USE OF A RESISTIVE NETWORK TO MEASURE AND DISPLAY THE ANGLE OF A VARIABLE GEOMETRY INLET GUIDE VANES OF A TURBOPROP ENGINE COMPRESSOR .

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ABSTRACT

This paper explains an experimental application carried out in Engine Factory Instrumentation Lab. to develop a pure resistive network and use it as a transmitter converting angular displacement into a linear electrical signal that tracks the angle of the inlet guide vanes (IGV) of the first stage of a turboprop engine compressor. The measuring is to be achieved during test running of the engine inour test cell. The transmitter sensitivity is first calculated and then used to estimate the other network parameters . the setup is then constructed to cover a measuring span of (- 99.99 to + 99.99 deg.) with accuracy +/- 0.I % of F.S. The stability of the results under varing ambient temperature is studied and verified experimentally. Other figure of merit : repeatability was checked. Immunity from noise and parasitic signals and durability ofthe components were also verified .The selected digital indicator can display the results in the desired engineering units and can match any linearization eq. It is shown that our system costed only I/3 to I/5 that of a similar conventional imported system of the same class of precision.

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I. INTRODUCTION.

I.I. Objective :

General Electric Turboprop Engine (CT 64-820-4) is to be tested in Engine Factory test cells. The test procedure includes the check of the correct operation of a Variable Geometry Inlet Guide Vanes (IGV)system acting on the 4 Ist. stages of the engine compressor. The check necessitates the continuous measuring and display of the relative angular positions of the IGV, during engine test run in test cell at different rotational speeds. Because the motion of the 4 stages IGV's is rigidly interconnected , the measuring of the position of the Ist. stage is sufficient.

Our trails explained hereinafter were directed to realize asimple locally constructed measuring and displaying setup tobe used instead of importing the expensive long-term delivery setup used normally insuch situation , and keeping the same degree of measuring precision and repeatability.

1.2. Variable Resistance Dissplacement Detectors : (VRDD)

VRDD were the first electromechanical trasmitters used since long time ago for a number of electromechanical measurements e.g. : pressure , torque, force , etc.. . Abundance of circuits were developed either of the potential divider type or the Wheatstone bridge type, energized by either DC or AC voltage. As the potential divider circuits are not adequate for steady and quasi-steady signal cases owing to the presence of a large steady voltage at the transmitter terminals .; Wheatstone bridge networks are in commen use , also due to its ability of sensing very small resistance changes and producing either floating or grounded signals owing to its symetrical circuit connection.

Although a lot of new displacement detectors have been invented during thelast decades implementing other circuit critera like : Synchro pairs, AC resolvers, Phase sensitive circuits , etc...; our trails were directed to the field of VRDD to make use of their advantages namely : Robustness, simplicity, need no special voltage or frequancy and having better normal and common mode rejection. On the other hand they are very sensitive to energizing voltage variations and also change of ambient temp.may introduce errors , hence the need for using high grade resistors and/ or temp. compensation circuits.

II. THE MEASURING SYSTEM.

The system composes of : a transmitter, an indicator , wiring and a measuring matching pad at the input of the indicator . The excitation voltage is drivenfrom a highly regulated power supply integrated with the indicator case. Technical data of the system components are given below.

II. I. Transmitter :

Type : Rotary Io turns -linear wire wound .
Model : Beckman - Heliopot A 8805 .
Value : 30.25 Kohm at 25 deg. C.
Tolarance: +/- 0.03 % resolution ; +/- 0.25 % linearity.
Temp. coeff. : IO^{-5} per deg. C.

II.2. Indicator :

Type : Digital programmable transducer indicator.
Model : DORIC 420 - EMERSON ELECTRIC CO. U.S.A.
Range : 4 digits + dead zero +sign LED.
max. counts 9999 with a resolution of one count.
Accuracy: Span : +/- 0.03% of reading +/- 0.02 of F.S. %.
Offset: +/- 0.02% of set value.
Sensitivity : I to I2 µv per active count (adjustable).
Program range: Gain : 24 to 270 V/V. or I0.4 µv/count to 0.9 µv/count.
Offset: 0 to IOIOO counts.
Built-in power supply : 4 selectable voltage values : 7.5 - I0 - I5 - 20. VDC.
Self protected against short circuit conditions.

