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DESIGN NOTES ON THE TANK AND DEBUNCHER AUTO TUNING SYSTEM FOR THE 70 MeV INJECTOR

R W Munn and E G Sandels

Nimrod Division
Rutherford Laboratory
Chilton
Didcot
Oxon.
OX11 0QX

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INTRODUCTION

The Auto Tuning Systems described below are part of the linac control equipment for maintaining the accelerating field to the correct amplitude and phase. The four tanks and the debuncher cavity must be held on tune to within a few Hz if phase errors are to be held within design limits. Very small dimensional changes in these cavities can cause serious detuning errors. These changes during operation are due mainly to fluctuations in temperature of the walls of the tanks which although water-cooled and temperature stabilised remain variable with $\pm\frac{1}{2}$°C.

In each cavity either copper tuning plates or a slug (ie, cylinder) are inserted or withdrawn appropriately to compensate for the dimensional changes. The general arrangement of the tuning system is shown in Figure 1. The tuned cavity is fed with RF current in a drive loop which is monitored by a pick up loop set in the coaxial power line a half wavelength from the cavity. The cavity field is monitored by a second pick up loop set in the wall of the cavity. The monitor signals are appropriately adjusted in phase via electronic phase shifters and compared in a phase bridge which produces a DC current in proportion to the phase error. (These components comprise the Phase Comparator). When the linac pulse occurs the output from the phase bridge is stored as a voltage on a capacitor in a sample and hold amplifier until the next pulse occurs. The sampled phase error signal is used to control an AC servo motor in its own feedback loop, the motor controlling the position of the tuner via a gear train and a coupling mechanism. When the cavity is exactly on tune there is a 90° phase difference between the RF drive current and the accelerating field and this is arranged to give zero phase error current in the comparator.

In tanks 2 and 3, the tuners comprise 4 copper plates mounted on flexible phospher bronze strips set in the tanks walls allowing radial movement. These are linked by hydraulic transmission to a cam actuator. The Debuncher has a single plate similarly mounted. Tanks 1 and 4 each have a single cylindrical brass tuning slug 5" diameter moving radially through vacuum seals and controlled by a ball bearing screw. In each instance the tuner position is monitored by a linear potentiometer coupled into the gear train and displayed remotely. The motor may be operated manually, the phase shift through the phase comparator controlled and monitored and the phase error current displayed all through the camac control system.

This report describes a criterion for stability in the auto tuning systems. The servo motor gear train and the electronic units are discussed with reference to this criterion and their parameters listed for each of the five cavities.

SYSTEM STABILITY

The auto tuning systems operate continuously at a velocity proportional to the tuning errors. The state of error is sampled at every machine pulse, ie about 24 pulses/minute. Since the time between samples is much longer than any lags due to servo motor or gear train inertia a simplified criterion for stability is readily obtained. The response of such a system to unit error is illustrated in Figure 2. Where T_s is the time between samples

T_c is the time to reduce unit errors to zero.

Figure 2a shows an instance where $T_c = \frac{3}{4} T_s$. Here the error is reduced to zero and then reverses in sign as the motor continues at constant velocity to the next sampled error, hence the optimum unit error reduction rate $= \frac{1}{TS} = 0.4 \text{ sec}^{-1}$ at 24 pulse/minute.

The product of the output/input transfer parameters of tanks, tuners, motors and electronic units gives the unit error reduction rate. These parameters are listed in Table 1 which is the basis for discussion of the parts of the systems and their design as described below.

TANK TUNERS

To a first approximation the frequency change expressed as a fraction of the resonant frequency is taken as half the fractional change in cavity volume due to the tuner displacement. However, this factor depends also on the shape of the tuner and its position in the cavity.

For example in a 900 mHz scale model of a linac tank section including 3 unit cells:

The fractional volumetric change $\Delta v/v$ was 62 parts per 10^6/mm tuner displacement
The fractional frequency change $\Delta f/f$ was 36 parts per 10^6/mm tuner displacement

Further data relating errors in tank dimensions to the resonant frequency can be found in References 1 and 2 where the effect of the tuner is assessed by assuming an effective cavity diameter change equivalent to the inserted volume of the tuner, but this predicts a much lower frequency shift than that measured in the model.

An estimated tank tuner constant based on the model measurements is given in Table 1 for Tanks 1 and 4. Those given for Tanks 2-3 are quoted from Reference 4 and that for the Debuncher estimated as for Tanks 1 and 4 above.

MOTOR AND GEAR TRAINS

The principle factors are:

1 The maximum rate of change of resonant frequency in an uncorrected tank. Here temperature variations in the tank walls exceed other factors mechanical and electrical (such as beam loading) by an order of magnitude.

From consideration of the ambient temperature variations and the temperature stability of the cooling water it is estimated that temperature change rates in the tank walls will not exceed 3°C/minute corresponding to a frequency detuning rate of 10 kHz/minute.

2 The tank tuner constant, 179 Hz/mm (Tank 4).

3 The friction and vacuum load on the tuning slug. In tanks 1 and 4 the slug moves through RF finger strip contacts and is actuated via a vacuum seal via a ball bearing screw. The maximum torque required at the screw allowing for screw efficiency and a safety factor to ensure static friction override is 7,800 gm cm with a ball-screw lead of 5 mm/rev.

combining 1 and 2 with the ball screw lead and the torque at the ball screw gives the power required:

7,800 gm cm at 11.2 rev/min for Tank 4

allowing 60% efficiency in the gear train a motor shaft power of 1.5 watts is required.

