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DIGITALIZED TRANSFER FUNCTION ANALYSER FOR PRECISION MEASUREMENTS

by

I. BREDAEL, A. GARRONI and F. SCIUTO

1968

Joint Nuclear Research Center
Ispra Establishment - Italy

Reactor Physics Department
Research Reactors

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Brussels, April 1968 - 24 Pages - 5 Figures - FB 40

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The reference signals may be generated internally, or by an 8192 bit diode matrix and delivered for perturbation use in the digital form by means of a stepping motor, the velocity of which is then sinusoidally modulated or by a

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This equipment is particularly useful in vibration analysis.

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SUMMARY

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KEYWORDS

TRANSFER FUNCTIONS
DIGITAL SYSTEMS
PULSES
SIGNALS
INTEGRATORS
DIODES
MEMORY DEVICES
MOTORS
VELOCITY
OSCILLATIONS
TESTING
FREQUENCY

DIGITALIZED TRANSFER FUNCTION ANALYSER FOR PRECISION MEASUREMENTS

1. Introduction (*)

This measuring device fulfils the following functions, as shown in Fig. 1 (ref. 1 and 2):

- It generates a pseudosinusoidal or sinusoidal perturbation with a known and adjustable frequency and amplitude. This perturbation is introduced into the system to be analyzed (e.g., nuclear reactor);

- It analyzes the system responses in order to determine the Fourrier fundamental:

$$a_1 = \frac{1}{nT} \int_t^{t+nT} S_{output} \times S_{input_{\Phi=0^o}} \cdot dt \qquad (1)$$

$$b_1 = \frac{1}{nT} \int_t^{t+nT} S_{output} \times S_{input_{\Phi=90^o}} \cdot dt \qquad (2)$$

This analysis is effected by multiplying the input signal (electric, mechanical, thermal or chemical) by the output signal (electric signal from the ionization chamber, for example). The multiplication process is carried out on two separate channels, one of the multipliers taking the signal in phase with the input signal, the other with the signal in quadrature in relation to the input signal. Each of the products obtained is to be integrated during one or n perturbation periods. The results a_1 and b_1 must further be divided by the duration of the perturbation period or periods.

(*) Manuscript received on March 1, 1968.

From these values it is then possible to determine as a function of the frequency the gain and phase angle specific of the system:

$$G_{f_m} = \frac{S_{output_m}}{S_{input_m}} = \frac{\sqrt{a_{1m}^2 + b_{1m}^2}}{S_{input_m}} \tag{3}$$

$$tg\Phi_{f_m} = \frac{b_{1m}}{a_{1m}} \tag{4}$$

These values then enable the system gain and phase angle diagrams to be plotted as a function of the frequency.

It should be noted that the perturbation amplitude generally has a low value (e.g., 1%) so as to disturb the system under examination as little as possible. The measuring equipment must accordingly be sensitive and reject appropriately every unwanted signal save the perturbation with which we are concerned here. This function devolves upon the multiplier/integrator chain. Its Q factor is called the rejection factor.

In the case of the analyzer described, the digital method makes it possible to obtain greater accuracy than 0.1% and a 100.000 rejection factor for all measurement or perturbation ranges.

2. Characteristics

2.1 Perturbation signal (output amplifier)

a) Sinusoidal: - reconstruction of a sinusoid defined by 1000 temporal digital data per period.

- $0{,}0005 \text{ Hz} \leq f \leq 50 \text{ Hz}$ adjustable in five ranges with digital reading of the period in sec. and msec.
  Period reading accuracy: 0.01%
  Period recording stability: 0.02%
- Output signal alternative component
  $\pm 0 \leq \text{AC V} \leq \pm 10$ V peak.
  V AC calibration: Helipot 10 revs.
  V AC stability: 0.05% FS.
  Output impedance: $\approx 0.01\,\Omega$ at plug.
- Output signal continuous component
  $\pm 0 \leq \text{DC V} \leq \pm 10$ V peak.
  V DC calibration: Helipot 10 revs.
  V DC stability: 0.05 FS.
  Output resistance: $\approx 0.01\,\Omega$ at plug.

b) Digital:

- Sine and cosine channels:
  1000 modulated pulses in time according to a sine or cosine per channel.
  Output V: 0 to +6 V over 470 ohms. Duration: 1 μ/sec.
- Sine and cosine sign channels:
  1 symmetrical pulse per channel corresponding to a sine or cosine angle of 180°.
  V output: 0 to +6V over 470 ohms.

c) Rectangular:

- Construction of a rectangular instead of a sinusoidal wave from the **"cosine sign"** channels. The other characteristics are equal to those set out in point a).

2.2 Measuring Chain

a) Input amplifier

- Separate mass input, ± 10V peak over 100 kohms. Overload indication and automatic measurement lock.