II. 3. Wiring :

Needed one cable consisting of 3 stranded copper conductors , each I.5 mm. sq. cross-section +copper shield + outer plastic jacket.

II. 4. Matching pad :

It composes of 3 high grade , low temp. coeff. resistors . Their value and way of connection will be discussed in the next paragraph.

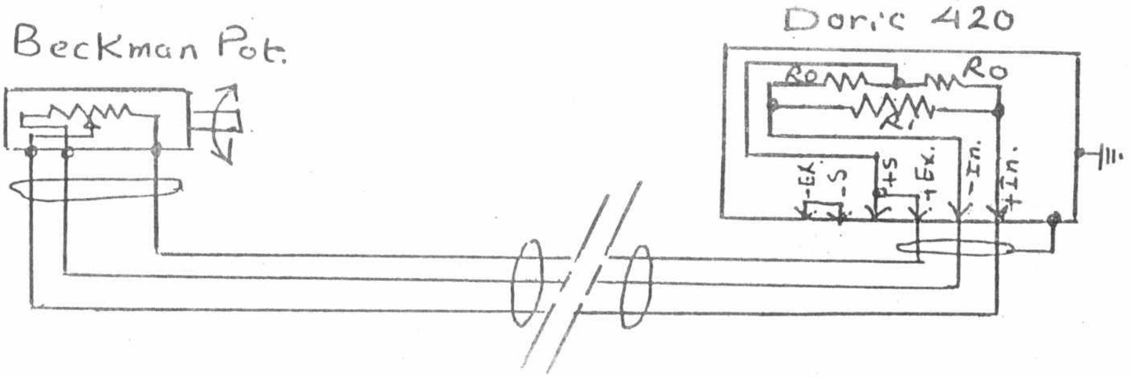


Fig. 1. Schematic of the System.

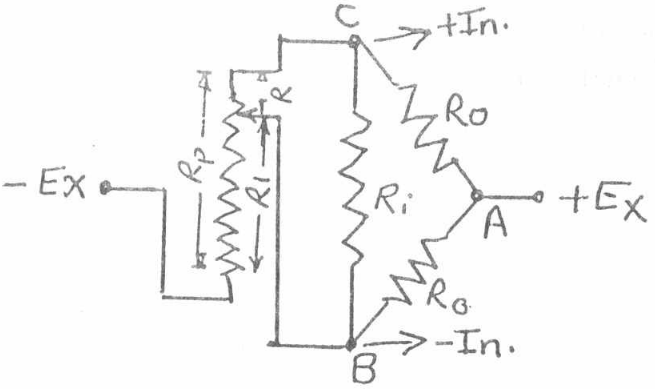
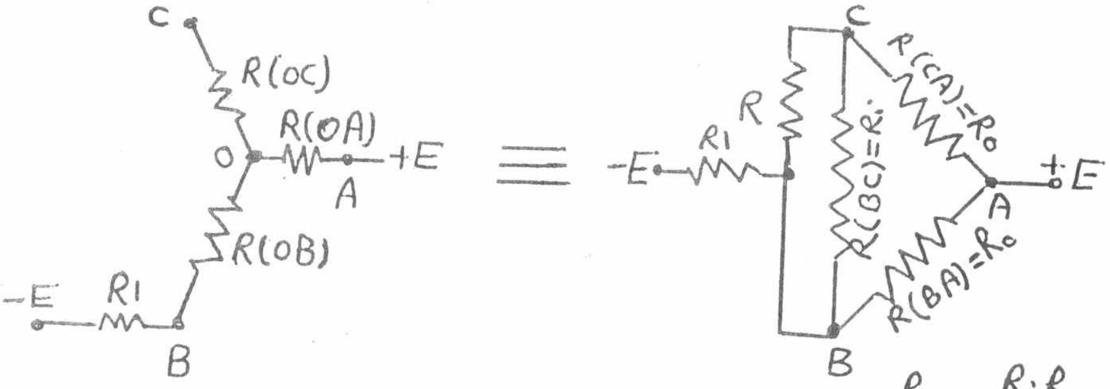


Fig. 2. Circuit Diagram



$$R_e = \frac{R_i R}{R_i + R}$$

$$R_p = R_1 + R$$

Fig. 3. Equivelant & Simplified Circuit Diagram.