This is shown at the point A in Figure 3a, the output power torque curves for a Vactric size 18 AC servo motor. The corresponding power for Tank 1 is shown at point B. These points designate, with suitable gear ratios, the maximum power and torque under normal running conditions. For Tank 4 this corresponds to 60% of maximum control volts. Reference point C (100% volts with speed unchanged) shows a working torque margin of about 70% and to point D (100% volts with torque unchanged) a speed margin of about 50%. It is considered that these place the motor near optimum working conditions.

For Tanks 2 and 3 and the Debuncher the existing PLA auto tuning system has been adapted with changes to new electronic units. However the ex PLA gear boxes are used unchanged apart from the new position read-out potentiometers and the Type 18 Vactric AC motor quoted above is comparable although somewhat more powerful than the Type 15 employed in the PLA. It is estimated that these motors will operate at about $\frac{1}{4}$ the rate of the Tank 4 motor and should not require more than about 20% of the full control volts under the maximum load. See point E in Figure 3a.

SERVO MOTOR SPEED CONTROL CIRCUITS

The motor speed and direction of rotation is controlled by means of the circuit represented by the block diagram, figure 4. The oscillator provides the 400 Hz excitation for both the reference and control windings of the motor, also the field winding of the tachogenerator which is integral with the motor frame. The reference and tacho-windings are supplied directly via a hybrid integrated circuit power amplifier and transformer T1. The control winding is supplied by a similar amplifier and transformer T2 but here indirectly via an integrated circuit four-quadrant multiplier, the output of which is added in phase opposition to the tachogenerator output in the summing amplifier A1, thus forming a velocity feedback loop. The combined output undergoes a 90° phase-shift in the amplifier A2 relative to the reference winding signal to provide a rotating magnetic field in the motor. The multiplier output is amplitude modulated and phase shifted by means of the bipolar DC control signal derived from the sample and hold circuit, the output amplitude being dependent on the amplitude of the DC signal and the phase, 0° or 180°, on the polarity, thus controlling the motor velocity and direction of rotation.

The stability of the motor servo loop and its performance in the auto tuning system depends on its loop gain ie, the product of its circuit transfer parameters and the motor characteristic slopes. Figure 3b shows the motor speed control voltage characteristic for three conditions of constant shaft torque. The voltage threshold for rotation increases with increasing load, however, the slopes of these characteristics are reasonably uniform above the threshold. Table 3 lists the parameters controlling the motor servo loop gain assuming constant slope and a rotating motor. The loop gain is given by their product. Table 1 lists the parameters controlling the auto tuning loop gain.

Tachogenerator constant Is a fixed parameter determined by the manufacturer and dependent only on the Reference winding voltage.

Servo amplifier Tacho O/P.control I/P Is determined by the ratio of the summing resistors in amplifier A2 ie, R2/R1.

Multiplier constant AC OUTPUT/DC INPUT Is determined by the two multiplier inputs; 400 Hz AC from the oscillator and the DC error voltage from the sample-and-hold amplifier, a maximum of 8v DC corresponding to 20 degrees phase error producing 0.57 V AC at the multiplier output.

PHASE ERROR CIRCUIT

As described in the Introduction the phase error circuit compares the phase of the drive current and cavity field the phase error current being proportional to their difference. The change of phase with resonant frequency depends directly on the Q of the cavity and is given closely by:

$$\frac{d\phi}{df} = \frac{2Q}{f_o}$$

where ϕ = phase difference (rads)
f = drive frequency
f_o = resonant frequency
Q = cavity Q factor
See figure 5

expected figures for the tank Q factors are given in Table 2 (Reference 4) with the calculated system parameter $\Delta\phi/\Delta f$.

The phase comparator is formed in strip lines on copper clad Rexolite substrates and it is described fully in Reference 7. 4

The terminated bridge is fed from two phase shifting bridges with varicap reactive elements on their terminals to provide controlled phase shifts. The phase shifted signals at A and B (Figure 1) feed power into the terminating loads at C and D respectively. If a phase difference exists between the A and B signals the power into the loads is shared unequally and rectification and subtraction of the load RF potentials in the diodes D_1 D_2 yield a corresponding phase error current. Figure 6a shows the calibration of a typical phase bridge with 100K detector impedances and 1V RMS inputs. Also shown is the output obtained when one input is changing in amplitude as from an off-tune cavity. Because of restrictions in the threshold potentials of detector diodes and large signal distortion in the varicap diodes operation of the device is limited to between 0.3V and 1.0V RMS. Figure 6b shows the calibration of the phase shifters ie, the relationship between DC bias potential applied to the varicap diodes necessary to nullify the phase difference between the incoming signals.

Phase Bridge rectified output/phase error Is given by the slope of the phase bridge calibration at zero phase error (Figure 6a). The quantity depends on the RF signal voltages and the detector impedances.

SAMPLE AND HOLD AMPLIFIER

This unit, Figure 7, is the means of storing the output current of the phase bridge at the time of the linac beam pulse in the form of an analogue voltage held on a storage capacitor. The differential current from the phase bridge detectors is fed into an operational amplifier. During a short period (10 microseconds) within the duration of the linac pulse, an integrated circuit switch is closed feeding the amplifier output to a storage capacitor. After this period the switch is opened leaving the analogue voltage stored on the capacitor and operating on the motor servo until updated by the next pulse. A high impedance voltage follower amplifier monitors the capacitor voltage and feeds the motor servo. The gain of the amplifier is made variable by choice of its feedback resistor to give an error reduction rate for the particular auto-tuning system as required by the stability criterion described above. A range from 0.03 to 1.0 volts/μamp is available.

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1 J J Wilkins, Design Notes on Resonators for proton linear accelerator. AERE GP/R 1613.

2 J J Wilkins, Design of RF Resonant Cavities for acceleration of protons from 50 to 150 MeV. PLAC 11.

3 PLA Handbook TK/2.

4 J E Ellis and E G Sandels, The construction and calibration of a prototype phase comparator for use on the 70 MeV Injector. N/INJ/43.

