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ROYAL AIRCRAFT ESTABLISHMENT

(FARNBOROUGH)

TECHNICAL NOTE No. I.E.E. 10

SOME PERFORMANCE DETAILS OF A PROTOTYPE TUNING-FORK GYROSCOPE, SERIAL No. K.H.I [U]

by

R. J. Pitt

NOVEMBER, 1962

MINISTRY OF AVIATION

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Technical Note No. IEE.10

November, 1962

ROYAL AIRCRAFT ESTABLISHMENT

(FARNBOROUGH)

SOME PERFORMANCE DETAILS OF A PROTOTYPE TUNING-FORK GYROSCOPE, SERIAL NO. K.H.1

by

R. J. Pitt

RAE Ref. IEE/3803

SUMMARY

A test schedule has been designed and it is shown that the information available after carrying out this schedule should be sufficient to enable a performance assessment to be made of any tuning-fork gyroscope.

Comparisons between open loop and closed loop behaviour are made and an overall value for the tuning-fork's reliability as a rate-of-turn indicator is derived. A modification to the instrument design which should result in an improved performance is suggested.

Long-term stability and the effects of temperature changes are amongst the measurements quoted.

Since this is the first investigation of this type an unusually large number of test records are included in this Note as a basis for future reference.

LIST OF CONTENTS

		Page
1	INTRODUCTION	4
2	ACCURACY OF MEASUREMENTS	4
3	CALIBRATION TESTS	5
	3.1 Gyro mounted on rate-table with table axis vertical	5
	3.2 Gyro mounted on rate-table with table axis horizontal	8
	3.3 Summary of calibration test results	9
4	POLAR AXIS TESTS	9
	4.1 Results	10
	4.1.1 Open loop tests	11
	4.1.2 Closed loop tests	11
5	TEMPERATURE EFFECTS	11
6	LONG TERM STABILITY	11
7	CONCLUSIONS	12
LIST OF REFERENCES		13
ADVANCE DISTRIBUTION LIST		14
APPENDICES 1 and 2		15-17
ILLUSTRATIONS - Figs.1-36		-
DETACHABLE ABSTRACT CARDS		-

LIST OF APPENDICES

Appendix		
1	K.H.1 tuning fork gyroscope test schedule	15
2	Some parameters for K.H.1	17

LIST OF ILLUSTRATIONS

	Fig.
Effect of ±10 volts change in torsion compensation voltages	1
Effect of rotations about a vertical input axis	2
Rotation about vertical YY' axis, open loop	3
Rotation about vertical YY' axis, closed loop	4
Rotation about vertical ZZ' axis, open and closed loop	5
Rotations about a horizontal input axis, open and closed loop	6
Open loop polar axis test. XX' axis X up. 1000°/hour	7
Closed loop polar axis test. XX' axis X up 1000°/hour	8
Open loop polar axis test. XX' axis X up 100°/hour	9

LIST OF ILLUSTRATIONS (Contd.)

	Fig.
Closed loop polar axis test. XX' axis X up 100°/hour	10
Open loop polar axis test. XX' axis X' up 1000°/hour	11
Closed loop polar axis test. XX' axis X' up 1000°/hour	12
Open loop polar axis test. XX' axis X' up 100°/hour	13
Closed loop polar axis test. XX' axis X' up 100°/hour	14
Open loop polar axis test. YY' axis Y up 1000°/hour	15
Closed loop polar axis test. YY' axis Y up 1000°/hour	16
Open loop polar axis test. YY' axis Y up 100°/hour	17
Closed loop polar axis test. YY' axis Y up 100°/hour	18
Open loop polar axis test. YY' axis Y' up 1000°/hour	19
Closed loop polar axis test. YY' axis Y' up 1000°/hour	20
Open loop polar axis test. ZZ' axis Z up 1000°/hour	21
Closed loop polar axis test. ZZ' axis Z up 1000°/hour	22
Open loop polar axis test. ZZ' axis Z' up 1000°/hour	23
Closed loop polar axis test. ZZ' axis Z' up 1000°/hour	24
Open loop polar axis test. ZZ' axis Z' up 100°/hour	25
Closed loop polar axis test. ZZ' axis Z' up 100°/hour	26
Effect of temperature variations within T.F.G. enclosure	27
Temperature variation test. 31°C to 30°C	28
Temperature variation test. 30°C to 31°C	29
Long-term stability X up	30
Long-term stability Y up	31
Long-term stability Z up	32
K.H.1 on polar axis test rig	33
K.H.1 detail	34
Section through XX', YY' axes of the gyroscope	35
The T.F.G. axis system	36

1 INTRODUCTION

A detailed theoretical analysis of the behaviour of a tuning-fork gyroscope (T.F.G.) in steady-state operation was published recently[1] together with some practical results obtained with an experimental model operated in a laboratory environment. The conclusions carried several suggestions for the improvement of later experimental instruments and these modifications have been embodied in a T.F.G., Serial No. K.H.1, designed at the R.A.E. and manufactured by S. Smith and Sons (England) (Kelvin Hughes Division) under M.O.A. contract.

Figs.34 and 35 show a photograph of K.H.1 and a unit scale diagram of a section through the instrument. It should be noted that one fundamental difference between K.H.1 and the instrument examined in Technical Note No. I.A.P.1139 is that the driving forces are now contained entirely within the tuning-fork assembly; the drive electrodes and tine pick-off assemblies are fixed to the centre stem so that deformations of the structure cannot introduce an in-phase signal which is due directly to a change in the relative positions of the electrodes and tines.

A theoretical study[2] has shown that the introduction of a suitable force-feedback system round the output torsion stem should modify the open-loop behaviour so that the T.F.G. becomes a more useful rate-of-turn indicating instrument. The effects would be to reduce the response time of the device and to lower the 'Q' of the torsion output, at the expense of a smaller signal to noise ratio. An electrical feed-back system was developed for use with the T.F.G. so that practical confirmation of this theory could be carried out.

The feed-back system used takes a proportion of the pick-off signal, amplifies it and feeds it back in the appropriate phase to a pair of electrodes adjacent to the torsion system. When combined with a stabilized polarizing voltage the electrostatic forces set up between the feed-back electrodes and torsion system oppose the oscillatory motion of the torsion stem and the torsion pick-off signal is correspondingly reduced. Random noise in the original torsion pick-off output arising from electrical, magnetic and mechanical interference will also be amplified and fed back to the electrodes, but only the small fraction of this noise which is at the exact, resonant, frequency of the torsion system will contribute to the damping. Therefore, since no attempt has been made at this stage to filter out random noise from the torsion pick-off output, a smaller signal to noise ratio is obtained when feed-back is applied. For the tests described, the torsion output is sampled at the feed-back amplifier and fed to a phase-sensitive rectifier (P.S.R). The P.S.R. itself is, under these circumstances, an adequate random noise filter for measuring purposes.

A series of tests was designed to examine and compare the open and closed loop performance of K.H.1, and the results of these tests are presented in this Note. The test schedule is given in Appendix 1, and some operating parameters are listed in Appendix 2.

Reference will be made in the text to the sensitivity of the T.F.G. under open and closed loop operating conditions. The term "sensitivity" is used here to express the ratio of torsion pick-off output to angular rate of the T.F.G. about its own input axis.

2 ACCURACY OF MEASUREMENTS

The output from the two series-connected torsion pick-offs was fed through a calibrated amplifier into a Resolved Components Indicator (R.C.I.) and compared in amplitude and phase with the tine pick-off voltage. Outputs

from the R.C.I. were then transferred to a Record Duoflex pen recorder and continuous records were made of the components of the output signal in phase with and in quadrature with the tine pick-off, or reference, voltage. Pen recorder friction and visual analysis of the recorded outputs were judged to contribute the major proportion of errors in this arrangement, and it is estimated that an accuracy of ±2 per cent of the recorder's full scale deflection (equivalent to ±½ small divisions on the recorder charts) was achieved. Since the majority of the functional tests were carried out with a recorder sensitivity equivalent to a detected input rate of 50°/hour for a full scale deflection, an accuracy of ±1°/hour is implied in the tabulated results unless otherwise stated.

3 CALIBRATION TESTS

Fig.36 is a schematic diagram of a T.F.G. showing the three orthogonal axes to which reference will be made in the text. The XX' axis is both the input and the output axis. An input rate about XX' will be converted, under the action of Coriolis forces acting on the vibrating tines, into an oscillatory motion of the torsion stem about XX' whose amplitude will be directly proportional to the input rate and to the maximum tine velocity. The line of motion of the tines is parallel with the YY' axis, and the ZZ' axis is orthogonal with XX' and YY'.

The T.F.G. was balanced to minimise lateral motions along the YY' axis and residual torques about the XX' axis. In general such lateral motion is due to a mass and/or stiffness difference between the two tines; residual torques arise from misalignment of the lines of motion of the tines with the YY' axis.

The tine and torsion system frequencies were then made equal (in tune) to achieve maximum sensitivity and minimum phase error in the response signal with X' upwards. By this means it would be possible to study the behaviour of the T.F.G. in both the tuned (X' up) and un-tuned (X up) states. After further small adjustments to the balancing a series of tests was carried out to calibrate the instrument.

3.1 Gyro mounted on rate-table with table axis vertical

3.1(a) Effect of ±10 volts change in torsion compensation voltages (Fig.1)

In the following two test values of compensating voltage were approximate (±0·5 volts) and the tests were intended primarily as functional ones to prove that changes in applied compensation would alter the output values.

T.F.G. Attitude: XX' vertical, X up. Y' North

Fork frequency: 522·449 c/s

Open Loop Test No.	Compensation applied		Output ($\mu V \times 10^3$)			
	In Phase	Quadrature	In Phase		Quadrature	
			-	+	-	+
1(a)o. (i)	0V 0°	0V 270°		6·9		5·0
(ii)	10V 0°	0V 270°	20·0		4·0	
(iii)	10V 180°	0V 270°		33·8		14·4
(iv)	0V 0°	10V 270°		17·6	17·1	
(v)	0V 0°	10V 90°	3·2			27·2
(vi)	0V 0°	0V 270°		6·9		5·3

i.e. A change of 10 volts in the compensation applied altered the torsion pick-off output by approximately 29×10^3 μV when in phase with the reference voltage, and by approximately 24×10^3 μV when in quadrature with the reference. These variations were accompanied by phase-shifts of the torsion pick-off output relative to the reference voltage of approximately 18° in the former case and 24° in the latter.

Closed Loop Test No.	Compensation applied In Phase	Compensation applied Quadrature	Output (μV) In Phase		Output (μV) Quadrature	
			-	+	-	+
1(a)c (i)	0V 0°	0V 270°	196		72	
(ii)	10V 0°	0V 270°		590	48	
(iii)	10V 180°	0V 270°	1000		96	
(iv)	0V 0°	10V 270°	259			580
(v)	0V 0°	10V 90°	153		715	
(vi)	0V 0°	0V 270°	196		72	

i.e. A change of 10 volts in the voltage applied altered the torsion pick-off output by approximately 800 μV when in phase with the reference voltage, and by approximately 650 μV when in quadrature with the reference. The associated phase-shifts of the output were approximately 2° and 5° respectively.

3.1(b) Effect of rotations about a vertical input axis (XX') (Fig.2)

T.F.G. Attitude	Open Loop Test No.	Applied Rate	Direction	Output ($\mu V \times 10^3$) In Phase	Quadrature	Fork Frequency
X up	1(b)o (i)	Stationary		+0·14	-0·48	
X up	(ii)	100°/hour	C.W.	-2·95	-1·57	
X up	(iii)	100°/hour	A.C.W.	+3·26	+0·54	
X up	(iv)	1000°/hour	C.W.	-28·2	-9·10	522·499 c/s
X up	(v)	1000°/hour	A.C.W.	+27·2	+7·10	
X up	(vi)	Stationary		0	-0·50	
X' up	(vii)	Stationary		+0·77	-0·32	
X' up	(viii)	100°/hour	C.W.	+4·37	0	
X' up	(ix)	100°/hour	A.C.W.	-2·84	-0·71	522·459 c/s
X' up	(x)	1000°/hour	C.W.	+31·2	-0·20	
X' up	(xi)	1000°/hour	A.C.W.	-31·2	-1·40	
X' up	(xii)	Stationary		+0·75	-0·29	

These figures show that, with the input axis vertical and fork base downwards, a change of rate of rotation of 200°/hour caused a change of the in-phase component of the output of $6{\cdot}2 \times 10^3$ μV or $3{\cdot}1 \times 10^3$ μV/100°/hour. A 2000°/hour change of input rate caused a change of $55{\cdot}4 \times 10^3$ μV or $2{\cdot}8 \times 10^3$ μV/100°/hour.

With the fork base uppermost, the corresponding sensitivities were $3{\cdot}6 \times 10^3$ μV/100°/hour and $3{\cdot}1 \times 10^3$ μV/100°/hour.

The difference in sensitivities between the two attitudes was the result of de-tuning, the fork frequency varying with attitude but not the torsion system frequency.

The differences between sensitivities at each input rate could have been attributed to non-linearities in the damping of the torsion pick-off motion.

The difference between the outputs at X up and X' up, stationary, was due to the difference in the components of Earth's rate detected by the T.F.G. in these attitudes.

T.F.G. Attitude	Closed Loop Test No.	Applied Rate	Direction	Output (μV) In phase	Output (μV) Quadrature	Fork Frequency
X up	1(b)c (i)	Stationary		-2·4	-15·4	
X up	(ii)	100°/hour	C.W.	-81·0	-14·4	
X up	(iii)	100°/hour	A.C.W.	+77·0	-17·3	
X up	(iv)	1000°/hour	C.W.	-775	+4·8	522·449 c/s
X up	(v)	1000°/hour	A.C.W.	+810	-24·0	
X up	(vi)	Stationary		-1·9	-14·9	
X' up	(vii)	Stationary		+15·4	-8·2	
X' up	(viii)	100°/hour	C.W.	+95·0	-9·6	
X' up	(ix)	100°/hour	A.C.W.	-63·5	-4·8	
X' up	(x)	1000°/hour	C.W.	+840	-30·0	522·459 c/s
X' up	(xi)	1000°/hour	A.C.W.	-760	+20·0	
X' up	(xii)	Stationary		+15·4	-7·2	

These figures show sensitivities of 79 μV and 79·3 μV/100°/hour for input rates of 100°/hour and 1000°/hour respectively, the tine base being downwards. With the base upwards, the corresponding sensitivities at 100°/hour and 1000°/hour were 79·3 μV and 80 μV/100°/hour. The negligible difference between these sensitivities working in a"closed loop" condition shows two major improvements over the "open loop"state. The variation of torsion pick-off damping with applied rate became very small, so that there was little difference between the sensitivities for 100°/hour and 1000°/hour input rates, and the reduction of the "Q" of the torsion system meant that there was little difference in response between the tuned and de-tuned state as the fork changed its attitude. In addition, two further features of closed loop operation discussed in Technical Note No. I.E.E.8 have been confirmed in practice. First, the difference in sensitivities between open and closed loop operation is in the same ratio as the difference between the open and closed loop values of torsion Q, i.e. just over 40:1. Secondly, as presented in the following table, there is considerably less phase error of the closed loop output than of the open loop output when the T.F.G. is in the poorly tuned attitude. There is a much smaller difference in the nearly-tuned attitude.

T.F.G. Attitude	Applied rate	Direction	Phase Error (to nearest 0·1°) Open Loop	Phase Error (to nearest 0·1°) Closed Loop
X up	Stationary		-	-
X up	100°/hour	C.W.	+19·4°	-0·6°
X up	100°/hour	A.C.W.	+18·4°	-1·4°
X up	1000°/hour	C.W.	+17·0°	-1·5°
X up	1000°/hour	A.C.W.	+15·6°	-0·6°
X up	Stationary		-	-
X' up	Stationary		-	-
X' up	100°/hour	C.W.	+5·1°	-1·4°
X' up	100°/hour	A.C.W.	+6·2°	-2·1°
X' up	1000°/hour	C.W.	+0·2°	-1·6°
X' up	1000°/hour	A.C.W.	+1·9°	-2·0°
X' up	Stationary		-	-

The phase error angles quoted were derived from the output voltages given in the results of tests 1(b)o and 1(b)c.

3.1(c) Effect of rotations about a vertical axis through the plane of the tines (YY' axis) (Figs.3 and 4)

When the T.F.G. is rotated about a vertical axis through the plane of the tines, the input (XX') axis moving in a horizontal plane, the instrument will detect a varying component of Earth's rate which is a maximum with the input axis along a N-S line and zero along an E-W line. At latitude 51°17', this maximum value is 9·38°/hour. The output amplitude in the open loop test was 332 μV, or $3{\cdot}54 \times 10^3$ μV/100°/hour. The output amplitude in closed loop was 7·56 μV, or 80·7 μV/100°/hour. The rate of table rotation was 1000°/hour in each case.

No acceptable reason has yet been discovered for the non-sinusoidal waveform of the in-phase signal in these two test runs. It is unlikely to be a function of the rate table behaviour, since it does not appear in the next test.

3.1(d) Effect of rotations about a vertical (ZZ') axis perpendicular to the plane of the tines and to the input axis (Fig.5)

For these tests, the input axis was still horizontal, detecting a maximum component (9·38°/hour) of Earth's rate along a N-S line. In open loop, the response was 288 μV, or $3{\cdot}07 \times 10^3$ μV/100°/hour. In closed loop, the output amplitude was 7·44 μV, or 79·5 μV/100°/hour. The rate of table rotation was 1000°/hour in each case.

It should be noted with these two tests that the difference between open and closed loop output signals is shown clearly in Figs.3 and 4. For open loop behaviour, Fig.3 shows a quadrature signal which is due almost entirely to a phase error of about 17 degrees in the output signal, and is one-third of the in-phase component. When the loop is closed, as in Fig.4, this phase error is practically eliminated and there is very little quadrature component of the in-phase signal. There is, however, more noise as indicated by the broader line drawn by the recorder during closed loop operation.

3.2 Gyro mounted on rate table with table-axis horizontal (Fig.6)

3.2(a) Input axis horizontal along a N-S line, X North.

Open Loop Test No.	Applied Rate	Direction	Output ($\mu V \times 10^3$) In Phase	Quadrature	Fork Frequency
2(o)(i)	Stationary		-0·05	+0·6	
(ii)	100°/hour	C.W.	-3·0	-0·5	
(iii)	100°/hour	A.C.W.	+2·9	+1·15	522·454 c/s
(iv)	1000°/hour	C.W.	-30·0	-0·6	
(v)	1000°/hour	A.C.W.	+29·0	+0·6	
(vi)	Stationary		+0·05	0	

i.e. An average sensitivity of $2{\cdot}95 \times 10^3$ μV/100°/hour.

Closed Loop Test No.	Applied Rate	Direction	Output (μV) In Phase	Output (μV) Quadrature	Fork Frequency
2(c)(i)	Stationary		+1·5	+9·6	
(ii)	100°/hour	C.W.	-79·0	+11·0	
(iii)	100°/hour	A.C.W.	+81·0	+6·7	522·454 c/s
(iv)	1000°/hour	C.W.	-790	+38·0	
(v)	1000°/hour	A.C.W.	+810	-5·0	
(vi)	Stationary		+1·5	0	

i.e. An average sensitivity of 80 μV/100°/hour.

3.3 Summary of Calibration Test Results

3.3.1 The R.M.S. value of any voltage applied to the compensating electrodes to counteract residual torques must remain stable to within 10 mV if the torsion pick-off output is to be correct to within 1°/hour. This applies for both the open and closed loop states.

3.3.2 The average sensitivity of the torsion pick-off system in open loop can be taken as $3{\cdot}3 \times 10^3$ μV/100°/hour, irrespective of attitude or applied input rate up to 1000°/hour. The output will then be within 10% of the correct value except when the input axis is vertical and the tine base is downwards; the error in this attitude may reach 15%. This could be substantially reduced by tuning the T.F.G. with the input axis horizontal.

3.3.3 The average sensitivity in closed loop operation can be taken as 80 μV/100°/hour. This will be correct to within 1½% for all T.F.G. attitudes and input rates up to 1000°/hour.

3.3.4 The sensitivities in open and closed loop operation are in the same ratio as that predicted in R.A.E. Technical Note No. IEE.8, i.e. in the ratio of the open and closed loop values of the torsion system Q.

3.3.5 One effect of closing the feed-back loop is to reduce the phase-error in the output signal caused by mis-matching the tine and torsion natural frequencies. This reduction virtually eliminates the appearance of quadrature components of in-phase rate signals. Where mass unbalance torques produce a quadrature signal, closed loop operation prevents the appearance of an in-phase component of these torques by the same process of reducing the phase error to very small proportions.

4 POLAR AXIS TESTS

Polar axis tests are designed to examine the effect of varying acceleration forces on the T.F.G. A full description of the tests and the mechanisms involved is given in R.A.E. Technical Note No. I.A.P. 1139.

The rate table, on which the T.F.G. was mounted, had its axis of rotation aligned with Earth's polar axis. When the T.F.G. input (XX') axis was along this axis of rotation, the rotation of the Earth was detected and appeared as a constant in phase signal. The rate table rotation was also detected and, since this was a constant, was 'backed-off' by the application of suitable voltages to the compensating electrodes. The T.F.G. detected no component of Earth's rotation if toppled about the YY' or ZZ' axes. Any change in the residual torque output signal under any of these conditions was therefore due to variations in the attitude of the instrument.

By examining the components of 'g' acting along each of the T.F.G. axes during these tests it was possible to determine a set of 'g' coefficients indicating the change of residual signal with T.F.G. attitude.

Figs.7-26 inclusive show the recorded outputs from the T.F.G. during rotations about a polar axis, with the XX', YY' and ZZ' axes in turn along the axis of rotation. A Fourier analysis of these curves gave the sets of 'g' coefficients shown below. The in-phase coefficients K_x, K_y and K_z are derived from the amplitudes of the in-phase records as each axis has the maximum component of 'g' acting along it. Thus, K_x represents the in-phase response to acceleration forces along the XX' axis. It is calculated from the recordings of rotations about the YY' and ZZ' axes. Similarly, the quadrature coefficients L_x, L_y and L_z are derived from the amplitudes of the quadrature recordings at the same attitudes. L_x represents the quadrature response to acceleration forces along the XX' axis.

The sets of 'g' coefficients were determined for 1000°/hour input rates, and for a representative number of tests at 100°/hour to establish repeatability standards and to study the effect of a lower input rate.