III . DESIGN CALCULATIONS.

III. I. Equivalent circuit :

Refers to fig. I&2&3 and to nomenclature :
Fig. 2 shows the equivalent circuit diagram of the setup . Fig. 3 shows the same circuit after simplification by replacing the mesh A B C by an equivalent star (Y) connection :

Given : $R(BC) = \frac{Ri \times R}{Ri + R} = R_e$,; $R(CA) = R(BA) = R_o$

We get : $R(OA) = \frac{R_o^2}{R_e + 2R_o}$; $R(OB) = R(OC) = \frac{R_o \times R}{R_e + 2R_o}$

Output Voltage $V = V(BC) = V(OB) = I \times R(OB) = \frac{E \times R(OB)}{RI + R(OB) + R(OA)}$

Defining : $S = \frac{V}{E} = \frac{R_o \times R}{RI\,(R + 2R_o) + R_o^2 + R_o R}$. V./V.

S is defined as circuit sensitivity expressed in volt output per volt excitation

Using the values : $RI = Rp - R$; $R_e = \frac{Ri \times R}{Ri + R}$

$$S = \frac{R_o\, Ri\, R}{(Rp - R)(R_o Ri + R_o R) + (R_o Ri + R_o R + Ri R)(R_o + Rp - R)}$$

$$= \frac{R_o\, Ri\, R}{(2Rp.R_o.Ri + R_o^2 Ri) + (R_o^2 + 2RpR_o + Rp\, Ri - R_o Ri)\, R - (2R_o + Ri)\, R^2}$$

$$S = \frac{K R}{L + MR - NR^2} \qquad (I).$$

Where : $K = R_o Ri$; $L = R_o^2 Ri + 2RpR_oRi$; $N = 2R_o + Ri$
$M = R_o^2 + 2RpR_o + RpRi - R_oRi$ (2)

The 2 terms MR & NR^2 introduce nonlinearities in the S-R relationship. We are going to make the necessary assumptions in order to reduce their contribution to the total net value of the denominator of equation (I) .

If : $|Q(R)| = |MR - NR^2|$; then the denominator = $L + Q(R)$.
$Q(R)$ could be neglected if its max. numerical value satisfies the relation :

$$1000\, |Q(R)|_{max.} = L . \qquad (3)$$

To find the max. value of $Q(R)$:

$$\frac{d\,Q(R)}{d\,R} = M - 2NR = 0 \quad \text{giving} \quad : R = \frac{M}{2N} \quad ; \quad Q(R)_{max.} = \frac{M^2}{4N}$$

Substitute in equation (3) :

$$L = I000 \frac{M^2}{4N} = 250 \frac{M^2}{N} \tag{4}$$

IF we neglect $Q(R)$ in the denom. of equation (I) , we can rewrite it as :

$$S = \frac{K\,R}{L} \quad \text{or} \quad S = \frac{R}{2\,R_p \mp R_e} \quad V./V. \tag{5}$$

To estimate the max. error resulting due to this linearization precedure ,we shall define the quantity (σ) expressed as :

$$\sigma = S_{actual} - S_{linearized} = \frac{KR}{L + 0.00I\,L} - \frac{KR}{L}$$

$$\sigma = 0.00I \times KR / L . = 0.00I \times S_{linearized.} \tag{6}$$

Equation (6) shows that the max. error of this approximation $\leqslant$ 0.I % of the new value .

III. 2. Estimation of Re , Ri & S :

To simplify calculations we are going to use some numerical values selected on physical occurance bases : We assume :

$R_p = 30.25$ Kohm . (measured of the exsisting potentiometer)

$R_e \cong R_p \cong 30$ Kohm.

