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POSITION TRANSDUCERS FOR NUMERICALLY CONTROLLED MACHINE TOOLS

by

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DEPARTMENT OF PRODUCTION AND INDUSTRIAL ADMINISTRATION

INSTRUMENTATION AND AUTOMATION SECTION

Position transducers for numerically controlled machine tools

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SUMMARY

The paper covers the basic text book theory of all forms of position transducer used on commercial numerically controlled machine tools. Some attempt is made to categorise and indicate the scope and usage of these devices. The descriptions deliberately set out to explain this essentially electrical topic in a manner not requiring expert electrical knowledge.

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Introduction

In the numerical control of drilling, milling and other similar machines, the table is positioned relative to the cutter by comparing the monitored table position with a demanded numerical input. The monitor, input and associated computation is in all instances electrical. Figure 1 shows the basic layout of a numerically controlled machine tool indicating the use of feedback control techniques.

This note deals solely with the elements used for monitoring table position which are referred to as position transducers. As already mentioned, they will all be electrical devices as pneumatic or hydraulic units are, not at the moment, suitable for other than short stroke monitoring.

The type of transducer used depends upon the cost, accuracy and adaptability to numerical control, and may be either linear or rotary. With rotary transducers it is necessary to convert to linear position by using a leadscrew or rack and pinion, most commonly by measuring displacement of the drive leadscrew. The control of leadscrew angular displacement is the simplest and the cheapest so that, using high class recirculating ball and nut leadscrews, overall positioning accuracies of the order of .001"/foot can be achieved. Much higher accuracies are claimed but these must be treated with reserve, particularly as a machine ages. Back-lash errors can be minimised by utilising unidirectional final positioning.

Linear transducers are used to give greater accuracy, since they measure actual table position, thus eliminating leadscrew errors. Since the table drive is inside the control loop, ageing of the machine does not cause much deterioration in performance. Overall accuracies of the order of .0002"/foot and better can be achieved, although it is probable that such accuracies are swamped by machining errors. Linear transducers must also be used for machines not driven by leadscrews, e.g. hydraulic rams. Rotary transducers and precision leadscrews could be used in these cases, but the total cost would be higher than a linear transducer with probably lower accuracy.

It is almost impossible and unnecessary accurately to categorise transducers but figure 2 gives a general idea. Two categories are introduced viz.: Analogue, in which a change in position gives a smooth change in output; and Digital, in which changes in output occur as a number of finite quanta.

Some transducers are absolute in that they give a unique output for any position over their whole range viz: - a slide wire potentiometer, but because of accuracy and resolution problems, most will only resolve within a limited range; common ranges are .01"; .1" linear or 1 revolution rotary, repetitive over the full range of the machine. Since one cycle is the same as any other it is necessary to use additional coarse, and possibly medium, transducers capable of positioning within one specific cycle.

Certain cyclic transducers such as the synchro are not truly analogue since they are always used at a null position. The position of the null can be varied by controlling the inputs to the transducer and are thus particularly suitable for numerical control. Cyclic transducers having a fixed null position and giving out a variable, usually roughly sinusoidal, signal proportional to displacement are not linear, and therefore not accurate enough for other than null positioning; they are generally used as line standards with a short stroke system to interpolate between two nulls.

Incremental systems are used in which the output is a number of pulses, each corresponding to a specific, small movement, say .0001". These pulses are counted and compared to the demanded number, the error being zero when these two numbers are equal.

In addition to the above continuously monitoring systems, cheaper transducers are now appearing which use a type of commutator on which a particular segment is excited so that, when the table is in position, the pick-off brush signals the machine to stop. In fact, due to inertia effects, the machine would first reverse and creep back before stopping so as to position accurately, but with noticeable overshoot. This is a form of discontinuous monitoring giving no feedback when the system is unpositioned.

Types of position transducer

1. Potentiometers

a) Resistive

Simple slide wire resistance potentiometers are analogue transducers which give a voltage proportional to linear or rotary displacement (Fig. 3). The accuracy is low over any length due to contact and uniform resistivity problems, so that their only application in machine tools is as a coarse positioning element for use with other fine elements.

b) Inductive

Inductive potentiometers are in effect tapped transformers, the tappings being positioned proportional to the displacement, the output being a series of discrete (a.c.) voltages (Fig. 4). Toroidally wound transformers are used so that the actual voltages can be set accurately, giving a high transducer accuracy, but a low resolution so that some other device must be used to interpolate between consecutive taps.

This system was used on the early E.M.I. continuous contouring machine, where the tapping was done by a multi-position rotary switch geared to the machine leadscrew. Three banks of switches were geared together through 10:1 ratios to give an extended range, and resolution between each fine tapping was done using a LINVAR which is a rotary transformer giving an output voltage proportional to rotation. Since these devices are linear only over ± 80°, they have two quadrature windings so that with suitable switching they cover the full 360° range. In fact the switching circuits involving the Linvar and the tapped switches were complicated by the possibility of shorting two segments together, ambiguity etc., but a simplified scheme is shown in fig. 5. The overall accuracy was limited to about ± .001".

c) Capacitive

Capacitive potentiometers are contactless and comprise two concentric cylinders, one much shorter than the other. The longer, reference bar is made up of accurately machined segments, 1" long, electrically insulated and fed with discrete a.c. voltages while the slider (outer) is two segments in length. Were the slider a point, the output voltage between the slider and one end of the bar would be stepped as shown in fig. 6(a). With the slider covering two segments, however, the output voltage will be proportional to displacement (Fig. 6(b)). To improve further the linearity of the device, the actual voltage applied to each segment can be finely adjusted by additional adjustable series transformers.

These transducers were developed by Riley Hydraulics Ltd., which are now part of Sogenique (Societe Genevoise Ltd.). They are made in any length, commonly up to 40", and when corrected are accurate to .0001". They are at present used as position indicators but are obviously suitable for numerical control applications.

All the potentiometers described give analogue outputs proportional to position but also dependent upon the magnitude of the reference voltage. This is eliminated as a source of error in practise by using the potentiometer in a bridge circuit (Fig. 7). Here the computer arm is set, either by hand, or by uniselector switches or solid state logic circuitry, operating from punched paper tape. To get high accuracy the computer arm can be a tapped, toroidally wound transformer arrangement or a Kelvin-Varley slide, Fig. 8. Each decade is set separately by the demanded signal, e.g. a demand of 5.631" would set decade 1 to position 5, decade 2 to 6, decade 3 to 3 and the least significant decade to 1. This device is only usable for transducers such as potentiometers which have directly proportional outputs, and not for devices such as synchros for which voltages proportional to sine and cosine must be resolved.

2. Synchros and Resolvers

This section will cover only the rotary variety of synchros and resolvers, the linear types being described in section 3.

Some confusion existed over terminology, but military specifications have led to standardisation of sizes, voltages, frequencies, etc., so that such items as Magslips, Selsyns, etc., are similar in principle but different in size. The resolver is also known as a synchro-resolver or a sine-cosine resolver.

There are a number of varieties of synchro, in size, frequency and mainly in the details of the windings, but basically the synchro is a '3-phase' type of winding and the resolver a '2-phase'. Since it is a 2 phase device the resolver is more suited to the computation of the input demand and so is in more general use on machine tools than the synchro.

The physical construction is similar to a motor, having a fixed cylindrical outer casing, carrying a winding and known as the 'stator', and a concentric rotatable 'rotor', also carrying a winding, connection to which is made through slip-rings. The '3-phase' (synchro) winding comprises three coils spaced physically by 120° (Fig. 9a) while the '2-phase' (resolver) winding has two coils at right angles (Fig. 9b). The basic rotor is single phase in both cases.

Since all position control will be of the rotor relative to the stator the following descriptions will assume that the stator is correctly mechanically aligned and fixed. In fact final datum setting is done by rotating the synchro stator.

The following symbols are used:-

Φ = the actual rotor angle (relative to the stator)

θ = the desired rotor angle, defined by the input command θ_i

ω = frequency of the excitation voltage, which lies between 50 c/s and 1000 c/s.

N.B. Care should be taken not to confuse sinusoidal variations of amplitude of signals as functions of position, i.e. Sin θ with sinusoidal variations with time, i.e. Sin ωt. Hence the voltage V Cos $(\theta-\Phi)$ Sin ωt is a sinusoidal voltage at a frequency ω ($\frac{\omega}{2\pi}$ c/s) whose amplitude is dependent upon the difference between demanded and actual rotor positions and for example will be of zero amplitude when Φ and θ differ by 90°.

There are two modes of operation using either alternating or rotating fields. An alternating field is a magnetic field of fixed direction, but sinusoidally varying amplitude, while a rotating field is of constant amplitude rotating at a constant speed equal to the excitation frequency (c.f. a permanent magnet rotated at 'synchronous' speed).

i) Alternating field. (Single phase - amplitude detected output).

To produce an alternating field, single phase voltages only are required. The two resolver stator windings are fed with a.c. voltages of amplitudes proportional to V_1 Sin θ (reference) and V_1 Cos θ. This produces a field at an angle $(90 + \theta)$ to the reference winding so that when the rotor angle Φ is equal to $(90 + \theta)$ there will be a maximum coupling and in general the rotor output will be $V_2 \text{ Sin } (\theta-\phi) \text{ Sin } \omega t$. The maximum amplitude V_2 will depend upon V_1, the number of turns on stator and rotor windings, and the coupling coefficient. It can be seen that when the rotor is at the desired angle i.e. $\phi = \theta$, the rotor voltage will be zero, thus acting as an error detector. Note however that a false null will also occur when ϕ and θ are 180° out of phase, making the transducer analogue over only half a revolution. The error voltage must be fed to a phase sensitive rectifier, which will rectify the a.c. signal to produce a d.c. voltage of polarity dependent upon whether the a.c. voltage is in phase or in anti-phase with the reference, thus producing an error voltage of the correct polarity to return the servo to the null from either direction.

