a pulse at the output of a coincidence circuit, selected in an array of four.

The pulse coding number k starts at time 4 θ, the pulse coding number $\mathcal{E}$ starts at time 8 θ. Indipendently from the origi=

nal pulse amplitude, analysis and coding operations are performed in our example, in a lenght of time 8 θ.

Reconsidering the circuits employed in the block diagrams of Fig. 6 and Fig. 7, we see that the operation's speed is probably limited by the speed at which the trigger discriminators are able to work with good reliability, all other active circuits being of a type which could be supposed to work with pulses of 10^{-8} seconds and with a time interval of the same order of magnitude. If we assume conservatively that a basic time interval $\theta = 10^{-7}$s can be realized, in a 16 channel analyser coding and sorting of a pulse will require about 0,8 µs; it is interesting to observe that in a 100 channels analyser of same type, and with a same basic time interval, the analysis of a pulse requires only about $(10 + 10) \times \theta = 2$ µs.

Besides, it can observed that recording of the pulses' number falling in each channel may be done, in our example, in conformity to the obvious schema of Fig. 8, that is making use of a 4 by 4 matrix which gives rise to 16 output wires.

Of course, the pulses coming out from the k-channels (at time 4 θ) must be delayed of 4 θ, as indicated, to meet the pulses coming out of the ε-channels (at a time 8 θ).

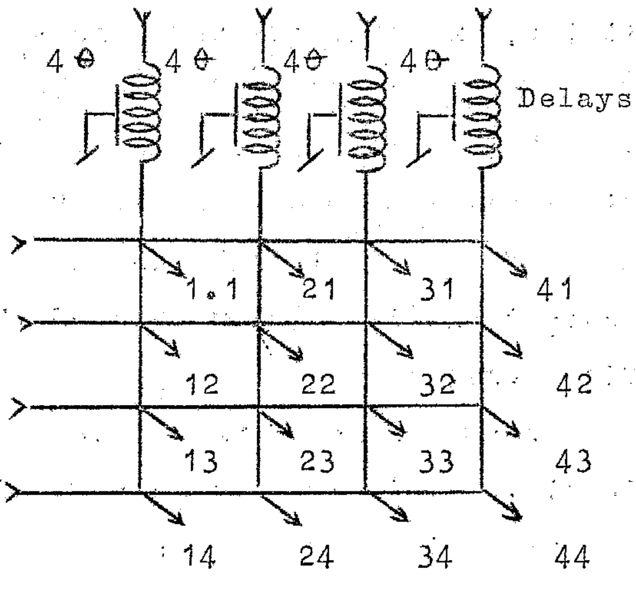


Fig. 8

The 16 crossings of this network can be done by coincidence circuits, each one driving a fast counter. The resolving power of the counters, in case of a basic time interval 10^{-7} sec, may be of about 1 µs, without any loss of counts. If fast enough trigger discriminators could be build, the operating speed may be rised by a factor of 10, by using counting circuits with higher resolving power.

§ 4 - Preliminary experimental tests were performed on the delay line coding network.

Fig. 9 shows the device used to inject pulses of the required shape into a four access delay line. Pulses of 0.25 µs, rise time 0.04 µs, roughly rectangular in shape are injected into the input. These pulses are stretched by means of the diode-condenser network. Purpose of the second cathode follower (EL34) and the reflecting delay line, is to form the stretched pulses into pulses of rectangular shape, with about 1 µs length, 0.25 µs rise time.

Pulses of standard rise time and length are injected in parallel into four compensated attenuators (R_i,R_i'). Of course, the resistance ratio R_i/R_i' of the attenuators is calculated by taking into account the attenuation induced by the different length of the pulse travelled cable. The four pulses coming out of the attenuators through the cathode followers and the diodes, are injected into the four access delay line.

This line is made up by three pieces of a delay cable (Dätweyler type HFk 5614) with 0.1 µs delay per meter length. Each piece has a length of about 20 m; giving rise to a delay of 2µs.

Both ends of the delay line are terminated by the 1000 ohm characteristic impedence of the cable, in order to avoid reflections.

