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THE COLLEGE OF AERONAUTICS

DEPARTMENT OF FLIGHT

M.S.760 'Paris' response to atmospheric turbulence

- by -

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Contents

1. Introduction

This report describes work carried out at The College of Aeronautics, Cranfield, during the first year of a contract to study the effects of atmospheric turbulence on the M.S.760 'Paris' aircraft.

The aircraft was fitted with an instrumentation system capable of recording ten aircraft quantities, the data being stored on magnetic tape.

From data recorded during flight tests, transfer functions for symmetric acceleration responses of the aircraft to turbulence may be obtained. Also, transfer functions may be determined for symmetric tailplane loads in turbulence, including the effect of the downwash from the wing elastic modes, and the tailplane elastic dynamic response.

The report contains detailed static and dynamic performance figures of the transducers used, and also descriptions of the three flight tests that have taken place so far, together with results obtained from the analysis of Flight 2.

2. Equipment

2.1 The aircraft

The Morane Saulnier M.S.760 'Paris' aircraft is a four-seat twin turbojet, all metal monoplane, its general arrangement being shown in figure 1. It is powered by two Turbomeca Marbore VI turbojets each producing 1040 lbs static thrust at sea level. Flying controls are operated manually by rods; the undercarriage, flaps, dive brakes and variable-incidence tailplane are operated electrically.

For the contract the aircraft had an extended nose-boom fitted, described later, which housed the incidence vane and boom accelerometer. This installation is shown in figure 4.

2.2 Instrumentation

The instrumentation system installed, measured the following quantities:

Angle of incidence
Boom acceleration
Pitch rate
Normal acceleration
Tailplane tip acceleration
Tailplane total load
Tailplane bending moment
Elevator velocity
Wing tip acceleration
Rear fuselage acceleration
Elevator hinge moment

Many of the transducers used were permanent installations on the aircraft, with the exception of the Normal Accelerometer and Pitch Rate Gyroscope, which were housed in a detachable floor-mounted pack.

The main instrumentation pack was fitted in the rear passenger compartment and consisted of the magnetic tape recorder, carrier-amplifier modules and signal conditioning panel. It is shown in figure 2.

2.3 Recording system

The ten quantities were recorded on magnetic tape using the Flexonics A4011 recorder. This recorder has provision for recording twelve channels, using either direct or frequency modulated record amplifiers, plus a voice track, and a timing or clock track.

The method of recording is shown in figure 3. This shows a single channel and is typical of the channels recording an acceleration. It consists of a variable inductance accelerometer connected in bridge form to the input of a carrier-amplifier. After resistor-capacitor filtering to remove the residual 3 Kc/s carrier frequency, the output of the amplifier is connected to a frequency modulated record amplifier in the A4011 magnetic tape recorder.

This record amplifier has a bandwidth of d.c. to 1.2 Kc/s at a tape speed of $7\frac{1}{2}$ inches per second, the speed used throughout the tests, and a linearity 1% of full scale. Plus and minus 1.2 volts at the input terminal of the amplifier corresponds to a frequency deviation of plus and minus 40% of centre frequency.

3. Instrumentation Calibration

3.1 General notes on calibrations

All measured values of output voltage from transducers during ground calibrations were those which appeared at the SIGNAL CONDITIONING/TAPE RECORDER interface, that is, at the input terminal of the FREQUENCY MODULATORS.

For scaling purposes an accurate reference voltage was generated and appeared at this interface during the in-flight system calibration sequence, operated at the commencement of each flight test. This sequence consisted of one minute periods of zero volts, plus one volt and minus one volt. Relating all transducer outputs to this level, allows scaling factors on replay to be adjusted accurately and simply.

It will be seen from the tape recorder graph (graph 1) that an input of plus and minus one volt represents a deviation from centre frequency of plus and minus 33.3%, that is in the case of a centre frequency of 6,000 cycles per second, a deviation of plus and minus 2,000 cycles per second. A positive voltage at the input terminal of the frequency modulators results in a negative deviation of centre frequency, a negative deviation being a decrease in frequency.

3.2 Static calibrations of transducers.

Accelerometers and rate gyroscope

The accelerometers and rate gyroscope were statically calibrated using the Genisco systems rate-of-turn table, which has a rate accuracy of 0.1% when used with the strobing attachment.

Incidence vane

This instrument was calibrated using an associated jig, consisting of a protractor-scale and pointer arrangement.

Tailplane total load, tailplane bending moment and elevator hinge moment

These quantities were calibrated using loading boards and weight pallets, section 4 of this report gives detailed descriptions of the calibration procedures.

3.3 Dynamic calibrations of transducers

Accelerometers

All accelerometers, with the exception of the normal accelerometer, were dynamically calibrated using a Goodmans Industries vibrator with its associated power amplifier, driven from a decade oscillator.

Amplitudes were measured using the Wayne-Kerr capacitive distance measuring equipment. The normal accelerometer was calibrated at R.A.E. Bedford using their 'Swinging Arm' rig.

Incidence Vane

For the dynamic calibration of this instrument a rig was manufactured which housed the assembled vane and pick-off and connected it via a link mechanism to a small vibrator. The vibrator was driven from an oscillator and power amplifier. Amplitudes were again measured using the Wayne Kerr distance measuring equipment.

Elevator velocity

For dynamic calibration of this instrument at the higher frequencies a rig was constructed similar to the one used for the incidence vane calibration. The Goodmans Industries vibrator was used, driven from its associated power amplifier and a decade oscillator. Angular distance of vibration was measured using a servo-potentiometer linked directly to the transducer. The potentiometer was connected in bridge form, its output voltage being viewed on an oscilloscope, and was statically calibrated using a protractor and pointer arrangement.

The instrument's response to the lower frequencies was checked by linking the transducer to a simple pendulum, the frequency being controlled by detachable weights. Angular distance was again measured by a potentiometer, linked to the shaft of the pendulum.

3.4 Graphical presentation and sign conventions

Graphs for the dynamic performance of accelerometers are drawn, and show their amplitude and phase response over a range of frequencies. In all cases amplitudes are output voltage per G of acceleration, and phase angles are in degrees of lag, with respect to the impressed frequency.

The sign convention used for all accelerometers was that an upward acceleration of the aircraft resulted in a positive voltage at the frequency modulators.

A positive voltage also resulted for a nose-up pitch rate and for a nose-up angle of incidence.

Upward tailplane total loads, tailplane bending moments and elevator hinge moments similarly resulted in positive voltages at the frequency modulators.

4. Notes on Actual Channels

4.1 Angle of Incidence

The instrument recording angle of incidence of the aircraft, consisted of a windvane manufactured to R.A.E. drawings linked to a variable transformer pick-off supplied by O.N.E.R.A. The initial scale of this instrument was 15-0-15 degrees, but from flight (1) it was evident that an increase in its sensitivity would be beneficial, and its associated carrier-amplifier was adjusted, increasing its sensitivity by a factor of four to one. The final static calibration is shown in graph 2.