With a synchro three stator voltages of amplitude $V_1 \text{ Sin } \theta$, $V_1 \text{ Sin } (\theta+120°)$ and $V_1 \text{ Sin } (\theta-120°)$ are required, otherwise the operation is as described above (Fig. 10).

Since the demand voltages are single phase they can be developed by selective switching of tapped transformers. The absolute overall voltage V_1 is not important, provided it is the same for each stator winding, which it will be if all supply transformers are excited from the same source.

ii) Rotating fields (polyphase - phase detected output).

To produce a rotating field, polyphase voltages are required, 3-phase for the synchro and 2-phase for the resolver. Since the rotating field produced is constant in amplitude and speed of rotation, the rotor voltage will be sinusoidal, of constant peak amplitude, but of phase dependant upon the position ϕ. Thus the resolver must be excited by equal amplitude, quadrative phase signals $V_1 \text{ Sin } \omega t$ and $V_1 \text{ Cos } \omega t$ and the induced rotor voltage will be $V_2 \text{ Sin } (\omega t-\phi)$. If a signal $V_3 \text{ Sin } (\omega t-\theta)$ is generated by the computing element, where θ is defined by the demanded input θ_i, then the error signal is developed by comparing this voltage with the induced rotor voltage. This requires a phase sensitive detector the output of which is a d.c. signal proportional to the phase difference $\theta-\phi$ which has an advantage over (i) in that there is only one null per revolution. The computing of the polyphase signals is more difficult than the single phase case and it is done in one system, the I.G.E., (Fig. 11), by using a crystal oscillator running at 250 Kc/s. and frequency dividing by 1000 to generate the basic reference frequency of 250 c/s and producing the phase advance or lag, by adding or subtracting the appropriate number of high frequency pulses.

The accuracy of synchros and resolvers can be as high as 5 minutes of arc but is usually ± 20 minutes, including errors in the associated circuitry.

Since the single phase case is controlled over only half a revolution and the polyphase case over one revolution, both will need a coarse positioning device to define the correct cycle. This is often another resolver, geared down, or a potentiometer (Fig. 12).

3. Linear resolvers

Linear resolvers are similar in principle to rotary resolvers but they are printed on linear scales with a pitch, corresponding to one revolution of a rotary resolver, of about .1″. Thus the 'stator' will be a multipole device giving one cycle of electrical output for a linear movement of one pitch. The output is an analogue of the position within any cycle but must be used in conjunction with a coarse position transducer to define the correct cycle. Very often the coarse positioning is done using a conventional resolver to measure the drive leadscrew position.

Two types are used commercially:-

i) The Farrand Inductosyn, used by E.M.I., which is inductively coupled and comprises a single phase rotor as long as the required traverse, and a two phase stator, or cursor, about 2″ long. (Fig. 13). The windings are of hairpin form, are copper or gold printed on glass or paxalin and should have a working gap of about .005″. To form the two phase cursor windings, the groups of windings are spaced relatively one quarter of a pitch. The stator windings are fed, as in the conventional resolver, with in phase currents at 1 Kc/s. and of amplitudes proportional to Cos θ and Sin θ so that the linear position of the null rotor output will be $\frac{\theta}{360}$ x pitch. Thus the two currents I Sin θ Sin ωt and I Cos θ Sin ωt must be simulated by the control equipment so as to define the required displacement, in addition of course to the coarse positioning. A circular version is also available.

ii) The A.E.I. Helixyn comprises two concentric cylinders carrying helical windings. As with the Inductosyn the full length fixed bar is the single phase 'rotor', while the shorter 'interpolator' has a double winding space to give a two phase effect (Fig. 14). The coupling is capacitive so that d.c. voltages, V Sin θ and V Cos θ fed to the stator will produce a null in the rotor output at the defined position. In practise instead of d.c., pulses are fed at a fixed rate to the bar so that transformer coupling of outputs and inputs can be used.

The bar is made of fibreglass and steel and the winding has a pitch of .1024″, chosen since $1024 = 2^{10}$, a fact which simplifies the digital computation of the input voltages in which .0001″ is the size of the smallest computed bit - note however that the error signal developed by the Helixyn is truly analogue, at the pulse repetition rate, so that an error signal will be developed for errors less than the smallest bit, thereby possibly giving greater resolution. The helical form of construction has an advantage that relative rotation will cause relative linear displacement, a fact which is used in setting zero positions and also in the use of corrector cams for improving overall accuracy.

In practice the amplitudes of the voltages (or currents) V Sin θ and V Cos θ need not be accurate individually, provided their ratio is exact, thus changes in reference voltage are not critical. In this way accuracies as good as ± .0001″ can be achieved.

4. Variable inductance bridge

This device, known as an Accupin, is the high accuracy linear transducer used by I.G.E. (International General Electric Company). It is also made in circular form. It comprises a comb-like structure a little longer than the required traverse, made of precision ground pins accurately positioned on .1″ centres. The pins are .098″ diameter to ensure no crowding, and are made of a magnetic steel while the base is non-magnetic. This 'scale' is bridged by a set of reading heads, wound on 'C -cores' (Fig. 15). Thus the scale acts as a variable reluctance path to the head so that the coil will have a maximum inductance when the head sits across the maximum pin diameter and a minimum inductance half a pitch later. To increase the accuracy a single head is made of four adjacent C-cores spaced one pitch apart and accurately centred. Each of these composite heads is called a 'quarter' head. A 'half' head comprises two 'quarter' heads spaced half a pitch different, in fact by 8½ cycles, i.e. .850″. Thus when one quarter head has maximum inductance the other has minimum, an arrangement which is used as an inductance bridge (Fig. 16).

The a.c. output is high (about 3 volts maximum) and varies reasonably sinusoidally in amplitude with displacement. Thus, similar to a resolver, the output will be $V \sin \phi \sin \omega t$. This however could only be used for measuring position by measuring absolute amplitudes $V \sin \phi$ which will be of very low accuracy.

The complete circuit comprises two half head assemblies spaced a convenient number of whole pitches plus a quarter of a pitch, i.e. 2.025″. Thus the second half head bridge output would be $V \cos \phi \sin \omega t$.

This system as described is used in a position control by simulating the a.c. voltages of amplitude $V \sin \phi$ and $V \cos \phi$, which is more accurate than using one half head only but will still probably only give accuracies of about .001″.

Much improved accuracy is obtained by using the two-phase resolver technique previously described and feeding one half head with $V \sin \omega t$ and the other with $V \cos \omega t$ (Fig. 17). Thus the bridge outputs are $V \sin \phi \sin \omega t$ and $V \cos \phi \cos \omega t$, which when added electrically give $V \cos (\omega t - \phi)$. Thus if a demand voltage is produced from input information θ_i of the required phase, the Accupin output can be phase compared to produce an error signal. This arrangement is completely compatible with the I.G.E. resolver system (Fig. 11) so that either a resolver or an Accupin can be used as the fine transducer using the same coarse positioning and computing systems. Overall accuracies of ± .0003″ can be achieved.

5. Diffraction gratings

The diffraction gratings used on machine tool systems are line and space types. The simple type comprises a glass scale ruled with opaque lines, such that the lines and spaces are of equal width, of a pitch of from 500 to 2500 lines per inch. Gratings must be used in pairs so that light shone through the pair of gratings can be detected by a photo cell. When the lines of the pair of gratings are coincident maximum light will be transmitted and when the lines of one grating and spaces of the other are coincident very little light will be transmitted. Thus by moving one grating relative to the other, a distance of one ruled pitch in a direction at right angles to the rulings, the photo cell output will vary roughly sinusoidally (Fig. 18). The index grating need only be as large as the photo-cells and is usually contained in a reading head along with the bulb, lens, etc. The main grating is fixed to the machine base and the reading head to the table or vice-versa. This is a d.c. system and due to inherent limitations of the d.c. amplification and the accuracy of the voltage - displacement curve it is only sufficiently accurate to detect the peaks and mean values of this waveform which can be converted into pulses and counted. Thus a 1000 line per inch grating when moved 1″ will generate 1000 cycles (or 4000 pulses if required) which can be counted and displayed as 1.000. This of course is an increment of 1″ and not an absolute dimension. Some means of detecting direction of motion must now be introduced so that in moving back to the starting point 0.000″ is displayed and not 2.000″. To do this a 'Moiré' fringe is produced by inclining the relative angle of the rulings of the two gratings. This produces a fringe of dark and light patches of say $\frac{1}{2}''$ pitch at right angles to the ruling which move one fringe pitch for a movement of the gratings of one ruled pitch. This can still be detected by photo cells. Obviously a high degree of magnification can be obtained since the actual fringe width is a function of the relative angle of inclination of the rulings and $\frac{1}{2}''$ is a reasonable figure giving enough spread with good definition. Of more importance however, is the fact that if the direction of relative motion of grating is reversed then the direction of movement of the fringe will also reverse. Thus using two photo-cells spaced $^1/_4$ of a fringe width apart the outputs will be $V \sin \theta$ and $V \cos \theta$ for one direction of motion and $V \sin \theta$ and $- V \cos \theta$ for the opposite direction of motion. This additional information fed to the logic circuits of the counter can demand, add or subtract signals as necessary. To avoid lost counts all logic (add or subtract) is determined from the leading edge of a derived pulse and the actual counting of the trailing edge. In practice four photo cells are used deployed across the fringe to give an averaging effect and also to facilitate the production of 4 pulses per fringe motion as previously mentioned.