Compensation of DC average level: 0 ± 100 mV or 0 ± 10V by Helipot.
Frequency range: DC to 50 Hz
Amplifier gain: 1 to 11.000
Amplifier drift: 0,5 µV/°C at input.

b) Sine and cosine generator

A voltage-frequency converter controlled by an adjustable reference voltage drives a 2048 base bidirectional counter after decade digital reduction. Of these 2048 points we take 250 placed correspondingly to the sine or cosine value on a circle quadrant by means of a diode pyramidal matrix.

c) Sine and cosine multipliers

Patented digital sequential completely built with micrologics.

d) Sine and cosine integrators

Bidirectional algebraic counters with sign indication. The integration time being a constant, division by $^1/_T$ is eliminated.

Display: - four-figure digital with digital multiplication of sensitivity by 1, 10, 100 or 1000;
- overload indication and automatic measurement lock.

Number of integration cycles: 1, 2, 5, 10, 20, 50, 100, ∞

e) Digital voltmeters

Input: 0/±10V to 0/± 1mV depending on full-scale input gain.

Display: - four figures in VRMS
- four figures in DCV plus sign.

f) Analogue voltmeter

Input: 0/± 10 DCV to 0/± 1mV depending on full-scale input gain.

3. Description of analyzer (fig. 2)

This device has been arranged in two consoles of 15 PO units in order to facilitate the frequent movements to which it will be subjected. A free volume enables any external device of up to 10 PO units to be added.

The measuring console comprises:

1) the output amplifier
2) the logic control unit
3) the input amplifier
4) the analogue-to-digital converter
5) the junction box
6) the overall feed system.

The display console comprises:

7) the perturbation period indicator
8) the digital integrator and voltmeter reading unit
9) the stepping motor power amplifier (option)
10) the distribution box
11) the sine-cosine generator.

3.1 Output amplifier

a) Analog channel

This consists of a three-input operational-type amplifier. The first input regulates the loop gain, the second introduces an adjustable continuous component for shifting the output between + and -10 DCV. The third makes it possible, after regulation of the level, to introduce a digital-to-analog converter output. This process ensures excellent stability and form in the output, especially at very low perturbation frequencies.

3.2 Logic control unit

This unit is constructed entirely of 250 micrologic modules divided into 14 cards.

a) Sine-cosine generator control

A start-stop luminous-confirmation push-button enables the generator to be controlled by hand.

A decade selector is used to select the desired period range.

By means of a vernier it is possible to select any point in a chosen period decade.

By means of fine regulation it is possible to adjust the chosen point between ±1% of a decade.

b) Measurement controls

A luminous-confirmation push-button controls the various measuring functions. A logic determines the following order of manual operations: stop - reset - start.

The integrator start signal does not light up instantaneously, but only after the sine-cosine generator has given a sine reference pulse, the index for the start of the operation.

It does not go out after the first integration cycle. In order to cut down the statistical error, in fact, integration is carried out for a total period of not less than 0.5 sec. This time can be increased by multiplying the number of integration cycles by 1, 2, 5, 10, 20, 50 or 100 by manual control.

A locking circuit stops the measurement process if any of the controls is modified during that process, except as regards the oscillation period vernier. Measurement is also stopped if one of the integrator of input amplifier circuits is overloaded, even if only instantaneously.

c) Multipliers and other circuits

Digital multiplication is performed continuously during measurement by a special patented process. Let us consider only the sine-cosine generator channel. It delivers 1000 pulses per period. These pulses have to be shaped. Therefore a gate circuit (fig. 3) takes the pulses of a 1 MHz clock to generate calibrated pulses of 5, 50 or 500 μ sec. For this purpose, each sine pulse is stored. At the first following 1 MHz clock pulse, the store is cleared and a 1 MHz 5, 50 or 500 pulse counter is triggered off. During the counting a pulse called a "sinus gate pulse" is delivered. This will therefore have a calibrated duration with 1000 of these pulses per perturbation period distributed at a time rate varying according to a sine law in phase with the perturbation reference.

To multiply the signal to be analyzed by the sine pulses, the analog signal is converted (if necessary) into a series of sequential digital pulses of extremely short duration (20 to 40 nsec) which are chopped by means of the sine gate pulses previously described (fig. 4).

It should be pointed out that there are in fact four gates for the sine multiplier, since on the one hand the digital multiplication has to be made on both the positive and the negative half-wave and on the other hand the analog-to-digital converter pulses emerge either along the channel corresponding to a positive input signal or along that corresponding to a negative signal. The outputs of the four gates are grouped in two's, one of the sums giving the increasing positive values (or decreasing negative values) and the other giving the decreasing positive values (or increasing negative values). These two channels are then applied to the corresponding inputs of the bidirectional phase counter, which thus integrates the value of the product obtained.

The process is the same for the cosine channel, but in this case it ends on the quadrature counter.