No dynamic performance results are shown, but extensive tests over the frequency range 0-200 c/s showed its sensitivity to be substantially constant and no phase shift occurred over this range.

4.2 Boom acceleration

For the contract the M.S.760 was fitted with an extended boom, which during May, 1966, was subjected to natural frequency tests. These tests were carried out with the boom installed on the aircraft, the boom being vibrated by a magnetic vibration generator of College manufacture. Amplitudes of vertical vibration were measured by visual means. The results of the tests showed the boom to have a lowest natural frequency of 20.5 cycles per second.

The accelerometer used for measuring boom vibration was an Electromechanism's variable-inductance type with oil damping. It had a range of ± 6G, graphs 3 and 4 showing its static and dynamic calibrations.

4.3 Pitch rate

From Flight (1) it was evident that the range of this instrument was too high and it was replaced by a Smith's miniature rate gyroscope having a range of ± 6 degrees per second. It was located in the floor mounted pack positioned on the centre line of the aircraft, behind the front seats.

The associated carrier amplifier was finally adjusted to give the channel full scale values of ± 3 degrees per second, graph 5 showing the calibration.

4.4 Normal acceleration

This instrument was of an R.A.E. design with a range of ± 1 G. It employed its own phase-sensitive demodulator, both units being located in the floor-mounted pack. For correlation purposes Normal Acceleration was recorded on two tracks, track twelve appearing on the second half of the split-stack record head in the magnetic tape recorder.

An R.M.S. indication of normal acceleration was also presented to the pilot and observer on the pilot's meter, the signal being derived from the output of the demodulator via a full-bridge rectifier.

The static and dynamic calibrations for the instrument are shown in graphs 6 and 7.

4.5 Tailplane tip acceleration

It was a requirement that only symmetrical accelerations of the tailplane tips be recorded, and for this purpose a matched pair of Electromechanisms accelerometers type A.E.M. (R.A.E. type ITI-22-F31) were used, housed in the port and starboard tailplane tips. Each accelerometer was of the variable-inductance type, normally used in the half-bridge circuit configuration. After initial tests to select a matched pair, the accelerometers were connected in a full bridge circuit configuration, and calibrated statically and dynamically for symmetrical and asymmetrical accelerations. The static calibration for symmetrical accelerations is shown in graph 8, the output for asymmetrical accelerations being undetectable during this calibration. Graph 9 shows the dynamic calibration for both forms of acceleration, the output for asymmetrical accelerations being extremely small.

4.6 Timing track

This track had a 10 Kc/s timing waveform recorded continuously on it, of amplitude approximately 1 m.V. peak to peak measured at the head at the normal replay speed.

4.7 Total tailplane load

The requirement of a channel measuring total load on the tailplane was met by combining the outputs of eight strain gauge bridges. The eight strain gauge bridges consisted of two symmetrical groups of four, positioned as in figure 5.

Determination of the influence coefficients of each bridge necessary to establish a valid total load signal, was the subject of an extensive investigation during May, 1966.

Load boards were manufactured for five different symmetrical span positions each with three chordwise loading points for both up and down loads. This gave a total of a possible thirty points per side (fifteen up and fifteen down). Down loads were obtained by slinging a loading pallet directly from the lower loading points. For up loads a cable was attached to an upper loading point via a spring balance and then passed over a spanwise beam supported by safety raisers, at the tailplane tip.

Care was taken to ensure vertical uploads by using two beams and moving them when changing load points. The total load used was normally 200 pounds per side including pallet with the exception of the tip points (13, 14 and 15) when 100 pounds was used to limit tip deflection. The output from each bridge was noted for load points 4 - 15 inclusive, points 1 to 3 not being investigated, as being only 5.5 inches outboard from the centre line, it was felt that no useful results would be obtained.

Analysis and results

The bridge output per pound of load was found from:

$$\Delta V/\mathrm{lb} = \frac{V_{\mathrm{load}} - V_{\mathrm{no\ load}}}{P_p + P_s - 2\,P_b} \quad \text{(for up-loads)}$$

where $P_p = P_s$ = load used per side

P_b = weight of load board used

From the results it was apparent that the outputs could be grouped into three sets in relation to their slopes.

These were:

i) Rear attachment box bridges, 7,8,9 and 10.
ii) Front attachment box bridges 11 and 14
iii) Front attachment box bridges 12 and 13.

A qualitative assessment was carried out to determine a combination of outputs required to give a consistent figure representing load, that was independent of load point and this combination was found to be:

$$\Delta V_{\text{combined}} = \Delta v \left\{ 7 + 8 + 9 + 10 + \left[\frac{11+14}{2.5}\right] + \left[\frac{12+13}{3}\right] \right\} \qquad (A)$$

The limits of centre of pressure movement were assumed to be within 20% - 60% of both the span and chord dimensions. Hence the results from load points 4 to 12 inclusive were considered as the most important.

Using the above combination (eqn. A), percentage errors were then calculated from the following results:

	Up Loads			Down Loads		
Load Point	ΔV/lb μV	$\Delta_{AV.} - \Delta V$ μV	% Error	ΔV/lb μV	$\Delta V_A - \Delta V$ μV	% Error
4	+3.59	-0.09	-2.4	-3.33	+0.06	+1.8
5	+3.77	+0.09	+2.4	-3.49	+0.22	+6.7
6	+3.73	+0.05	+1.4	-3.28	+0.01	+0.3
7	+3.71	+0.03	+0.8	-3.24	-0.03	-0.9
8	+3.74	+0.06	+1.6	-3.50	+0.23	+7.0
9	+3.67	-0.01	-0.3	-3.49	+0.22	+6.7
10	+3.59	-0.09	-2.4	-3.03	-0.24	-7.3
11	+3.81	+0.13	+3.5	-3.20	-0.07	-2.1
12	+3.61	-0.07	-1.9	-2.90	-0.37	-11.3
$\Delta V_{AV.}$	$= + \frac{33.22}{9} = + 3.68$ μV			$- \frac{29.46}{9} = - 3.27$		

From the results, carpets were drawn of percentage error versus load point, for both up and down loads. These were then used to draw error contours on a plan form of the tailplane, as in figures 6 and 7.

From this investigation it was decided that the combination eqn. (A) established a valid signal representing total load on the tailplane, the method of summation being shown in figure 8. This consisted of an integrated circuit operational amplifier, followed by a unity gain inverting amplifier to allow the differential input of the main amplifier to be used. This circuit formed the input to a carrier-amplifier channel, the strain gauge bridges being excited from a common 3 Kc/s oscillator in the equipment.

The combination was achieved by using summing resistors in the ratios given, each bridge output being connected to the summing points on the amplifier via two identical resistors.