Thus the Ferranti co-ordinate measuring machine uses a 2,500 line per inch grating and divides by 4 circuits to read in increments of .0001″.

The early Ferranti Mk III continuous contouring control (Fig. 19) also used this system by feeding pulses from magnetic tape into a reversible store and subtracting from the store pulses from the gratings, the error signal being a d.c. voltage proportional to the number of pulses left in the store. This was complicated by the complex design of the reversible store since it needed to be synchronous, i.e. input and grating pulses could occur simultaneously and must not be lost, and so has now been replaced by the phase modulated Mk IV system described below.

The accuracy of such systems is high since the actual rulings, manufactured by error eliminating photographic reproducing techniques, are accurate to about ± 20 micro inches. The average effect of the large number of rulings under the photo cell also maintains accuracy so that most error comes from associated equipment. Accuracies of ± .0001″ can be achieved.

Phase modulated diffraction grating systems

In order to utilise the coarse pitch (100 lines per inch) stainless steel reflection type gratings with the inherent advantage of steel over glass it is necessary to sub-divide each fringe by 100 if .0001″ resolution and accuracy is to be achieved. Obviously an a.c. system must be introduced and this is done by rotating at constant speed a ruled drum which produces interference patterns with the index and moving gratings giving constant frequency signals from the photo-cells (Fig. 20). The relative phase of the two signals however will depend upon the relative displacement of the gratings and a displacement of 1 ruled pitch (.010″) will cause a phase change of 360°. Thus to obtain accuracies of .0001″, the phase must be controlled to 3.6°. Figure 21 shows a circuit for utilising this system in which magnetic tape feeds continuous signals to the control system and motion and position are controlled by varying the phase of the tape recorded signal.

This is used, much modified in detail, in the Ferranti Mk IV and Staveley systems. The Ferranti system uses a large radius spiral ruled disc which is rotated at constant speed by a synchronous motor to produce the a.c. signals while the Staveley system uses Moiré fringes and 4 photo cells and generates the a.c. phase modulated signals electrically by sampling the photo cell signals cyclicly.

6. Quantisers

A Quantiser is very similar to a diffraction grating but of such a pitch as to provide no optical problems and is used just to produce a train of pulses with no direction sensing. They comprise ruled radial lines on a circular disc and are mounted on the leadscrew. They can only be used for sequential operations, i.e. position control in which the demand will be to move x pulses in a particular direction. The accuracy is limited by low resolution to about ± .001″ linear equivalent as on the Pratt and Witney Tape-O-Matic.

It would obviously be possible to produce an electro-magnetic quantiser.

7. Encoders

Encoders take the quantiser one step forward in that the displacement is split into a number of discrete increments but each one is identified by a code, either binary, Gray or binary-coded-decimal. The system is thus absolute. Fig. 22 shows a typical linear Encoder or Coded Commutator Plate, constructed of conducting segments printed on a non conducting base. A set of brushes thus reads off the indicated number, the number of tracks required being determined by the largest number to be defined. A refinement would be to use an optical system of transparent and opaque spaces detected by photo cells, this having the advantage of no contacts.

The biggest problem is resolution, since while linear optical scales can be made with increments of about .001″ they are very prone to reading errors and are costly so that the only application so far is a circular device used with a leadscrew as on the Renault machine.

8. Differential transformers

Two very different types are used, the variable coupling type, typified by the Nultrax unit and the variable reluctance type used by the A.E.I. as an 'inch bar'.

i) The Nultrax differential transformer (Fig. 23) comprises a steel cylindrical bar with a shorter concentric steel sleeve. Each is wound with a biflar winding (i.e. consider a hair pin wound around a pencil) so that a voltage applied between the two ends will cause adjacent conductors to carry current in opposite directions. The inner bar is the full length required by the traverse and the outer is wound with about 50 turns, thus giving an averaging effect. The pitch of adjacent turns is about 0.1″.

When the inner winding is excited a voltage will be developed in the sleeve winding which will be a maximum in fig. 23a, and zero in fig. 23b. There will obviously be another maximum of opposite phase so that within one cycle the output will be a.c. of amplitude proportional to the sine of the position. A null will therefore be produced every .1″. The position of the null within a cycle can be varied, because of the helical winding, by rotating the inner bar. A coarse positioning element is needed to select the correct cycle and angle of the inner winding the servo then positioning the table to the null of the differential transformer. A phase sensitive rectifier must be used as with a resolver. This system is not in use in England at present.

ii) The A.E.I. inch bar is intended as a 1 inch pitch line standard. A coarse positioning element defines the required section and fine positioning is achieved by using further synchros to sub-divide the inch by moving the reading head. Since the stroke is limited to 1″ and this servo has only to position the head and not the table, high accuracy can be achieved. The main table drive servo is then actuated by an error signal from the 'inch bar' (Fig. 24).

The inch bar itself comprises a series of accurately machined and mounted 1″ square pieces with a $^3/_4$″ diameter hole drilled through, which is filled by a non-magnetic insert (Fig. 25a). The reading head (Fig. 25b) is a differential transformer so that equal voltages are induced in the transformer secondaries only when the head is square with the inch insert. By subtracting these voltages a null is achieved. This system is very accurate (better than ± .0001″) but is now mainly superseded by the Helixyn. It is however of additional interest in the use of two servos, the positioning and the power drive units.

9. End position indicators

End position indicators are discontinuous monitoring devices, so called since they only give a signal when the demanded position is reached, being effectively open circuits otherwise.

Basically these devices are used to monitor leadscrew position and comprise a set of commutators, one particular set of segments (coarse, medium, fine) of which are energised by the input demand θ_i. The table is then driven towards the required position at maximum traverse rate, usually by an a.c. motor, until the energised segments are finally reached. The signal then stops the motor, reverses and reduces the traverse rate to creep back to the final position to eliminate the overshoot. When final position is again reached the signal stops the machine completely, there being no overshoot due to the creep traverse rate of final approach. A slight sophistication is to ensure that final positioning creep traverse is always in the same direction thus reducing back-lash errors.

Some logic circuitry is required to determine the direction of motion required to move to the next point and refinements to the brush arrangements etc., are made to improve the resolution. E.P.I's are used by A.E.I. and Airmec and are only suitable for position control.

10. Scales

Scales, or line standards, are very accurately ruled lines of fairly coarse pitch (about .050″). They are sensed usually by a photo electric microscope and are used in a similar manner to the A.E.I. 'inch bar' with a fine resolver to sub-divide the line increments and a coarse resolver system to locate one particular ruled line. The Societe Genevoise system as used on their jig boring machines is based on line standards and the accuracy is better than ± .0001″.