The duration of the 5, 50 and 500 μsec gates is commuted automatically so as to maintain a constant integration time. Thus in the 50 to 5 Hz perturbation period range (i.e. 20 to 200 msec) the integration time is:

$$5\ \mu\text{sec} \times 1000\ \text{pulses/rev} \times 100\ \text{integration cycles} = 500.000\ \mu\text{sec} = 0.5\ \text{sec},$$

while the duration of the measurement varies from 2 to 20 sec.

The maximum number of data is 500.000. With 5 decades the maximum read is 10.000 having a 2% error in the least significant digit.

In the 5 Hz to 0.5 Hz range (200 to 2000 msec), the 50 µsec gate is selected and the integration time becomes:

50 µsec x 1000 pulses/rev x 10 integration cycles = 500.000 µsec.

In this range, the other characteristics remain unchanged.

Between 0.5 Hz and 0.05 Hz (2 sec to 20 sec) and in the subsequent ranges, a single automatic integration cycle with a 500 µsec gate is used. The integration time will therefore be:

500 µsec x 1000 pulses/rev x 1 integration cycle = 500.000 µsec.

This constant time integration process makes it possible to simplify the equipment appreciably by eliminating division by 1/T.

It is obvious that by means of the manual selector for the number of integration cycles we succeed in decreasing considerably the influence of noise and of statistical errors but in this case the measuring time is proportionally longer.

The logical unit comprises two further auxiliary circuits, namely, digital voltmeters and the perturbation period display.

In the "voltmeter" position, the circuits between the analog converter and the bidirectional counters are modified as follows: the two converter outputs are connected to the phase counter inputs. This voltmeter therefore gives the average value of a DC signal during the 0.01 second measuring period repeated every 0.08 seconds. In the case of the other voltmeter, the converter outputs are summed at one of the quadrature counter inputs. This voltmeter therefore gives the effective average value of an AC signal during the 0.01 second measuring period repeated every 0.08 seconds.

The perturbation period display consists of a counter which receives on the one hand the 1 MHz clock pulses and, on the other hand, a gating pulse given by the sine-cosine generator with a duration between 20 and 200 msec, depending on the period recorded. The range decade selector shifts the sec/msec reading and also the point. The reading is comprised between 2000 and 20.000, which ensures a maximum error of 0.05%.

3.3 Input amplifier

This unit consists mainly of a high-gain operational amplifier having three inputs. One of these is the feedback loop providing a gain of 1 to 11.000 and is designed in such a way as to introduce the least possible error into the average DC level. In consequence, the low wire of the input signal to be analyzed is not linked to the frame but to the mass-signal of this amplifier. The second input (± 10V) is the high wire of the signal to be analyzed which originates from a function selector. This selector chooses and indicates the two main modes of functioning: TFA (transfer function analyzer) and digital voltmeter (DVM). Other positions make it possible to carry out control and calibration of the phase, quadrature and voltmeter measuring chains by connecting them either to mass or to a calibrated signal. Thus, in the "phase calibration" a calibrated rectangular sine-reference signal is sent so that the amplitude of the fundamental of this rectangular wave is equivalent to a 10 volt RMS. This value will then be read on the phase indicator and zero value on the quadrature indicator. For quadrature calibration a cosine-reference signal is sampled and zero is read on the phase.

The third input is for the elimination, if necessary, of a superposed continuous component at the output signal (or DC mean level). A push-button selects either the 10μV-100mV range or the 1mV-10V range. The input selector chooses the polarity. Such compensation can only be effected in the TFA positions.

A central zero analog voltmeter is used to assess the adjustment of this compensation between +10 and -10V so as not to overload the amplifier.

In the event of overloading, a threshold circuit locks the measurement and the overload (OVL) indication is maintained until the system is hand-reset.

The thermal drift of the amplifier is kept down to a low value by means of a differential transistorized stage, the three transistors of which are contained in the same TO-5 container.

3.4 Analog-to-digital converter

This is used for converting the information to be measured (if not in sequential digital form) into a set of pulses with a frequency depending on the input voltage. The ± 1 MHz for ± 10V conversion ratio at the input enables satisfactory precision to be obtained in the multipliers and consequently affords a good rejection factor for the various frequencies of the fundamental and also of the continuous component.

3.5 Junction box

This comprises the system general switch and fuse and also an elapsed time meter. It collects all the signals which have to go into the second rack.

3.6 Power supply

This supplies the ± 24 DCV for the amplifiers, telltales and manual information.

The ± 6 V is for the output digital signals and interface. The +3V6 is for the logics. All these voltages are stabilized at 0.1%. Only the +3V6 is controlled by remote sensing because of the high 6A consumption and the sensitivity of the micrologic to the supply variations.

3.7 Perturbation period indicator

(See 3.2).

3.8 Algebraic bidirectional counters

These two counters integrate the sequential informations and detect the sign of the result, one for the phase or DCVM channel and the other for the quadrature or ACVM channel.

Each of the channels has eight biquinary decades, three of them without decimal number indication. These three decades can be eliminated separately so as to permit multiplication of the reading chain sensitivity by 10, 100 or 1000.