TABLE I

Auto Tuning System Parameters

Auto Tuning System Parameters	Units	Tank 1	Tank 2	Tank 3	Tank 4	Debuncher
Cavity $\Delta\phi/\Delta f$	deg/Hz	.034	.057	.057	.034	.0099
Phase Bridge rectified output/phase error	μa/deg	.28	.28	.28	.28	.28
Sample and Hold gain max.	Vdc/μa	1.8	.40	0.4	2.0	0.4
Sample and Hold gain min.	Vdc/μa	0.18	0.040	0.040	0.2	0.04
400 Hz Oscillator Multiplier constant $\frac{\text{AC OUTPUT}}{\text{DC INPUT}}$	Vac/Vdc	.071	.071	.071	.071	.071
Servo Amplifier Tacho Output/Control Input	Vac/Vac	32.9	32.9	32.9	32.9	32.9
Tachogenerator constant	Rev/Sec.Vac	4.9	4.9	4.9	4.9	4.9
Tuner to Motor velocity ratio	mm/Rev	.0154	.0028	.0028	.0230	.0028
Tank Tuner Constant	Hz/mm	312	4330	4330	179	26,250
Unit Error Reduction Rate (product of Parameters) max.	1/sec	0.94	0.89	0.89	0.91	0.93
Unit Error Reduction Rate (product of Parameters) min.	1/sec	0.094	0.089	0.089	0.091	0.093

TABLE 2

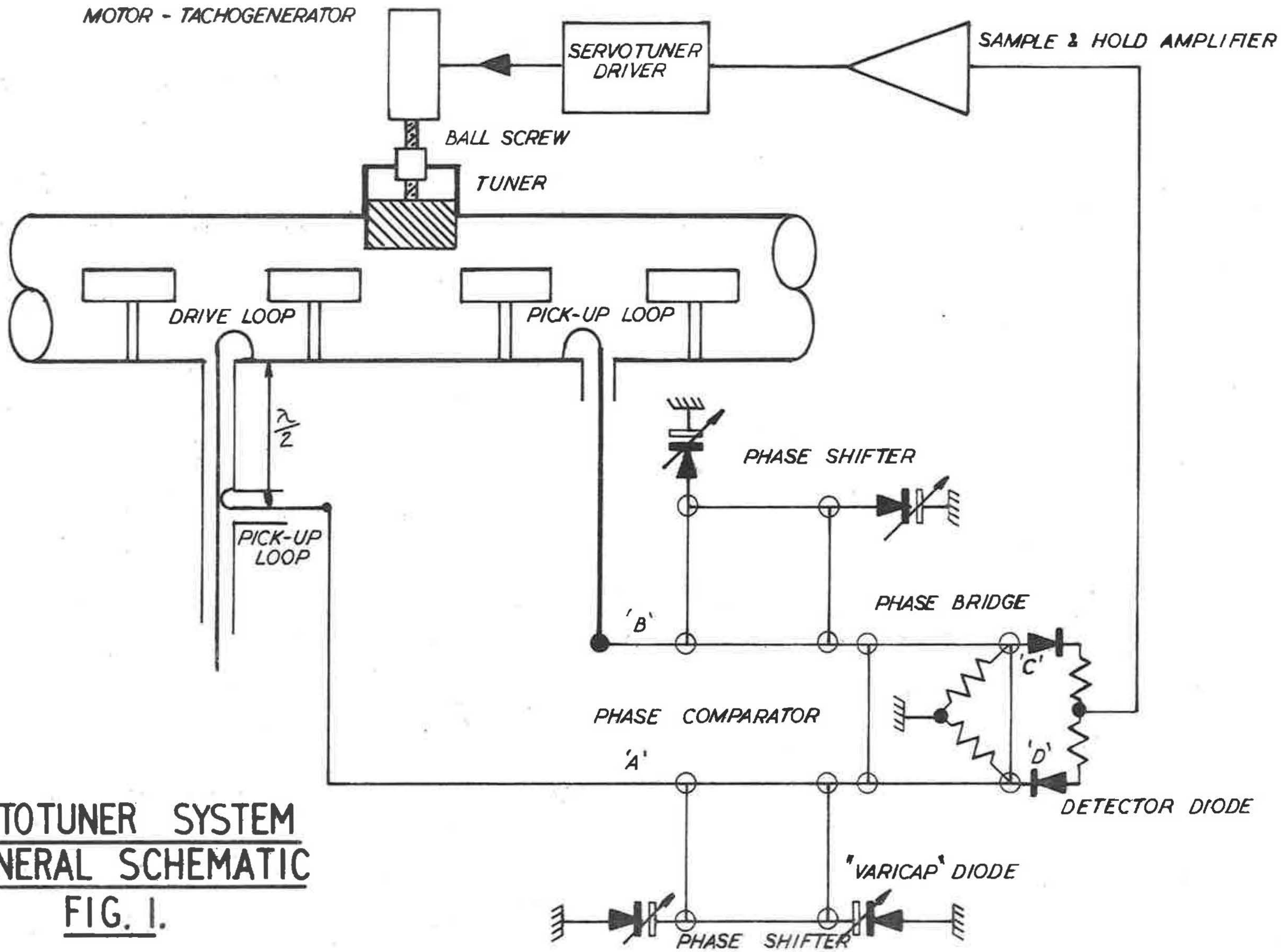
Cavity Q Factors

Tank No	1	2	3	4	Debuncher
Cavity Q	60,000	100,000	100,000	60,000	17,500
Cavity $\Delta\phi/\Delta f$ deg Hz^{-1}	.034	.057	.057	.034	.0099