Values chosen were:

1)	For bridges 7, 8, 9 and 10	10 KΩ
2)	For bridges 11 and 14	25 KΩ
3)	For bridges 12 and 13	30 KΩ

High stability resistors were used, these being mounted with the amplifier on a fibre-glass board and installed under a detachable cover in the leading edge of the fin.

For final tests and overall system calibration, once again the tailplane was loaded, using load points four to twelve inclusive. Each point was loaded with down loads of up to 100 lbs in 20 lb increments, the total combined output being noted at each step.

Up loads were not thoroughly investigated, but several 'spot check' up loads were applied, the results of which giving complete agreement with down loads already applied.

Results

	Down Loads Total Load Applied - lbs					
Load Point	40	80	120	160	200	% Error at 200 lbs
4	-0.193	-0.285	-0.578	-0.770	-0.963	-7.4
5	-0.192	-0.284	-0.580	-0.772	-0.964	-7.4
6	-0.201	-0.403	-0.604	-0.799	-1.010	-2.88
7	-0.203	-0.405	-0.609	-0.809	-1.017	-2.21
8	-0.209	-0.417	-0.624	-0.836	-1.044	+0.38
9	-0.215	-0.431	-0.647	-0.857	-1.074	+3.27
10	-0.220	-0.437	-0.657	-0.875	-1.090	+4.86
11	-0.219	-0.436	-0.658	-0.876	-1.094	+5.2
12	-0.222	-0.443	-0.663	-0.884	-1.104	+6.15

From the results, error percentages were calculated and these were drawn as error contours on a plan form of the tailplane as shown in figure 9. The overall calibration is shown in graph 10 which has been plotted using averaged values of the above results.

4.8 Total tailplane bending moment

Bending moments of the tailplane were measured using a pair of full bridge strain gauges, mounted on trunnions at the roots of the tailplane. Total bending moment was achieved by adding the outputs of each strain gauge bridge. The form of addition is shown in figure 10, each bridge output being connected to the primary of a small transformer. The secondaries of the transformers were connected in series forming the input to a carrier amplifier channel, the strain gauge bridges being excited from a common oscillator in the equipment. Each transformer was wound on a ferrox cube FX2238 core and these were mounted on the board in the fin leading edge section.

For calibration, existing load boards were used, points 10 and 10A being loaded to 200 lbs per side in 20 lb increments. Total bending moments were then calculated, the overall calibration being shown in graph 11.

4.9 Elevator velocity

Elevator velocity was measured using a torsional vibration transducer (R.A.E. type IT3-6-40) which had a constant sensitivity range of ± 20°.

The shaft of the transducer was connected directly to the elevator pivot, in the port tailplane tip.

The overall sensitivity of the instrument increased by using it in conjunction with integrated circuit operational amplifier which had a gain of 50. Graph 12 shows the final calibration.

4.10 Wing tip acceleration

This instrument was a single variable-inductance accelerometer of the R.A.E. type ITI-22-F31 and was mounted in the starboard wing, inboard of the tip fuel tank.

Initially it had a range of ± 9G but from Flight (1) it was evident that an increase in sensitivity would be beneficial, and the gain of the associated carrier-amplifier was increased by a factor of two.

The final range was therefore ± 4.5G, graphs 13 and 14 showing the static and dynamic calibrations.

4.11 Rear fuselage acceleration

This instrument was also of the R.A.E. type ITI-22-F31, mounted on a cross member in the tailcone. It had a range of ± 3G, graphs 15 and 16 showing the static and dynamic calibrations.

4.12 Elevator hinge moment

Elevator hinge moment was measured by a single strain gauge bridge, mounted on the elevator operating lever inside the top of the fin section. The strain gauge bridge formed the input to a carrier amplifier, gauge excitation being the common 3 kc/s oscillator supply.

The channel was calibrated by attaching weights to the rear edge of the elevator, with the control column locked in the neutral position. Loads used were up to 40 lbs in 5 lbs increments. Moments were then calculated about the elevator hinge point, graph 17 showing the final calibration.

5. Flight tests

Flights (1) and (2) - 16/11/66

For both flights the aircraft was only partially instrumentated, incidence angle, boom acceleration, pitch rate, normal acceleration and wing tip acceleration, being the channels recorded.

Each flight was divided into two parts:

Part A: Flight in turbulent conditions.
Part B: Flight in still air.

Pilot instructions were:

Part A. Maintain flight for as long as possible, preferably at least 4 minutes, with commentary on:

(a) Flight condition
(b) Speed
(c) Height
(d) Fuel state
(e) Control actions

Keep the aircraft's wings level, and control pitch smoothly where necessary, with comments on corrections made. Elevator trimmer changes are not to be made.

Part B.

(a) Speed to be 250 knots.
(b) Roller-coaster manoeuvres to be performed with a 15 second period, keeping mean speed and height constant.
(c) A moderate turn to the left and right.

From Flight (1) it was evident that the sensitivities of certain channels were too low, and the gains of the carrier amplifiers associated with incidence angle and wing tip acceleration were adjusted accordingly, before Flight (2).

During Flight (2) the aircraft was flown in moderate turbulence, the average level being approximately 0.3G R.M.S. A successful recording was made, the timetable of events as follows:

Event	Time
End of flight calibrations	1.30
Descending into turbulence for Part (A)	
Start of first run	2.30
End of first run	7.30
Adjusting elevator trim and turning for second run	
Start of second run	8.00
Turning back on course	9.30
Re-start of second run	10.30
End of second run	15.00
End of Part (A) climbing climbing to 8000 ft. for Part (B)	
Start of 'Roller Coaster' (1)	17.00
Turning	
Start of 'Roller Coaster' (2)	18.00
Turning	
Start of 'Roller Coaster' (3)	19.00
Start of moderate left turn	19.40
Start of moderate right turn	20.40
End of recording	22.00

Times given are in minutes and seconds from the observer saying 'RECORDER ON'.

Flight (3) 15/3/67

The aircraft was now fully instrumentated and a successful recording of all channels was made during this flight. However, turbulent conditions could not be found and it was felt that the recording was not suitable for a detailed analysis.

6. Analysis

It was considered that the signal levels recorded during Flight (2) were adequate for analysis using analogue techniques, this being performed at O.N.E.R.A. in December, 1966.

Graphs 18 to 21 illustrate the results obtained.