A circuit for each of these two channels detects whether all the decades indicate 9. In this case overload indication and blocking of the measurement in progress are permitted. Indication and blocking reset is done by the "reset" push-button.

3.9 Mechanical perturbation by stepping motor power amplifier

The motor used has five windings which work with 3.5A constant current pulses in accordance with a preset sequence.

The amplifier is therefore made up of 5 transistorized power circuits, each with a network increasing the R/L factor in order to minimize the influence of the windings' self-inductance, the maximum frequency being 8000 Hz. Each of these amplifiers is piloted by a logic giving the following excitation sequence, if A, B, C, D and E are the designations of the five windings: ABC, BC, BCD, CD, CDE, DE, DEA, EA, EAB, etc. This logic consists of a five-bistable shift register.

3.10 Distribution box

This is used to distribute the feeds and the signals arriving from the first rack in the second.

3.11 Mechanical sine-cosine generator (fig. 5)

This assembly consists of a patented special encoder. Optical beams parallel to the axis of rotation and at right angles in the perpendicular plane to and at equal radii from this axis are intercepted by 250 lines not transparent to the light traced on the optical disc locked on the axis. These lines are parallel to each other, and to one of the disc diameters and also equidistant. In rotating, therefore, the disc permits the passage of light pulses at a time rate which varies sinusoidally. As the two photoelectric transducers are angled at 90° to each other, the one will be called sine and the other cosine.

The 250 lines give 500 pulses per axis revolution, which after differentiation and summation become 1000 on each sine or cosine channel.

A semi-circular annular secondary track will give the sine-reference and cosine-reference symmetrical pulses in two other photoelectric transducers, placed at two different radii from the first two, but also at right angles to each other, in the plane of the disc. These reference pulses are used to determine the sign of the sine and cosine, as the digital information for each revolution is divided into two groups from 0 to 180° with the + or - sign, depending on the position of the half wave.

Each of these four photoelectric cells is followed by an operational amplifier connected directly between mass and "virtual earth". A Zener diode circuit in the feedback network ensures a very high gain during commutation, an excellent wave shape during the information time and a very short saturation recovery time, the saturated position gain being about 100 and the band-pass 150 kHz.

In order to avoid cell thermal drifts and the influence exerted by aging of the illuminating lamp (6V fed at about 3V7), a fifth cell directly controls the colour temperature of the lamp through the lamp feed, the optical loop gain being 1000.

All these features guarantee excellent precision in sine and cosine generation, and consequently also in the measuring results.

4. Use of the transfer function analyzer

In view of its high precision, this analyzer is particularly suitable for recording partial transfer functions in a complex-equipment chain.

Summing the various partial results with an average accuracy (to about 1%) analyzer induces glaring errors incompatible with the accuracy required, for instance, in nuclear or thermal plants.

Again, certain phenomena such as undamped mechanical oscillations (cables, tubes, etc.) generate perturbations of the theoretical curve, not only locally (fundamental or harmonics) but over a considerable stretch of this curve, which can only be analyzed accurately and reproducibly if the perturbation frequency is very stable (variations of less than 1.10^{-4}).

In addition, the perturbation level must be small because many plants work in critical phase or amplitude zones. The analyzer must therefore be stable in time and sensitive.

In order to render the analyzer as flexible as possible, the plant can be perturbed either with analogue electric signals (sinusoidal or rectangular wave) or mechanically (adjusting a valve, for example) by means of a digital stepping motor.

If the plant cannot be perturbed but if it already has a mechanical control device, the angular digital rotation to digital sine/cosine converter can be connected up to the axis of this device by using the encoder as a reference signal generator.

List of figures

References

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2) HOOVER et al. Physical Review, 74, 851 (1948)