TABLE 3

Motor Servo-Loop Parameters

Parameter	Dimension	Value
Tacho Generator Inverse Constant	Vac Sec Rev^{-1}	0.2
Summing Amplifier voltage gain	none	0.56
90° Phase Shifter gain at 400 Hz	none	1
Servo Power Amplifier Voltage Gain	none	32
O/P Transformer Step-up ratio	none	9:1
Motor Speed/control volts on load	Rev Sec^{-1} Vac^{-1}	1.5
Motor Servo Loop Gain Product	None	48.4

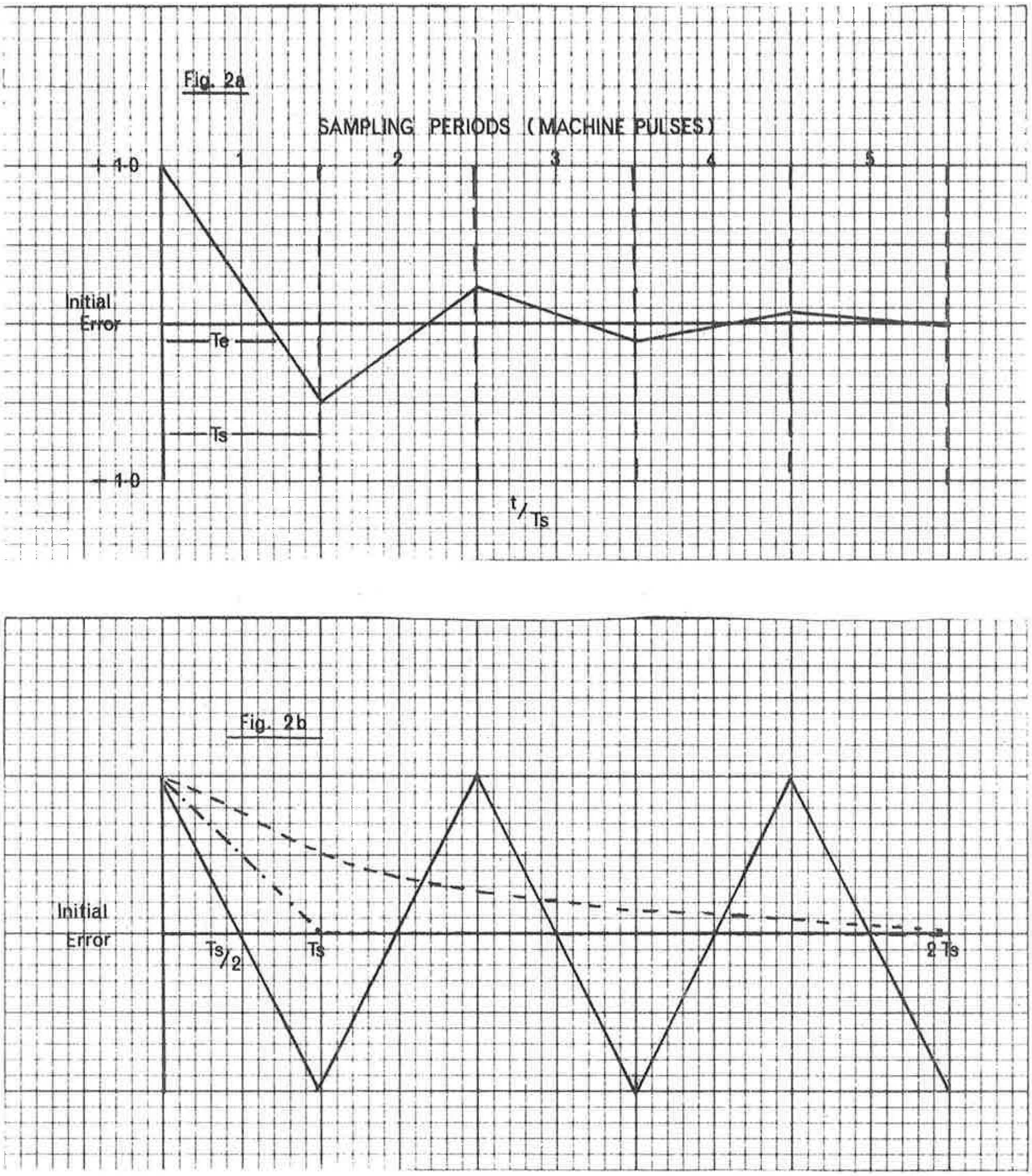


AUTOTUNER SYSTEM GENERAL SCHEMATIC

FIG. 1.

FIG. 2

Transient Responses to Unit Error



Te > Ts : Overdamped, quasi-exponential reduction of initial error

Te > Ts : Critically damped, quasi-exponential reduction of initial error

$Ts > Te > \frac{Ts}{2}$: Underdamped, quasi-exponential reduction of initial error