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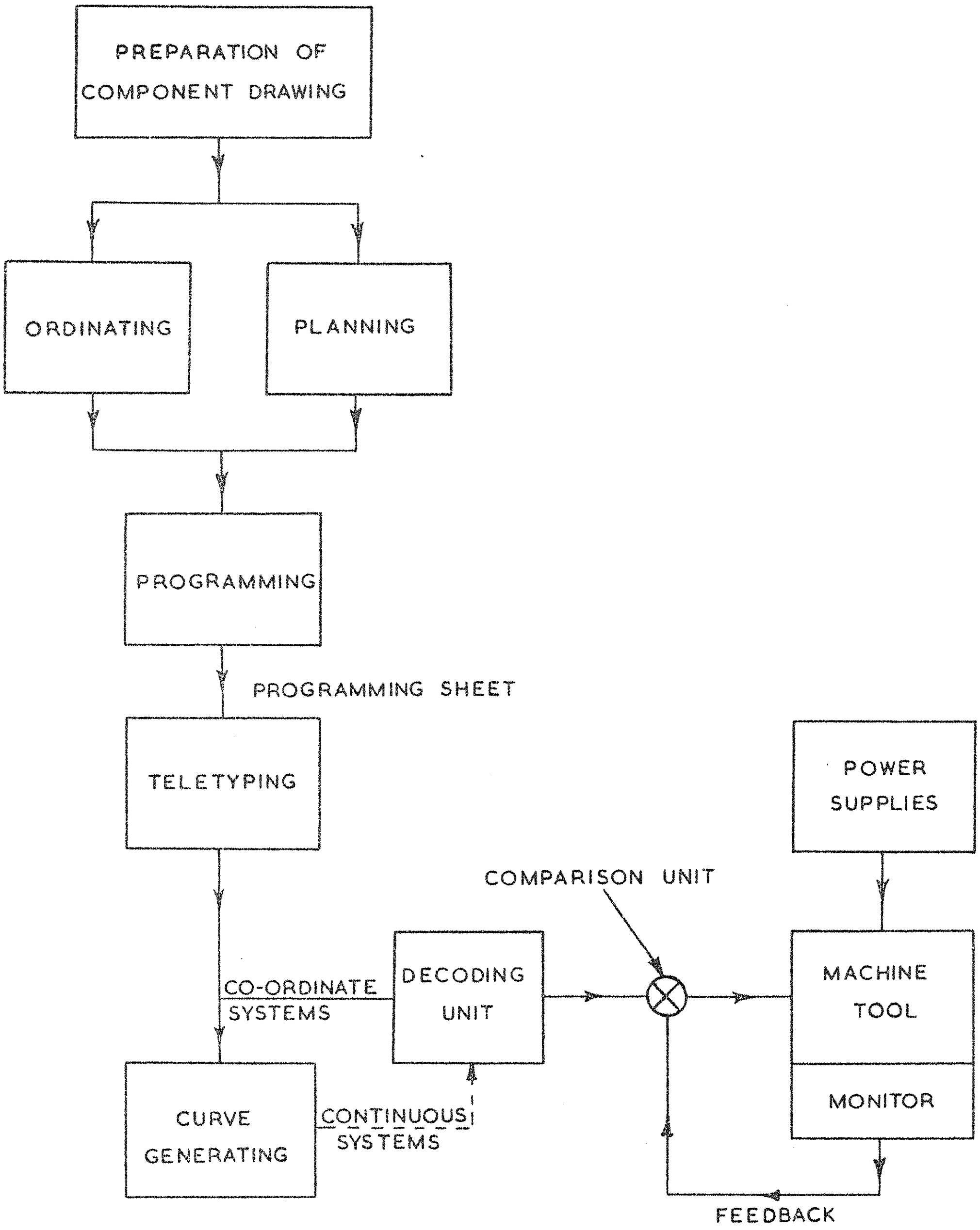
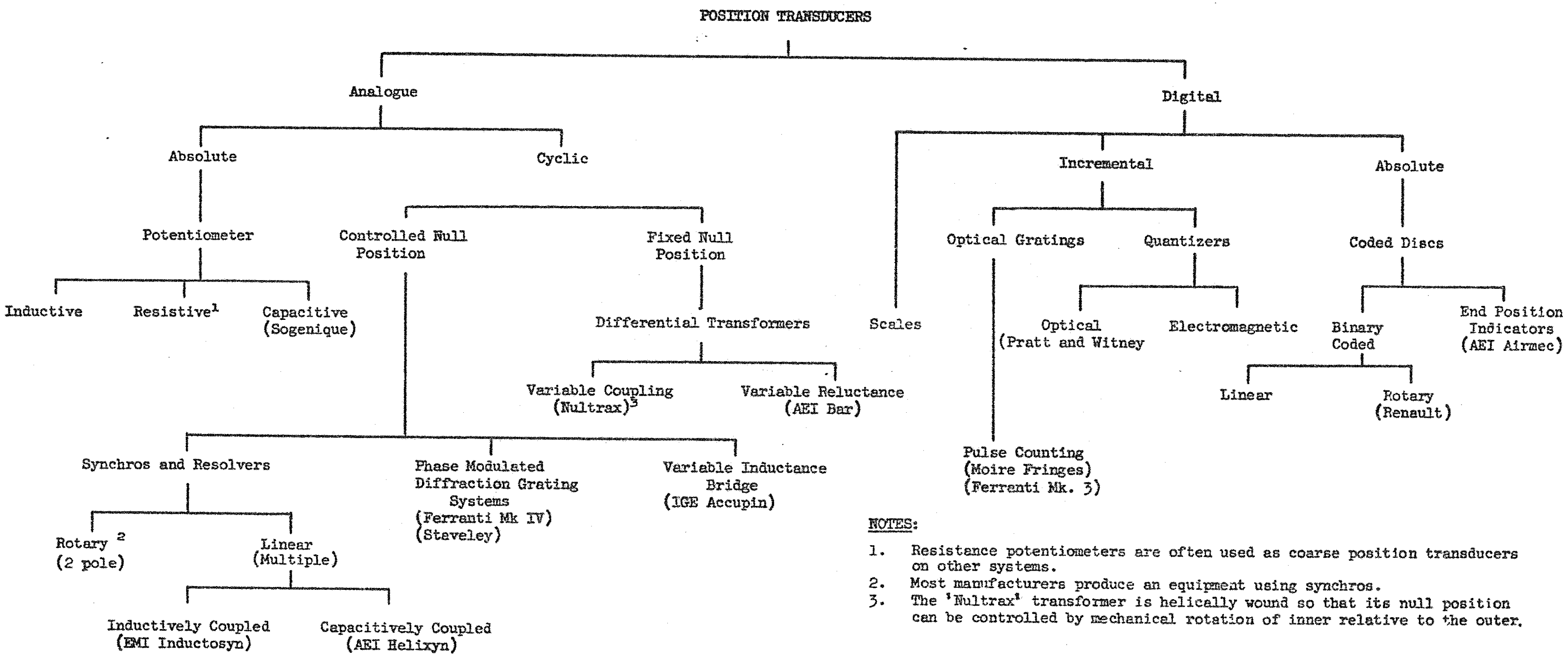


FIG.1. SCHEMATIC DIAGRAM OF NUMERICAL CONTROL SYSTEM.



NOTES:

1. Resistance potentiometers are often used as coarse position transducers on other systems.
2. Most manufacturers produce an equipment using synchros.
3. The 'Nultrax' transformer is helically wound so that its null position can be controlled by mechanical rotation of inner relative to the outer.

FIG. 2

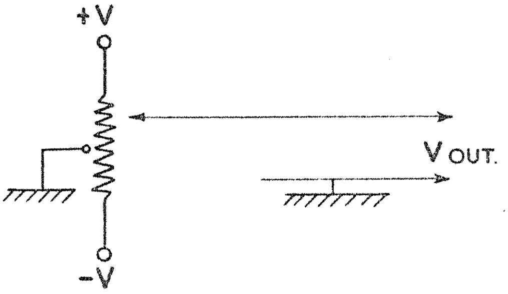


FIG.3. RESISTIVE POTENTIOMETER.

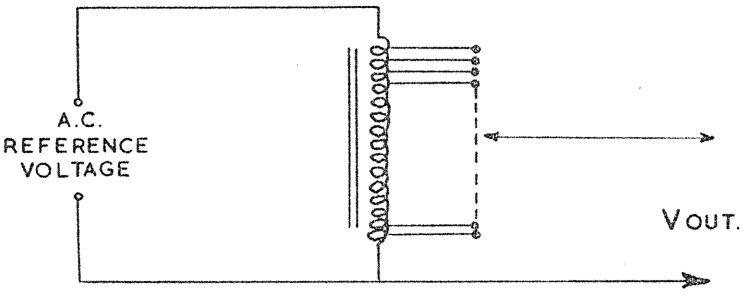


FIG.4. INDUCTIVE POTENTIOMETER.

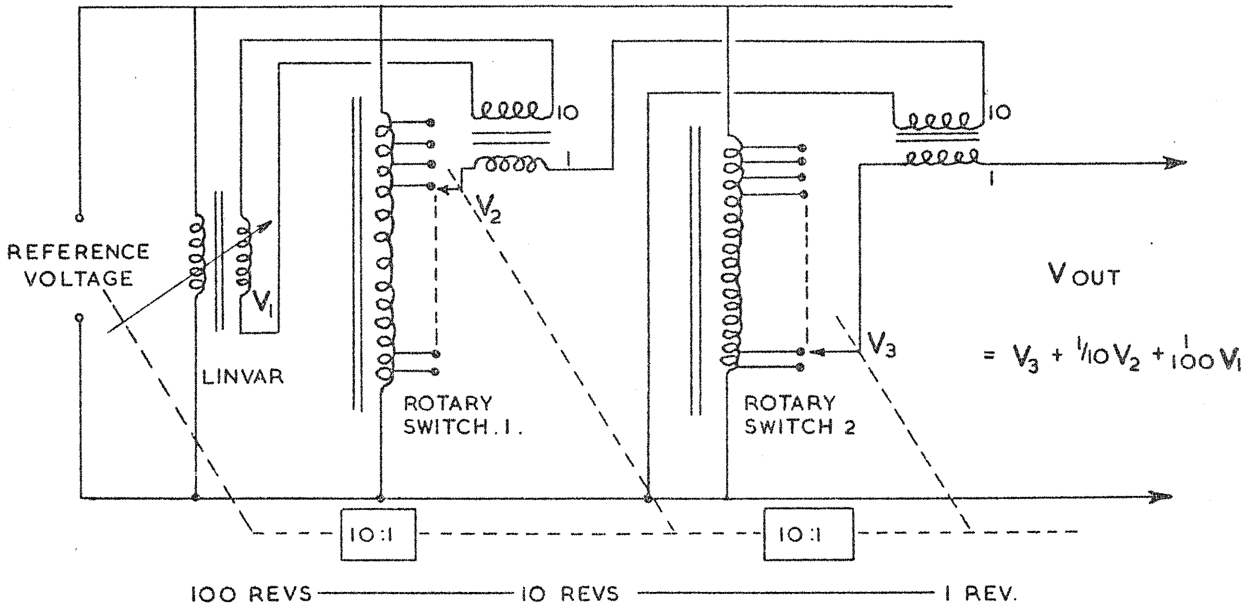


FIG.5. EMI INDUCTIVE POTENTIOMETER (SIMPLIFIED.)