4.1 Results

'g' coefficients for tuning-fork gyroscope K.H.1

°/hour/g for in-phase coefficients.

j°/hour/g for quadrature coefficients.

		OPEN LOOP						CLOSED LOOP					
		X Up	X Down	Y Up	Y Down	Z Up	Z Down	X Up	X Down	Y Up	Y Down	Z Up	Z Down
1000°/hour Input	K_x	-	-	+6.3	+0.7	+3.0	-0.2	-	-	-0.4	-0.6	+1.1	-0.1
	K_y	+0.4	+4.0	-	-	+3.2	+3.3	+2.5	+3.4	-	-	+3.5	+3.6
	K_z	-18.2	-14.9	-19.6	-15.6	-	-	+0.3	-1.6	+0.3	+2.2	-	-
	L_x	-	-	-9.1	-1.7	-3.2	-1.3	-	-	-7.9	-0.9	-3.3	-0.3
	L_y	+6.0	-3.2	-	-	+2.9	-0.1	+2.0	-0.6	-	-	+1.9	-0.6
	L_z	+39.6	+43.5	+40.8	+40.2	-	-	+46.9	+50.3	+50.0	+47.5	-	-
100°/hour Input	K_x	-	-	+4.7	-	-	-0.5	-	-	+0.6	-	-	*
	K_y	+1.4	+4.1	-	-	-	+2.2	+2.3	+2.8	-	-	-	*
	K_z	-21.0	-14.6	-18.9	-	-	-	-0.5	+0.4	-2.2	-	-	-
	L_x	-	-	-5.9	-	-	-2.0	-	-	-6.6	-	-	*
	L_y	+2.6	-3.1	-	-	-	0	+0.6	+0.5	-	-	-	*
	L_z	+35.7	+42.0	+38.4	-	-	-	+45.0	+49.4	+50.9	-	-	-

* Interference from local sources, both electrical and vibrational, made analysis of this test run impracticable. The coefficients are certainly no larger than those obtained at 1000°/hour input.

4.1.1 Open Loop Tests (Figs.7,9,11,13,15,17,19,21,23, and 25)

The variation in sensitivity of the residual in-phase torsion signal to acceleration along the XX' axis was from +6·3°/hour/g in the Y upwards attitude to +0·7°/hour/g for Y' upwards, whilst the change from Z to Z' upwards was from +3·0°/hour/g to -0·2°/hour/g.

For accelerations along the YY' axis the sensitivity of the residual in-phase signal varied from +0·4°/hour/g to +4·0°/hour/g between X and X' upwards and from +3·2°/hour/g to +3·3°/hour/g between Z and Z' upwards.

The residual signal was much more sensitive to accelerations along the ZZ' axis. The change from X to X' upwards resulted in a change of sensitivity from -18·2°/hour/g to -14·9°/hour/g, and from -19·6°/hour/g to -15·6°/hour/g as the T.F.G. was moved from Y to Y' upwards.

4.1.2 Closed Loop Tests (Figs.8, 10,12,14,16,18,20,22,24, and 26)

The application of electrostatic damping forces derived from and in anti-phase with the torsional motion of the T.F.G. torsion system had the effect of lowering the "Q" of the system and decreasing the response time. Under the conditions applied, the new "Q" of the torsion system was approximately 1/40th of the open loop "Q", and the sensitivities of the residual signals to accelerations along the major axes were correspondingly smaller.

Sensitivities of up to +1·1°/hour/g and +3·6°/hour/g to accelerations along the XX' and YY' axes respectively showed only small changes from the open loop values. There was, however, a marked decrease in sensitivity to accelerations along the ZZ' axis, the maximum value being +2·2°/hour/g.

5 TEMPERATURE EFFECTS

There are two types of temperature variation which may affect the T.F.G. performance.

5.1 A change in the mean value of the ambient temperature within the instrument container will alter the natural frequency of the tuning-fork and also that of the torsion system; the two systems will change at different rates and the state of tuning will therefore alter. This will give rise to a change in sensitivity and a phase change between the input and output signals. In closed loop operation the effect of this change of tuning and the phase change will be extremely small and will not affect the performance, except that a T.F.G. with some residual torques will require adjustment of the applied compensation voltages. K.H.1 required a change of approximately 1 volt in the in-phase compensation after a 1°C change, corresponding to a spurious signal of 100°/hour. For open loop conditions, re-tuning would be necessary for less than 1°C change.

5.2 The torsion output will vary in both open and closed loop operation when there is a rate of change of ambient temperature. Fig.27 shows that with the T.F.G. mounted with its input axis vertical, base downwards, the temperature control of the enclosure was such that air temperature variations of ±1/70th °C at a frequency of 1 cycle every four minutes caused changes in the residual in-phase torsion output equivalent to ±3/4°/hour. This effect varied a little with T.F.G. attitude, and could always be allowed for in the analysis of the recorded output.

6 LONG TERM STABILITY

The stability of the gyro output when stationary and in closed loop operation was determined over 8 hour periods with the X,Y and Z axes vertical.

Recordings of the output during 3 hour intervals selected at random in each of the three attitudes are reproduced in Figs.30, 31 and 32. They show that variations in the residual torques which produced the output signal did not contribute more than 1/2°/hour/hour change in the apparent detected input rate, once the most stable state had been achieved.

After rotation from the X vertical to Y vertical position, the T.F.G. took approximately 2 hours to stabilise, the indicated output changing during this period from +9°/hour to -1°/hour. No settling down period was required after rotation from Y vertical to Z vertical. 1 hour after rotation from Y vertical to X vertical the indicated output had changed from +2°/hour to +1°/hour and remained stable to within 1/2°/hour/hour thereafter.

Small changes (less than 0·2 volts) in the compensation voltages were made after attitude changes. These were necessary to keep the recorded outputs near zero.

One measurement of long term drift which became available during the polar axis tests is shown in Fig.13. After a test in which the T.F.G. had been rotated at 100°/hour about a ZZ' polar axis, the instrument was left operating over a period of nearly 54 hours, the recorders having been switched off. On re-starting the recorders it was found that the fork output had drifted by 3·6°/hour, an average drift rate over the stationary period of less than 0·07°/hour/hour.

7 CONCLUSIONS

The performance of a T.F.G. must ultimately depend on the pattern of its behaviour in various attitudes when no rate of turn is being applied about the input axis. This pattern is defined by the size of the in-phase 'g'-coefficients which in a practical system will present themselves as errors in the rate-of-turn indication.

In-phase 'g'-coefficients arise either from effects which are proportional to tine-velocity and include viscous damping, eddy current damping, rate of change of temperature, and variations of sensitivity with de-tuning, or to components of quadrature effects which are proportional to tine acceleration or tine displacement and arise as a result of de-tuning.

Quadrature g-coefficients can be caused by mass unbalance between the tines (L_z), lack of symmetry of the tines about the YY' axis (L_y), or by components of in-phase g-coefficients resulting from de-tuning.

7.1 These tests have provided practical confirmation of the theory of closed loop operation discussed in R.A.E. Technical Note No. I.E.E.8. The components of the originating torques arising from the de-tuning are virtually eliminated in closed loop operation. When the fork is correctly adjusted for dimensional symmetry about the input axis the quadrature g-coefficients should disappear and the limiting factors on T.F.G. performance will be the in-phase effects listed above which are proportional to tine-velocity.

7.2 Modifications to the torsion pick-off system which will reduce the effects of viscous and eddy current damping should limit the amplitude of the zero input rate signal to a much smaller value than K.H.1 gives in its present form.

7.3 A more critical assessment of the change of apparent rate with attitude will be required for future tests. Changes of 10 mV in the compensation voltages are known to contribute 1°/hour changes in the indicated output, and minor modifications to the existing test equipment should be made before examining more advanced T.F.G.'s.

7.4 Whilst the temperature control system surrounding K.H.1 is adequate in relation to the performance of the T.F.G. in its present form it is likely that temperature fluctuations of ±1/70°C will be too great for satisfactory control in later models. Since the value of the ambient temperature is not as important in closed loop operation as it is in open loop, a container which will reduce the rate of temperature fluctuations within the T.F.G. space to a much longer period is required.

It is also believed that large temperature gradients exist within the enclosure which are a function of the temperature difference between the enclosure and the laboratory ambient. These may account for the change in compensation voltage required after changing the enclosure temperature. It is expected that the provision of thicker walls to future enclosures will reduce these gradients.

7.5 The long period required for reaching a stable output after changing attitude from X up to Y up is possibly due to the breakdown of temperature stratification within the container caused by the T.F.G. having been in the X up attitude for several days prior to this test.

7.6 Once stable, long-term drift rates of as little as 0·07°/hour/hour are possible, although a general figure of ½°/hour/hour would cover most situations.

7.7 It is reasonable to assess the closed loop performance of the T.F.G. as being that of a 2°/hour instrument on closed loop over long periods. In its present form, g-sensitivities can contribute 2 to 3°/hour/g spurious signal in addition to the basic reliability figure.

7.8 The test schedule quoted appears to be adequate for a performance analysis of a T.F.G. to be made, and could be adopted as a standard test procedure.

7.9 Whilst the phase-sensitive rectifier in the measuring circuit was, during these tests, an adequate filter against random noise in the torsion pick-off output, it may be necessary under some circumstances to incorporate suitable filtering in the feed-back loop and to sample the feed-back signal for performance data. This could arise if a pick-off system with a substantially higher noise content in the output were required in order to meet, say, limitations on available space, or to reduce reaction torques.

LIST OF REFERENCES

No.	Author	Title, etc.
1	Hobbs, A.E.W.	Some sources of error in the tuning-fork gyroscope. R.A.E. Technical Note No. IAP 1139 April 1962.
2	Hunt, G.H.	Damping the torsion stem of a tuning-fork gyroscope. R.A.E. Technical Note No. I.E.E.8. October 1962.

ATTACHED: Appendices 1 and 2
Drg.Nos. IEE 163-4
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APPENDIX 1

K.H.1 TUNING-FORK GYROSCOPE TEST SCHEDULE

GENERAL

The gyro must be completely set-up and in tune inside a temperature controlled enclosure. Before starting tests the relevant operating voltages and temperature must be noted, and the 'Q's measured by noting the delay times of oscillation.

Unless otherwise stated, all tests will be carried out in open loop and closed loop operation.

All tests below marked RECORD imply recording on a chart recorder the in-phase and quadrature output from the gyro. All relevant details must be noted on the record.

Each test may be regarded as distinct, and except where otherwise noted adjustments of compensating voltage may be made only between tests. The compensating voltages must be noted for each test.

1 Gyro mounted on rate-table with table axis vertical

(a) With XX' axis vertical, apply ±10 volts change to the voltages on each of the compensating plates, and RECORD.

(b) With XX' axis vertical. Rotate table at ±100°/hour, ±1000°/hour note frequency and RECORD for X up and X' up.

(c) With YY' axis vertical. Rotate table at 1000°/hour through 2 cycles of revolution and RECORD. Repeat at 100°/hour and RECORD.

(d) With ZZ' axis vertical, repeat 1(c) and RECORD.

2 Gyro mounted on rate-table with table axis horizontal

(a) With the XX' axis along the rate-table axis, rotate table at ±100°/hour, ±1000°/hour, RECORD, and note fork frequency.

3 Gyro mounted on rate-table, with rate-table axis parallel with Earth's polar axis

(a) With XX' axis parallel with table axis and X up. Rotate at 1000°/hour, backing off input rate by altering compensating voltages, note frequency at 45° intervals and RECORD. Continue for 2 cycles, and repeat at 100°/hour input rate.

(b) Repeat 3(a) with XX' parallel with table axis and X' up. RECORD.

(c) With YY' axis parallel with table axis and Y up, repeat 3(a) and RECORD. Note frequency at 90° intervals.

(d) Repeat 3(c) with Y' up and RECORD.

(e) Repeat 3(c) with ZZ' parallel with table axis, Z up, and RECORD.

(f) Repeat 3(e) with Z' up and RECORD.

(g) Repeat 3(f) with 100°/hour input rate, and RECORD.

(h) Repeat 3(c) with 100°/hour input rate, and RECORD.

For tests 3(a) to 3(h) calculate the 6 sensitivity coefficients from Fourier analysis of the results (See T.N.I.A.F.1139)[1].

4 Gyro mounted on rate-table with table axis vertical

(a) With XX' axis vertical, X up, zero input rate. RECORD over 8 hour period. Note frequency.

(b) With YY' axis vertical, Y up, zero input rate. RECORD over 8 hour period.

(c) With ZZ' axis vertical, Z up, zero input rate. RECORD over 8 hour period.

(d) Repeat 4(a), but with temperature control adjusted to reduce ambient temperature inside container by 1°C. RECORD for 8 hours after stability has been achieved. Note compensating voltages and tine and torsion system frequencies.

(e) Repeat 4(a), after restoring gyro container to normal ambient temperature, and RECORD. Note tine and torsion system frequencies.

APPENDIX 2

SOME PARAMETERS FOR K.H.1

Drive electrode gaps: Y = 0·014" Y' = 0·015".

Tine pick-off gaps: Y = 0·028" Y' = 0·029".

Compensating and feed-back electrode gaps: YZ = 0·023"; Y'Z = 0·024"; Y'Z' = 0·024"; YZ' = 0·023".

F.23 thermistor temperature recorder balance: 1380 Ω.

M.53 + F23 T.F.C. thermistors on heater bridge balance: 5468 Ω.

Heater cycling time with 15 Ω series resistance: 82 seconds on, 120 seconds off.

Difference between torsion pick-offs: Input 1: 39 mV pk-pk, Input 2: 38 mV pk-pk } for 1000°/hour input rate.

Tine Q ≏ 12,500

Torsion Q ≏ 8,000

Closed loop Q ≏ 170

Response time (closed loop) = 0·1 seconds

Tine-drive voltages: 84V. R.M.S. A.C. 350V. D.C.

Compensation voltages XX' vertical X up. 0V 0° 0V 270°

Operating temperature within container + 31°C.

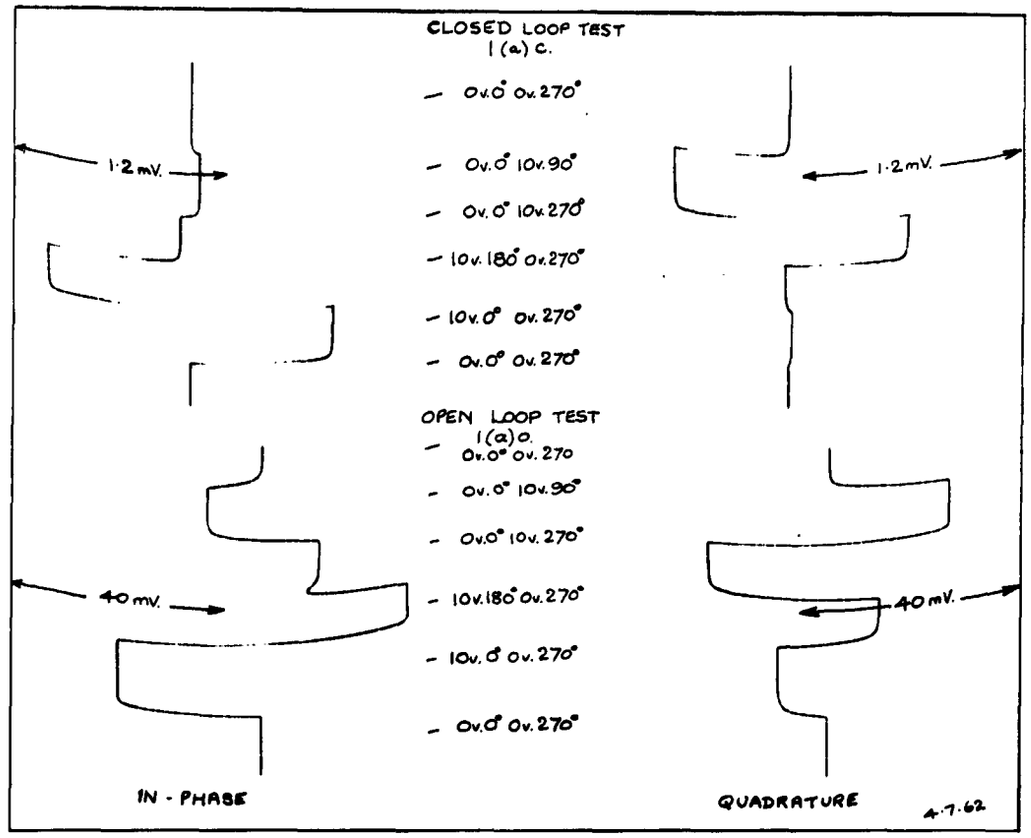


FIG. 1 EFFECT OF ±10 VOLTS CHANGE IN TORSION COMPENSATION VOLTAGES. OPEN LOOP AND CLOSED LOOP OPERATION.

T.F.G. ATTITUDE:- XX' VERTICAL, X UP
Y' NORTH

FORK FREQUENCY:- 522.449 C/S

CHART SPEED:- 12 INCHES/HOUR

R.A.E. 160031 62

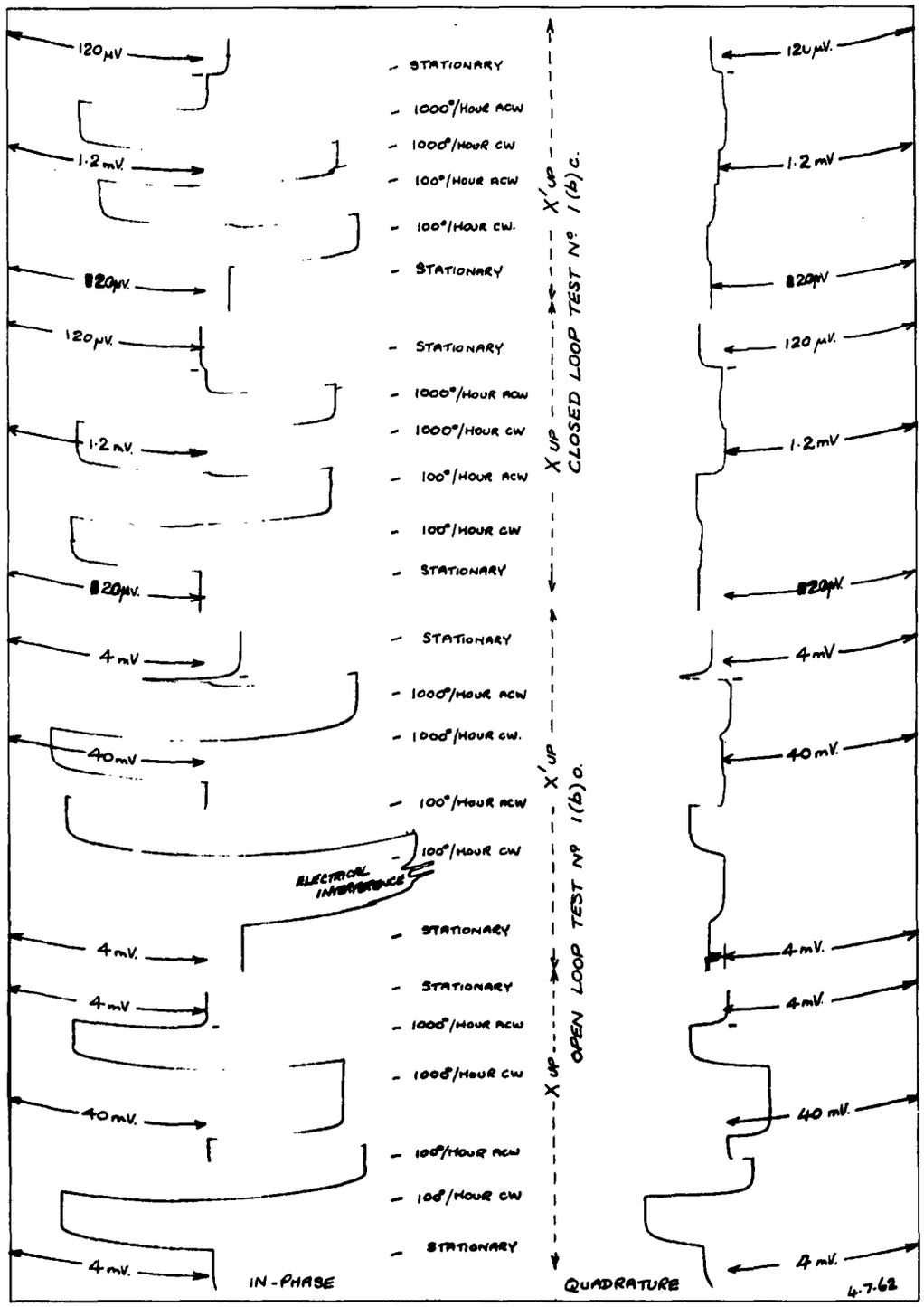


FIG.2 EFFECT OF ROTATIONS ABOUT A VERTICAL INPUT AXIS. OPEN LOOP AND CLOSED LOOP OPERATION.