$Te < \frac{Ts}{2}$: Oscillatory, quasi-exponential growth of error

FIG. 3a Vactric 18 ac motor characteristics

Power vs Torque

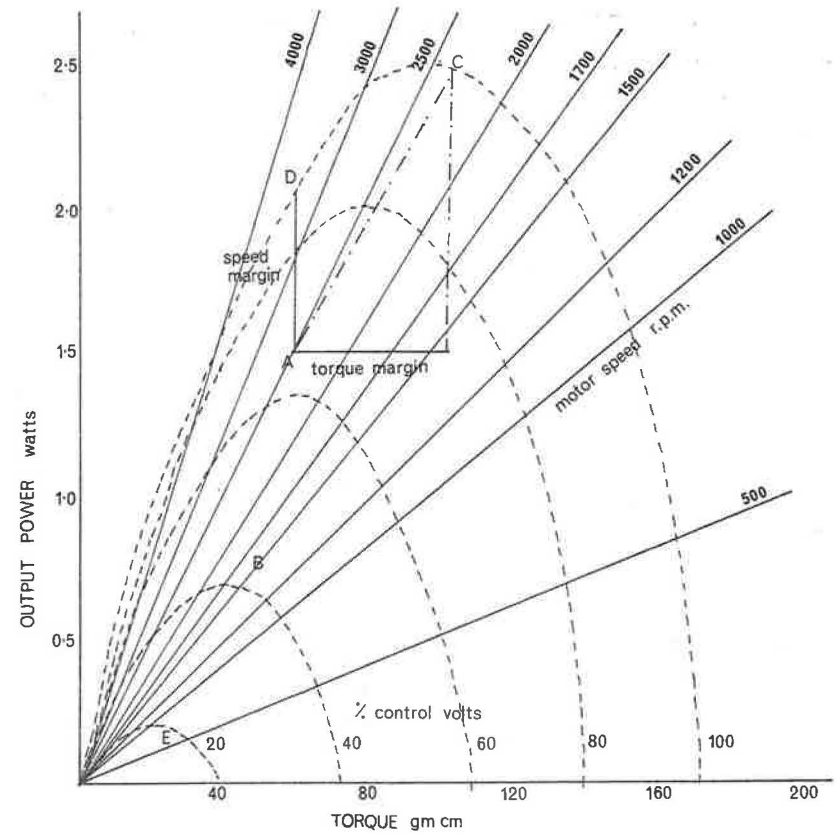
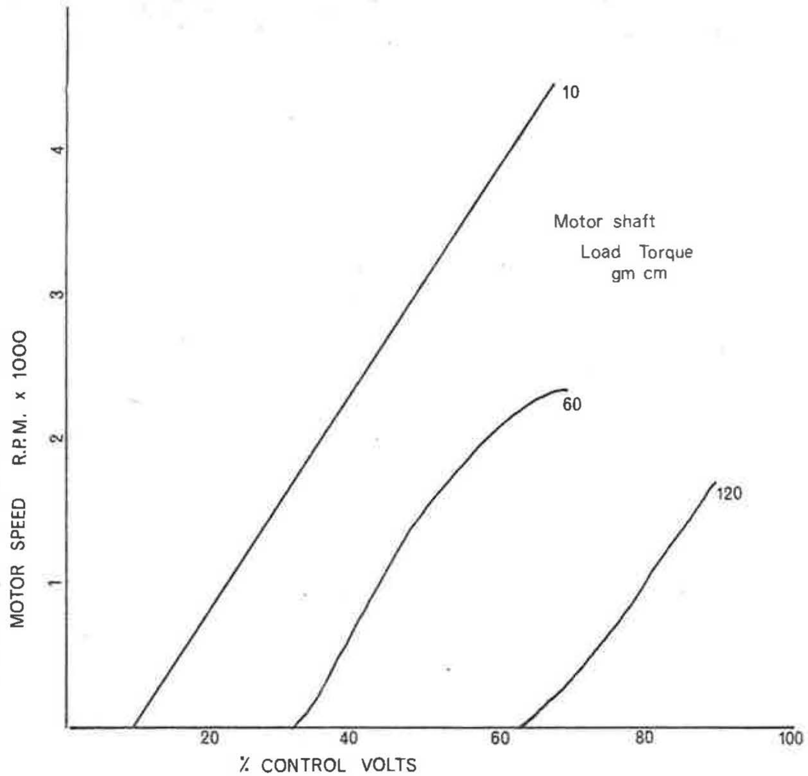