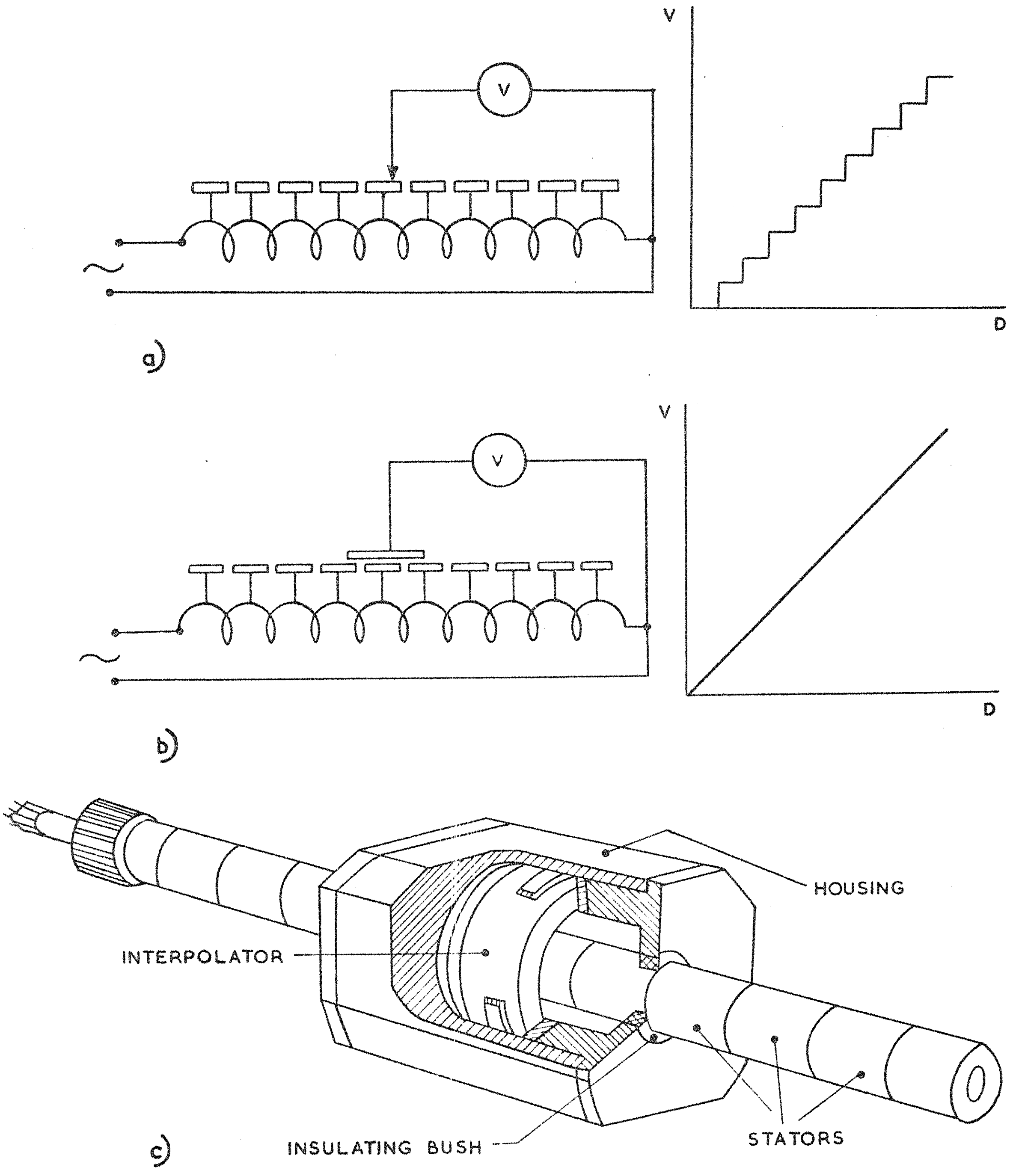


FIG.6. SOGENIQUE CAPACITANCE TRANSDUCER.

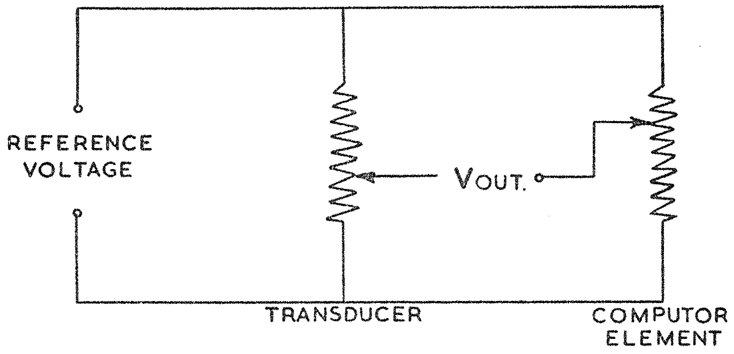


FIG.7. BRIDGE CONNECTION.

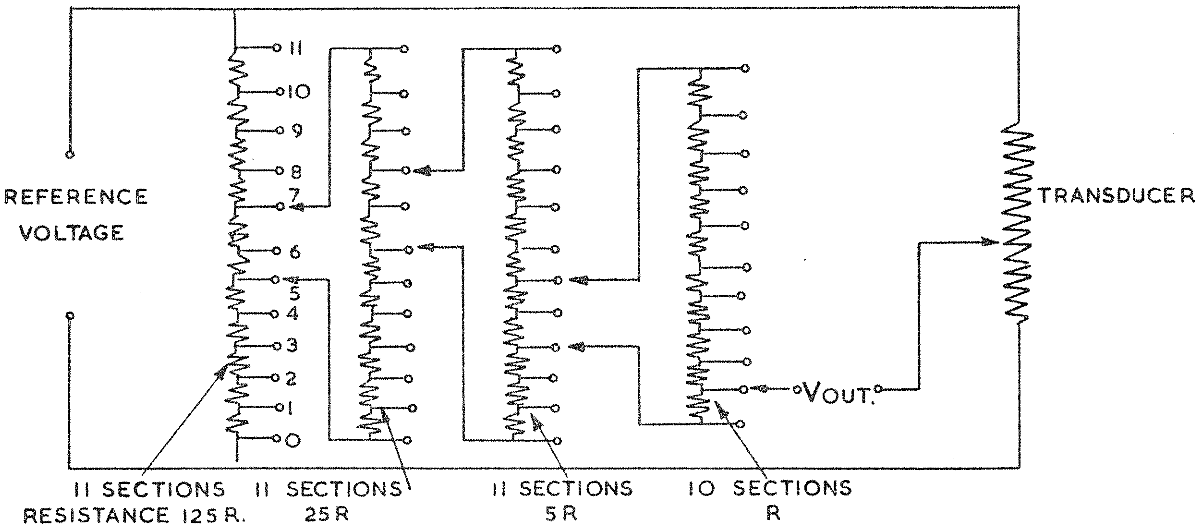


FIG.8 a. KELVIN VARLEY SLIDE (a.c. or d.c. system.)

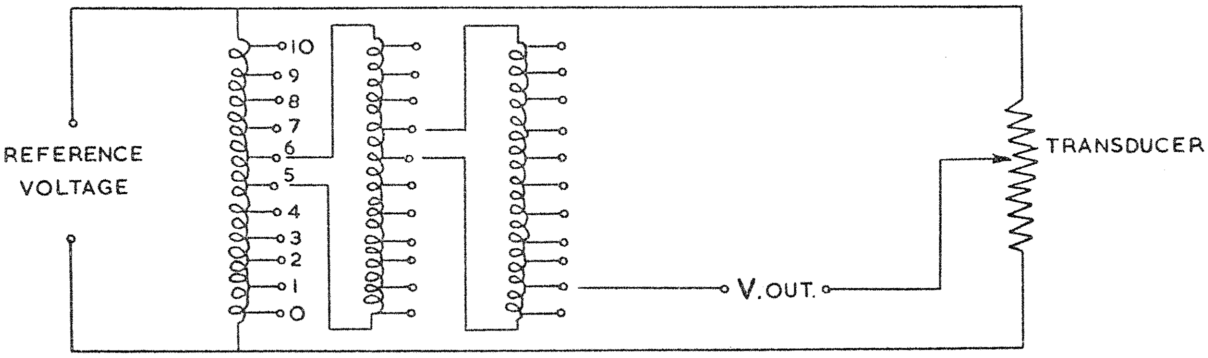


FIG.8 b. TAPPED TRANSFORMER BRIDGE.

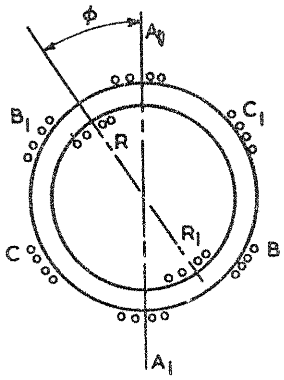


FIG. 9 a. TYPICAL SYNCHRO.

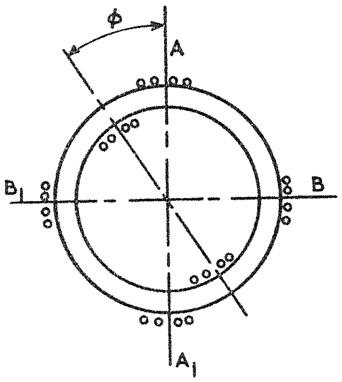


FIG. 9 b. TYPICAL RESOLVER.

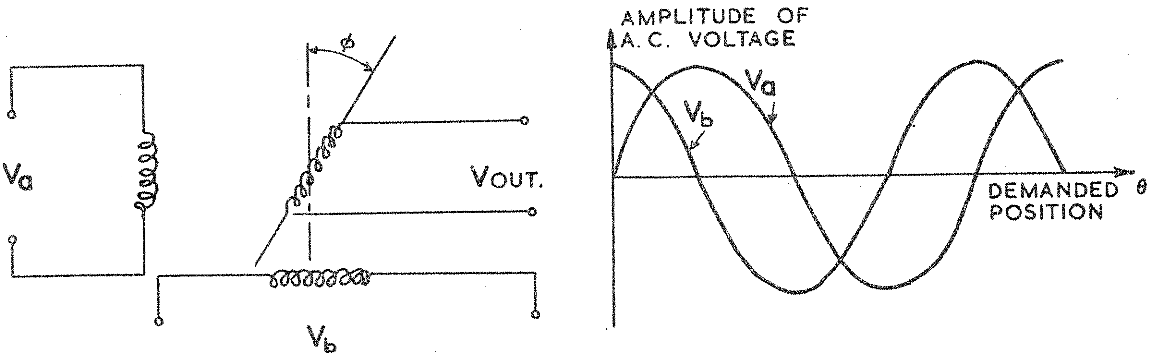
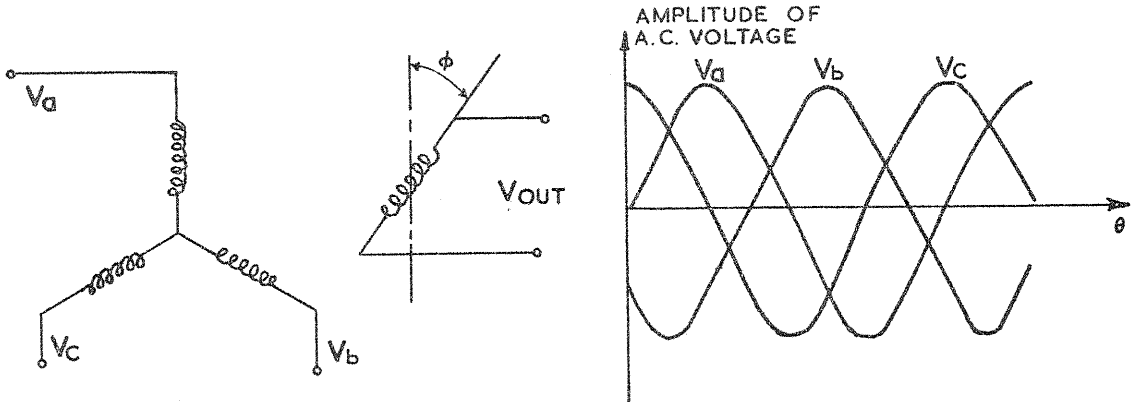