FORK FREQUENCIES:- X UP, f = 522.449 C/S
X' UP, f = 522.459 C/S

CHART SPEED:- 12 INCHES/HOUR

R.A.E. 140032 62

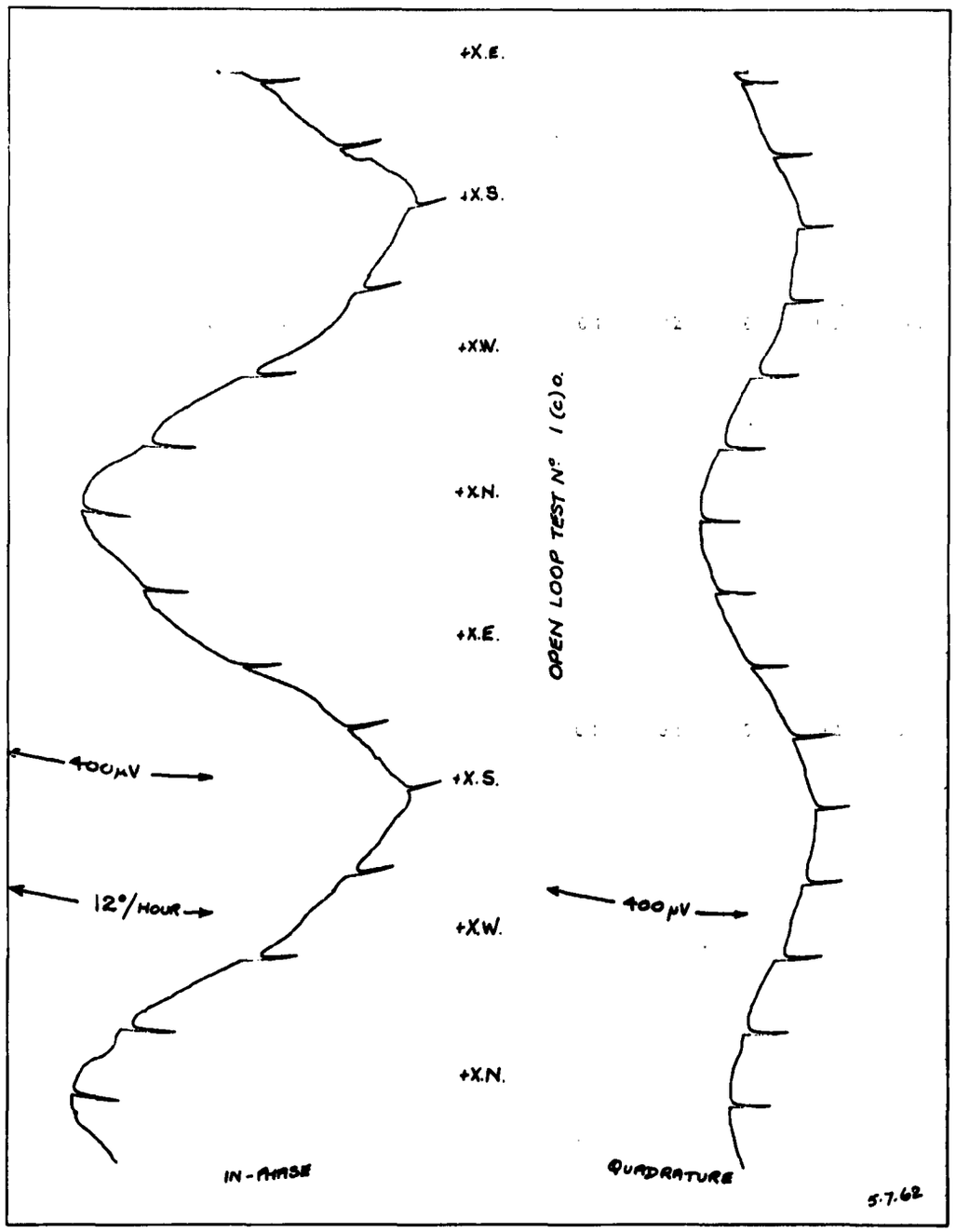


FIG.3 EFFECT OF ROTATIONS ABOUT A VERTICAL AXIS THROUGH THE PLANE OF THE TINES (YY' AXIS). OPEN LOOP OPERATION.

FORK FREQUENCY:- 522.456 C/S
CHART SPEED:- 12 INCHES/HOUR
RATE OF TURN:- 1000°/HOUR

R.A.E. 160033 (2)

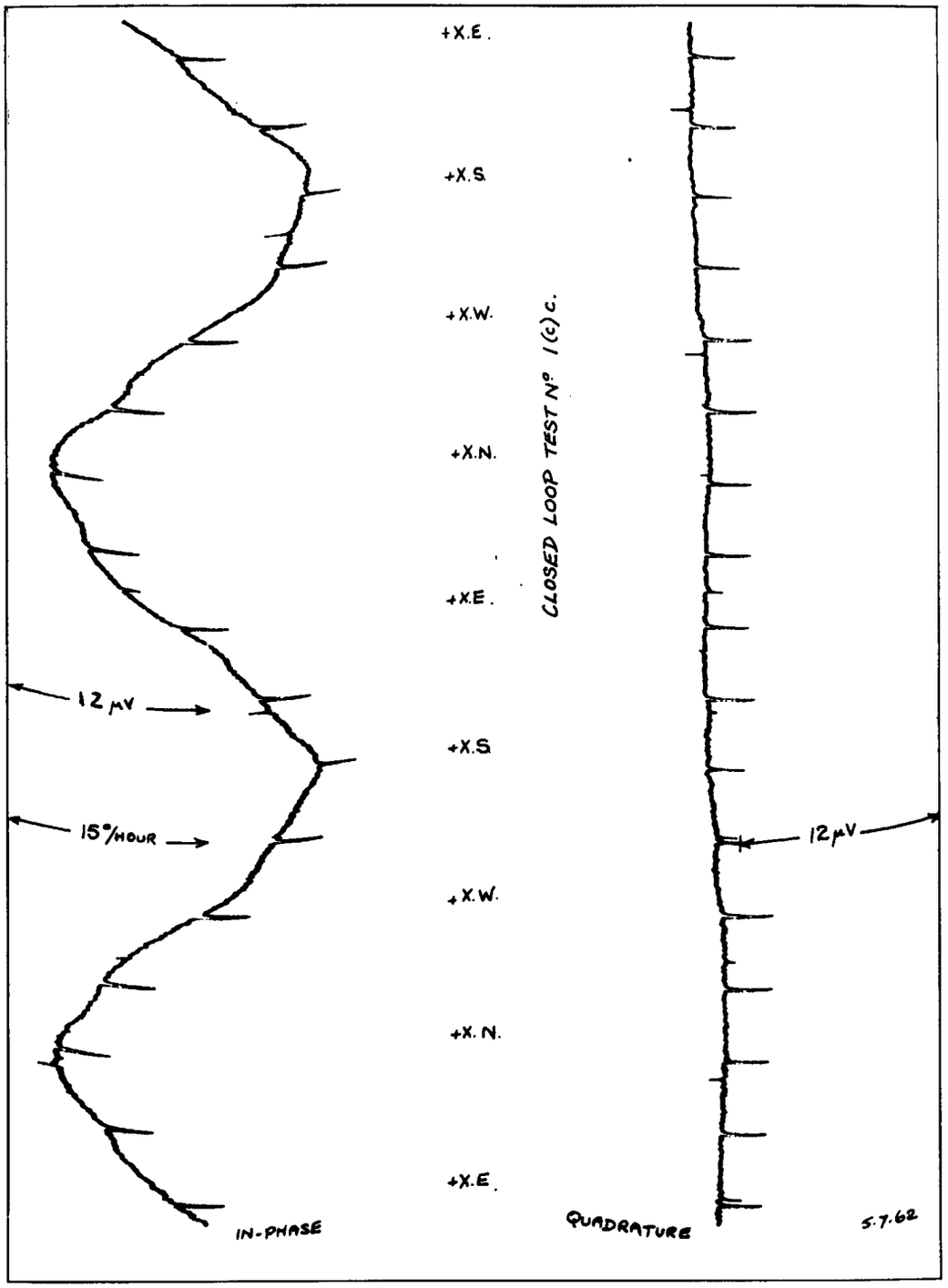


FIG.4 EFFECT OF ROTATIONS ABOUT A VERTICAL AXIS THROUGH THE PLANE OF THE TINES (YY' AXIS). CLOSED LOOP OPERATION.

FORK FREQUENCY:- 522.455 C/S
CHART SPEED:- 12 INCHES/HOUR
RATE OF TURN:- 1000°/HOUR

R.A.E. 140034 62

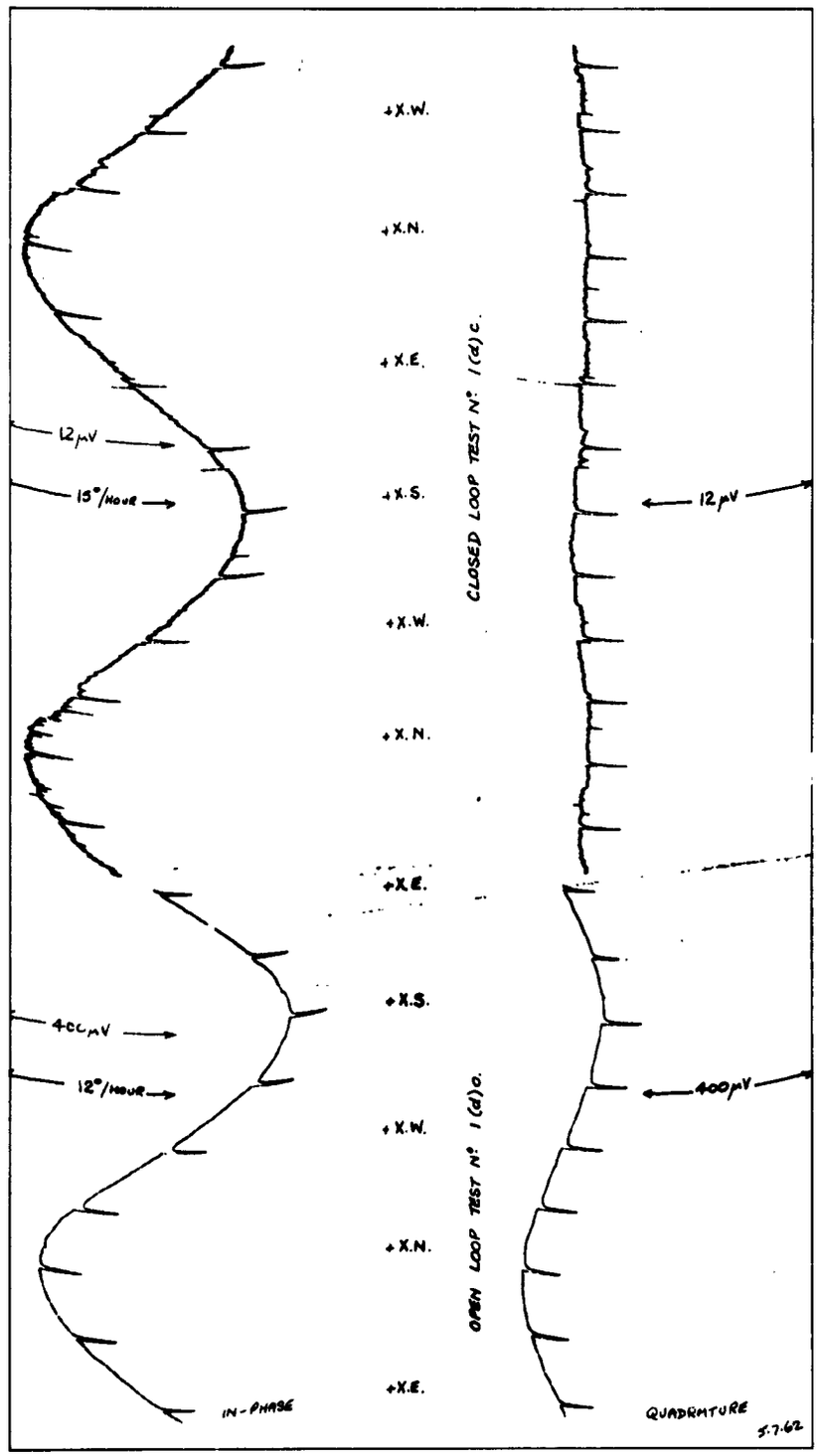


FIG.5 EFFECT OF ROTATIONS ABOUT A VERTICAL (ZZ') AXIS PERPENDICULAR TO THE PLANE OF THE TINES AND TO THE INPUT AXIS. OPEN LOOP AND CLOSED LOOP OPERATION.

FORK FREQUENCY:- 522.455 C/S
CHART SPEED: 12 INCHES/HOUR
RATE OF TURN:- 1000°/HOUR

R.A.E. 146035 (2)

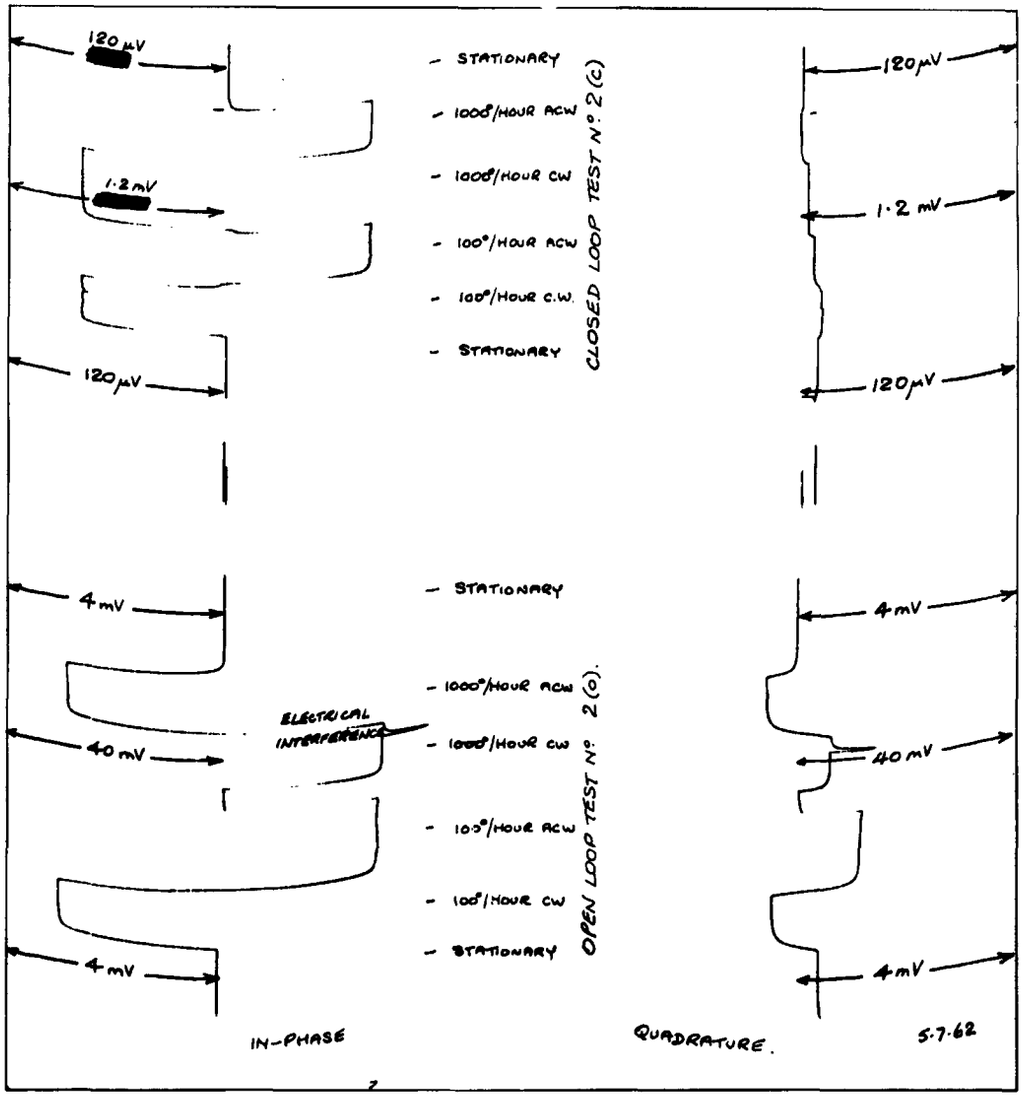


FIG.6 EFFECT OF ROTATIONS ABOUT A HORIZONTAL INPUT AXIS. X NORTH. OPEN LOOP AND CLOSED LOOP OPERATION.

FORK FREQUENCY:- 522.454 C/S

CHART SPEED:- 12 INCHES/HOUR

R.A.E. 140036 62

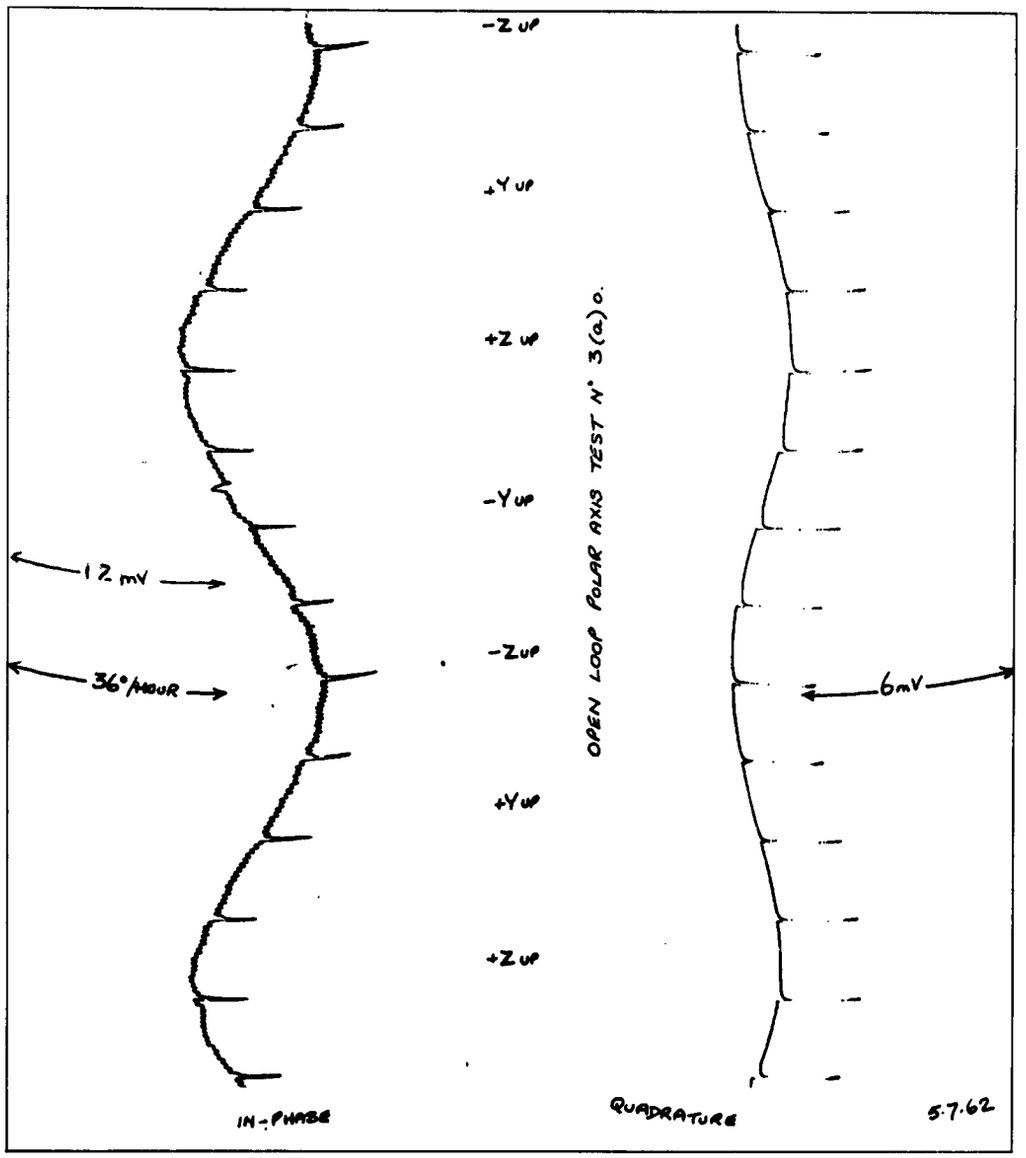


FIG.7 OPEN LOOP POLAR AXIS TEST. ROTATION ABOUT INPUT (XX') AXIS. X UP
1000°/HOUR INPUT RATE: BACKED OFF BY 14V 0° OV 270° COMPENSATION.
FORK FREQUENCY AT EACH 45° POSITION = 522.451 C/S
CHART SPEED:- 12 INCHES/HOUR

R.A.E. 160037 62

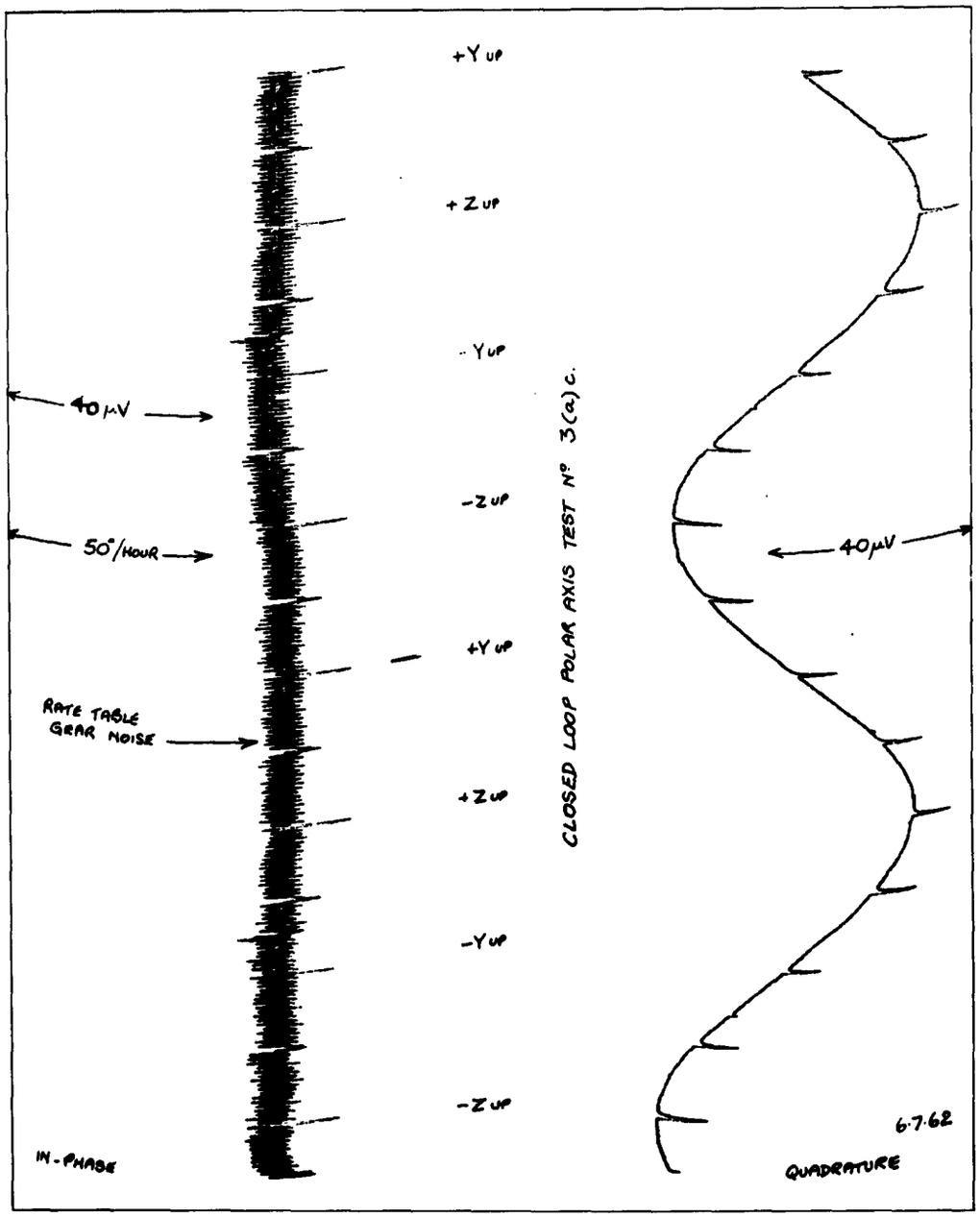


FIG.8 CLOSED LOOP POLAR AXIS TEST. ROTATION ABOUT INPUT (XX') AXIS. X UP
1000°/HOUR INPUT RATE: BACKED-OFF BY 15V 0° 0V 270° COMPENSATION.
FORK FREQUENCY AT EACH 45° POSITION = 522.452 C/S
CHART SPEED = 12 INCHES/HOUR