FIG. 3b

Speed vs Volts



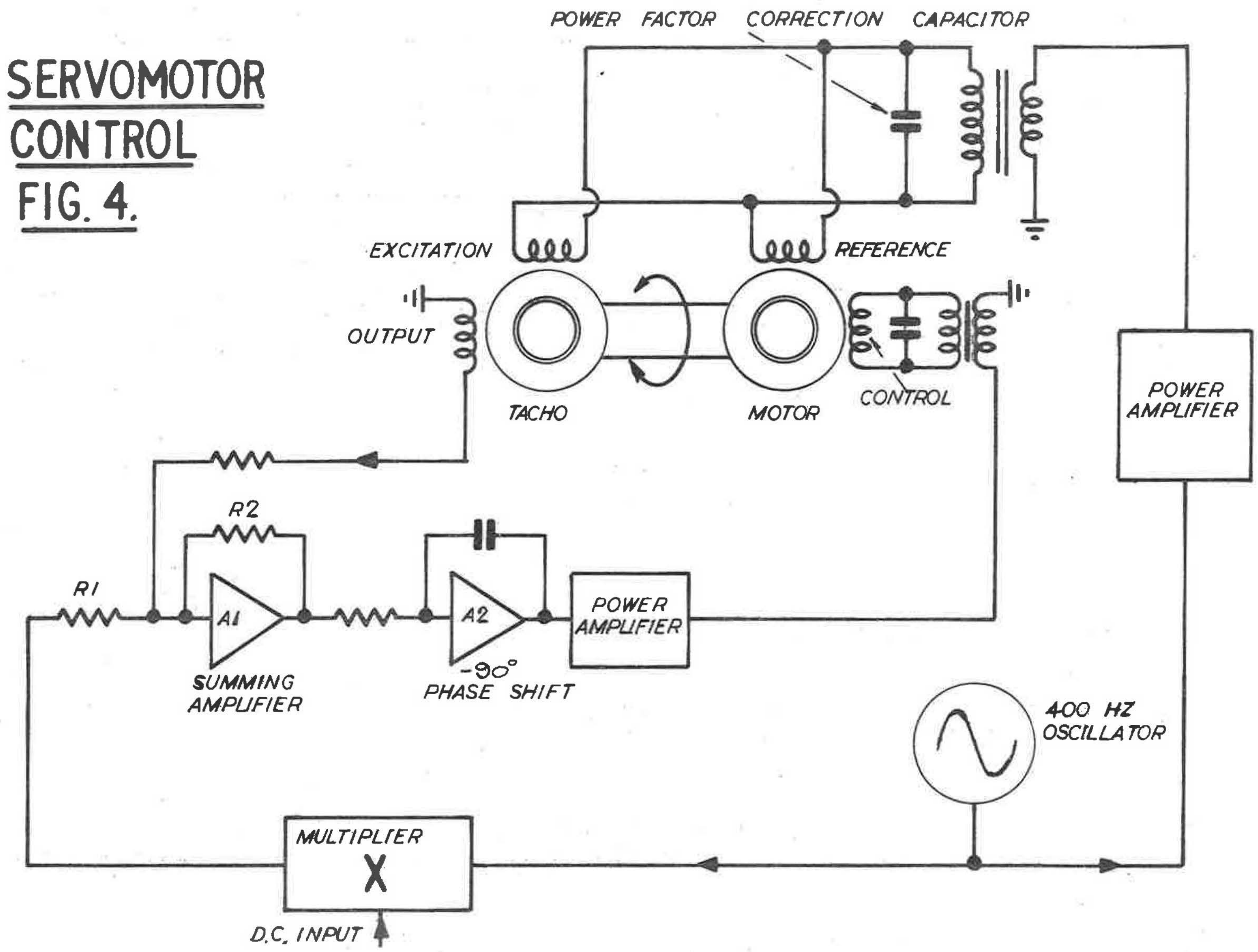
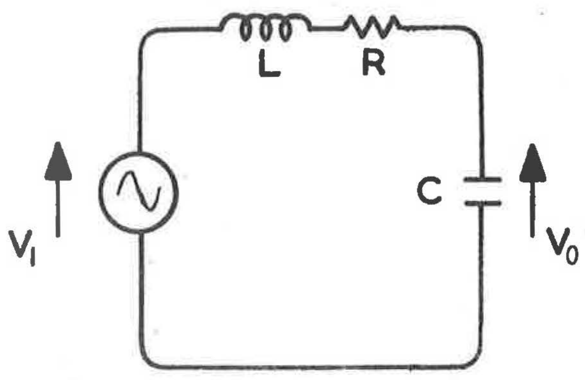
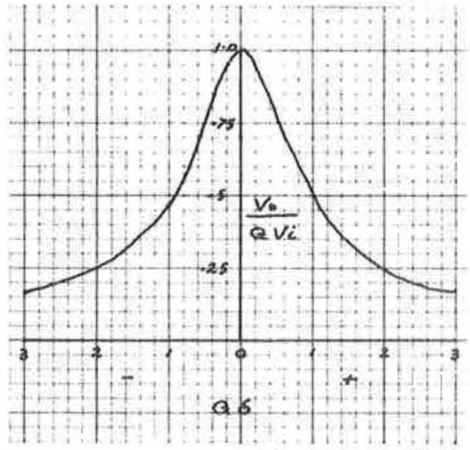

SERVOMOTOR
CONTROL
FIG. 4.
POWER FACTOR CORRECTION CAPACITOR
EXCITATION
REFERENCE
OUTPUT
TACHO
MOTOR
CONTROL
POWER AMPLIFIER
R2
R1
A1
A2
POWER AMPLIFIER
SUMMING AMPLIFIER
-90°
PHASE SHIFT
400 HZ
OSCILLATOR
MULTIPLIER
X
D.C. INPUT