Substituting in equation (5) :

$$S = II.0497\,R \quad mV./V. \tag{7}$$

Ri is chosen using equation (4) by substitution of new values of : L, M &N:

$$3R_e^2\,R_i = 250 \frac{(3R_e^2)^2}{(2R_e + R_i)}$$

$$R_i^2 + 2\,R_e\,R_i - 750\,R_e^2 = 0.$$

Solving for the Positive (Real) values of Ri :

$$R_i = I/2 \left(-2\,R_e + \sqrt{4R_e^2 + 3000\,R_e^2}\right).$$

Or $R_i = 26.40444\,R_e = 792.I3$ Kohm .

Summarizing these results : $R_p = R_e = 30$ Kohm. ; $R_i = 792$ Kohm.

$S = II.0497\,R$ mV./ V.

III.3 .Setting of digital indicator :

Equation(7) can now be modified to give a relation between sensitivity in mV./V. and the angle of rotation Θ .

Assuming a linear variation of pot. resistance , if R(θ) is the value of R in Kohm at any angle of rotation measured from the outer stop datum :

$$R\ (\Theta) = (R_p / IO) \times (\Theta / 360) = 8.4027 \times IO^{-3}\ \theta \quad \text{(deg)}. \qquad (8)$$

Equation (6) is rewritten as :

$$S\ (\Theta) = II.0497\ R\ (\theta) = 92.8473I4\ \theta \ \text{Deg.} \times IO^{-3} \ \text{mV/v.} \qquad (9)$$

III.3.I. Gain setting :

Equation (8) is the basis of calculating the gain setting of the indicator using basic indicator amplifier formula, ref[I] , page 2-6 :

$$\text{Preamplifier Gain} = \frac{\text{Display Counts.}}{4 \times E\ (\text{volt}) \times S\ (\text{mV/V})} \ . \quad \text{V./V.} \qquad (IO)$$

If we consider the number of counts / deg. =IOO representing I.oo deg. , and if we choose E = IO volts , using equation (9) :

$$\text{Preamp. Gain}\ (G) = \frac{IOO}{40 \times 92.8473I4 \times IO^{-3}} = 26.926 \ \text{V/V.} \qquad (II)$$

The required gain setting is (26.926) V/V or 9.2847 uV / count . Using the table of ref [I]- page 2-6 ; choose the setting of the 2nd. row : (IOI0000). This setting gives a gain :(29.52) V/V ,- IO % = 26.568. This value is fine tuned using internal adjustment pot. R49.

III.3.2. Offset Setting :

To allow for -ive angle settings , the zero datum should be moved forward beyond the outer pot. stop . This means that equation (8) should be modified by using a transformation $\Theta = \varphi + 20$. This means that for a value $\theta =$ 20 deg. $\varphi = 0$ and this will be the datum for measuring rotation angles , i.e. : For all values of $\theta \geqslant 20$: φ is +ive while for all values $0 \leqslant \Theta \leqslant 20$: φ is -ive.

Equation (8) becomes : $R(\theta) = 8.4027 \times IO^{-3} \ (\varphi + 20)$. (I2)

Equation (9) becomes : $S(\theta) = 92.847314 \times IO^{-3} (\varphi + 20)$

$= \left[92.847314 \times IO^{-3} \varphi + I.8569463\right]$ mV/V. (I3)

Equation (9) & (I3) represents a straight line equation with the same slope , The st. line of eq. (9) passes through the origin while that of eq. (I3) intersects the S-axis at a value = I.8569463 .This value represents an offset which should be tared using the tare (offset) adjustment.

To find the amount of taring needed in counts. . : 20 deg. x I00 = 2000 counts. This is true since itcan be calculated by eq. (IO) :

Display Counts = G x 4 x E x offset value (mV/V)
=26.926 x 4 xIO x I.8569463 = 2000 counts.

Refere to table 2-6 page 2-9 ref.[I] ; choose the setting (OIOIIII) giving the value of I984 counts , the exact value can later be fine tuned using internal adjustmentpot. R33 &R3I .

IV. THERMAL STABILITY.

If the ambient temperature changes from To to T , the resulting change in Rp & R causes a change in the value of S as calculated before.