FIG. 10 a. RESOLVER - SINGLE PHASE.



eg. $V_a = V_1 \sin\theta . \sin wt.$

FIG. 10 b. SYNCHRO - SINGLE PHASE.

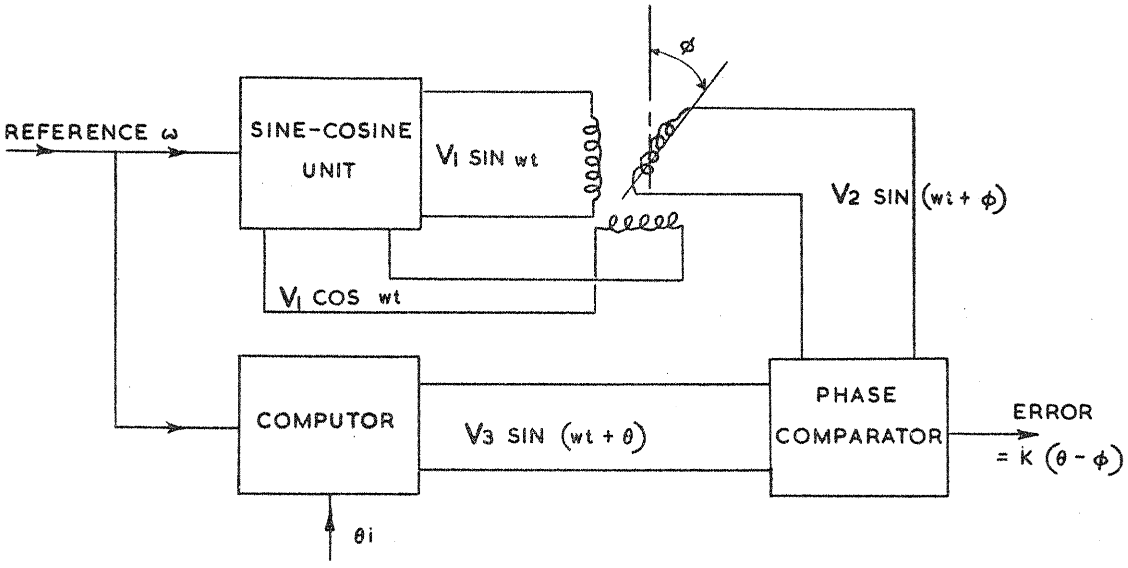
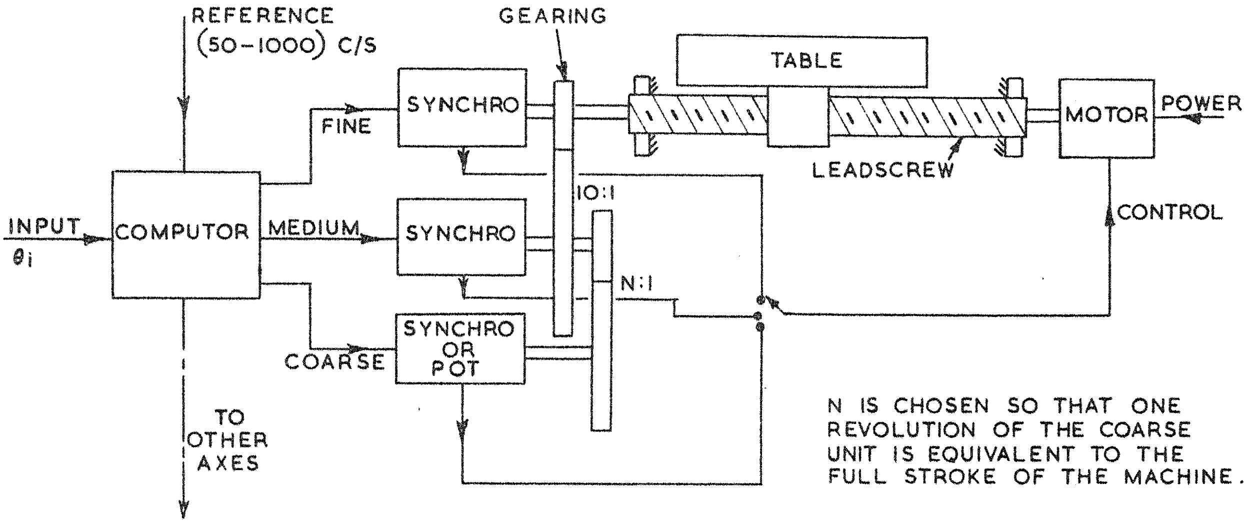


FIG.11. I.G.E TWO PHASE RESOLVER CIRCUIT.



N IS CHOSEN SO THAT ONE REVOLUTION OF THE COARSE UNIT IS EQUIVALENT TO THE FULL STROKE OF THE MACHINE.

FIG.12. COARSE-MEDIUM-LINE POSITIONING SYSTEM.

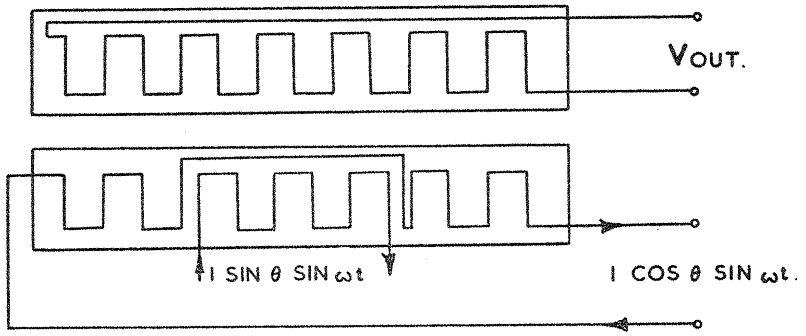


FIG.13. E.M.I. INDUCTOSYN

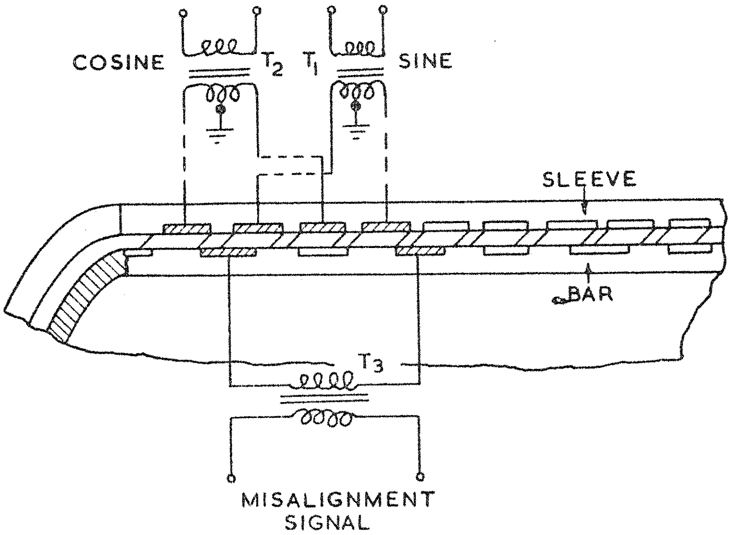


FIG.14. A E.I. HELIXYN.

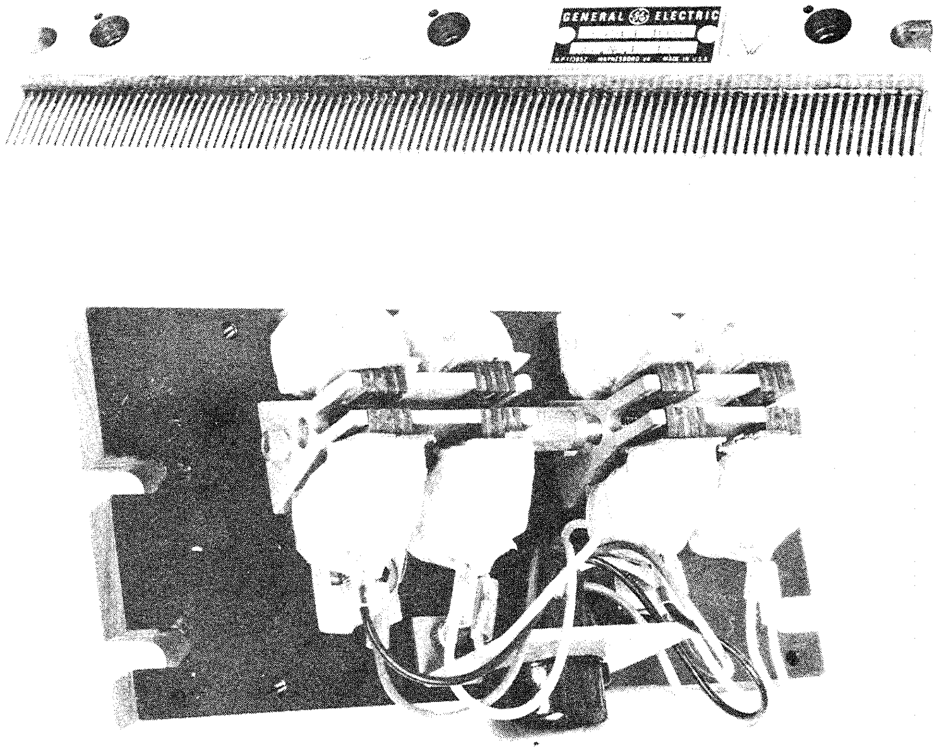


FIG.15. I.G.E 'ACCUPIN' SCALE AND READING HEAD.