R.A.E. 160036 62

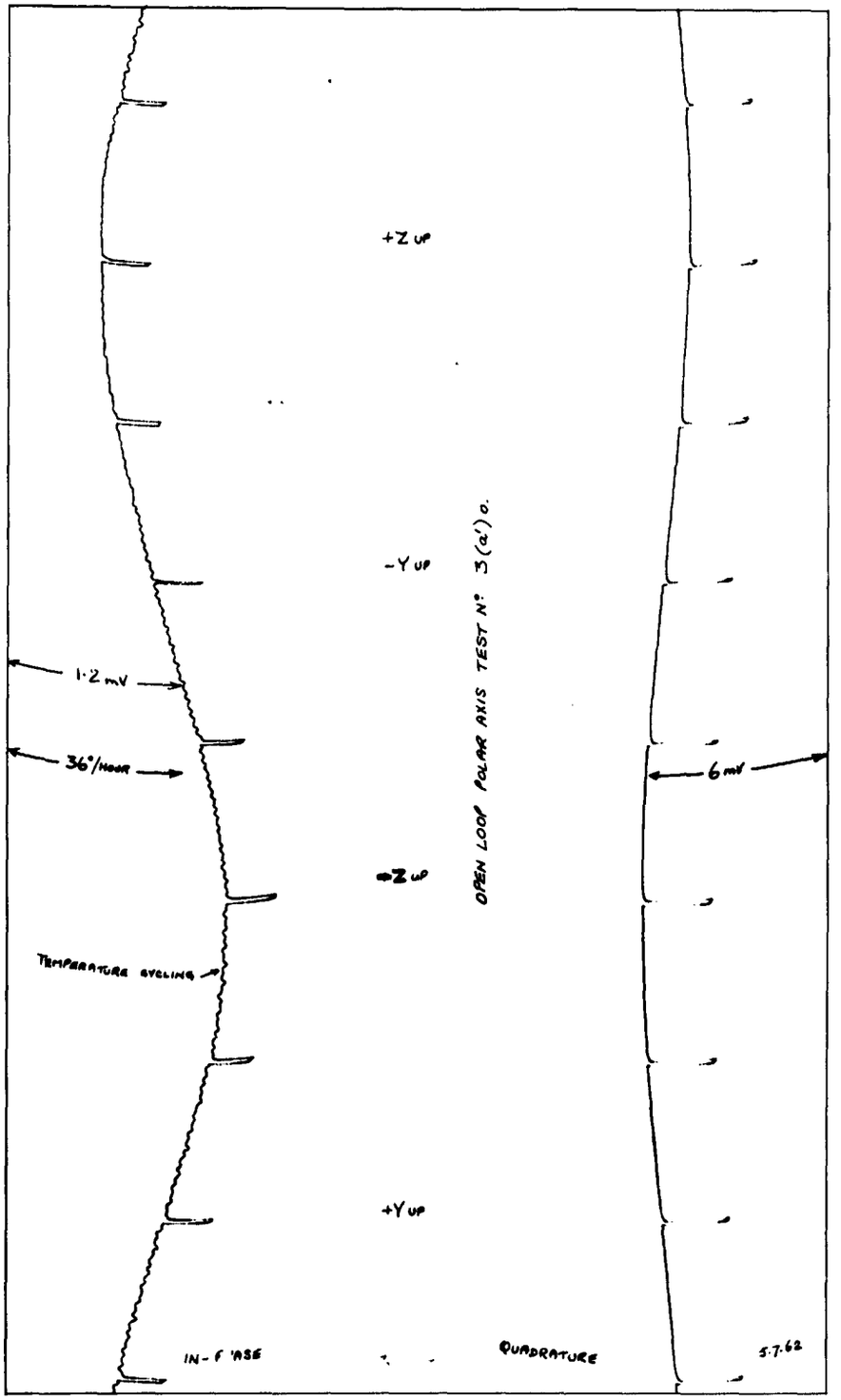


FIG.9 OPEN LOOP POLAR AXIS TEST. ROTATION ABOUT INPUT (XX') AXIS. X UP 100°/HOUR INPUT RATE: BACKED-OFF BY 2V 0° 0V 270° COMPENSATION.
FORK FREQUENCY AT EACH 45° POSITION = 522.451 C/S
CHART SPEED = 3 INCHES/HOUR

R.A.E. 160039 G2

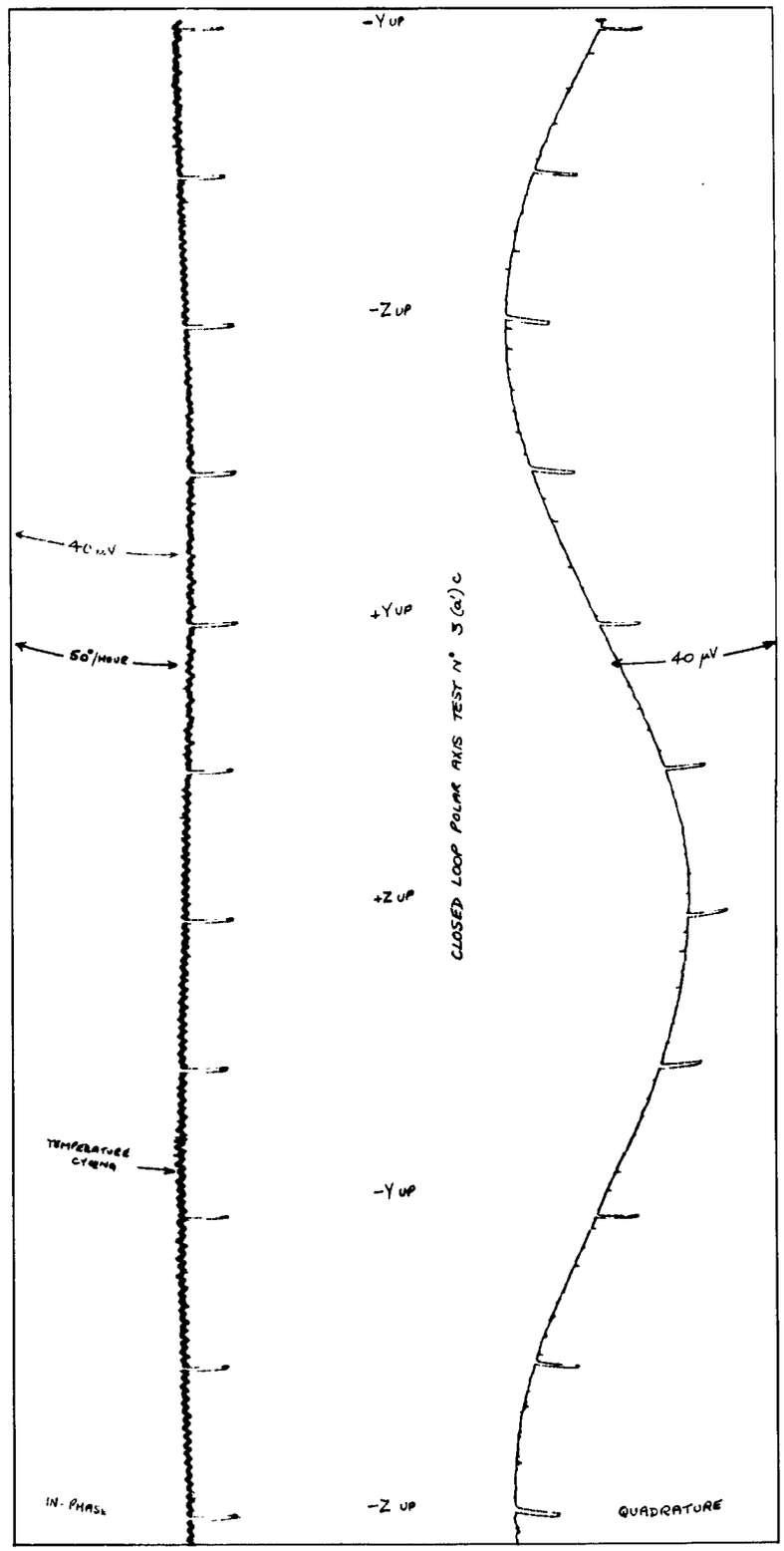


FIG. 10 CLOSED LOOP POLAR AXIS TEST. ROTATION ABOUT INPUT (XX') AXIS. X UP
100°/HOUR INPUT RATE: BACKED OFF BY 2V 0° 0V 270° COMPENSATION
FORK FREQUENCY AT EACH 45° POSITION = 522.452 C/S
CHART SPEED = 3 INCHES/HOUR

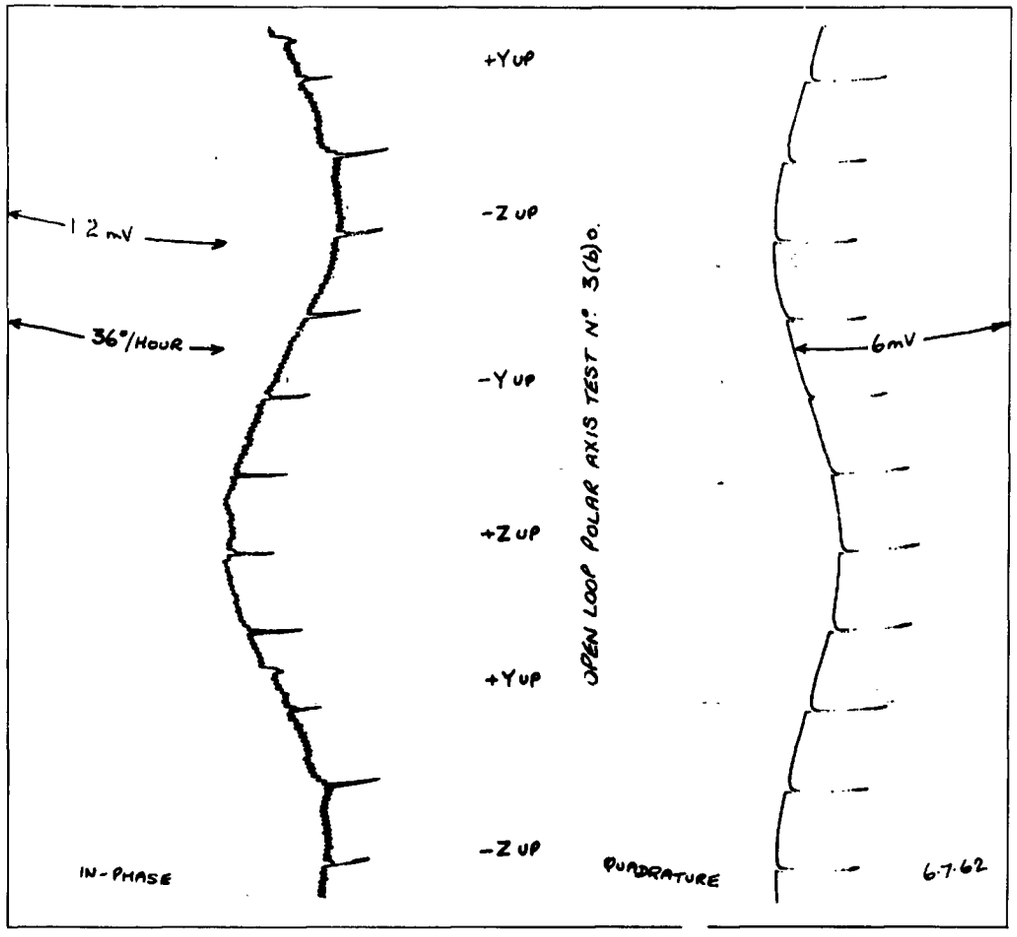


FIG.11 OPEN LOOP POLAR AXIS TEST. ROTATION ABOUT INPUT (XX') AXIS. X' UP
1000°/HOUR INPUT RATE: BACKED-OFF BY 6V 180° 0V 270° COMPENSATION.
FORK FREQUENCY AT 45° POSITIONS = 522.456 - 7 C/S
CHART SPEED = 12 INCHES/HOUR

R.A.E. 16041 (2)

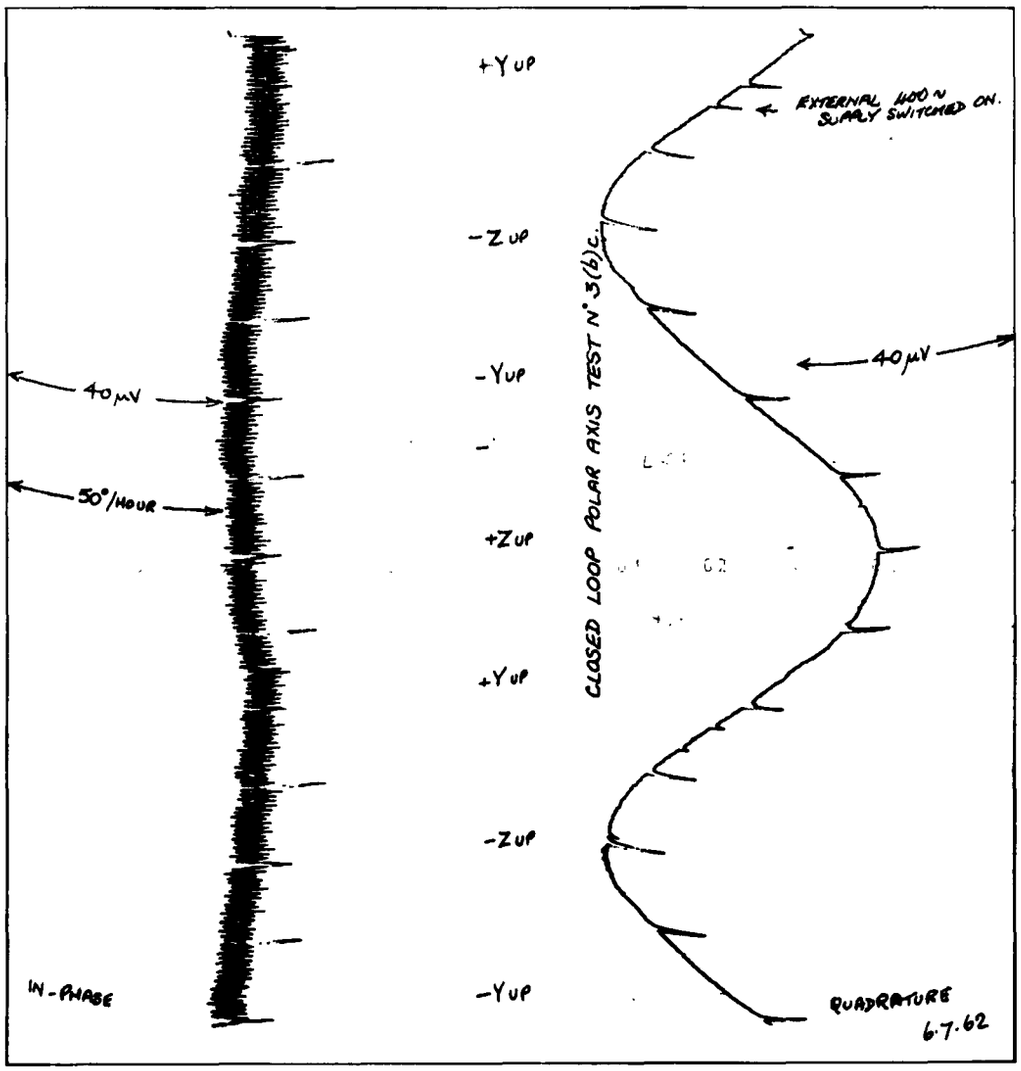


FIG.12 CLOSED LOOP POLAR AXIS TEST. ROTATION ABOUT INPUT (XX') AXIS. X' UP 1000°/HOUR INPUT RATE: BACKED-OFF BY 6V 180° 0V 270° COMPENSATION.
FORK FREQUENCY AT EACH 45° POSITION = 522.458 C/S
CHART SPEED = 12 INCHES/HOUR

R.A.E. 160042 62

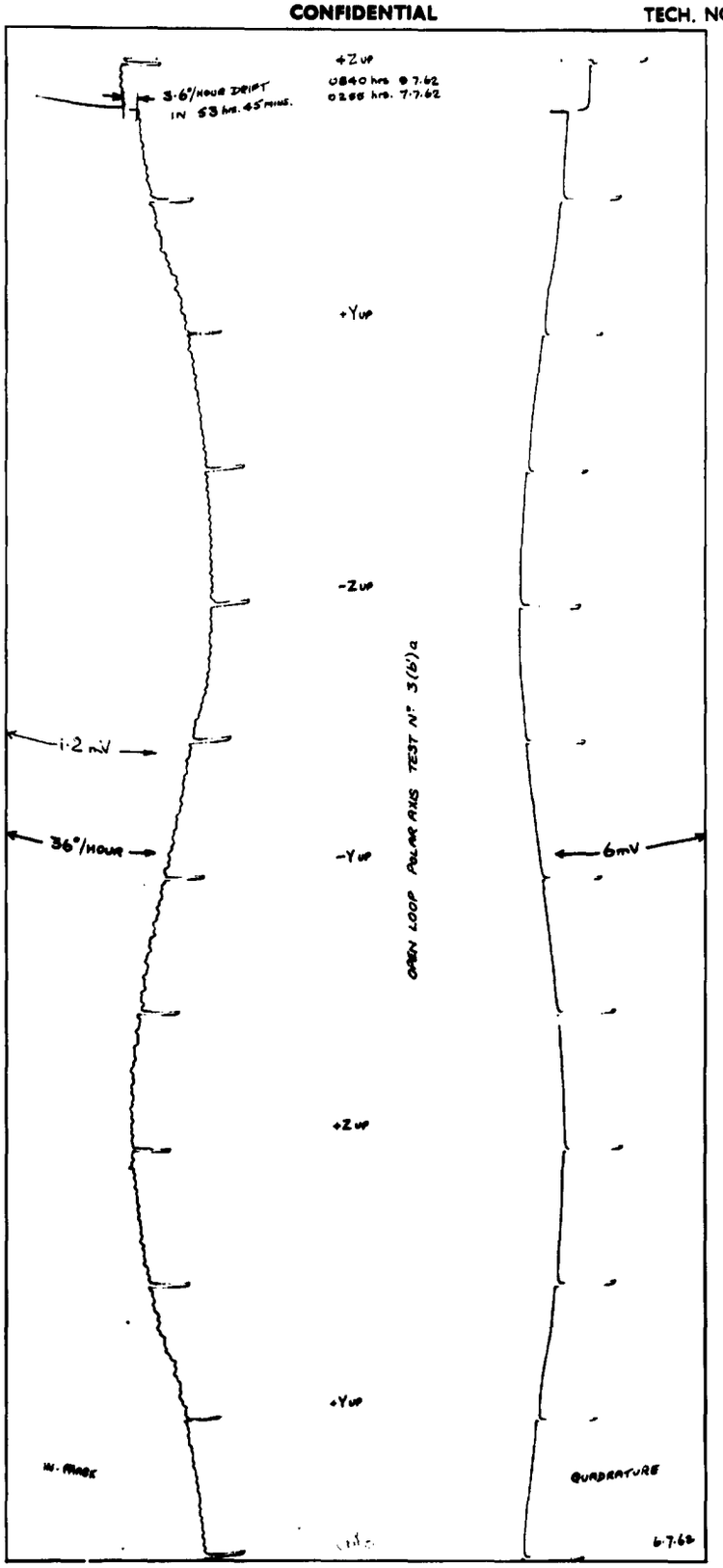


FIG. 13 OPEN LOOP POLAR AXIS TEST. ROTATION ABOUT INPUT (XX') AXIS. X' UP.
100°/HOUR INPUT RATE. NO BACKING OFF REQUIRED.
CHART SPEED = 3 INCHES/HOUR.