The following analysis shows how to estimate the value (S +△S) when the temp. changes from To by an amount △T such that : T = To +△ T.

The R-T relationship of the metal used in manufacturing the pot. resistor wire (Rp & R), can be expressed by Callender-Van Dussen eq. Ref. [2& 3]

$$R(T) / R(To) = I + \alpha\left[\left(T - \delta\left(\frac{T}{I00} - I\right)\frac{T}{I00}\right) - \beta\left(\frac{T}{I00} - I\right)\left(\frac{T}{I00}\right)^3\right] \quad (I4)$$

α , δ & β are constants of the metal ; $\beta = 0$ for all temp.$\gg$ 0.

IF we assume :

$$f(T) = \left(T - \delta\left(\left(\frac{T}{I00}\right) - I\right) . \frac{T}{I00}\right) \quad (I4)$$

$R(T) / R(To) = I + \alpha f(T)$.

Rewrite eq.(5) in the form : $S = R \,.\, (2Rp + Ro)^{-I}$. Diff. w.r.t. T :

$$\frac{dS}{dT} = -(2Rp + Ro)^{-2} \,.\, 2R\alpha\, (Rp)_{To} \,.\, \frac{d\, f(T)}{d\, T} + (2Rp + Ro)^{-I} \,.\, R(To) \,.\, \alpha \,.\, \frac{d\, f(T)}{d\, T}$$

$$\frac{d\, f(T)}{d\, T} = (I - 2\delta T \times I0^{-4} + \delta \times I0^{-2}) = \mathring{f}(T) \quad \text{So :}$$

$$\frac{dS}{dT} = R \,.\, (2Rp + Ro)^{-I} \,.\, \alpha \,.\, \mathring{f}(T) \,.\, \left(\frac{R(To)}{R} - \frac{2Rp(To)}{2Rp + Ro} \right)$$

$$= \alpha \,.\, S \,.\, \mathring{f}(T) \,.\, \left(\frac{I}{I + \alpha f(T)} - \frac{I}{I + \alpha f(T)} \times \frac{I}{I + Ro/2Rp} \right).$$

Since $Ro = Rp \therefore (RO / 2Rp) = 0.5$

$$\frac{dS}{dT} = \frac{\alpha S}{3} \,.\, D \qquad (I5)$$

$$\text{where} \quad D = \frac{\mathring{f}(T)}{I + \alpha f(T)} = \frac{I - 2\delta T \times I0^{-4} + \delta \times I0^{-2}}{I + \alpha T \left(I - \frac{T \times \delta}{I0^4} + \frac{\delta}{I0^2} \right)} \qquad (I6)$$

From elementry calculus :

$$\Delta S = \frac{dS}{dT} \Delta T = I/3 \,.\, \alpha S \Delta T \; D$$

If we define ϵ asthe value of the % change in sensitivity S per deg. C. temp. change :

$$\epsilon = \Delta S / (S \Delta T) \,.\, I00 = I/3\, \alpha D \,.\, I00 \quad \% \qquad (I7)$$

A good approxmation can now be made if we consider the nmmerical values of α , δ where $\alpha = I0^{-5}$ & $\delta = 0$

Eq. (I6) reduces to $D \cong \frac{I}{I + \alpha T}$ (I8)

Eq. (I7) reduces to $\epsilon \cong (I00\, \alpha / 3)(I - \alpha T)$. (I9)

If $\alpha = I0^{-5}$, higher power of α can be neglected and the value of ϵ is very close to : $\epsilon = 3.33$ ppm. /deg. C.

See fig 5 for Experimental results.

V. SYSTEM CALIBRATION.

An adjustment and calibration sequence was made to realize the relationship between calculated data and physical (actual) performance . First a static check was made by using compressed air supply to actuate the VG mechanisim . The results taken are compared to that taken by a precise protractor fixture (measurement resolution 5 min.) This protractor was supplied by GE under p.N. (2ICI6642-po3) for ground check purposes. Our results were checked again during actual engine run in test cell. The calibration relation is shown in fig. 4 , and the data taken were used to find the best st. line equation using the least square method of linearization. IF the protractor reading = X (deg) ; Digital indicator reading = Y counts.