Shape of the four pulses coming out of the device is shown in Fig. 10. We introduced a small amount of overcompensation in the four attenuators with the aim of obtaining pulses with a peak following closely the leading edge. This shape is particularly suitable for triggering a Schmitt discriminator (see reference 7 of Bibliography).

Further tests of this part and of the other devices described in the project of paragraphs 2 and 3 are under progress.

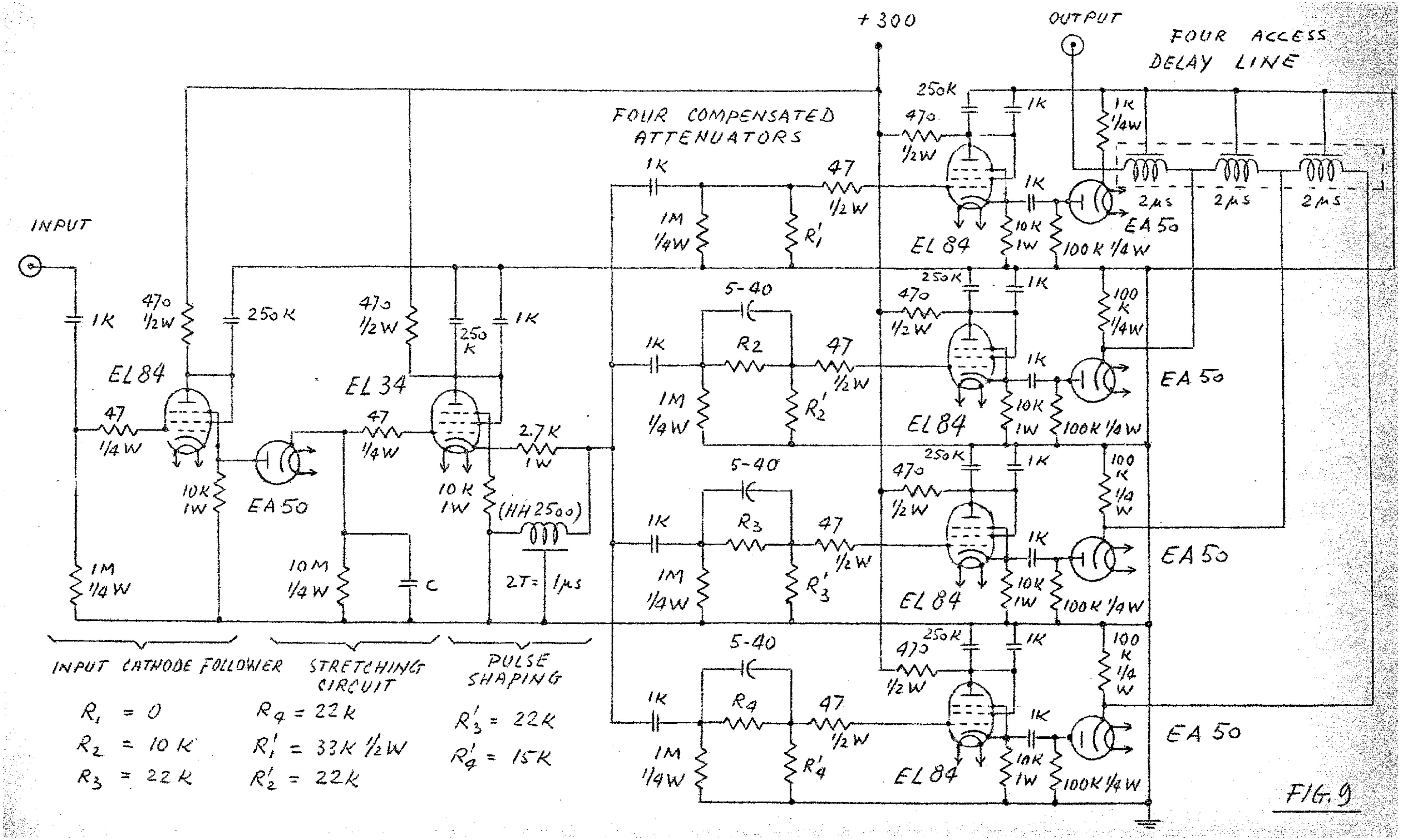

INPUT
OUTPUT
+300
FOUR ACCESS DELAY LINE
FOUR COMPENSATED ATTENUATORS
EL84
EL34
EA50
1K
250K
470 1/2W
47 1/4W
47 1/2W
10K 1W
1M 1/4W
10M 1/4W
C
2.7K 1W
(HH2500)
2T = 1µs
5-40
R2
R3
R4
R'1
R'2
R'3
R'4
100K 1/4W
100 K 1/4 W
1K 1/4W
2µs
INPUT CATHODE FOLLOWER
STRETCHING CIRCUIT
PULSE SHAPING
R1 = 0
R2 = 10K
R3 = 22K
R4 = 22K
R'1 = 33K 1/2W
R'2 = 22K
R'3 = 22K
R'4 = 15K

FIG. 9

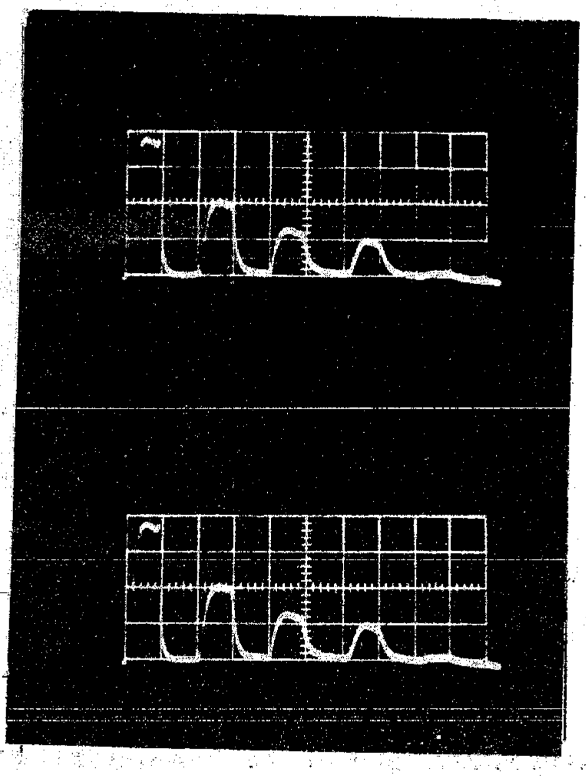


Fig. 10 - 1.8 volt/cm; 1 μsec/cm

Bibliography

For an extensive review of the actual stage of Pulse Height Analyzers, see following papers:

1) - W.A. Higinbotham: Today's Pulse Height Analysers, Nucleonics, April 1956, pag. 61

2) - J.L.W. Churchill, S.C. Curran: Pulse Amplitude Analysis, Advances in Electronics and Electron Physics, Vol. VIII, pag. 317, 1956

3) - Proceedings of the Conference of Gatlinburg (Tenn.), Sept. 1956: Multichannel Pulse Height Analysers

The original idea of digital coding of pulse heights for amplitude analysis is described in the papers:

4) - D.H. Wilkinson: Cambridge Philosophical Soc. Proceedings, 46, 508, (1950)

and its improvments are described in the paper:

5) - G.W. Hutchinson and G.C. Scarrott: Phil. Mag. 42, 792, (1951)

and in the more recent paper:

6) - H.L. Schultz, G.F. Pieper, L. Rosler: R S I, 27, 437, 1956.

For an accurate survey of the working characteristics of a trigger circuit, see the following papers:

7) - A. Fairstein: R S I, 27, 549 (1956)

8) - K. Kandiah: P I E E (London) II, 101, 248, (1954)

An accurate bibliography covering the subject is to be found in 1) and 2). As far as we know, the most recent paper on this subject is:

9) - Russel, Lefevre: An F.M. Multichannel Pulse Height Analyser, Nucleonics, 15, 2, 76, (1957).