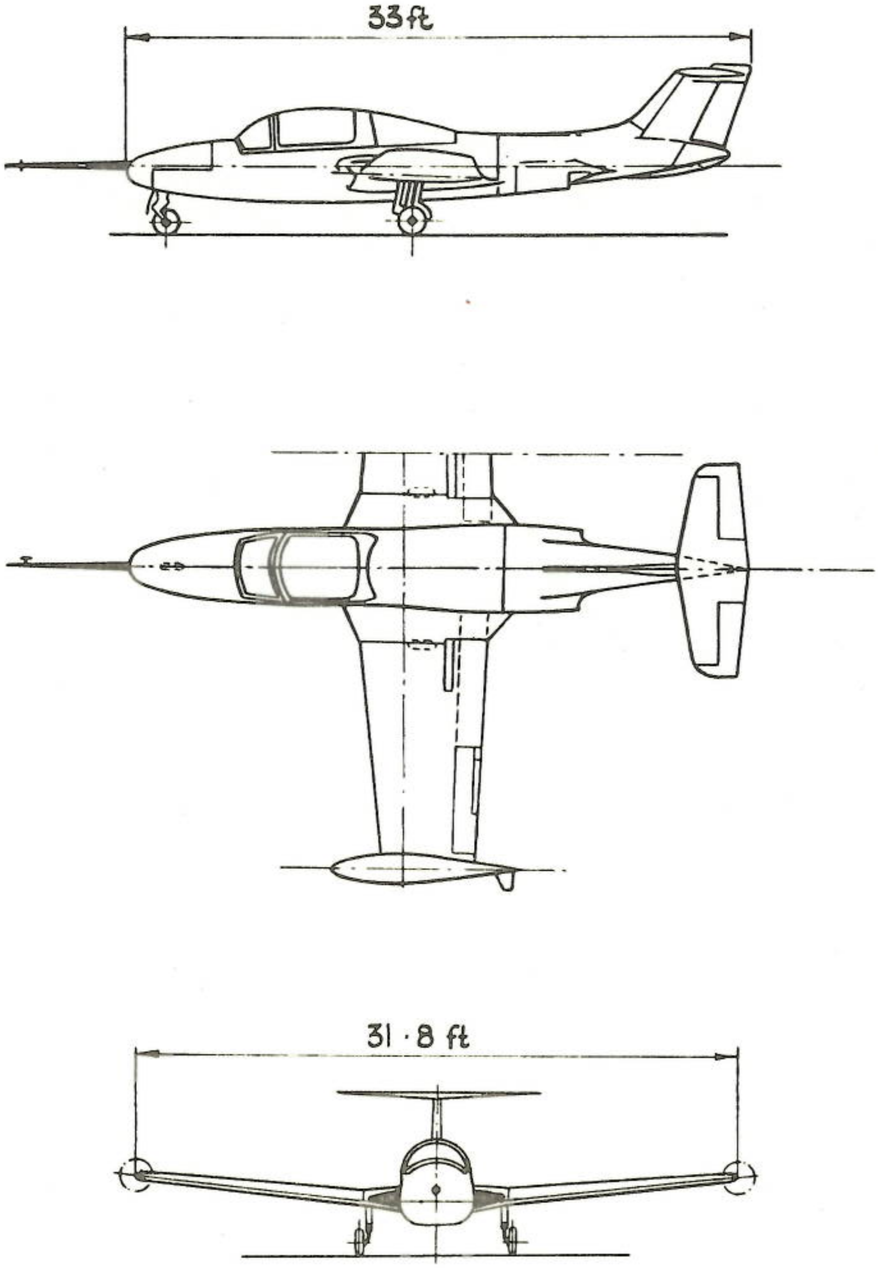
Future Work

Weather conditions during the first part of 1967 have restricted the flying programme, turbulent conditions being extremely difficult to find locally. However, it is hoped that this problem will be overcome by choosing a low-flying area over suitable terrain, probably in Wales.

On completion of the flying programme it is envisaged that most of the work during the second year will be applied to analysis and data reduction.

It is felt that digital processing of the flight data would lead to a faster and more effective method of analysis, using a medium-sized digital computer.

A suitable digital conversion process is currently being investigated.



GENERAL ARRANGEMENT OF M.S. 760 "PARIS" IA

FIGURE 1.