The relation is stated as : $Y = X - 60.40$ (20)

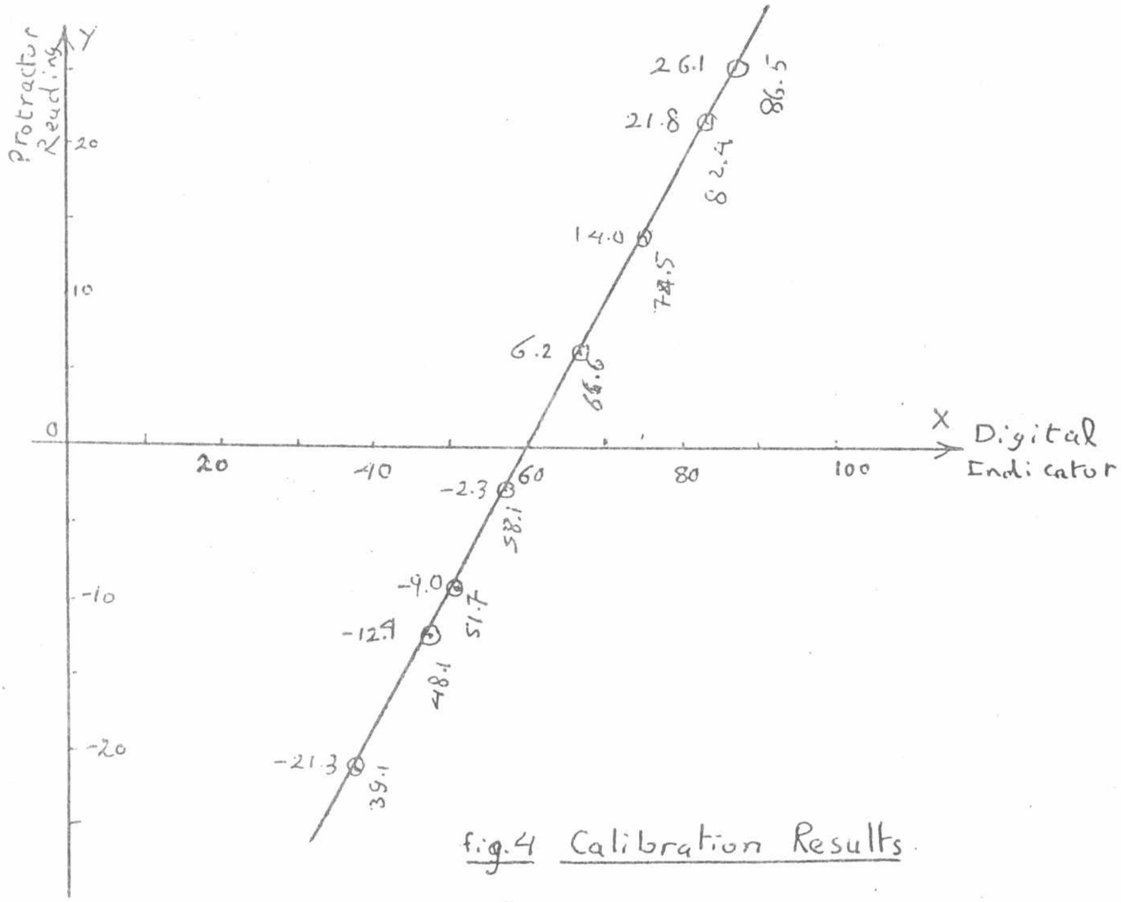


fig.4 Calibration Results

VI. CONCLUSIONS.

The setup discussed here was practically realized and used in Engine Factory test cell facilities under actual field environments. Rough estimation of cost reduction could be made comparing the approximate cost of our system and one of the ready made systems proposed to be imported from abroad.

The cost of our system composed of the followingg :

Beckman pot.	$ 30.
DORIC indicator	$ 800.
Wirings , hardware etc...	$I70.