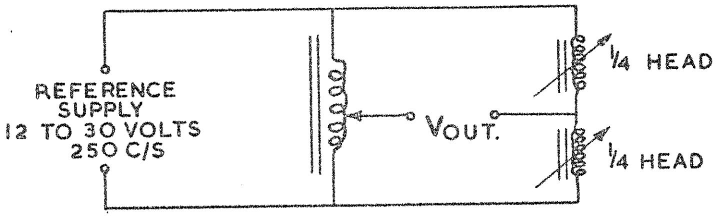


FIG.16. SINGLE PHASE 'ACCUPIN' SYSTEM.

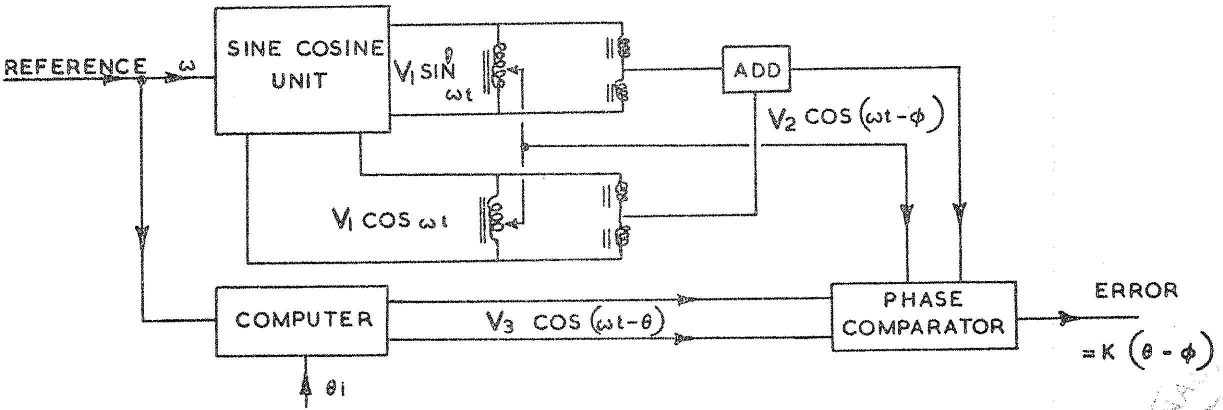
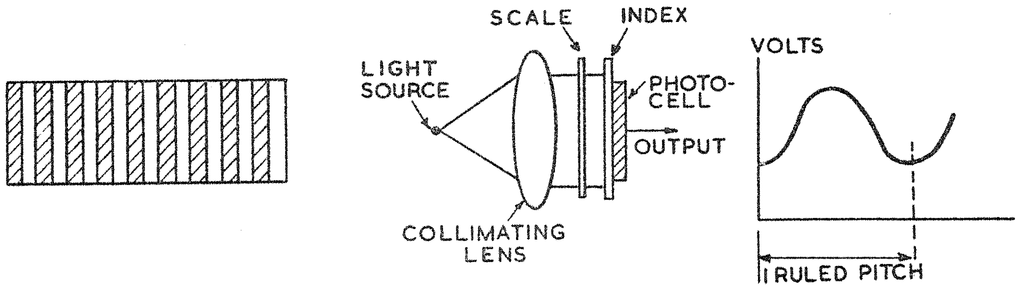


FIG.17. PHASE DETECTED 'ACCUPIN' SYSTEM.



a) LINE AND SPACING GRATING b) LIGHT ARRANGEMENT c) PHOTO CELL OUTPUT

FIG.18. DIFFRACTION GRATING ELEMENTS.

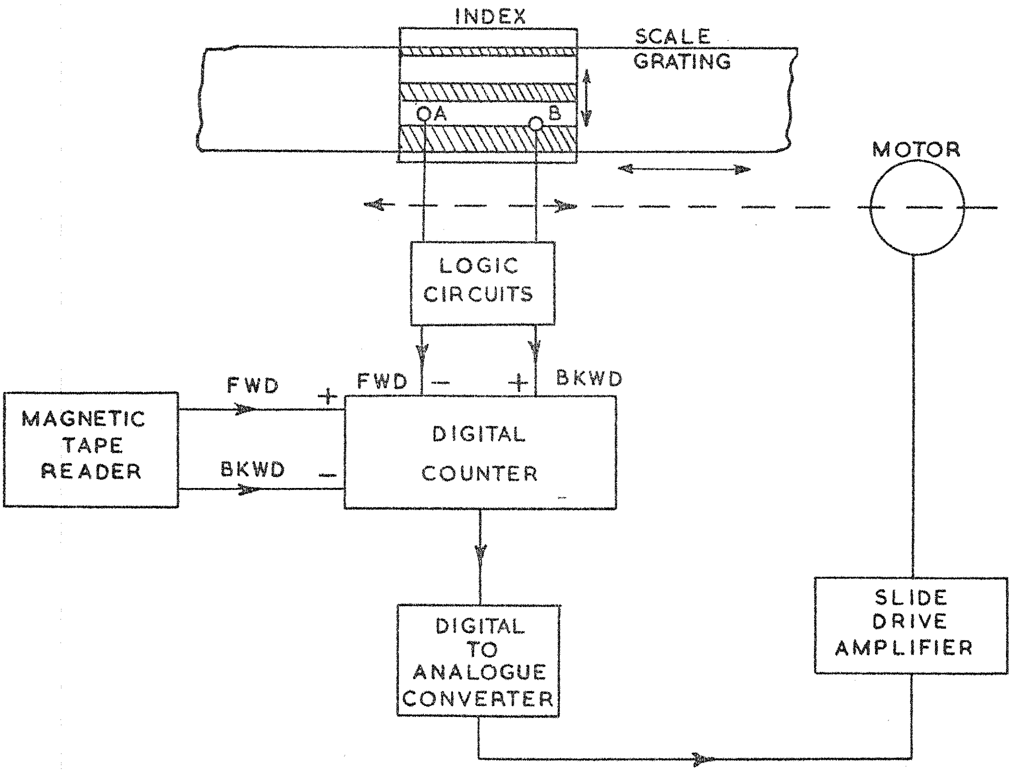


FIG.19. PRINCIPLE OF MOIRÉ FRINGE CONTROL SYSTEM.

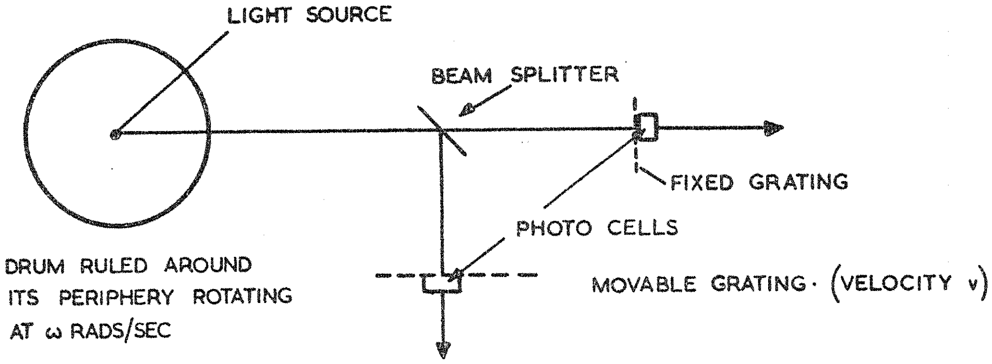


FIG.20 PHASE MODULATED SYSTEM.

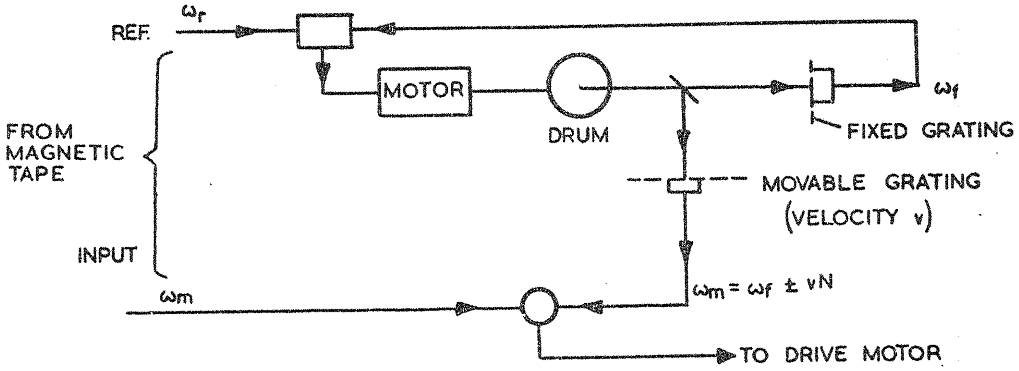


FIG. 21. THE FERRANTI SYSTEM. (SIMPLIFIED)

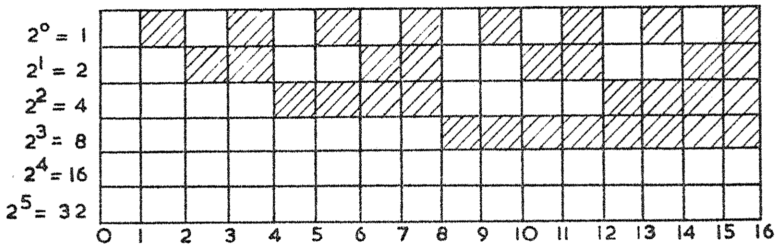


FIG.22. STANDARD BINARY CODED LINEAR SCALE.