FIG. 5

Phase change with frequency for a Resonant Cavity



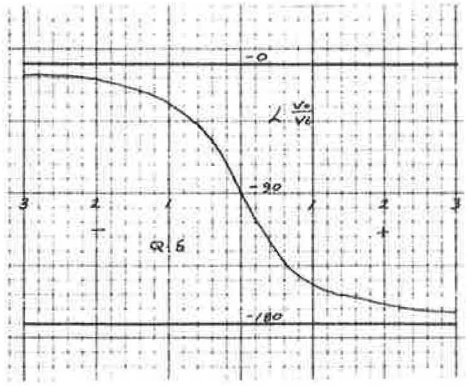


$$\frac{V_o}{V_i} = \frac{1/j\omega C}{R + j\omega L + 1/j\omega C}$$

$$= \frac{1}{1 - \left(\frac{\omega}{\omega_o}\right)^2 + j\omega C R}$$

$$\frac{V_o}{Q V_i} = \frac{1}{Q\left(1 - (1+\delta)^2\right) + j}$$

$$= \frac{1}{Q\left(2\delta + \delta^2\right) + j}$$



WHEN $\delta \ll 1$:-

$$\frac{V_o}{Q V_i} \doteq - \frac{1}{2Q\delta + j} \quad \text{— (1)}$$

for $2Q\delta \ll 1 \quad Q \doteq 2Q\delta$

AND $$\frac{d\phi}{df} = \frac{2Q}{f_o} \quad \text{— (2)}$$

(1) IS PLOTTED ABOVE AS A UNIVERSAL RESONANCE CURVE