The total cost amounts to about$ I000. On the other hand the cost of a system of the same accuracy class , e.g. : GE. P.N. (2ICI520GC02) was about $ 8500.

One main feature of our system is the use of prgrammable amplifier which make it easy to check periodically the gain and offset adjustments . Change of these values is done on the spot with no need to circuit-components replacement.

Sprious emisson isa actually negligable while common mode rejection is good and further improved by screening . thermal stability in the temp. band (0 - 70) C° can be assumed with fairly enough correct results.

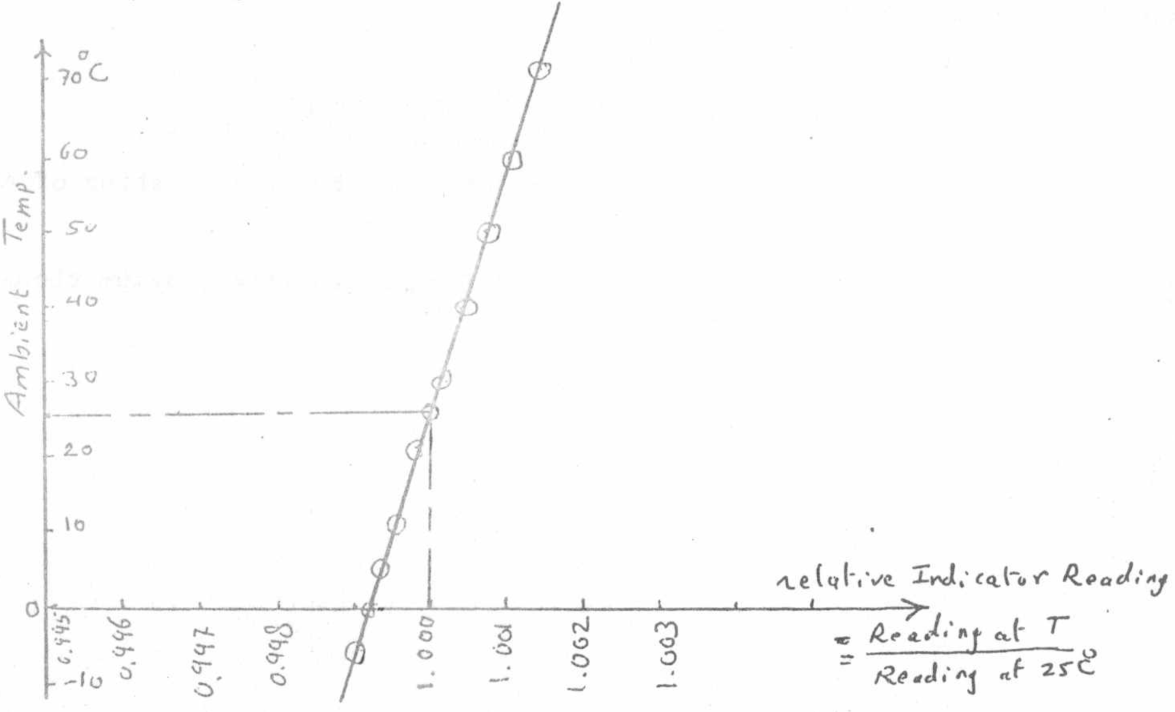


Fig.5 Temperature Satbility

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NOMENCLATURE

E = Excitation supply voltage in volts DC.

G = Indicator preamplifier gain in V/V .

I = The total current drawn from the supply in amp.

R = Electrical resistance in Ohm.
next letters designates specific points as shown in fig I ,2 &3 .

S = Network sensitivity in mV/V .

T = Temperature in deg. centigrade (C^o).

V = Voltage at specific points as shwon in fig I , 2 & 3 .

Δ = Small change in values of S & T .

α , δ = Resistance temp. coefficients .

ϵ = % change of sensitivity S per deg. C^o temp. change.

θ = Angle of pot shaft rotation measured from outer stop in deg.

σ = Max. percentage error in calculation of S due to linearization of eq. (I)
i.e. , using eq. (5) .

φ = Angle of pot shaft rotation measured from an arbitrary datum chosen to allow +ive & -ive angle measurements.