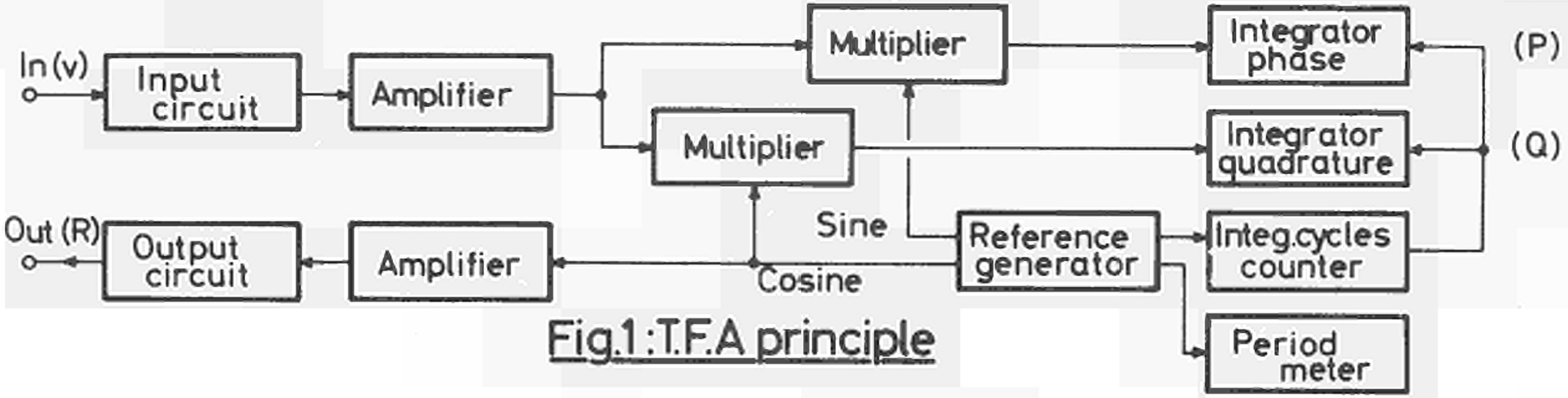


Fig.1 : T.F.A principle

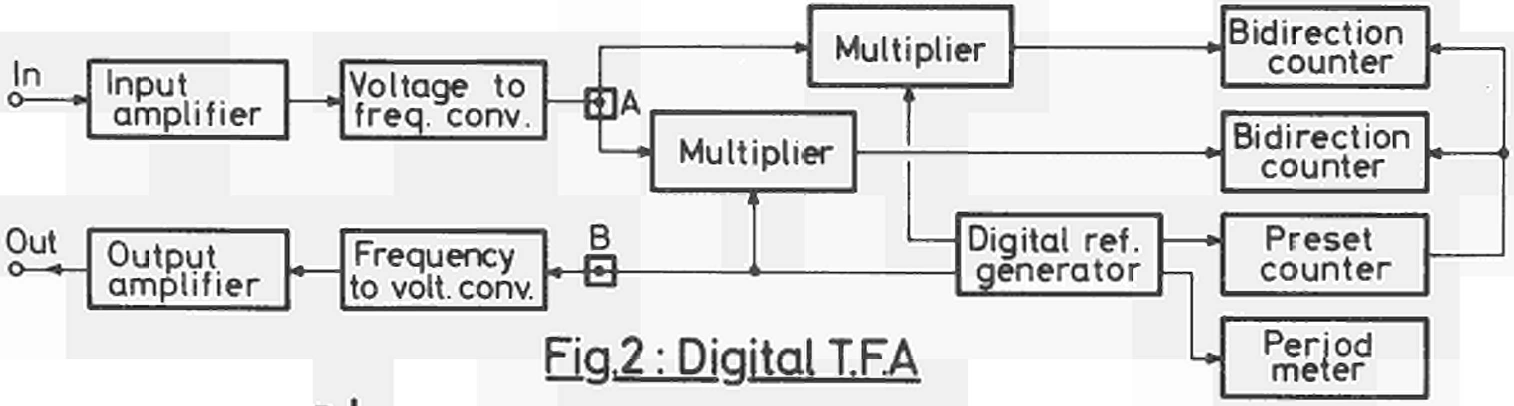
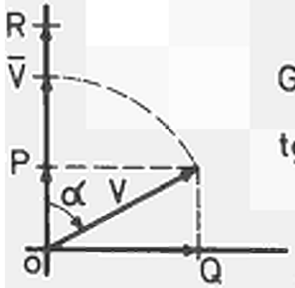