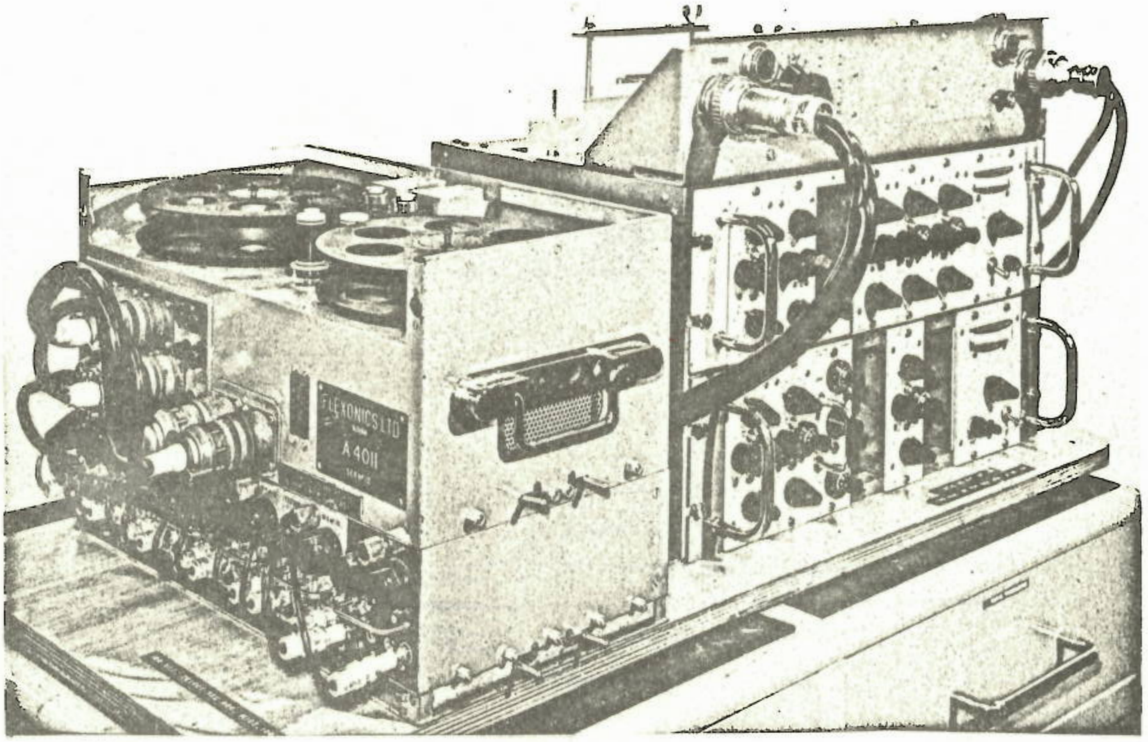


FIG . 2 MAIN INSTRUMENTATION PACK

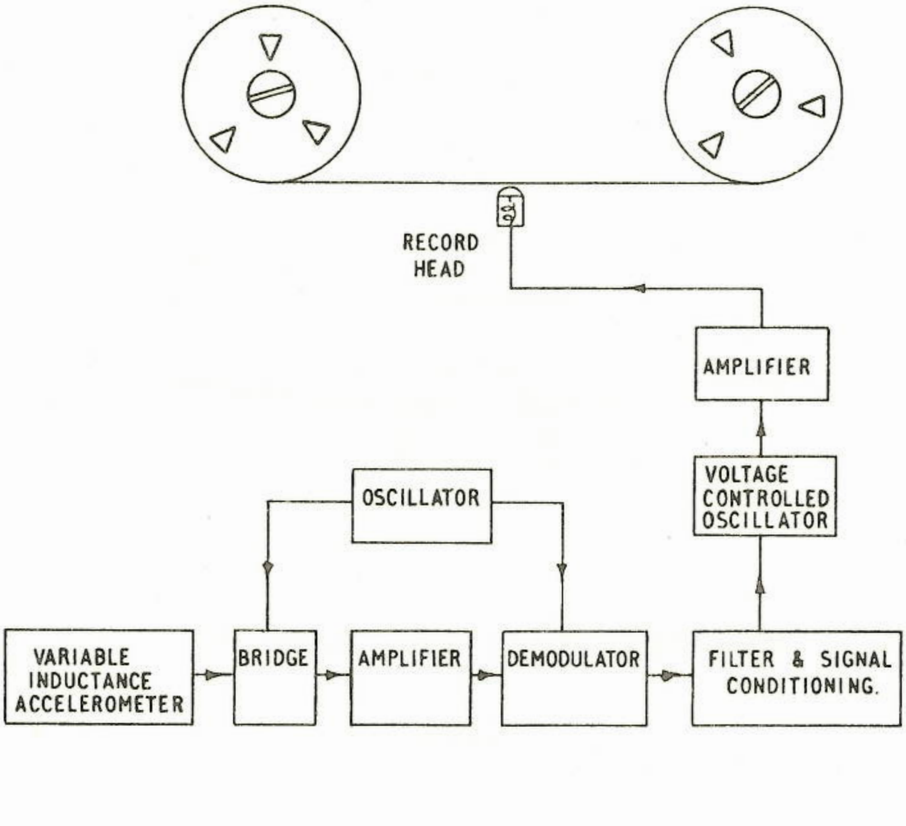


FIG. 3. BLOCK DIAGRAM OF RECORDING SYSTEM.

(SINGLE CHANNEL)

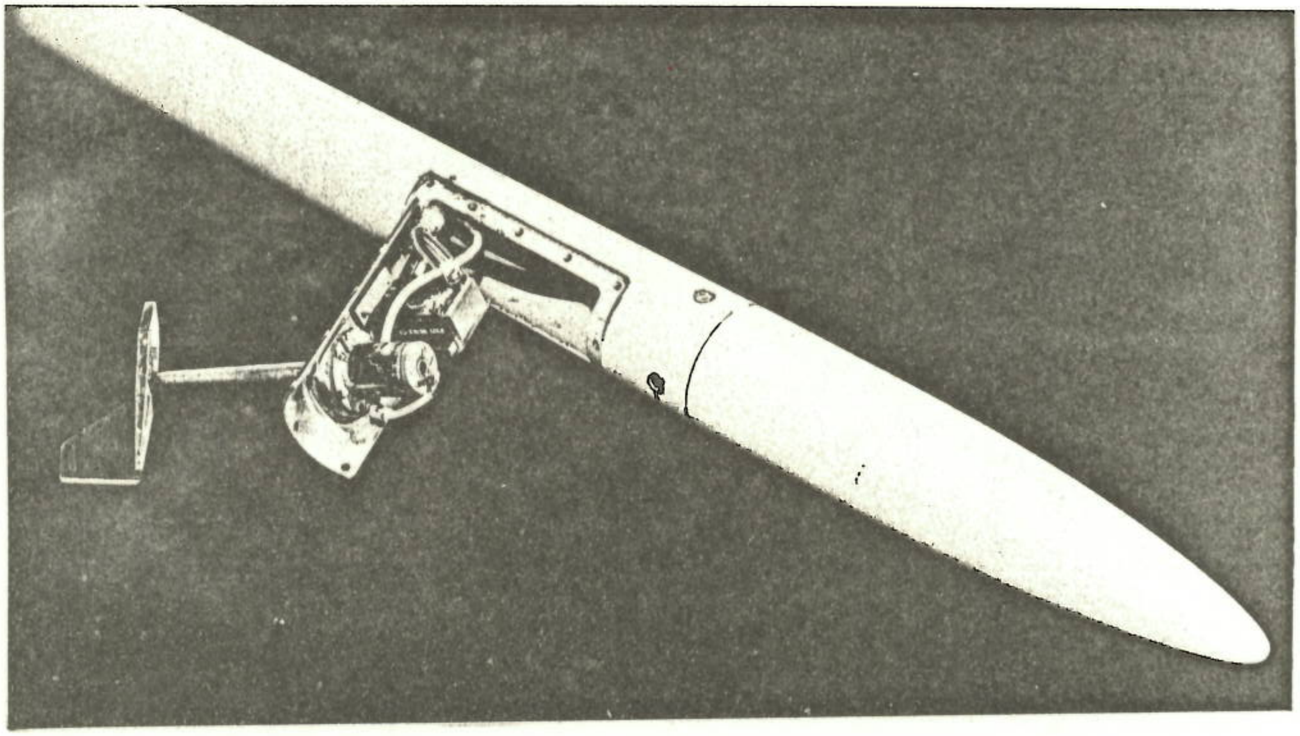


FIG. 4 WINDVANE INSTALLATION

FIG. 5. TOP VIEW OF M.S. 760 TAILPLANE SHOWING STRAIN GAUGE AND LOADING POINT LOCATIONS.