WHERE:-

$V_o \equiv$ CAVITY FIELD

$V_i \equiv$ VOLTAGE ACROSS COUPLED INDUCTANCE OF DRIVE LOOP

$L \equiv$ CAVITY INDUCTANCE

$C \equiv$ CAVITY CAPACITANCE

$R \equiv$ CAVITY LOSS RESISTANCE

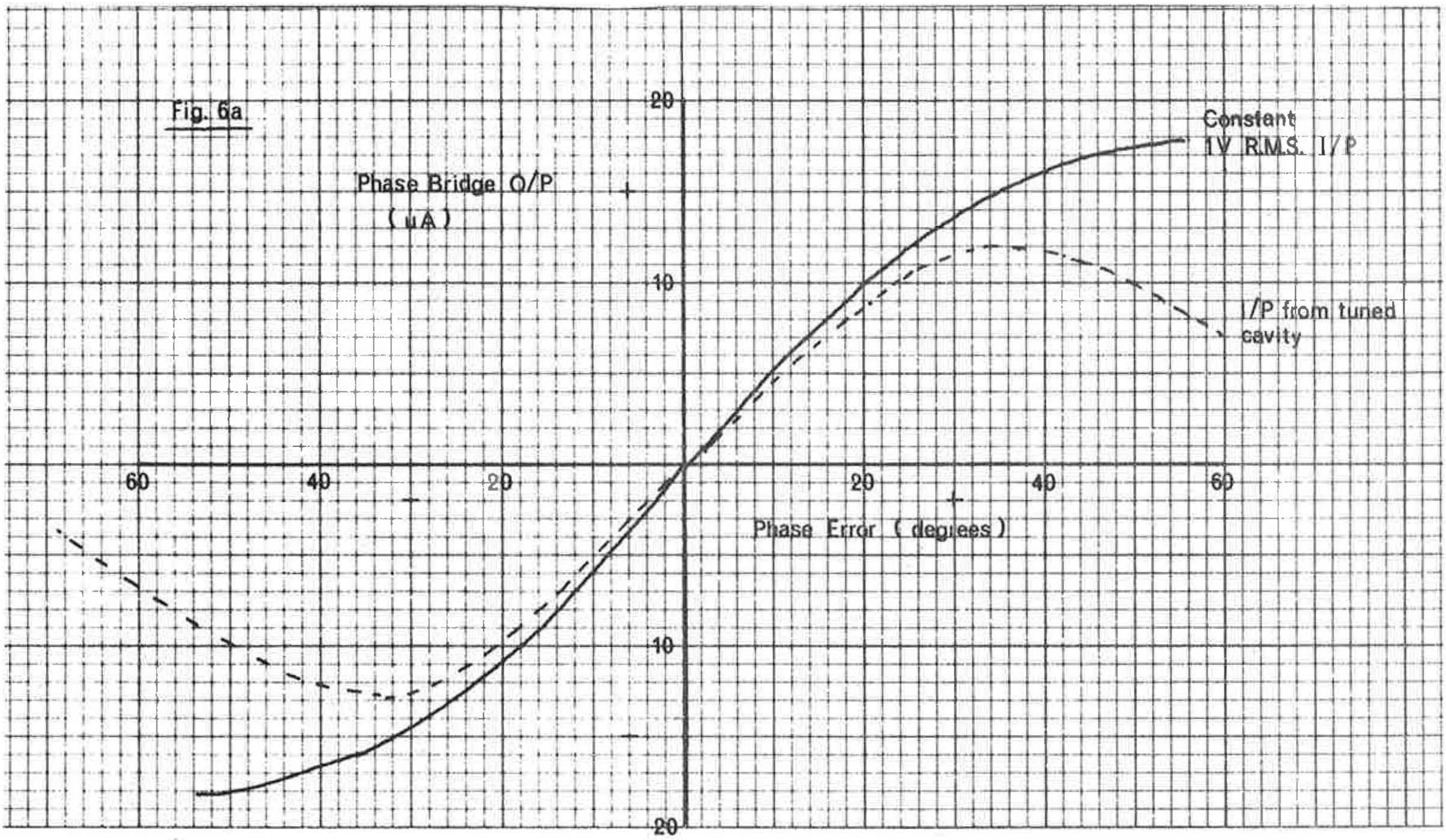
$$W_o = \frac{1}{\sqrt{LC}}$$

$$\delta = \frac{\omega}{\omega_o} - 1$$

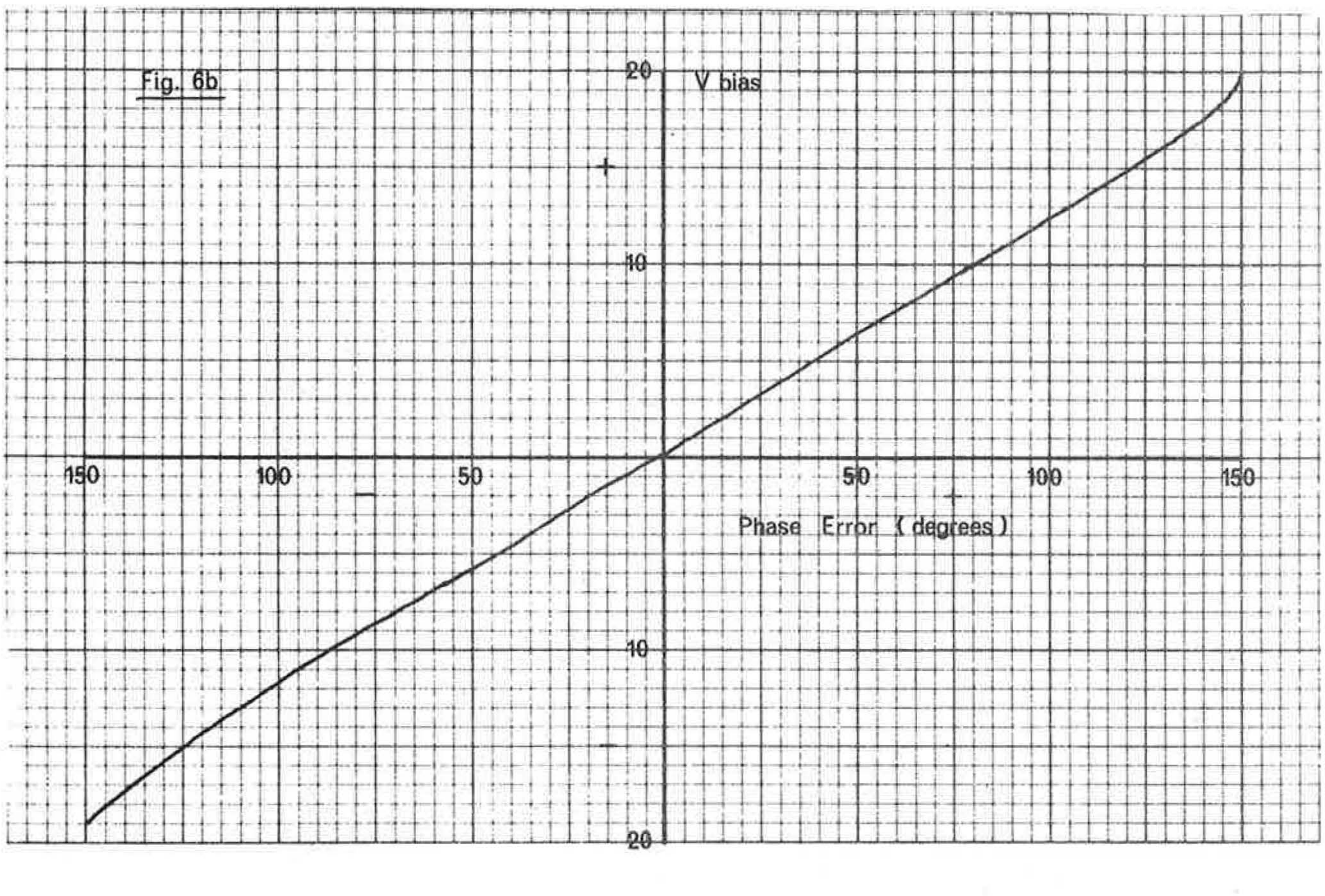
$$Q = \frac{1}{\omega_o C R}$$

FIG 6

Phase Bridge rectified output against Phase Error



Phase Bridge reset bias for phase null against phase error



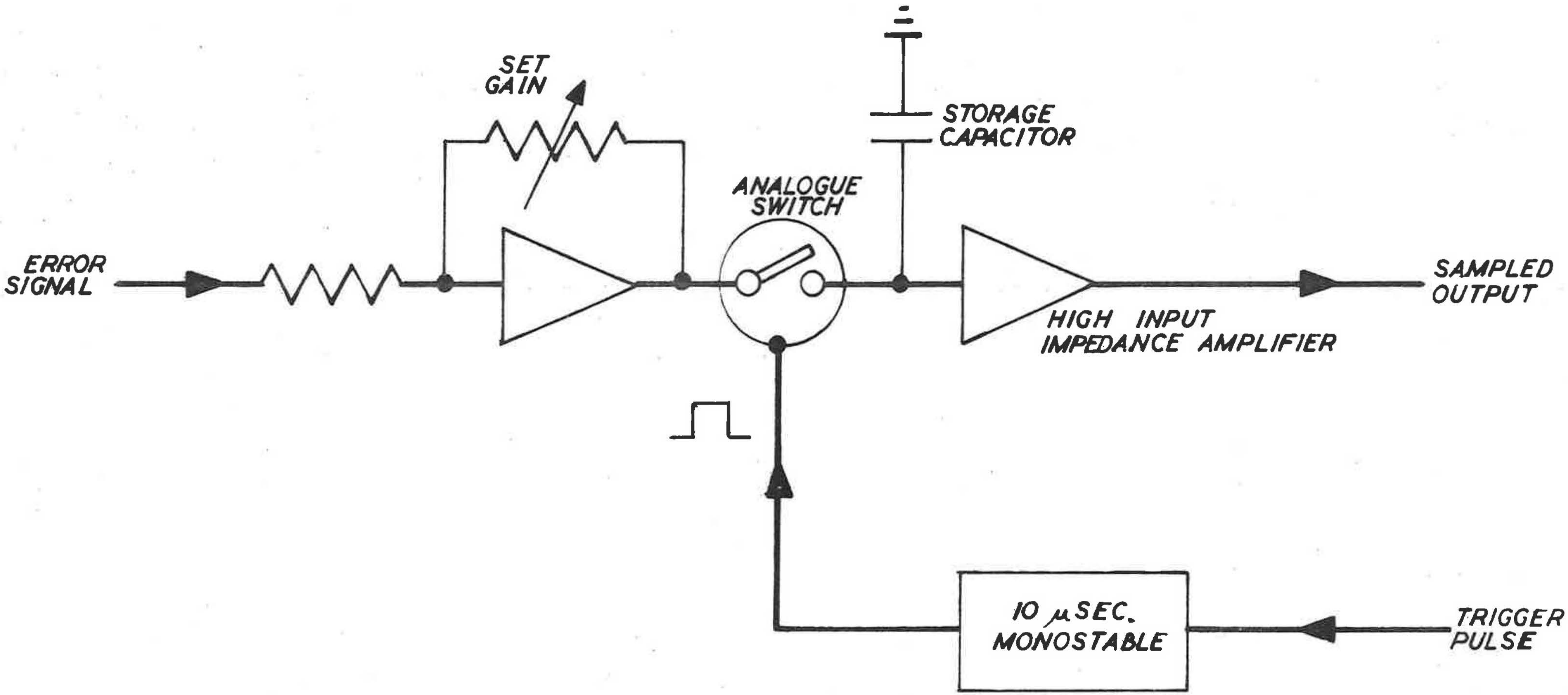


DIAGRAM OF SAMPLE & HOLD AMPLIFIER

FIG. 7