Fig.2 : Digital T.F.A



$$\text{Gain} = \frac{V}{R} = \frac{\sqrt{P^2+Q^2}}{R}$$

$$\text{tg}\ \alpha = \frac{Q}{P}$$

Fig.1 : T.F.A.working

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T.F.A. 037 : LOGIC DIAGRAM

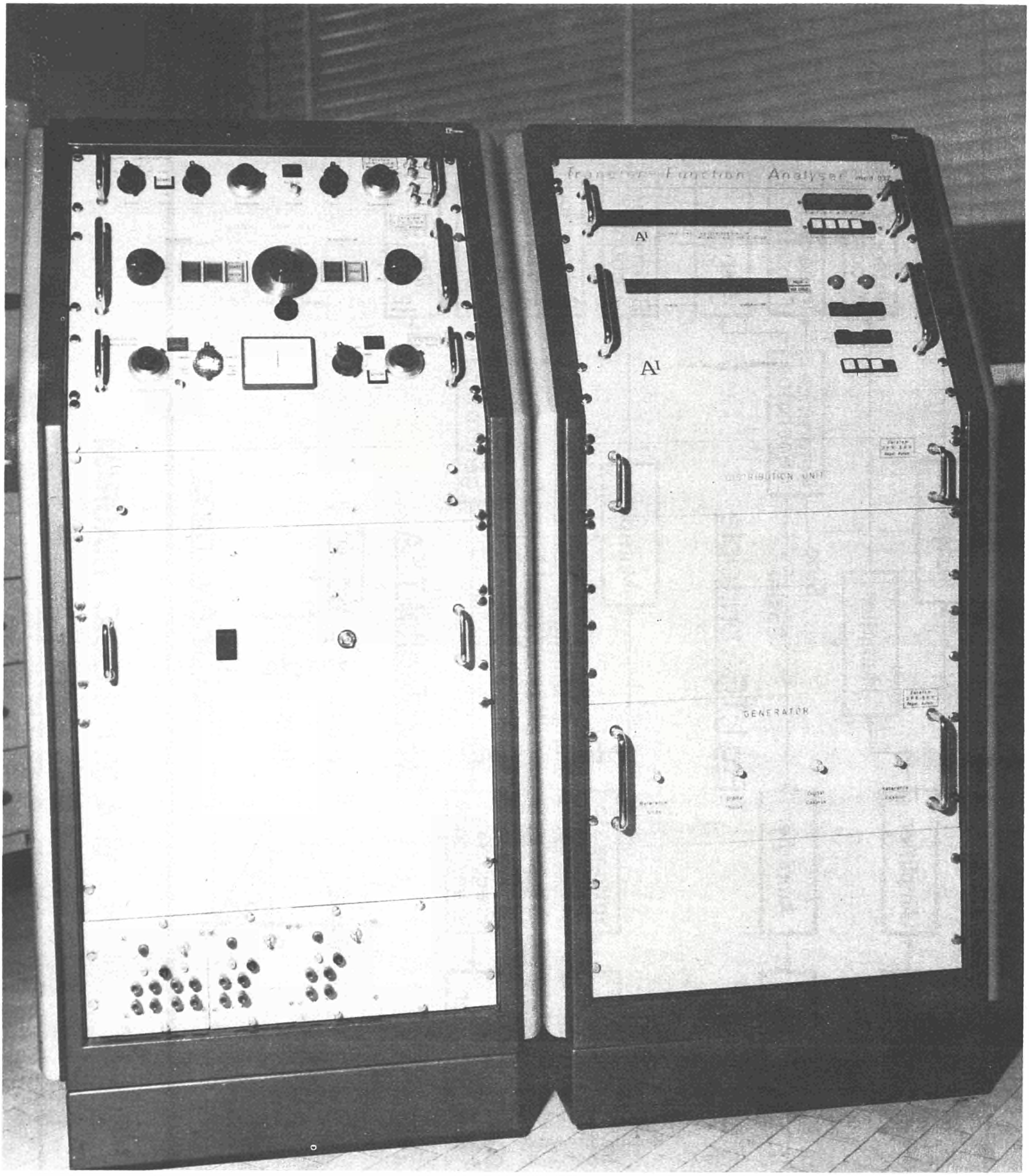
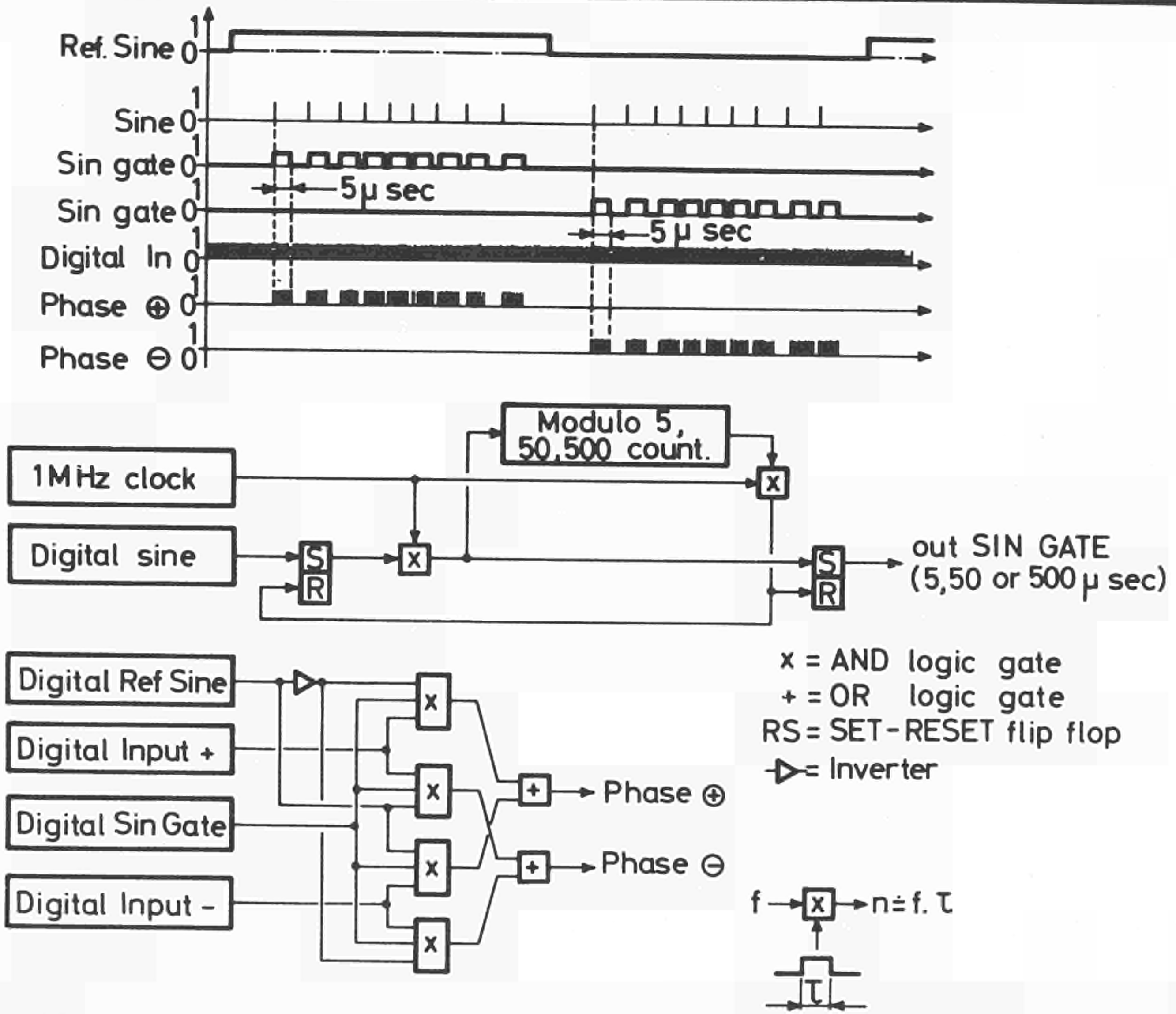