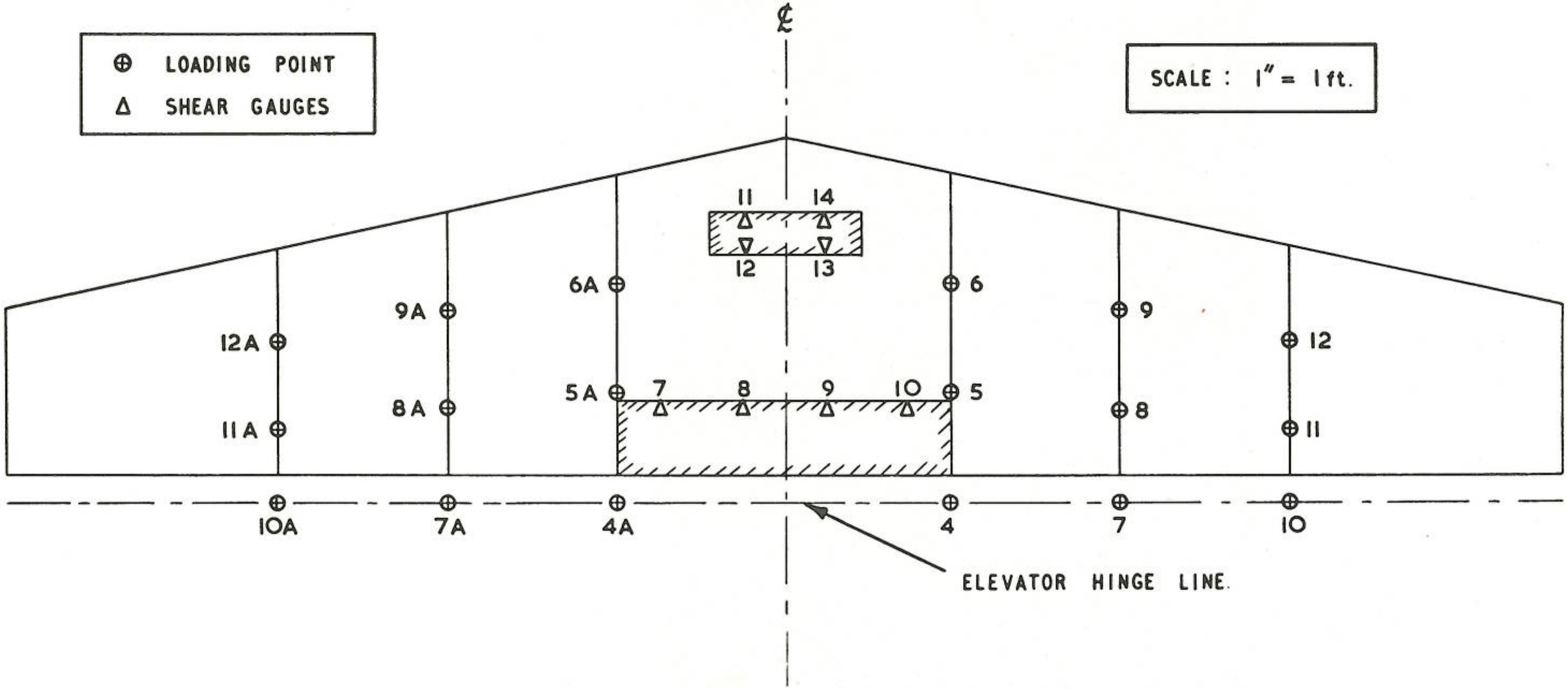


FIG. 6. M.S. 760 TAILPLANE

CALCULATED PERCENTAGE ERROR CONTOURS RESULTING FROM TOTAL LOAD COMBINATION, DOWN LOADS.

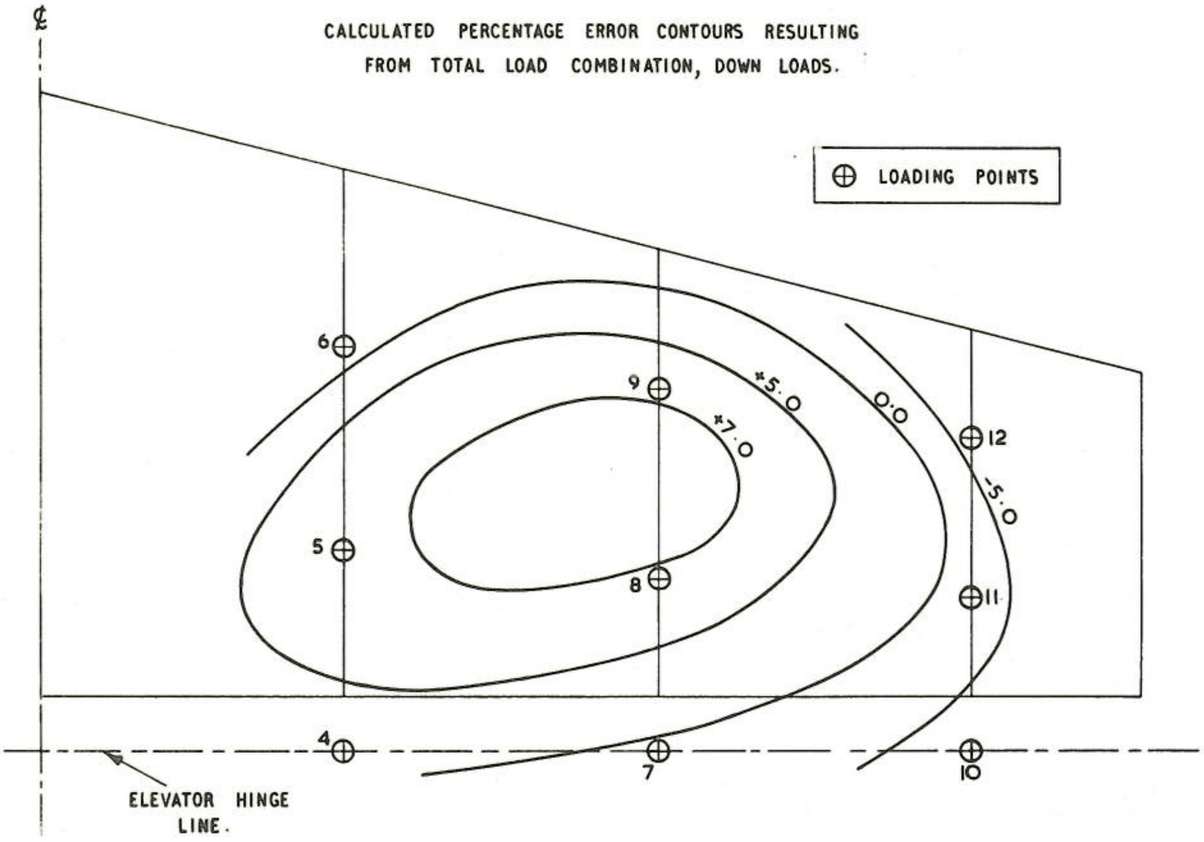
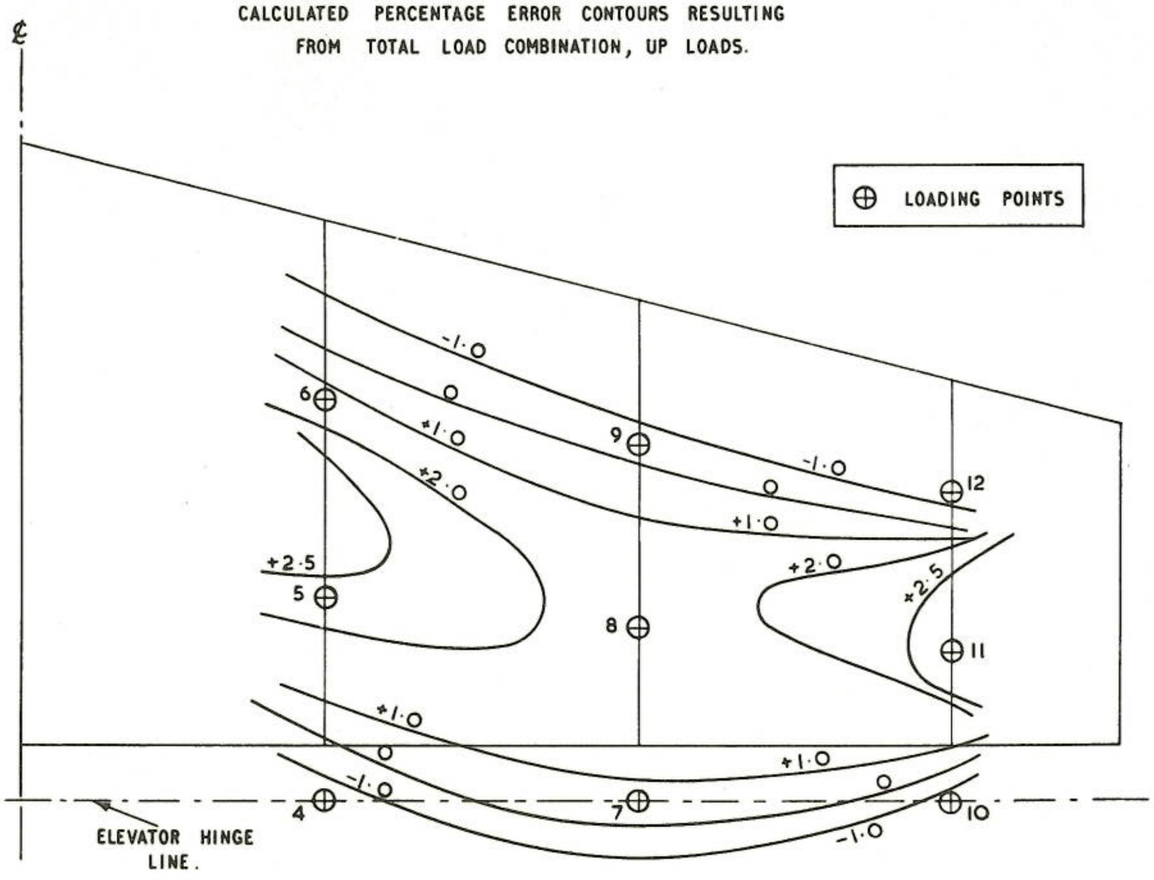