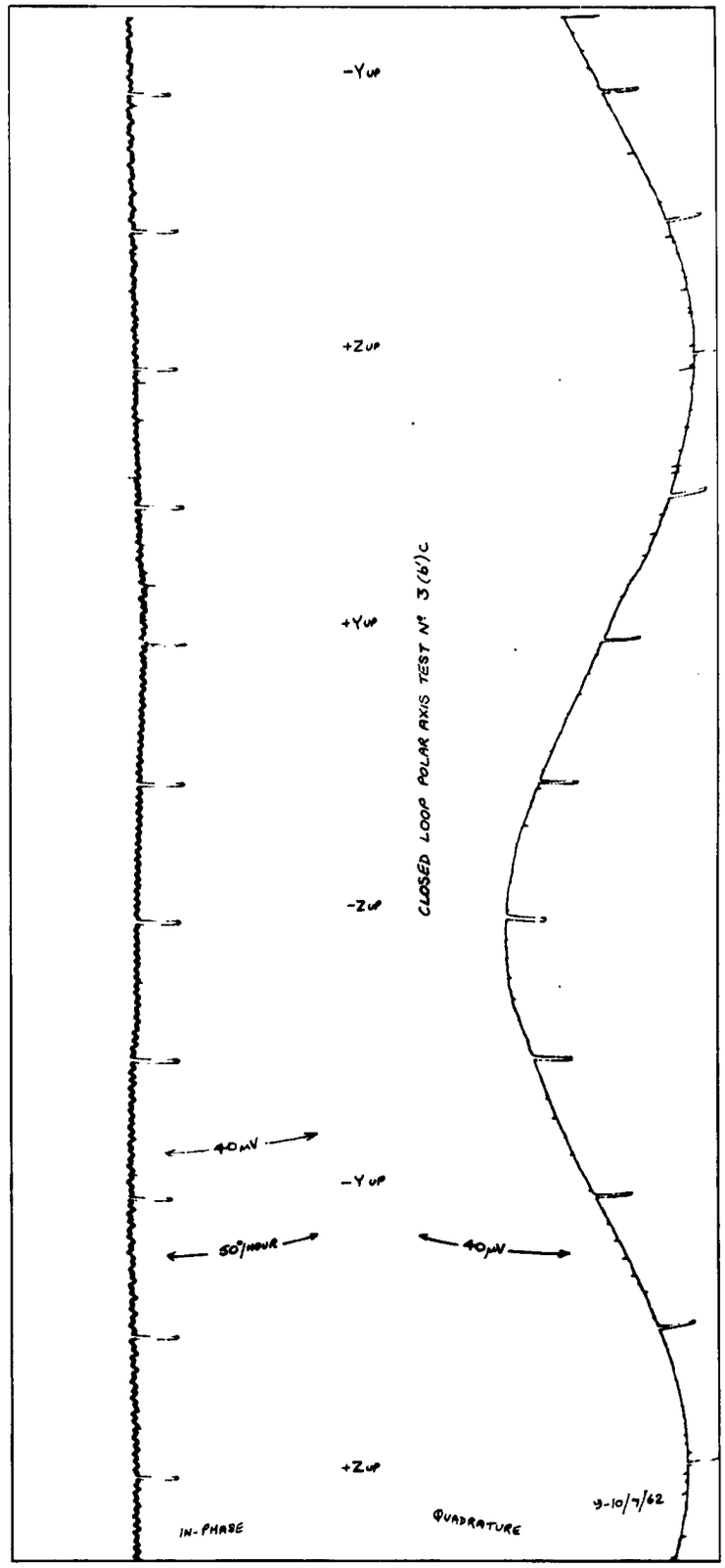


FIG. 14 CLOSED LOOP POLAR AXIS TEST. ROTATION ABOUT INPUT (XX') AXIS. X' UP. 100°/HOUR INPUT RATE. NO BACKING OFF REQUIRED.
CHART SPEED = 3 INCHES/HOUR.

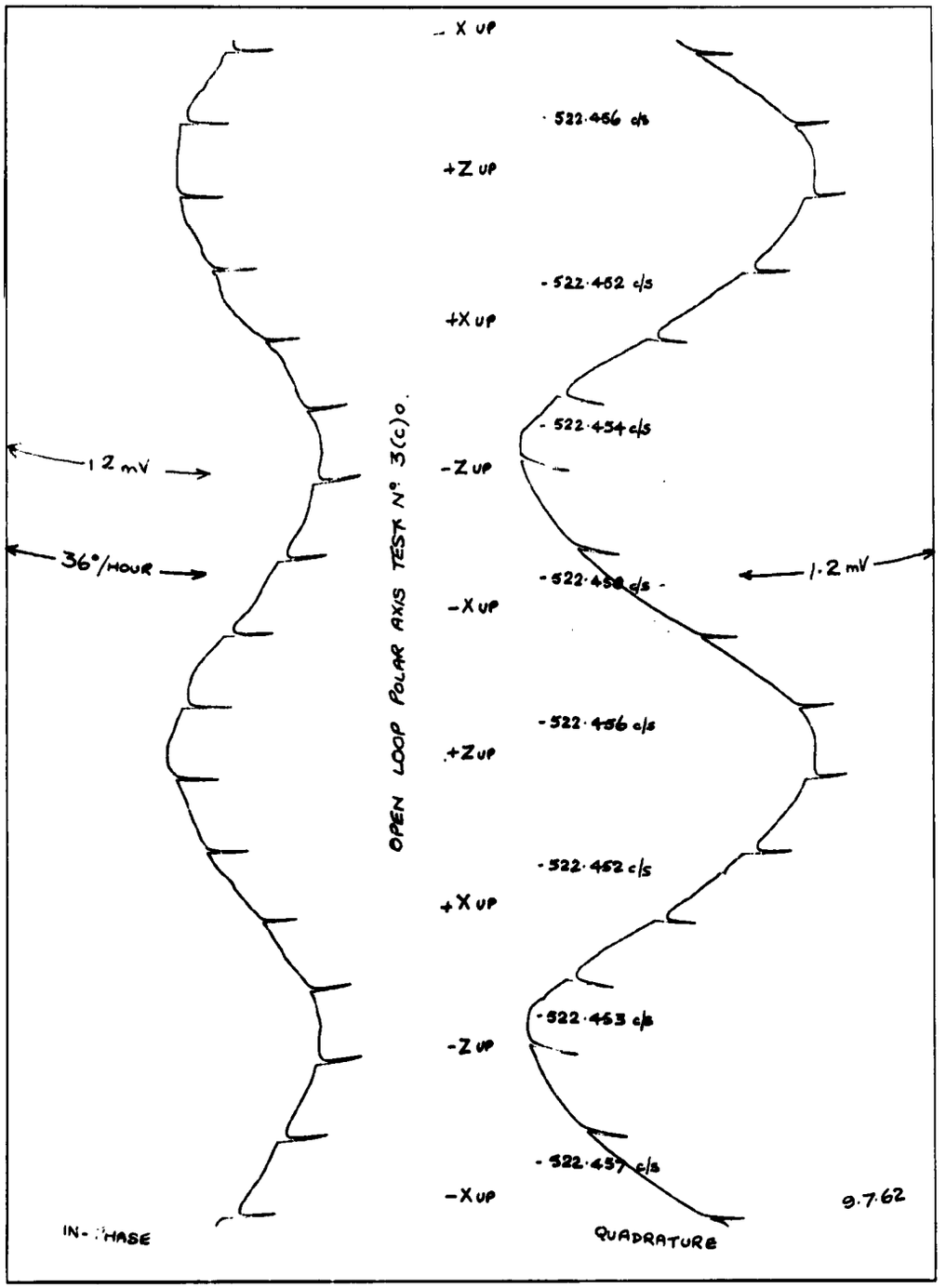


FIG.15 OPEN LOOP POLAR AXIS TEST. ROTATION ABOUT YY' AXIS. Y UP.

RATE OF TURN: 1000°/HOUR
COMPENSATION: 0V 0° 0V 270°
CHART SPEED: 12 INCHES/HOUR

R.A.E. 160045 62

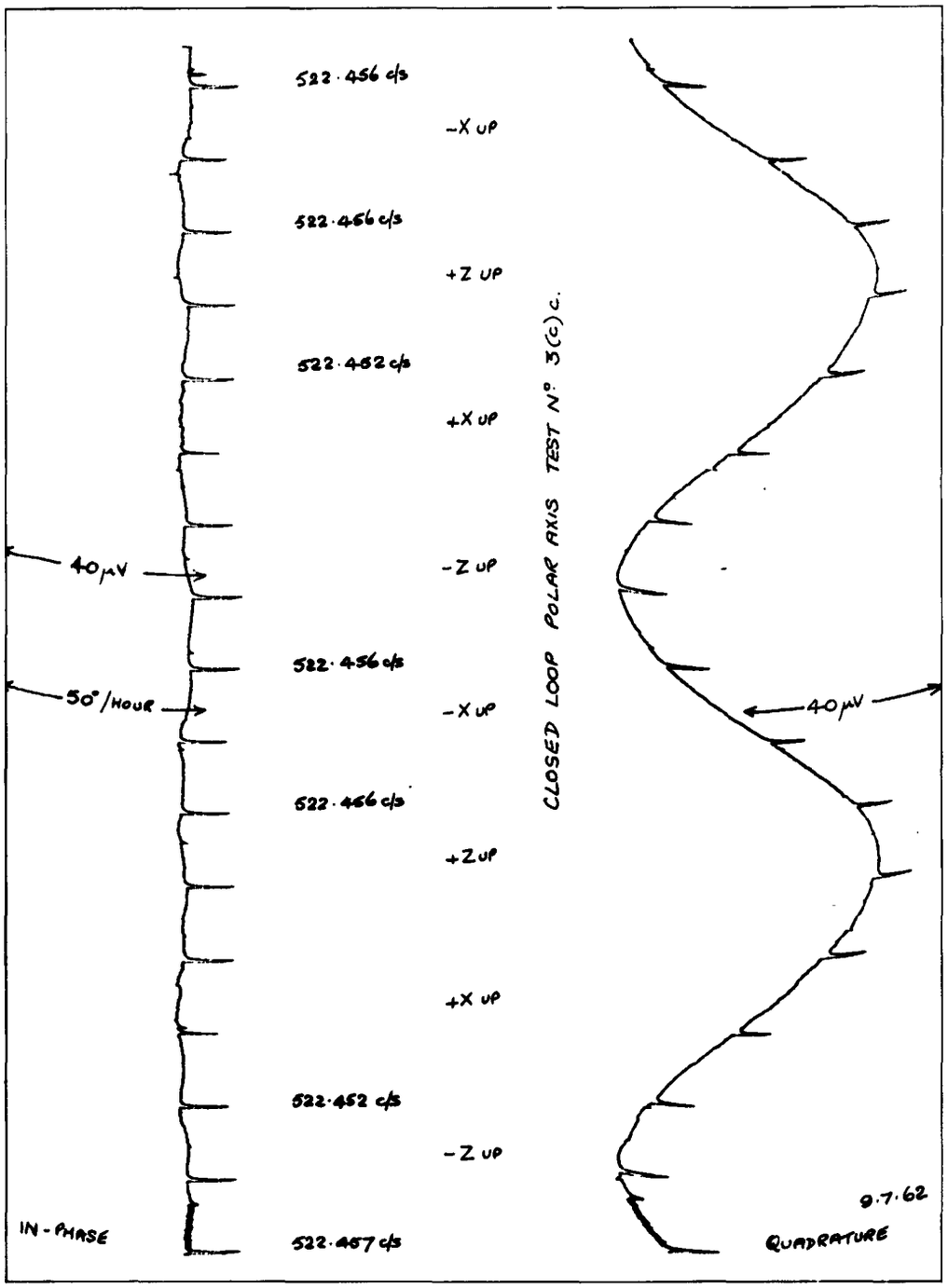


FIG. 16 CLOSED LOOP POLAR AXIS TEST. ROTATION ABOUT YY' AXIS. Y UP.

RATE OF TURN: 1000°/HOUR
COMPENSATION: 0V 0° 0V 270°
CHART SPEED: 12 INCHES/HOUR

R.A.E. 160046 62

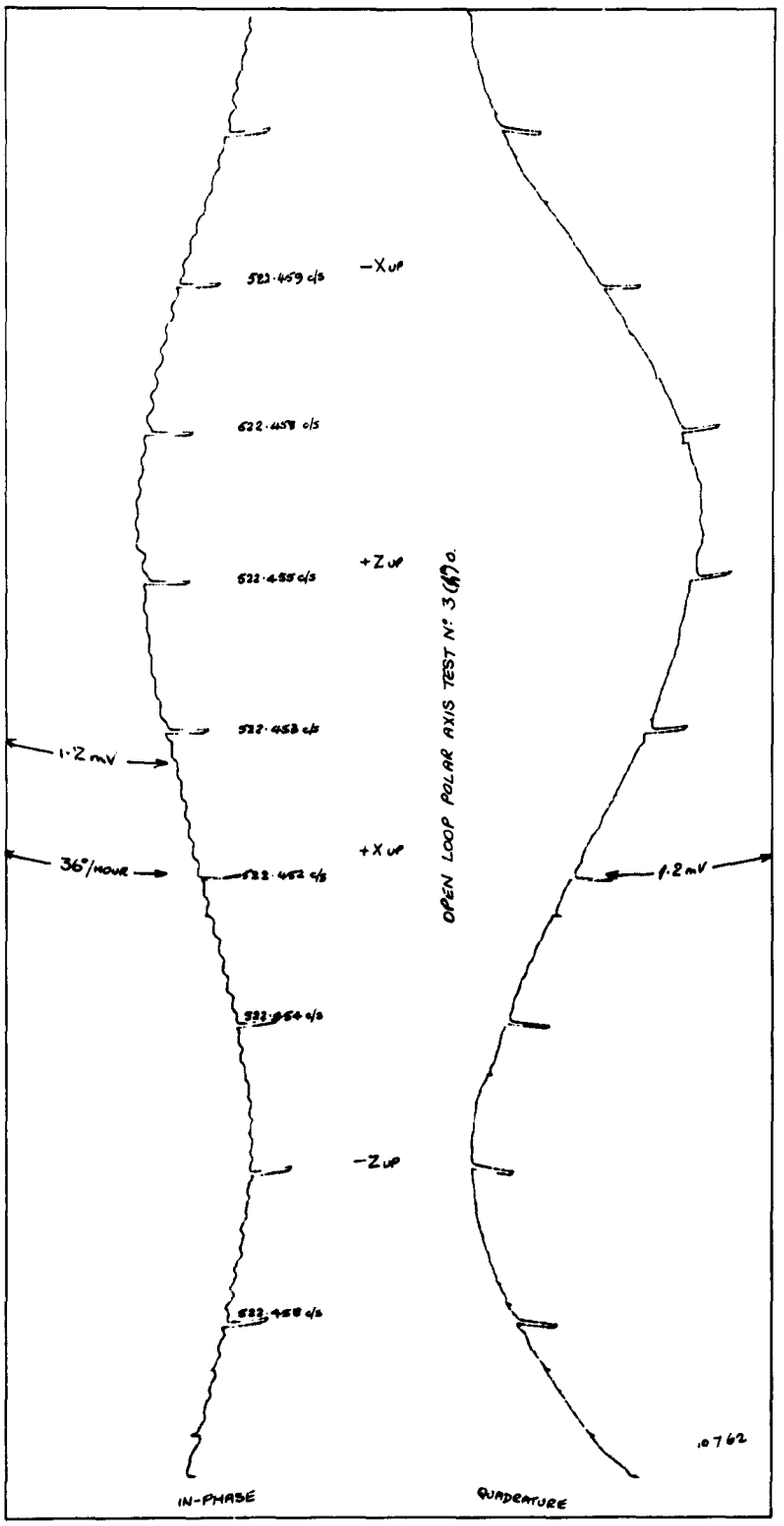


FIG.17 OPEN LOOP POLAR AXIS TEST. ROTATION ABOUT YY' AXIS. Y UP.
RATE OF TURN: 100°/HOUR.
COMPENSATION: 0V 0° 0V 270°.
CHART SPEED: 3 INCHES/HOUR.

R.A.E. 100947 G2

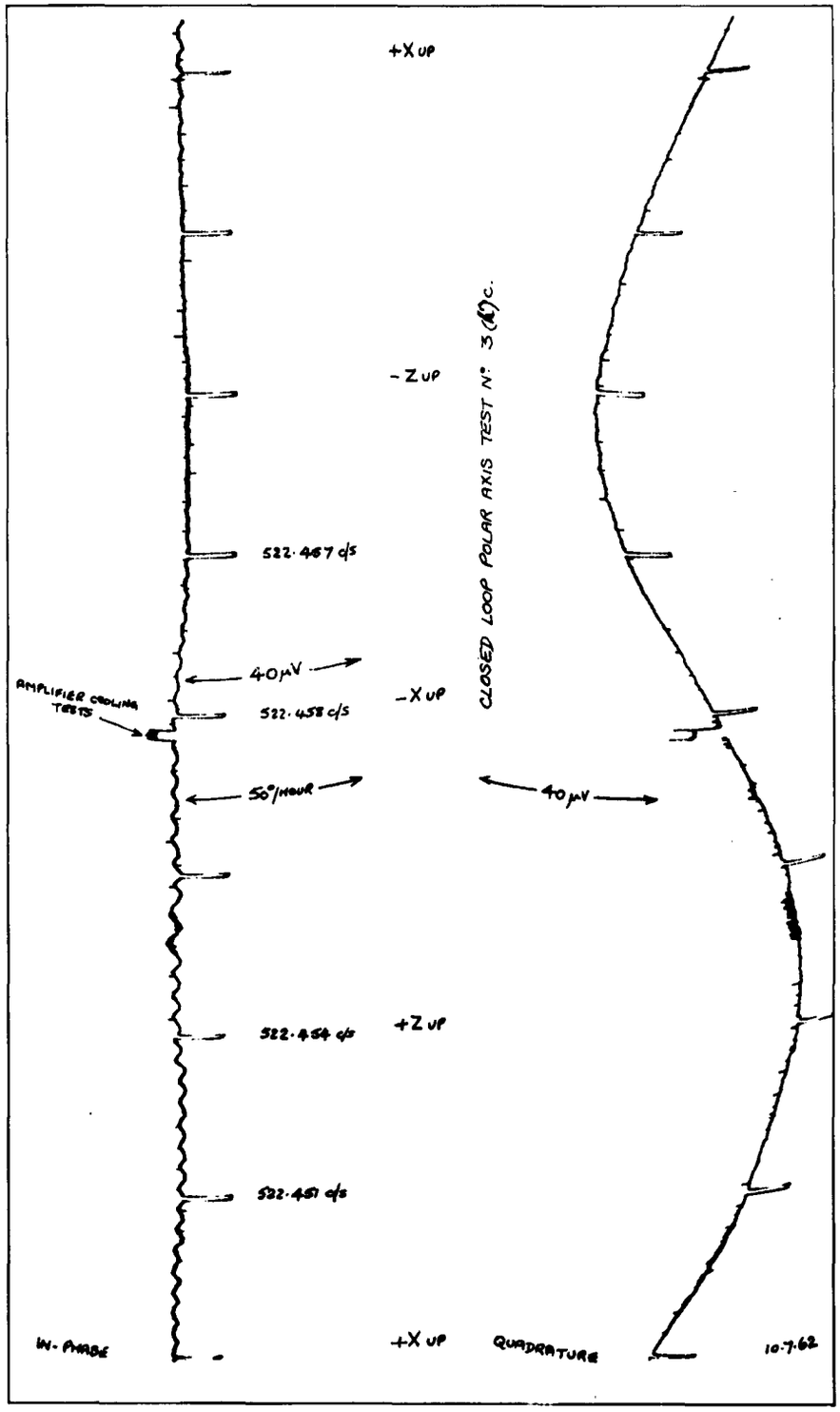


FIG.18 CLOSED LOOP POLAR AXIS TEST. ROTATION ABOUT YY' AXIS. Y UP.

RATE OF TURN: 100°/HOUR

COMPENSATION: OV 0° OV 270°

CHART SPEED: 3 INCHES/HOUR

R.A.E. 160048 62

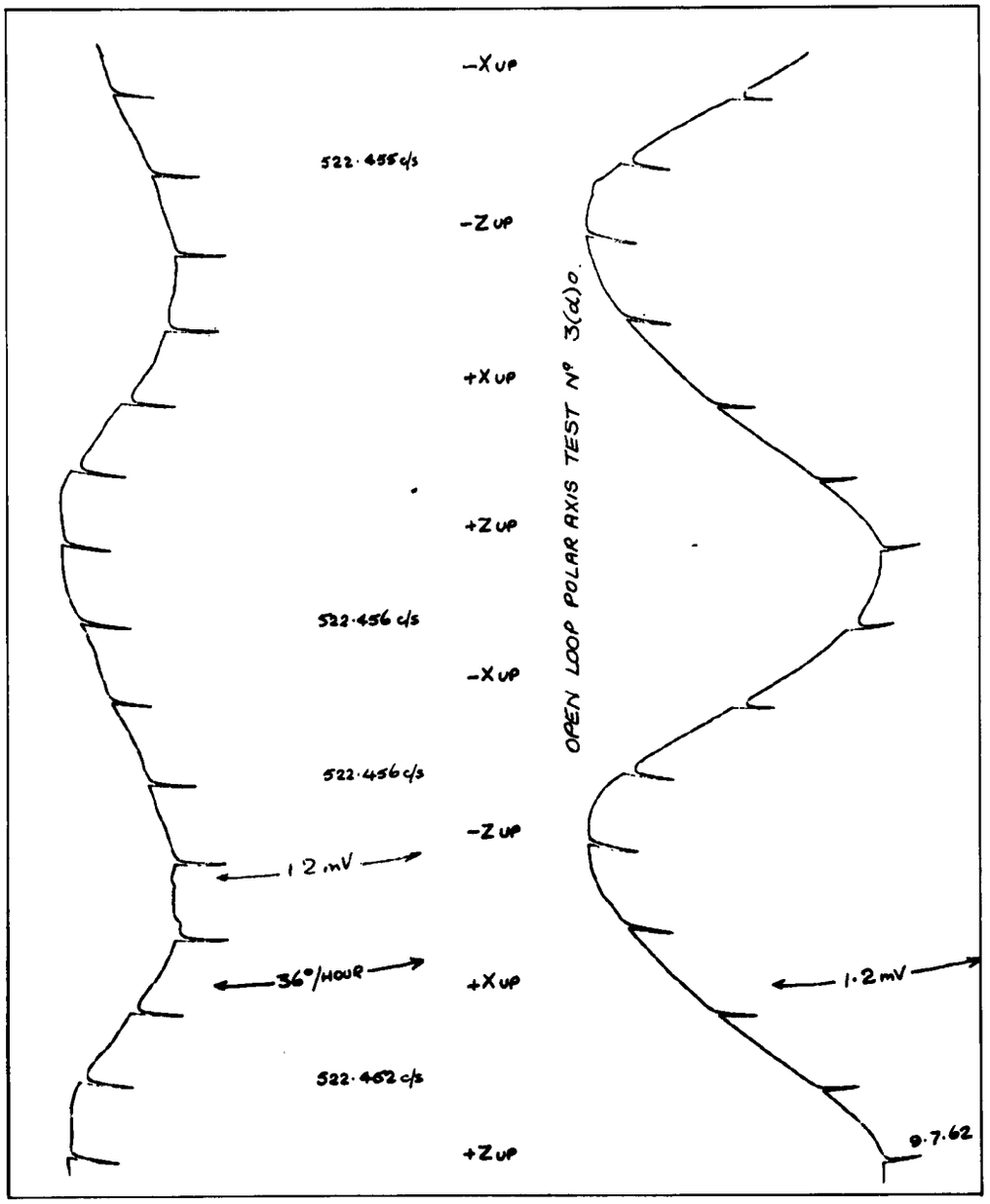


FIG. 19 OPEN LOOP POLAR AXIS TEST. ROTATION ABOUT YY' AXIS. Y' UP.