Transfer Function Analyser
AI
AI
DISTRIBUTION UNIT
GENERATOR

Fig. 2



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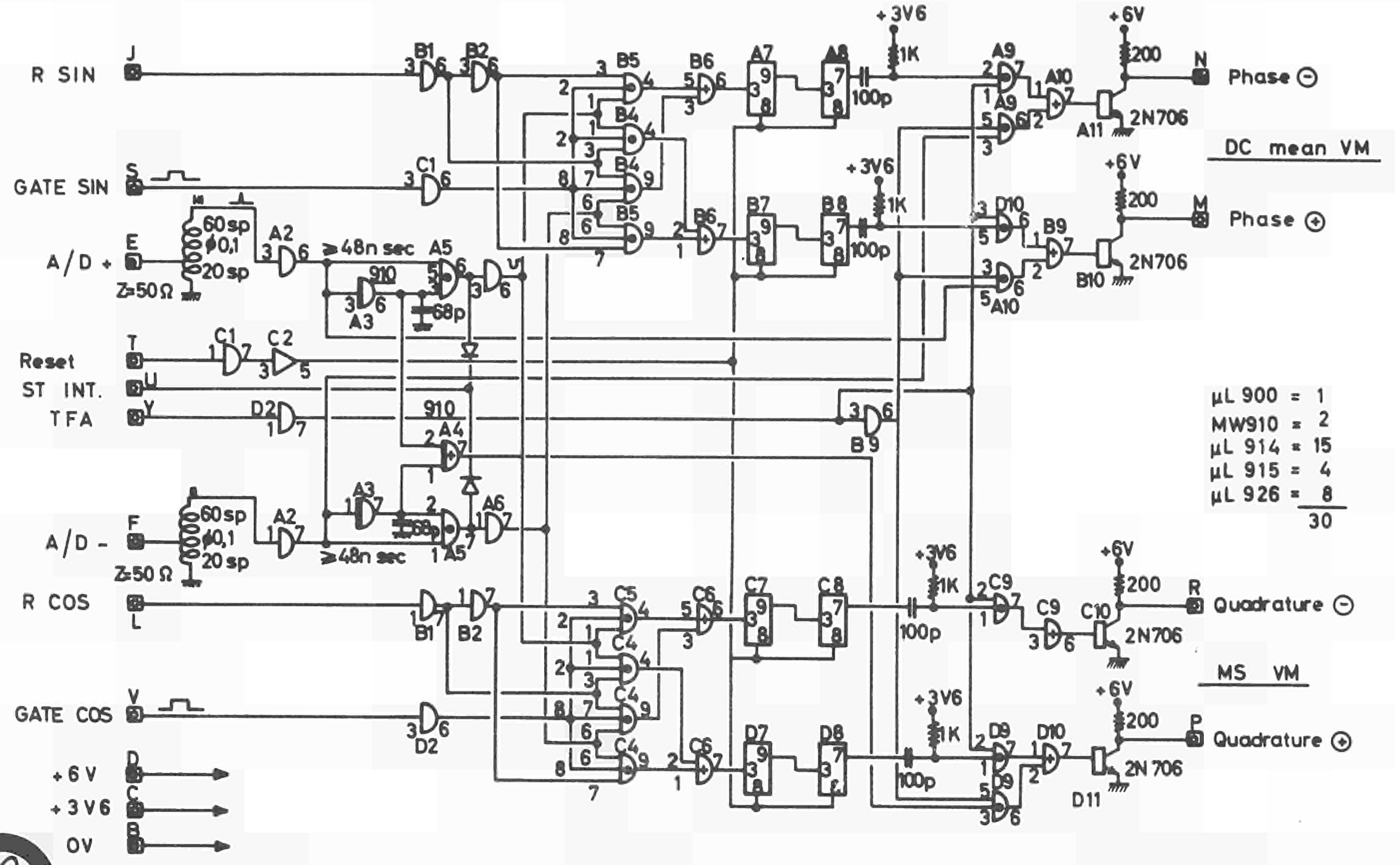
T.F.A. 037 : DIGITAL MULTIPLIER LOGIC DIAGRAM