FIG. 7. M.S. 760 TAILPLANE.

CALCULATED PERCENTAGE ERROR CONTOURS RESULTING FROM TOTAL LOAD COMBINATION, UP LOADS.



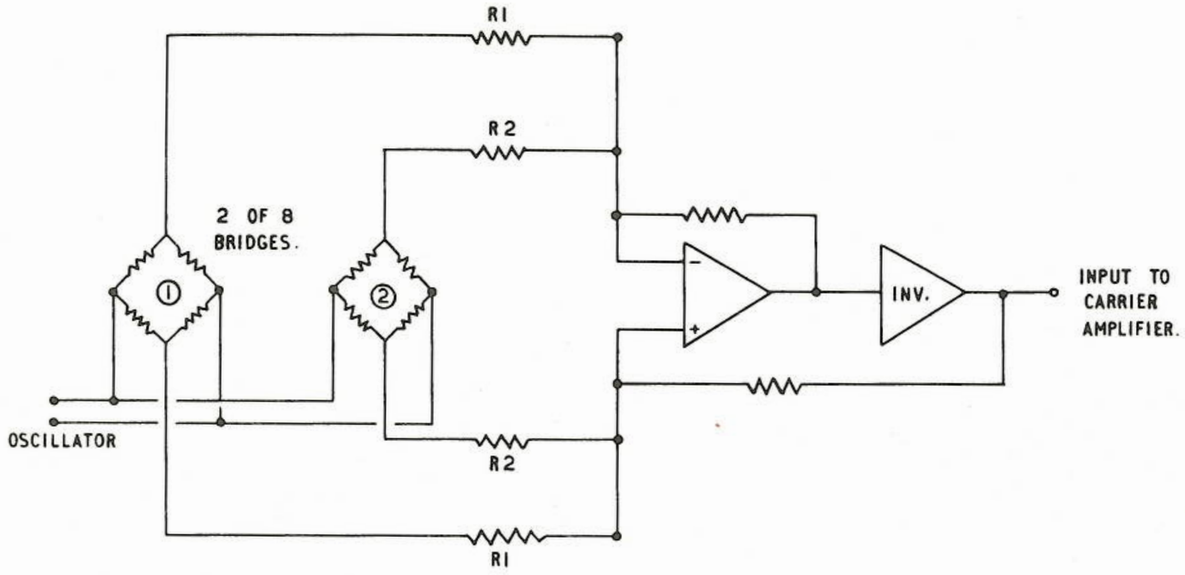
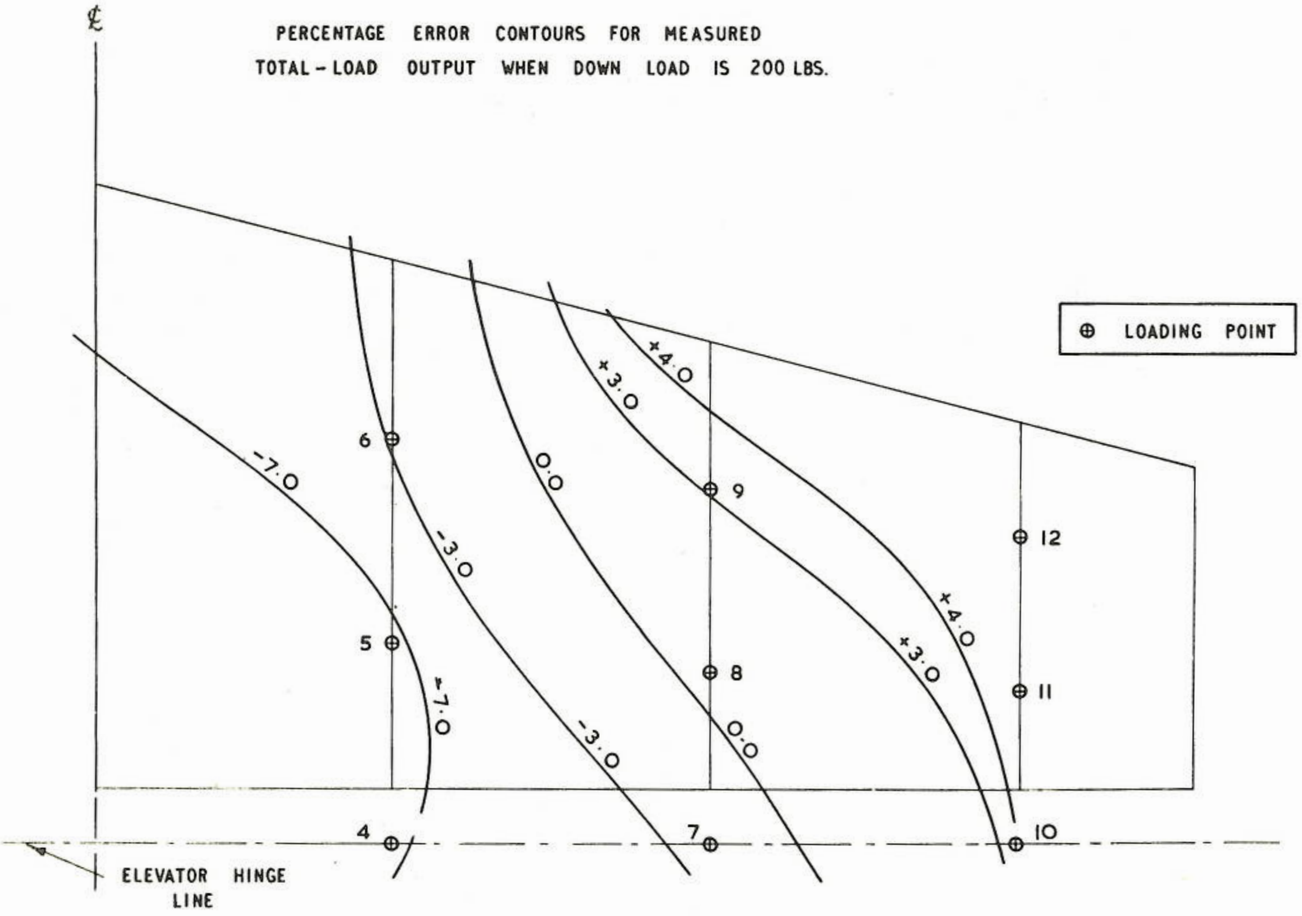