RATE OF TURN: 1000°/HOUR

COMPENSATION: 0V 0° 0V 270°

CHART SPEED: 12 INCHES/HOUR

R.A.E. 160049 62

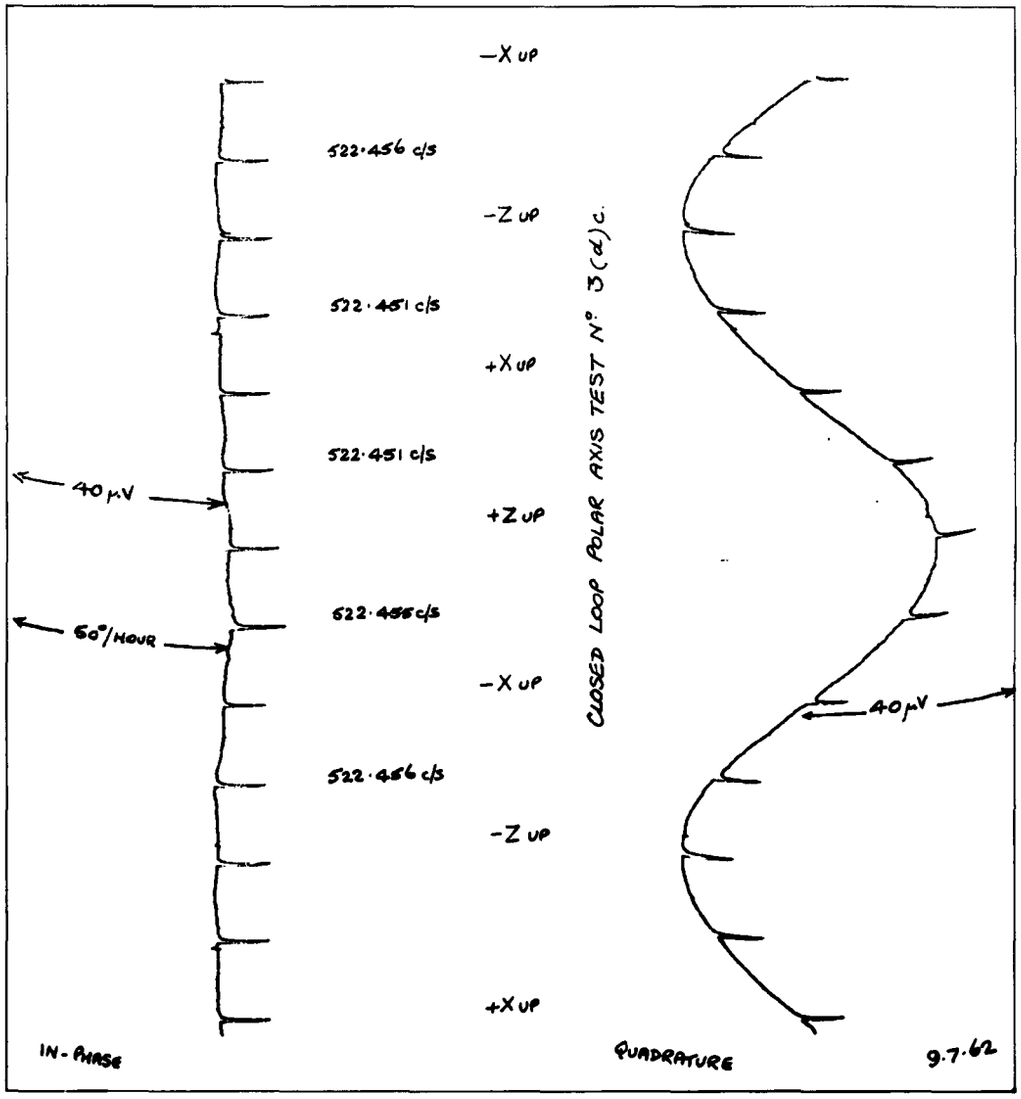


FIG.20 CLOSED LOOP POLAR AXIS TEST. ROTATION ABOUT YY' AXIS. Y' UP.
RATE OF TURN: 1000°/HOUR
COMPENSATION: 0V 0° 0V 270°
CHART SPEED: 12 INCHES/HOUR

R.A.E. 160050 62

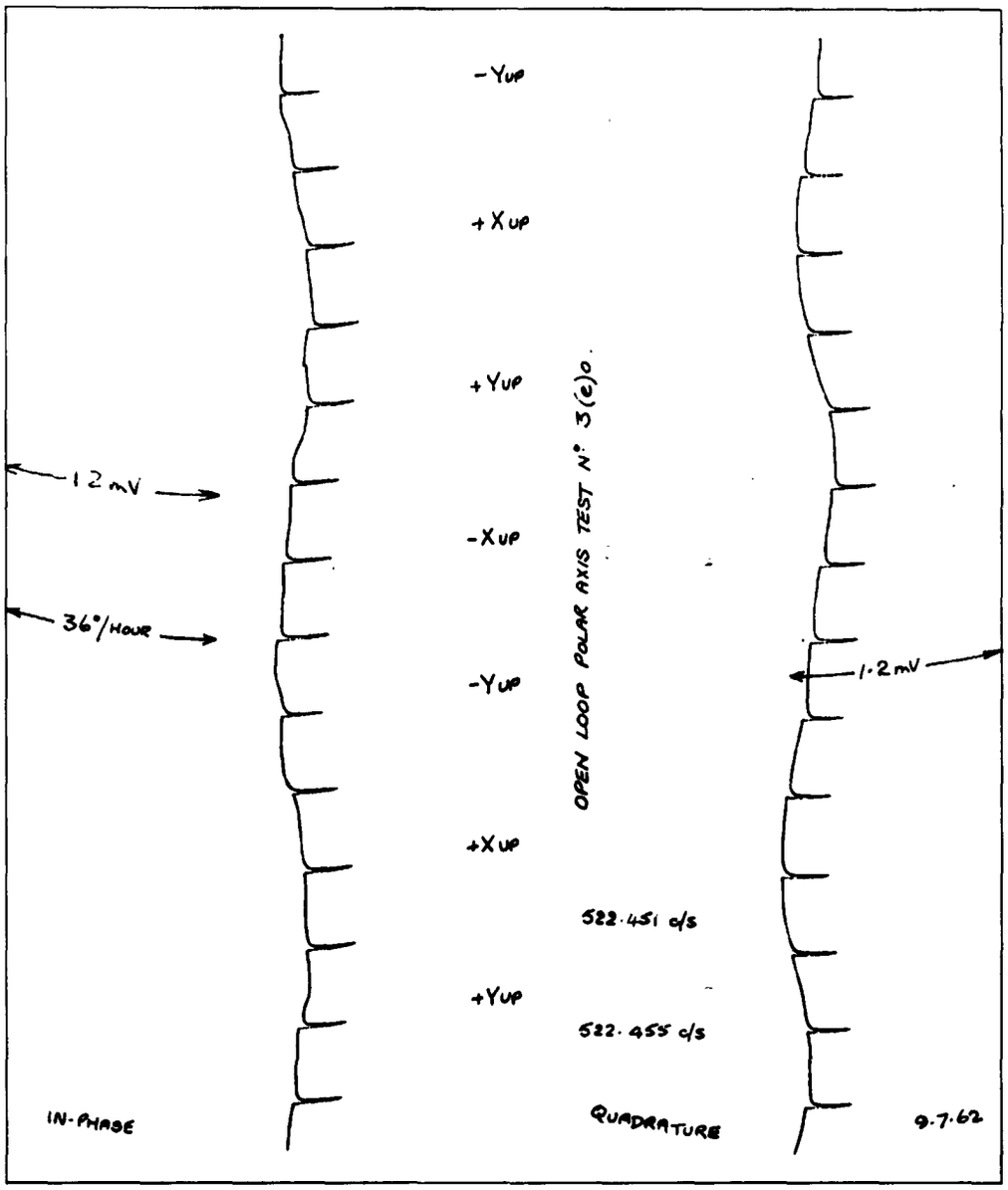


FIG.21 OPEN LOOP POLAR AXIS TEST. ROTATION ABOUT ZZ' AXIS. Z UP.
RATE OF TURN: 1000°/HOUR
COMPENSATION: 0V 0° 0V 270°
CHART SPEED: 12 INCHES/HOUR

R.A.E. 160051 62

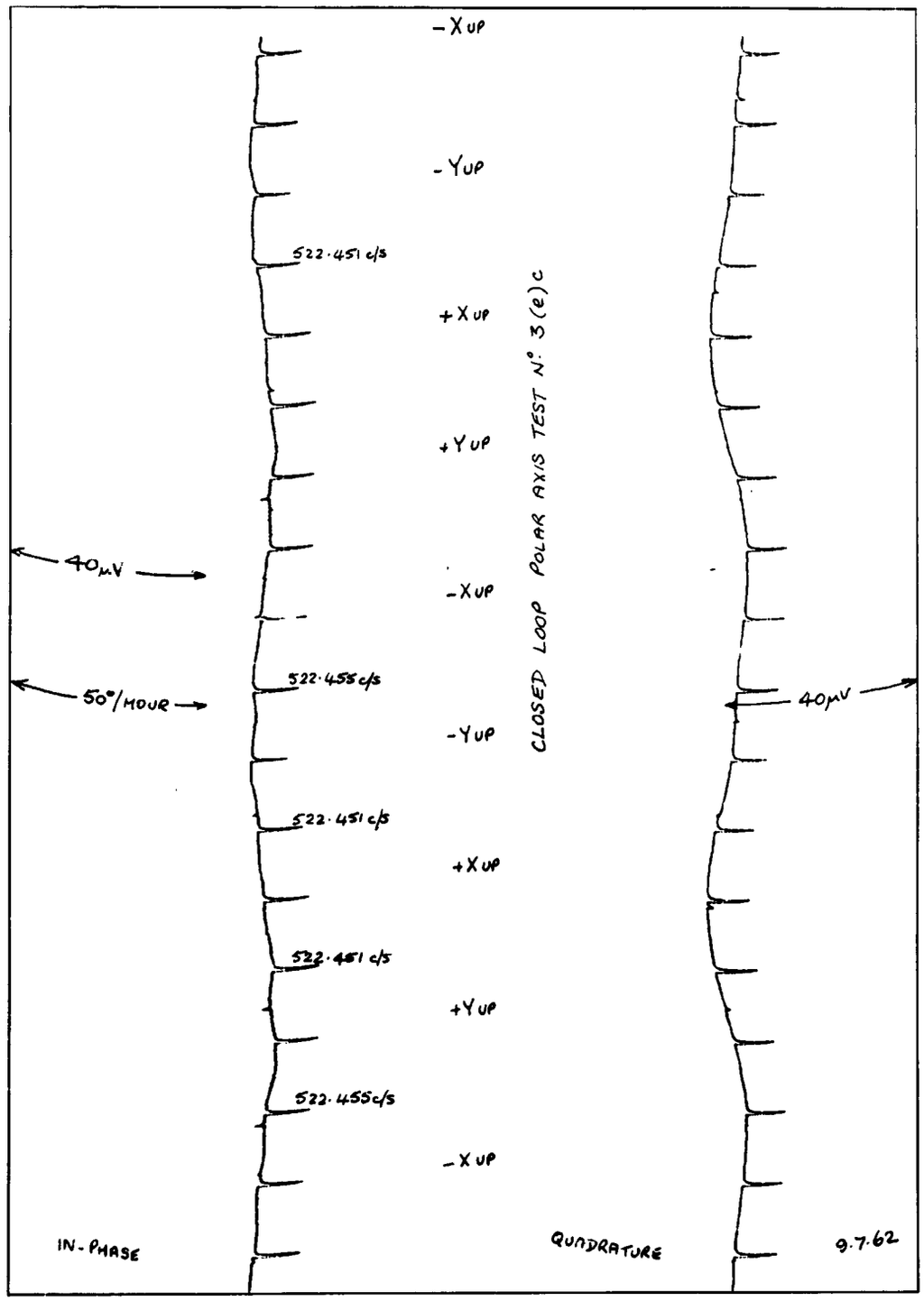


FIG.22 CLOSED LOOP POLAR AXIS TEST. ROTATION ABOUT ZZ' AXIS. Z UP.

RATE OF TURN: 1000°/HOUR

COMPENSATION: 0V 0° 0V 270°

CHART SPEED: 12 INCHES/HOUR

R.A.E. 160052 62

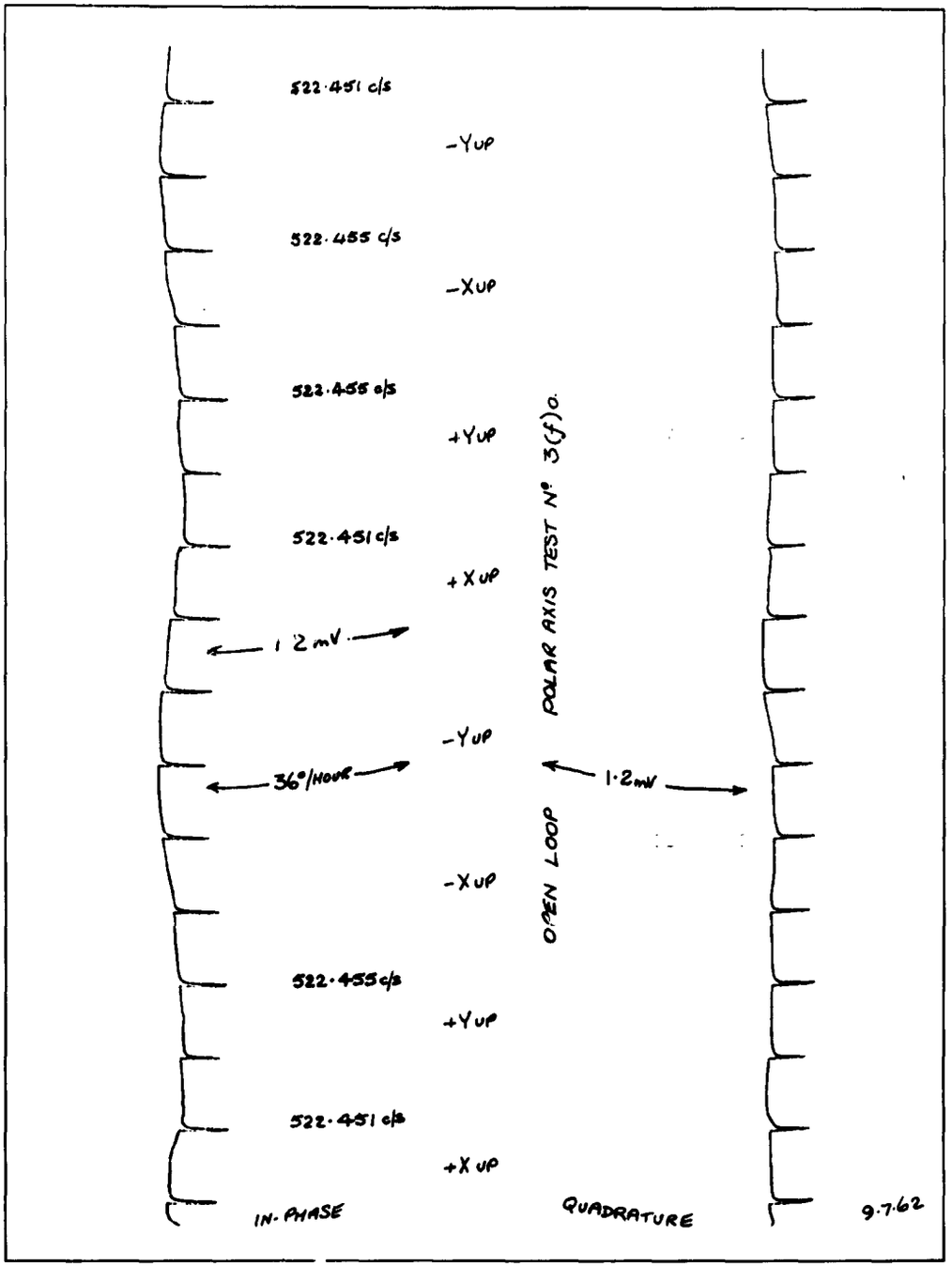


FIG.23 OPEN LOOP POLAR AXIS TEST. ROTATION ABOUT ZZ' AXIS. Z' UP.
RATE OF TURN: 1000°/HOUR
COMPENSATION: 0v 0° 0v 270°
CHART SPEED: 12 INCHES/HOUR

R.A.E. 160053 62

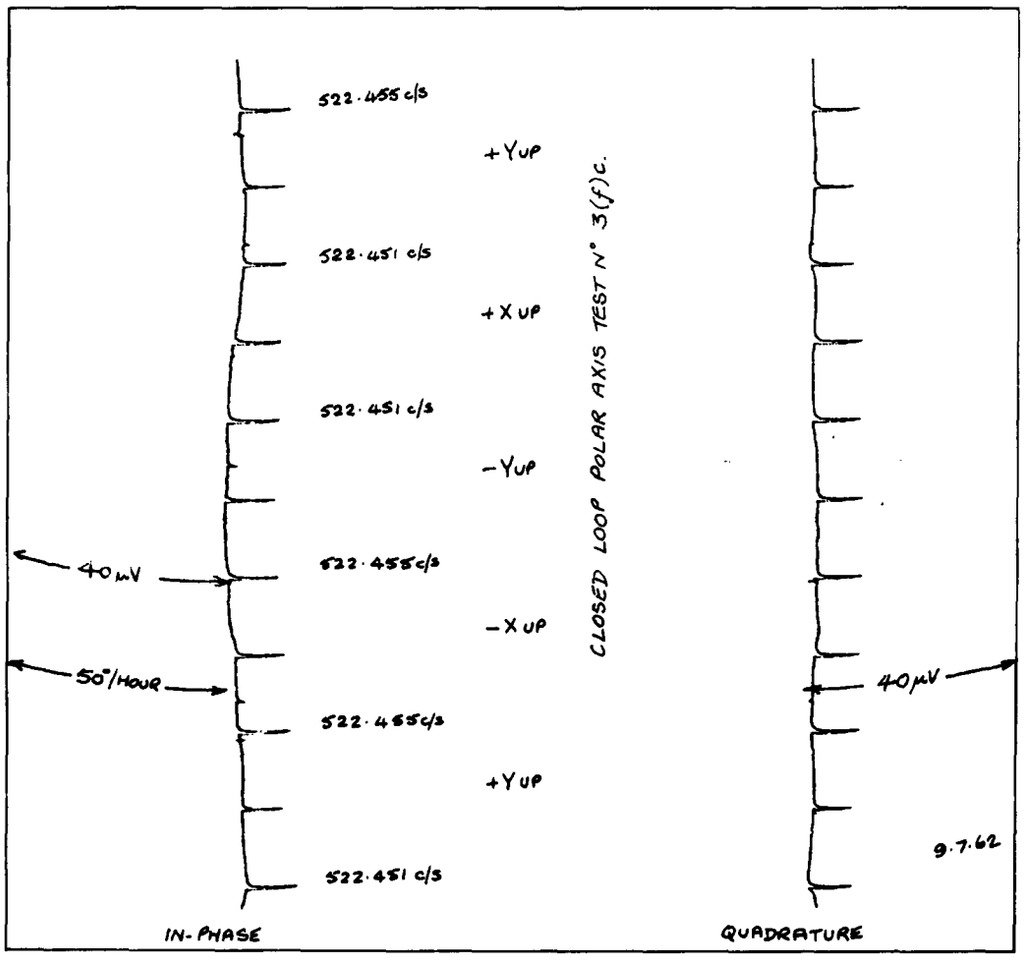


FIG.24 CLOSED LOOP POLAR AXIS TEST. ROTATION ABOUT ZZ' AXIS. Z' UP.

RATE OF TURN: 1000°/HOUR

COMPENSATION: 0V 0° 0V 270°

CHART SPEED: 12 INCHES/HOUR

R.A.E. 160054 62

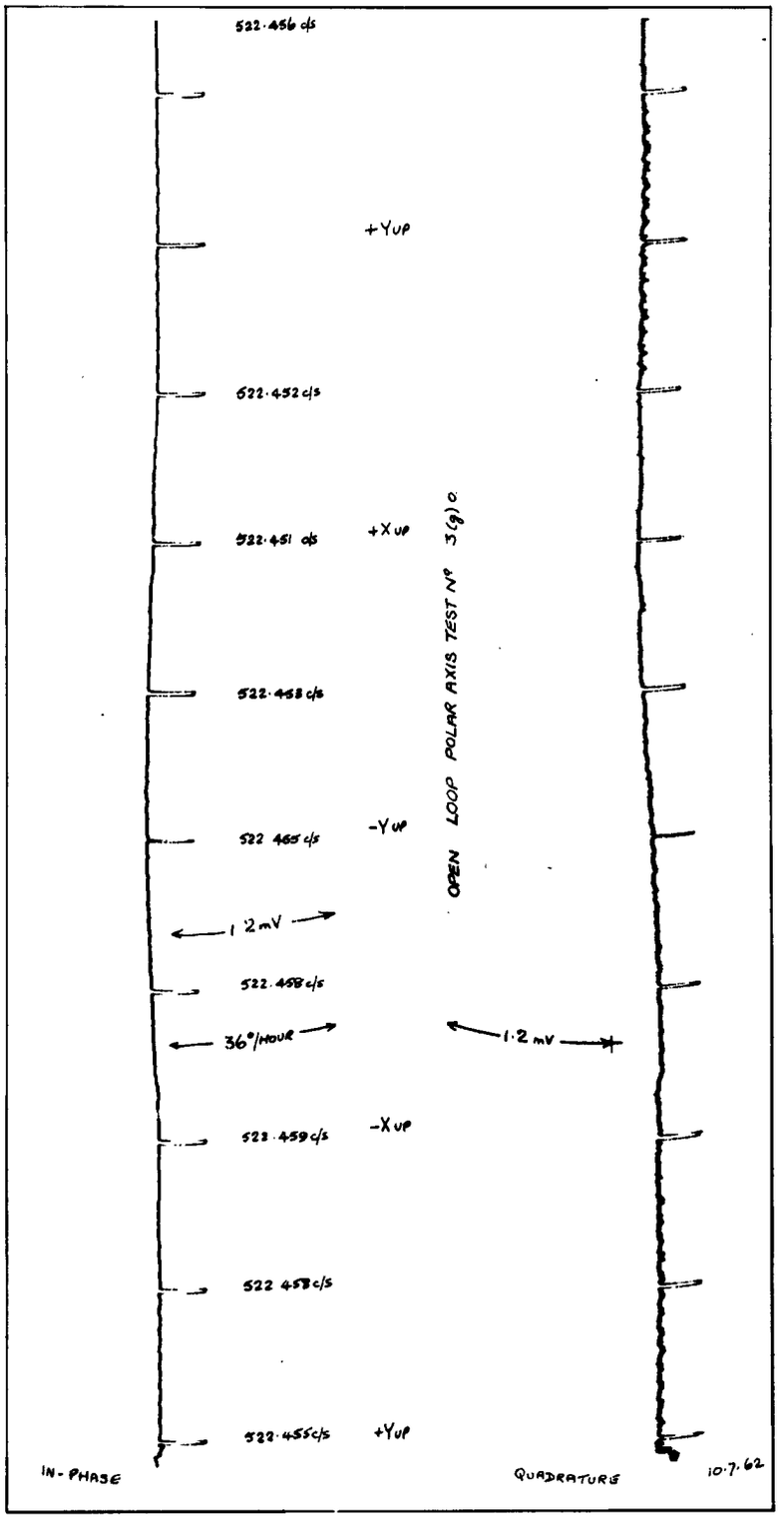


FIG.25 OPEN LOOP POLAR AXIS TEST. ROTATION ABOUT ZZ' AXIS. Z' UP.