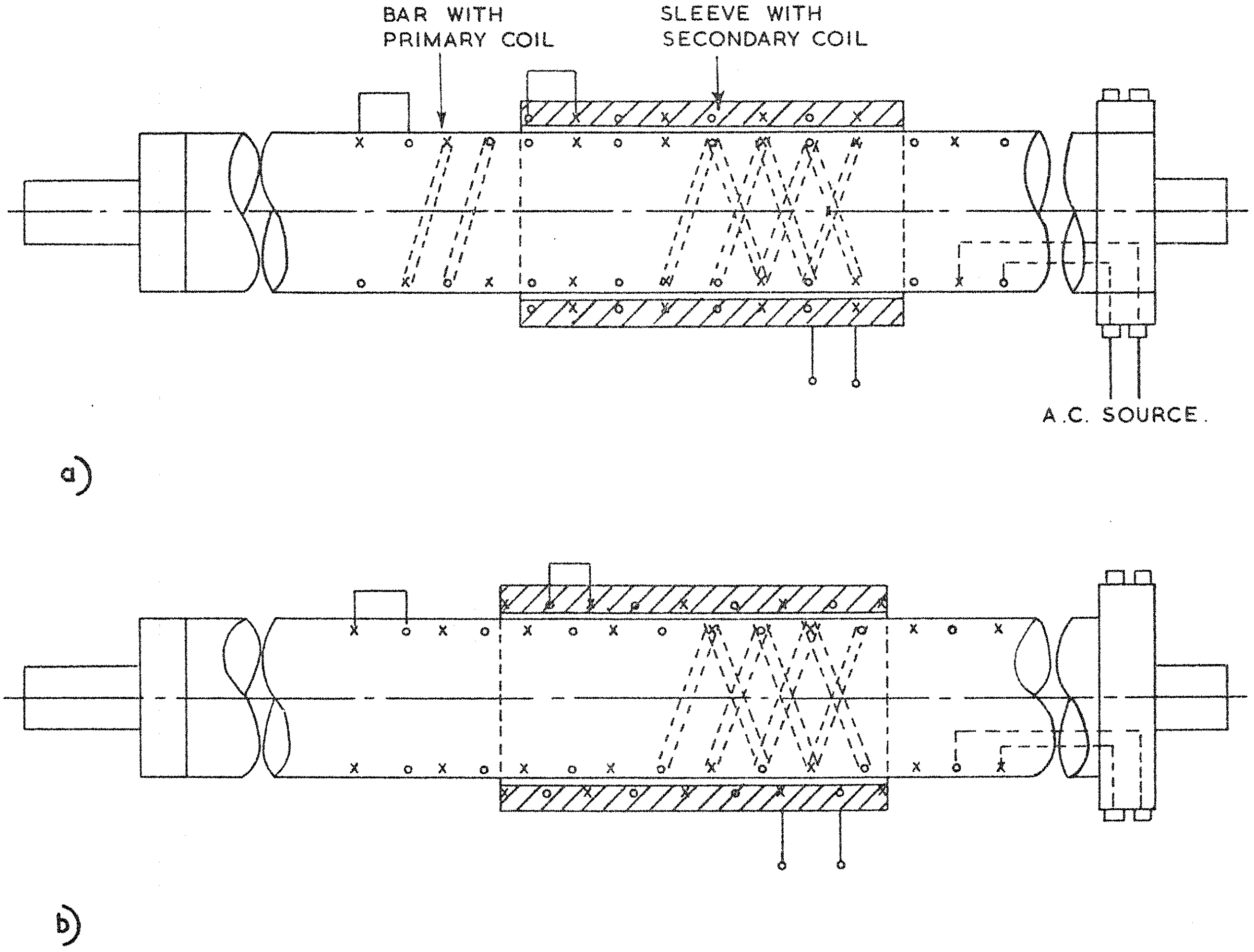


FIG.23. NULTRAX DIFFERENTIAL TRANSFORMER.

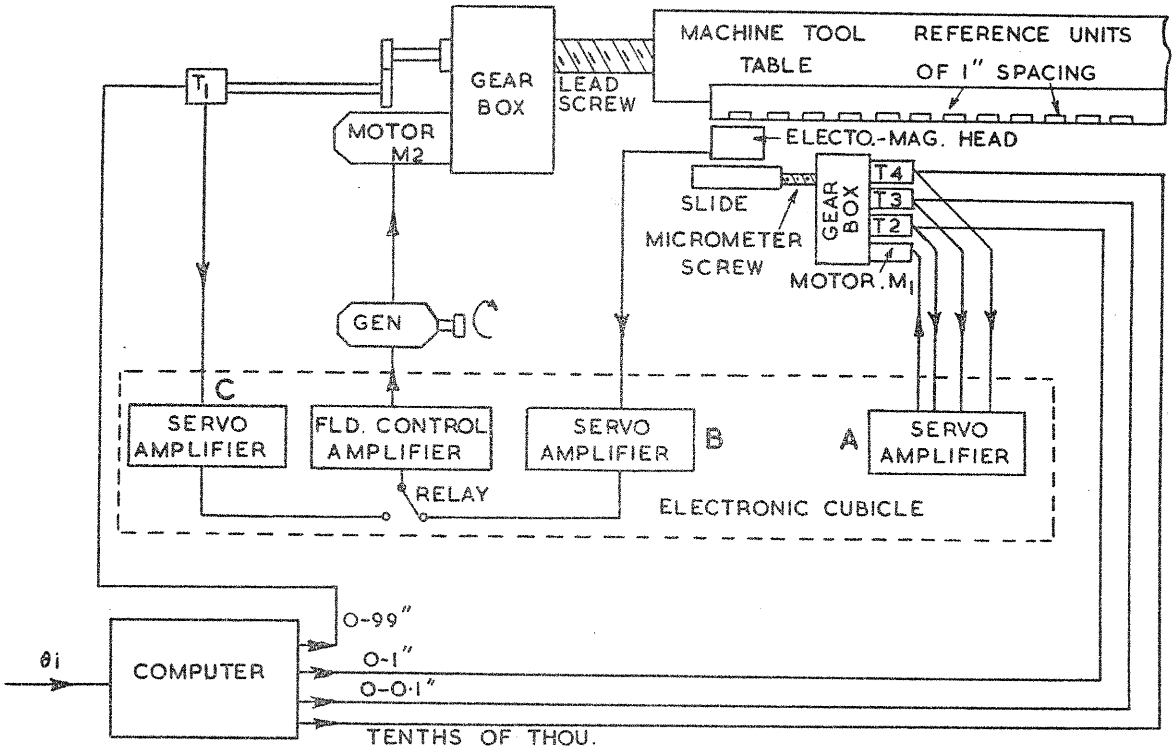


FIG. 24. A.E.I. INCH BAR CIRCUIT

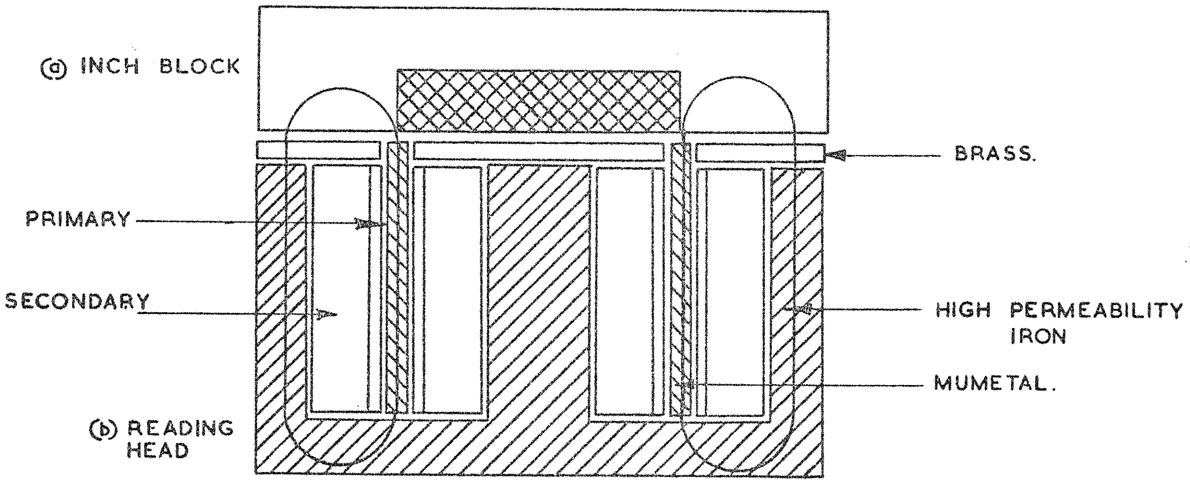


FIG.25. CROSS SECTION OF READING HEAD.