3



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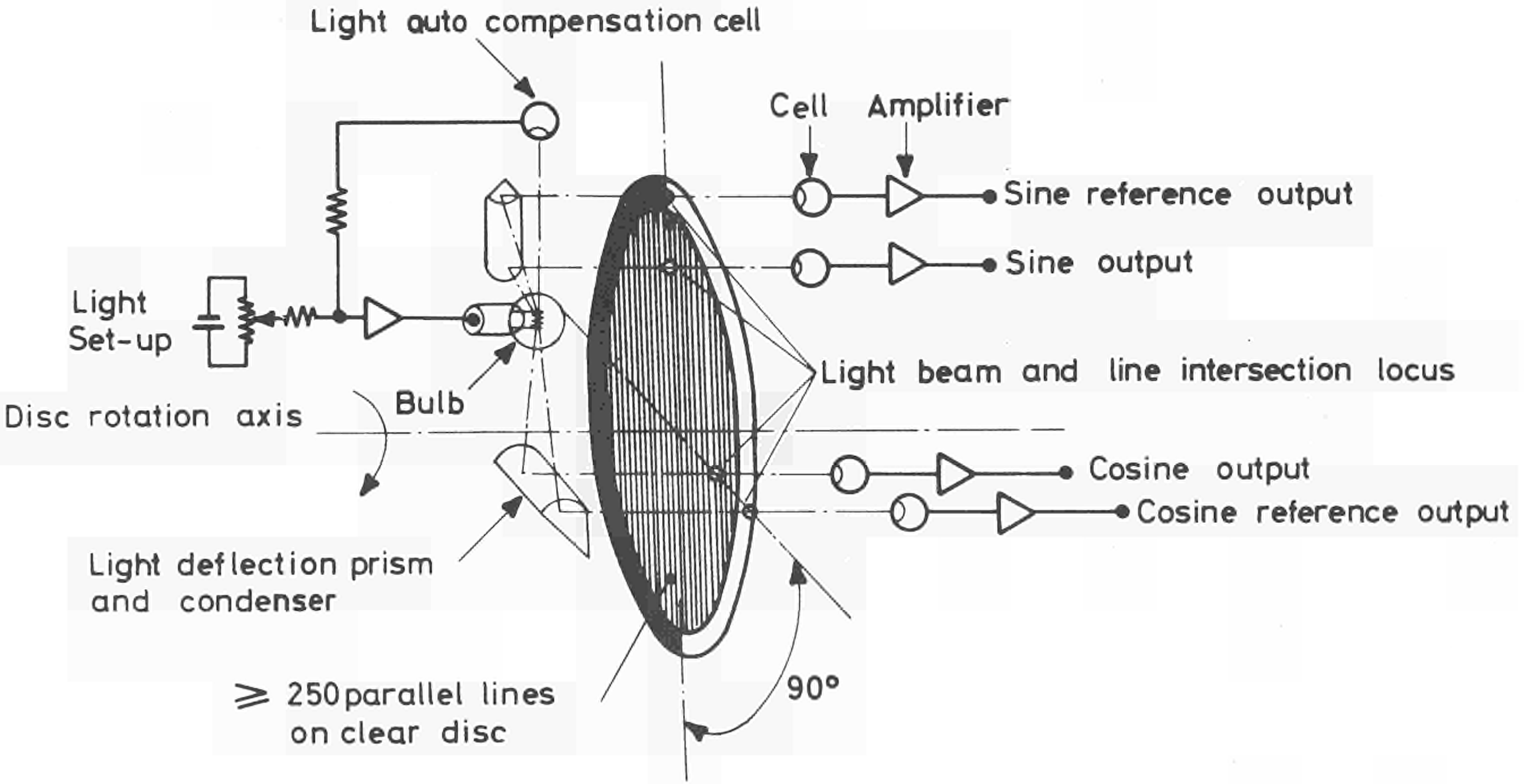
LOGIC UNIT - SINE AND COSINE MULTIPLIER PC N°4



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PRINCIPLE SCHEME OF GENERATOR SINE - COSINE

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> Alfred Nobel

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