RATE OF TURN: 100°/HOUR.
COMPENSATION: 0V 0° 0V 270°
CHART SPEED: 3 INCHES/HOUR

R.A.E. 160855

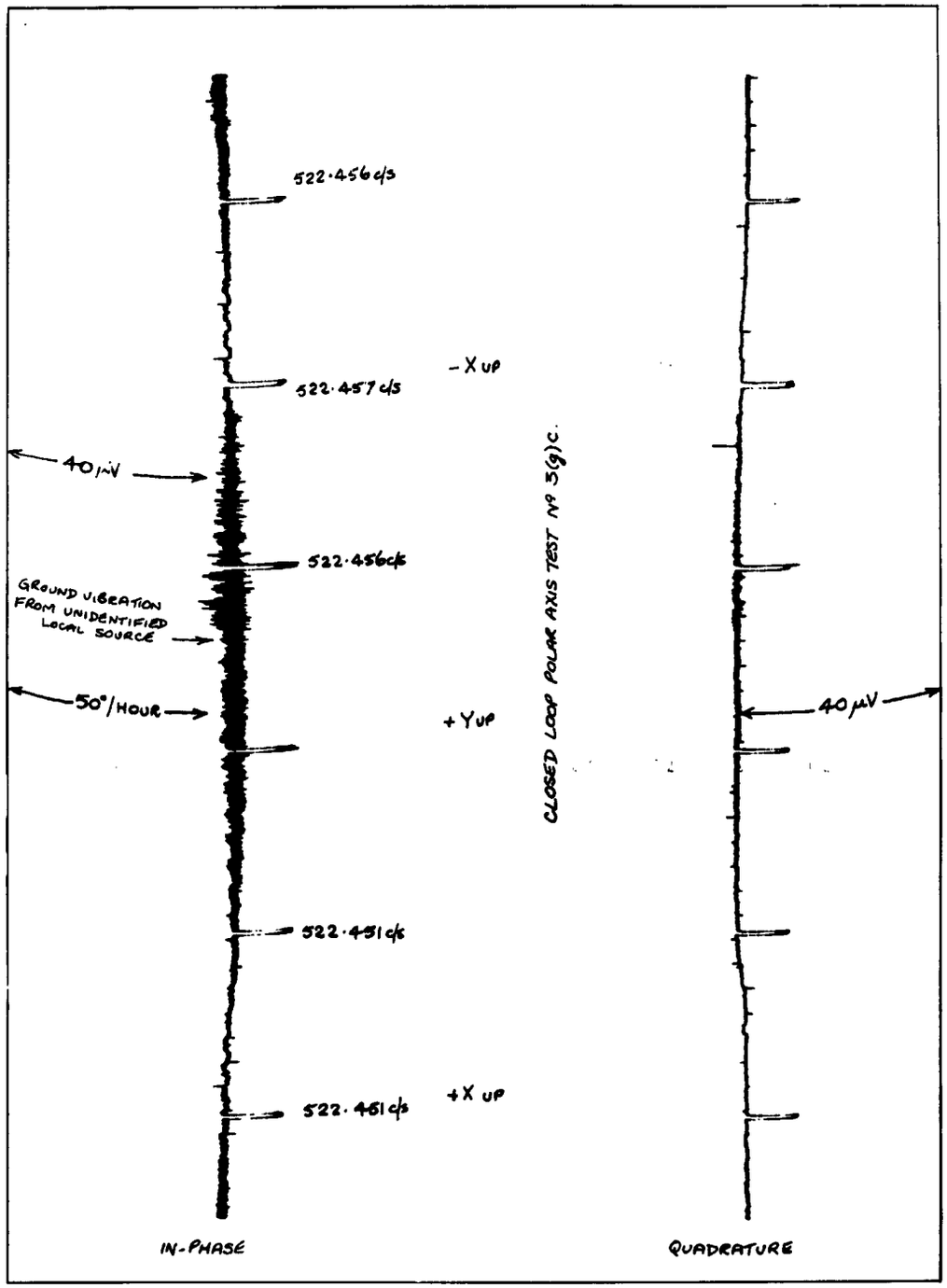


FIG.26 CLOSED LOOP POLAR AXIS TEST. ROTATION ABOUT ZZ' AXIS. Z' UP.

RATE OF TURN: 100°/HOUR

COMPENSATION: 0V 0° 0V 270°

CHART SPEED: 3 INCHES/HOUR

R.A.E. 160056 62

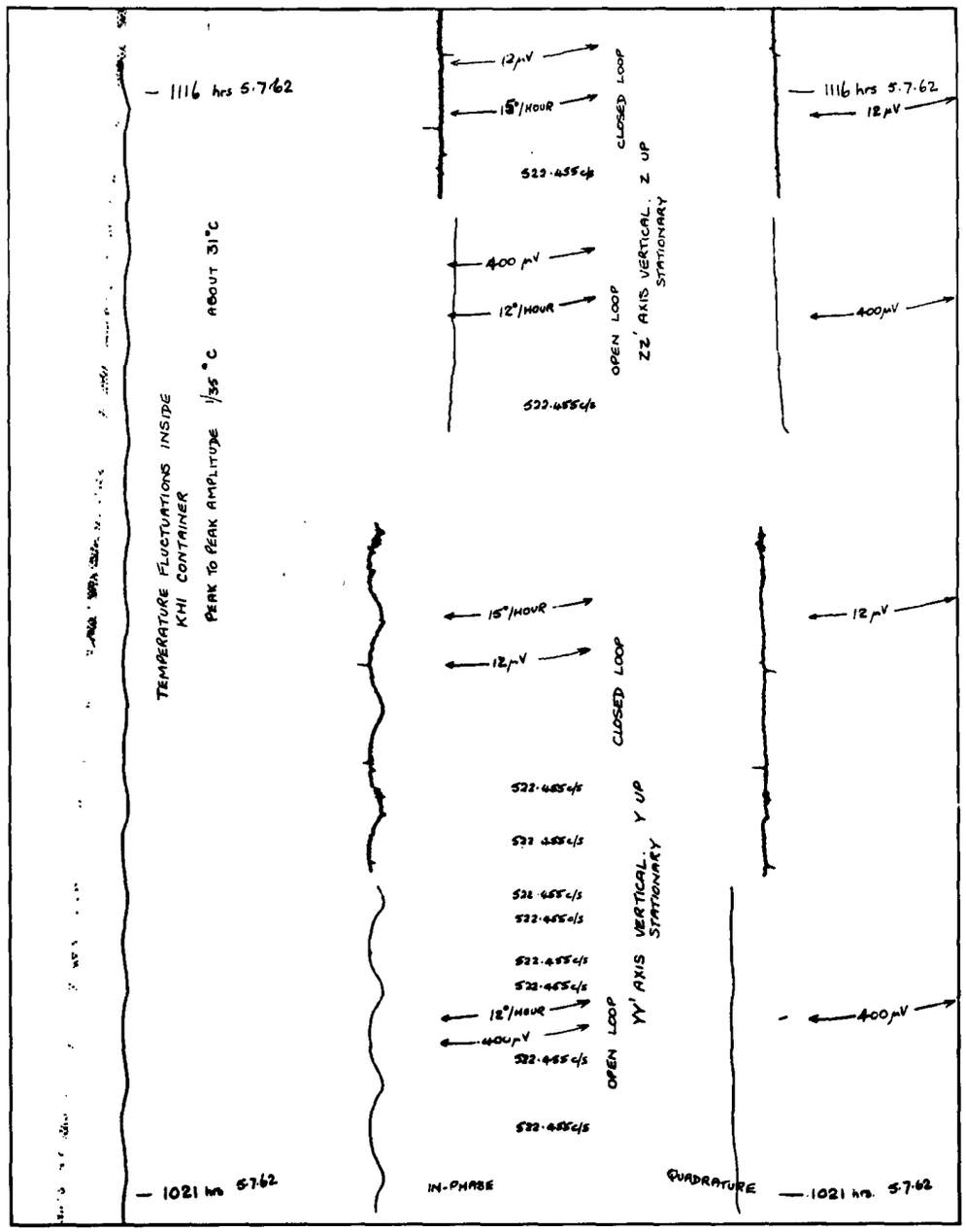


FIG. 27 EFFECT OF TEMPERATURE FLUCTUATIONS WITHIN T.F.G. ENCLOSURE.

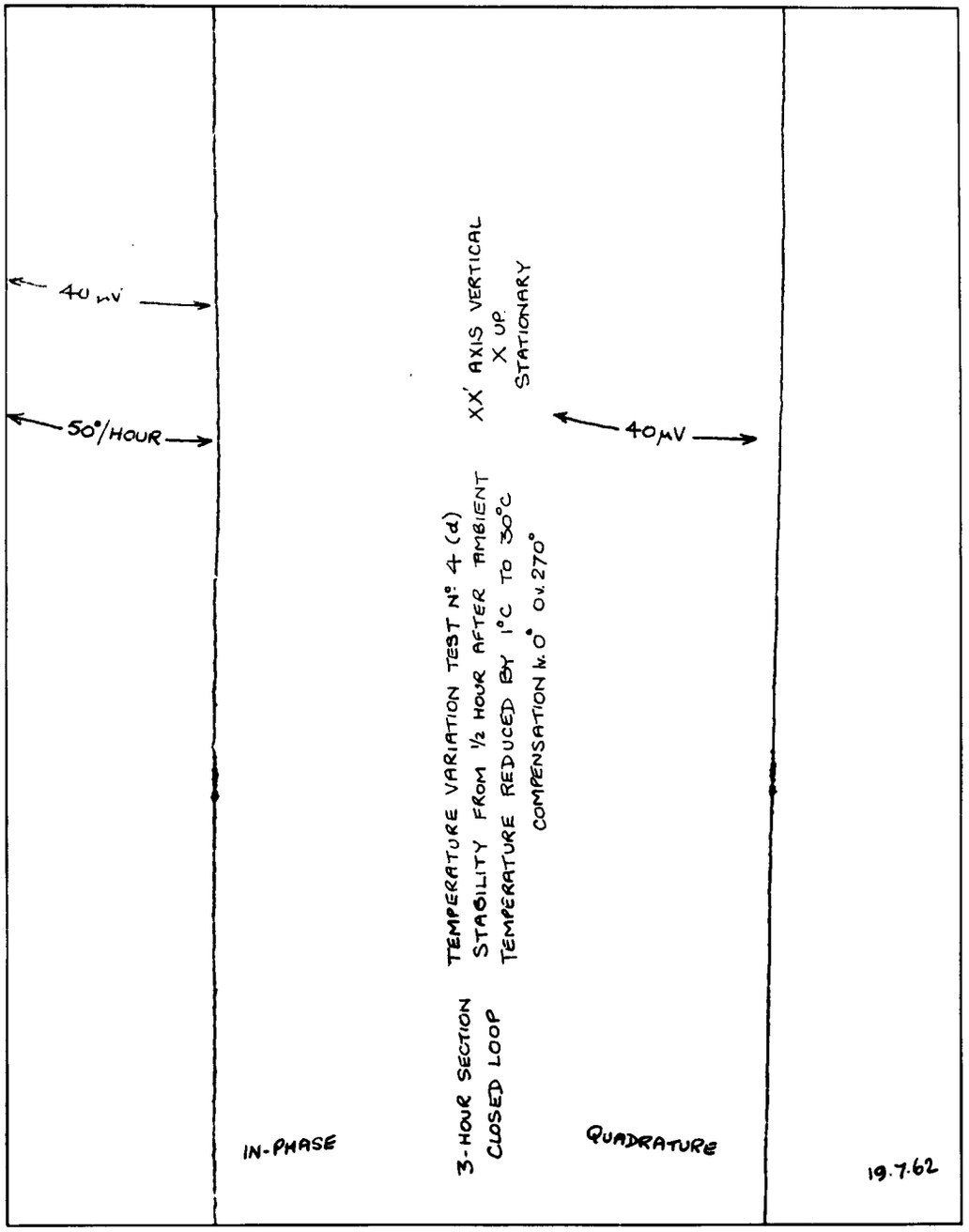


FIG.28 TEMPERATURE VARIATION TEST. STABILITY AFTER AMBIENT TEMPERATURE INSIDE T.F.G. ENCLOSURE REDUCED FROM 31°C TO 30°C.

XX' AXIS VERTICAL. X UP STATIONARY

COMPENSATION: 1V 0° 0V 270°

CHART SPEED: 3 INCHES/HOUR

CLOSED LOOP OPERATION.

R.A.E. 160050

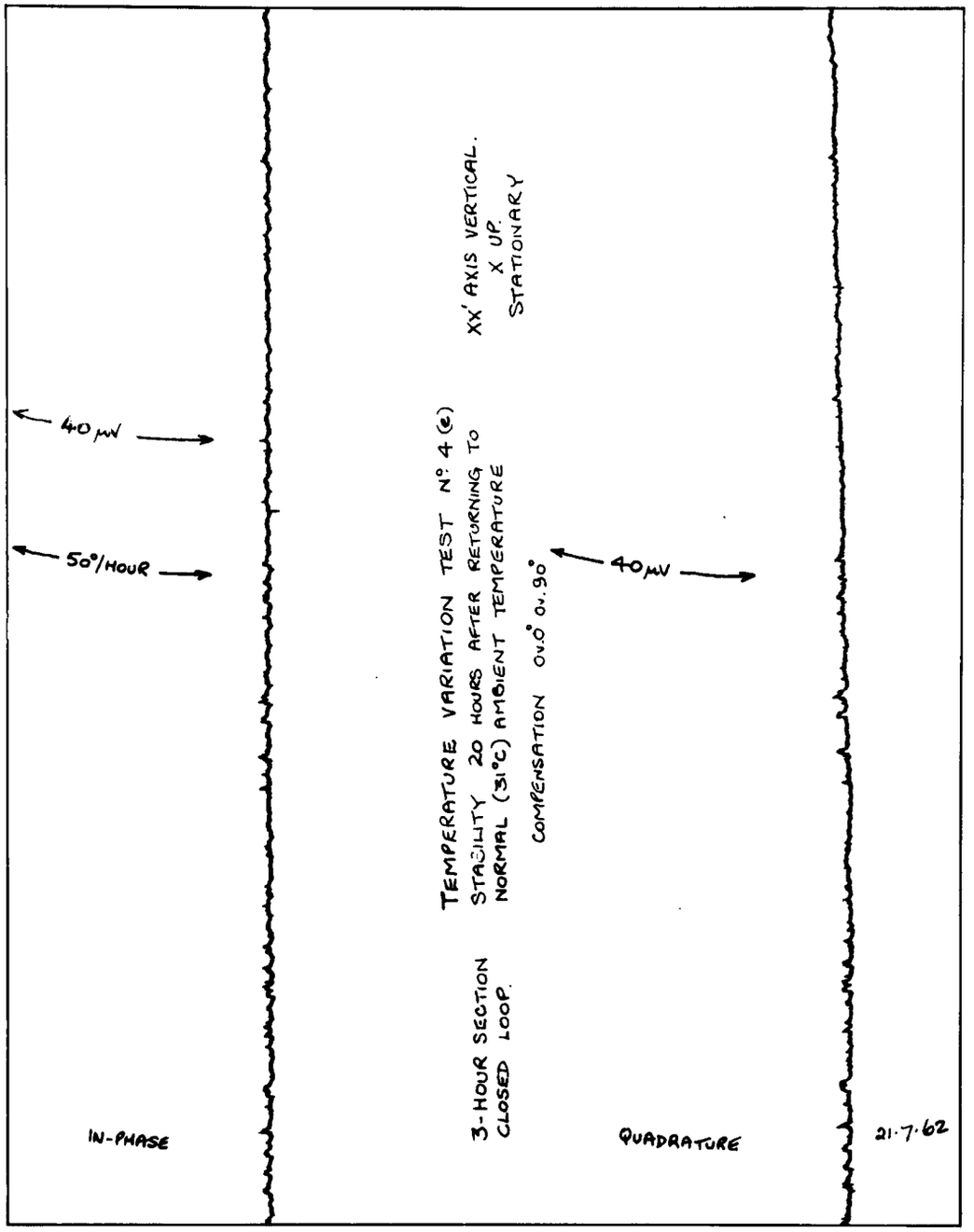


FIG.29 TEMPERATURE VARIATION TEST. STABILITY AFTER AMBIENT TEMPERATURE INSIDE T.F.G. ENCLOSURE RESTORED FROM 30°C TO 31°C.

XX' AXIS VERTICAL. X UP STATIONARY.

COMPENSATION: 0V 0° 0V 90°

CHART SPEED: 3 INCHES/HOUR

CLOSED LOOP OPERATION.

R.A.E. 160059 62

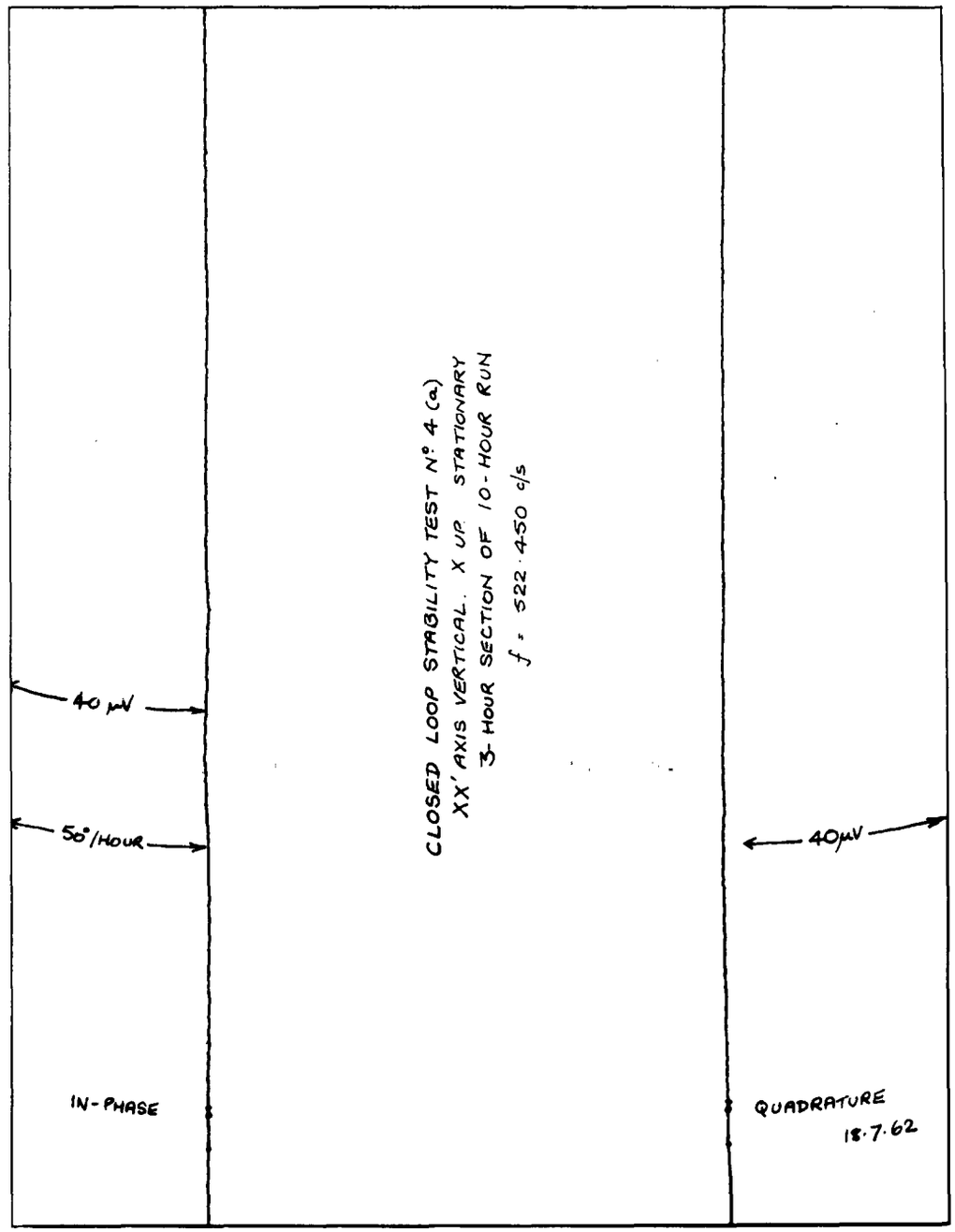


FIG.30 LONG-TERM STABILITY TEST.
XX' AXIS VERTICAL. X UP STATIONARY.
COMPENSATION: 0V 0° 0V 270°
CHART SPEED: 3 INCHES/HOUR.
3-HOUR SECTION OF 10-HOUR RUN.
CLOSED LOOP OPERATION.

R.A.E. 160060 62

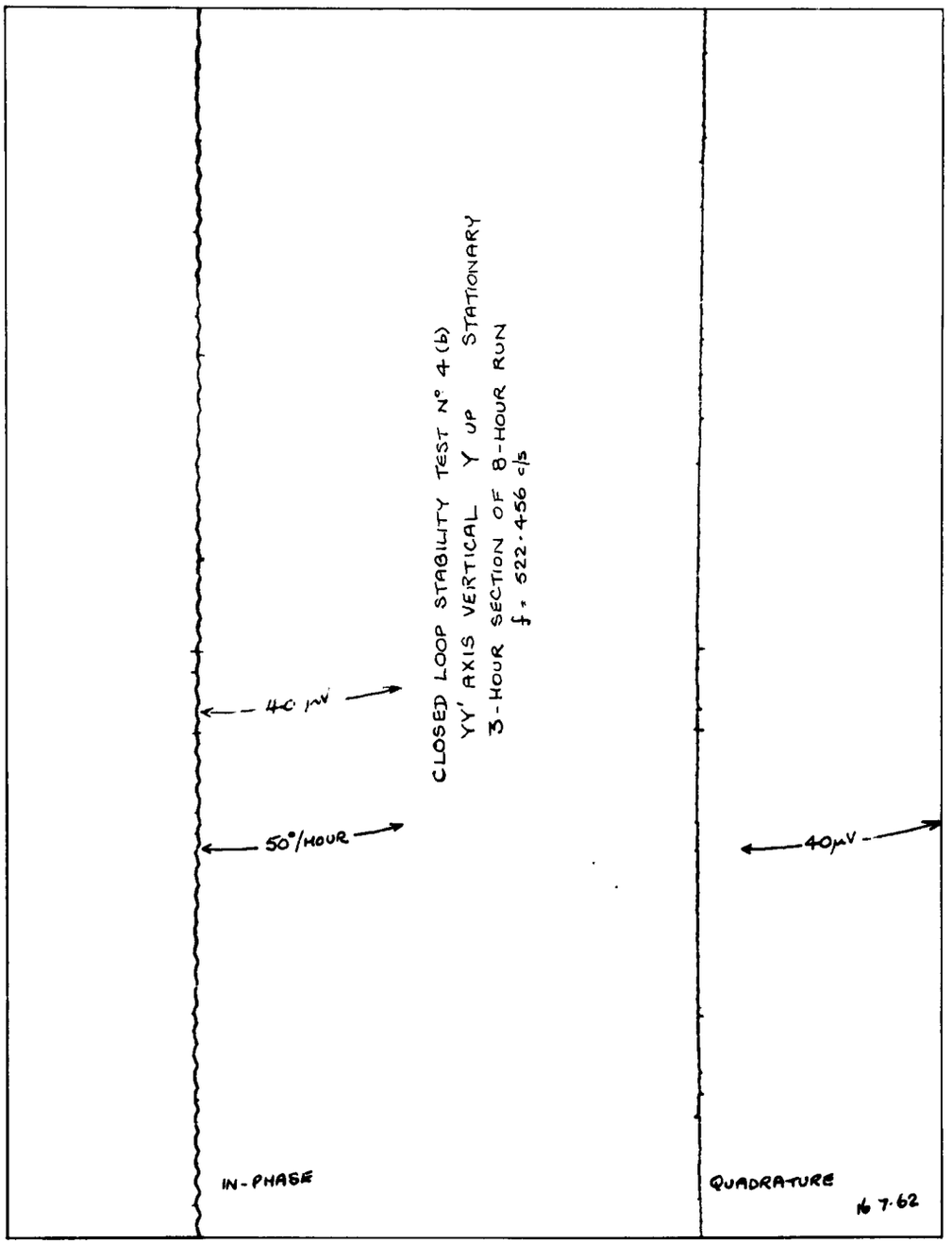


FIG.31 LONG-TERM STABILITY TEST.
YY' AXIS VERTICAL. Y UP STATIONARY.
COMPENSATION: 0V 0° 0V 90°
CHART SPEED: 3 INCHES/HOUR.
3-HOUR SECTION OF 8-HOUR RUN.
CLOSED LOOP OPERATION.

R.A.E. 16006 Q2

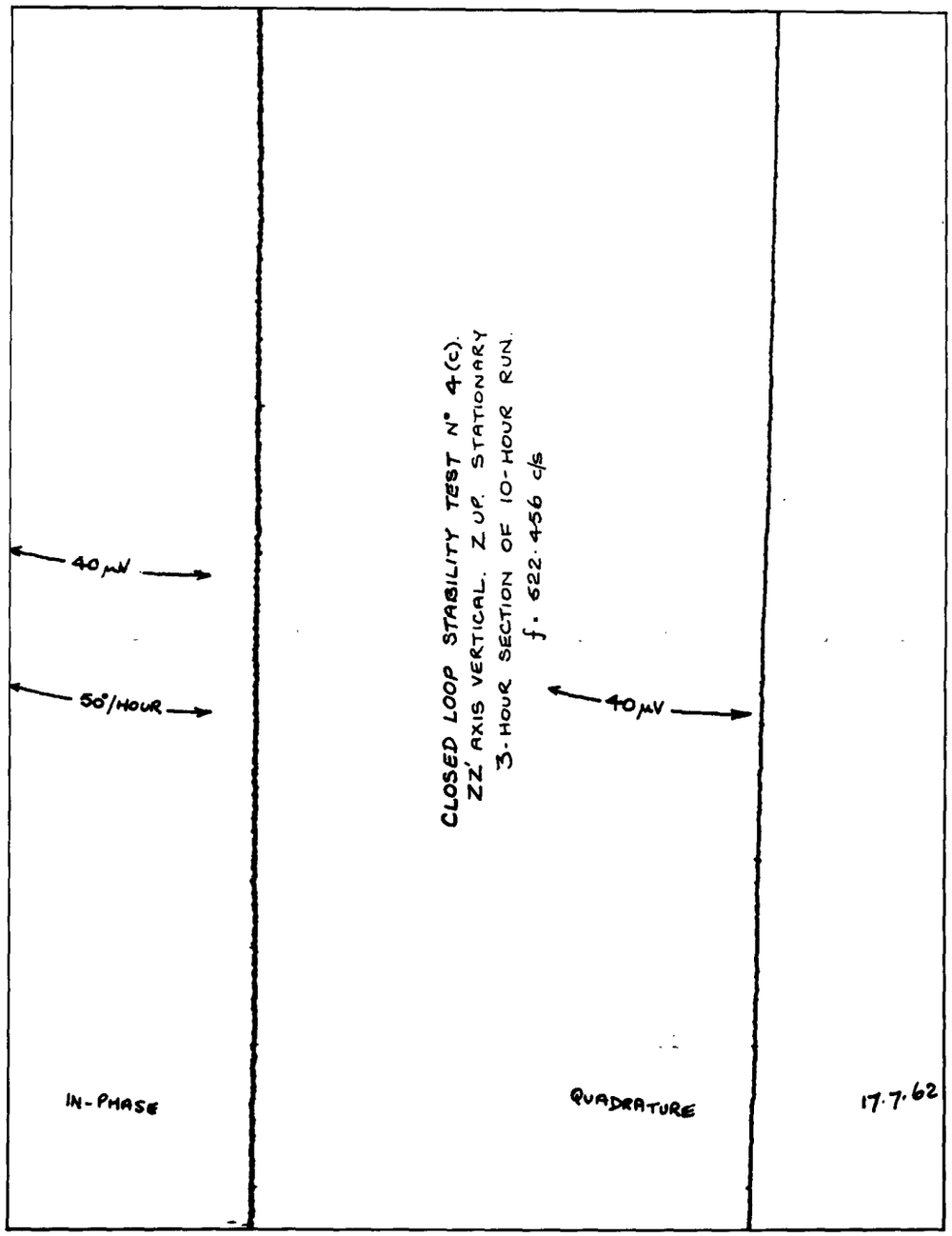


FIG.32 LONG-TERM STABILITY TEST.
ZZ' AXIS VERTICAL. Z UP STATIONARY.
COMPENSATION: 0V 0° 0V 27°
CHART SPEED: 3 INCHES/HOUR
3-HOUR SECTION OF 10-HOUR RUN.
CLOSED LOOP OPERATION.

R.A.E. 140062 (2)

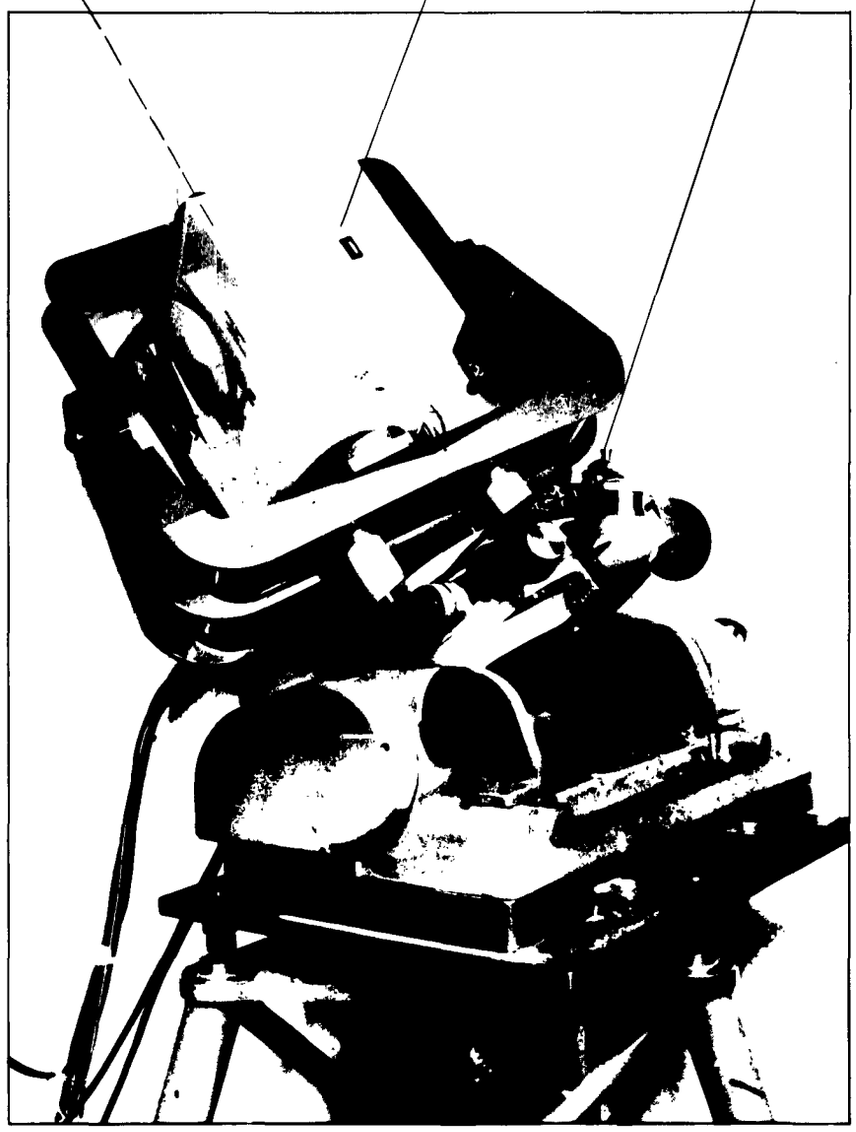


FIG.33 T.F.G. IN POSITION FOR POLAR AXIS TEST ABOUT YY' AXIS. Y UP.

R.A.E. 160063 62

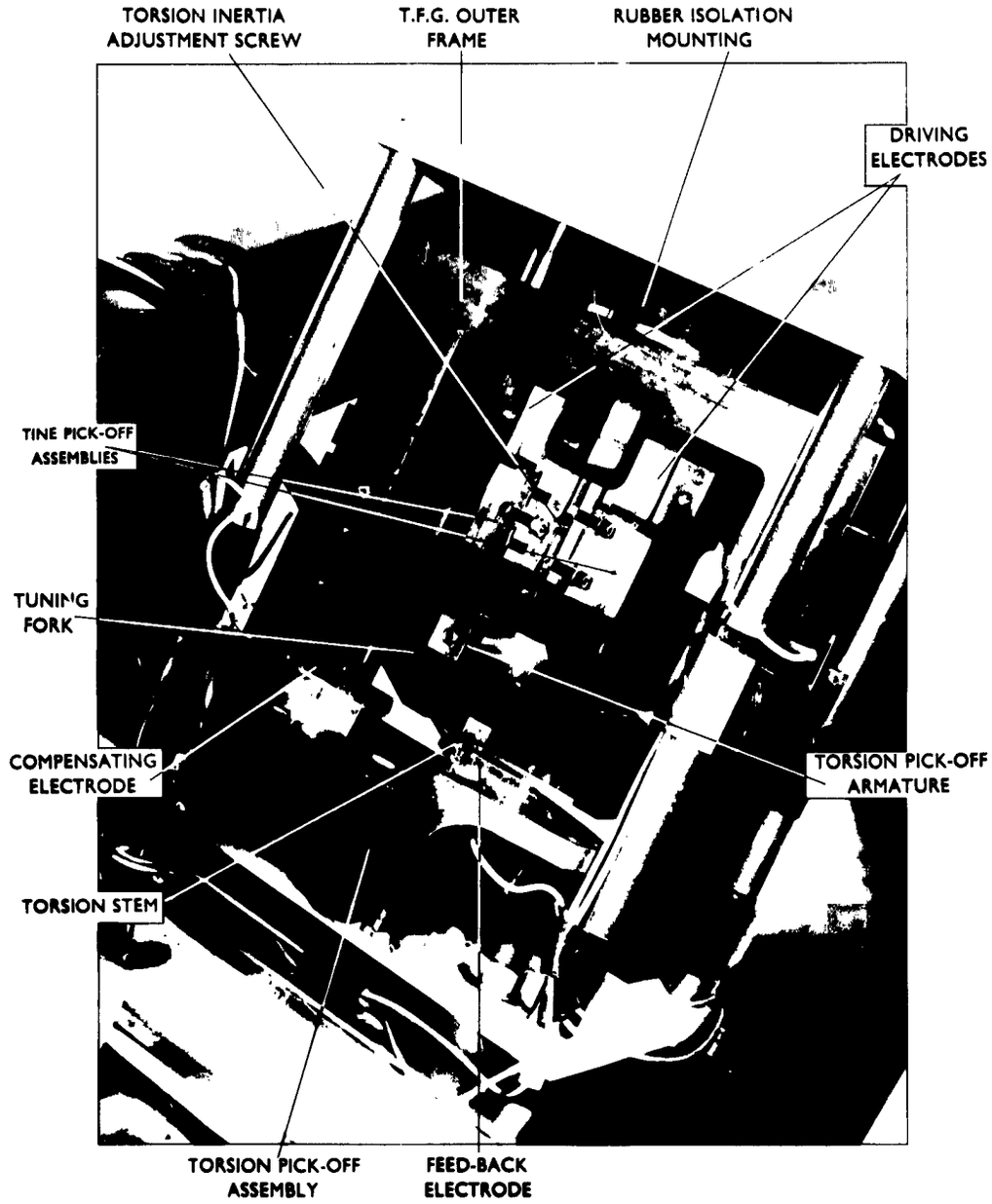
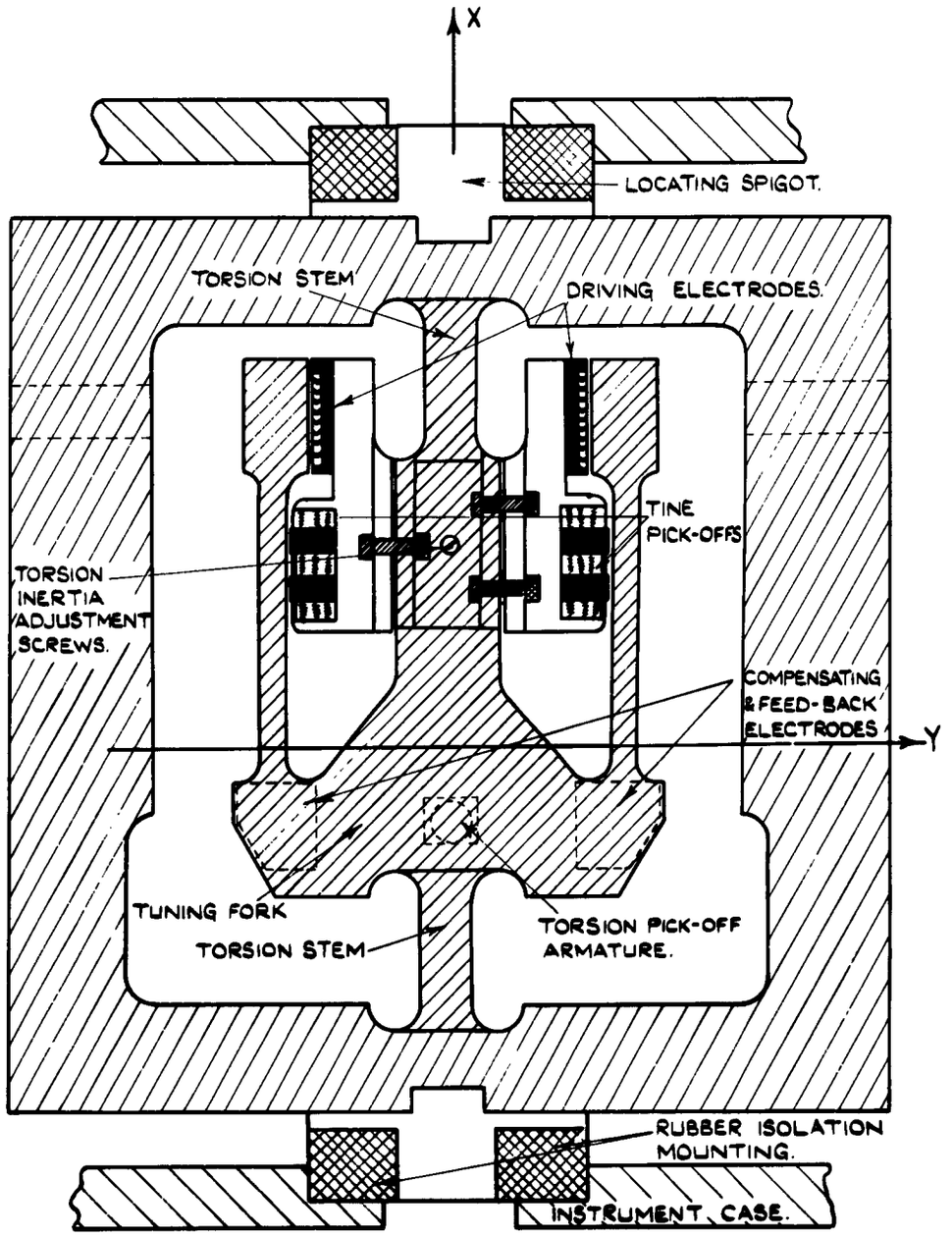


FIG.34 CONSTRUCTION DETAILS OF T.F.G. SERIAL NO. K.H.1.

R.A.E. 160064



SCALE. 1:1

FIG. 35. SECTION THROUGH XX′, YY′ AXES OF THE GYROSCOPE.

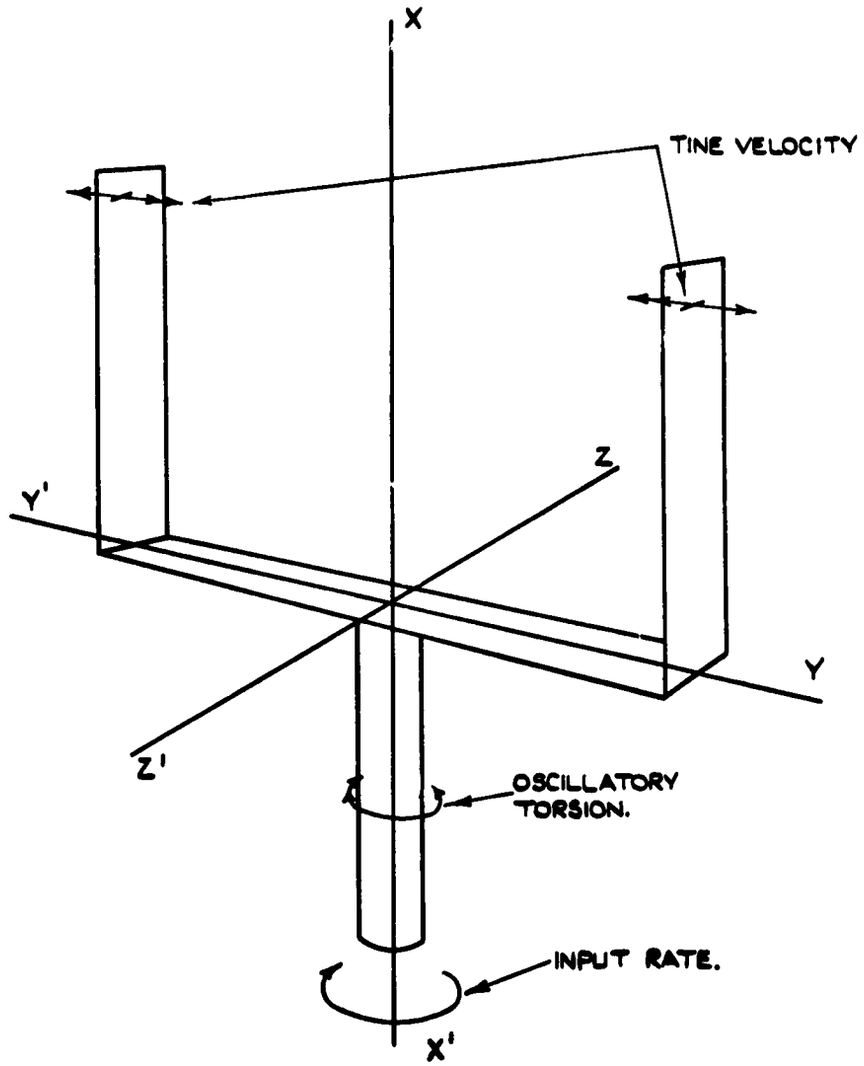


FIG. 36. T.F.G. AXIS SYSTEM.

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Technical Note No. IEE.10 — 531.383:
Royal Aircraft Establishment — 53.803.22

SOME PERFORMANCE DETAILS OF A PROTOTYPE TUNING-FORK GYROSCOPE, SERIAL NO. K.H.1. Pitt, R.J. November, 1962.

A test schedule has been designed and it is shown that the information available after carrying out this schedule should be sufficient to enable a performance assessment to be made of any tuning-fork gyroscope.

Comparisons between open loop and closed loop behaviour are made and an overall value for the tuning-fork's reliability as a rate-of-turn indicator is derived. A modification to the instrument design which should result in an improved performance is suggested.

Long-term stability and the effects of temperature changes are amongst the measurements quoted.

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