FIG. 8. TOTAL – LOAD SUMMING AMPLIFIER.

FIG. 9. M. S. 760 TAILPLANE.

PERCENTAGE ERROR CONTOURS FOR MEASURED TOTAL – LOAD OUTPUT WHEN DOWN LOAD IS 200 LBS.



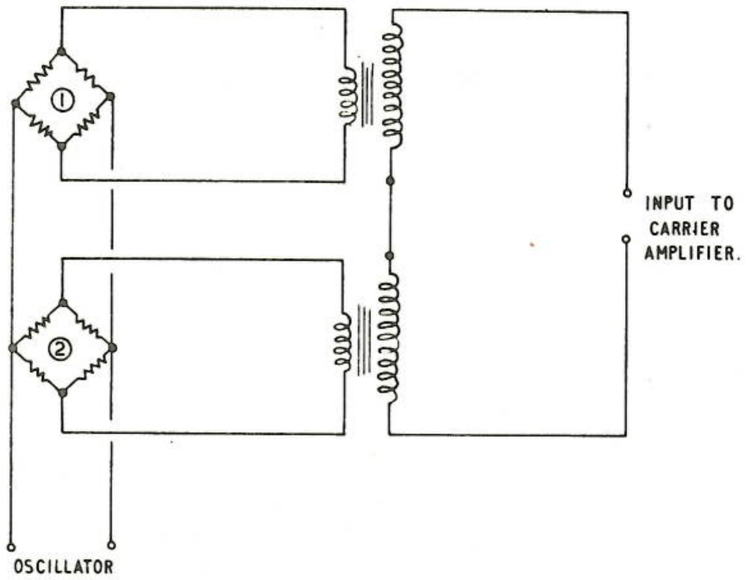


FIG. 10. TRANSFORMER SUMMATION OF BENDING MOMENT GAUGES.

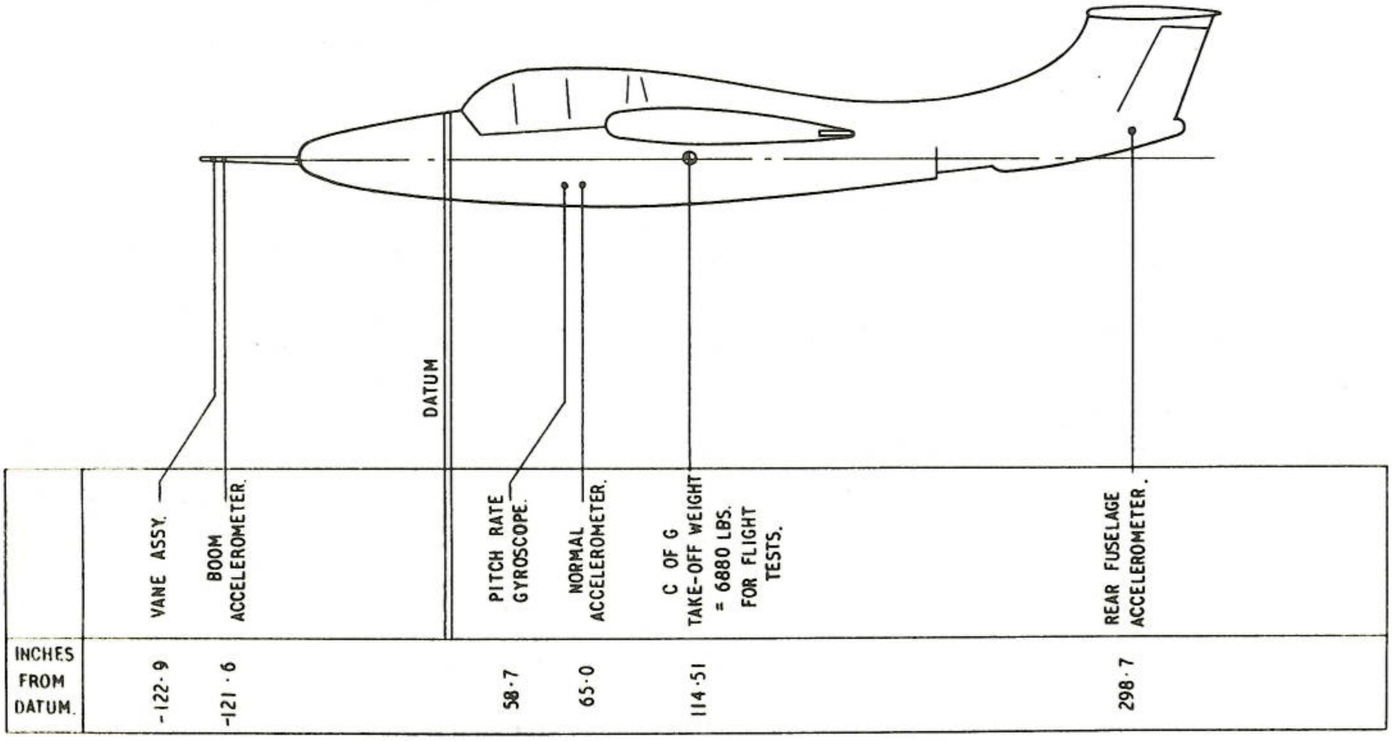
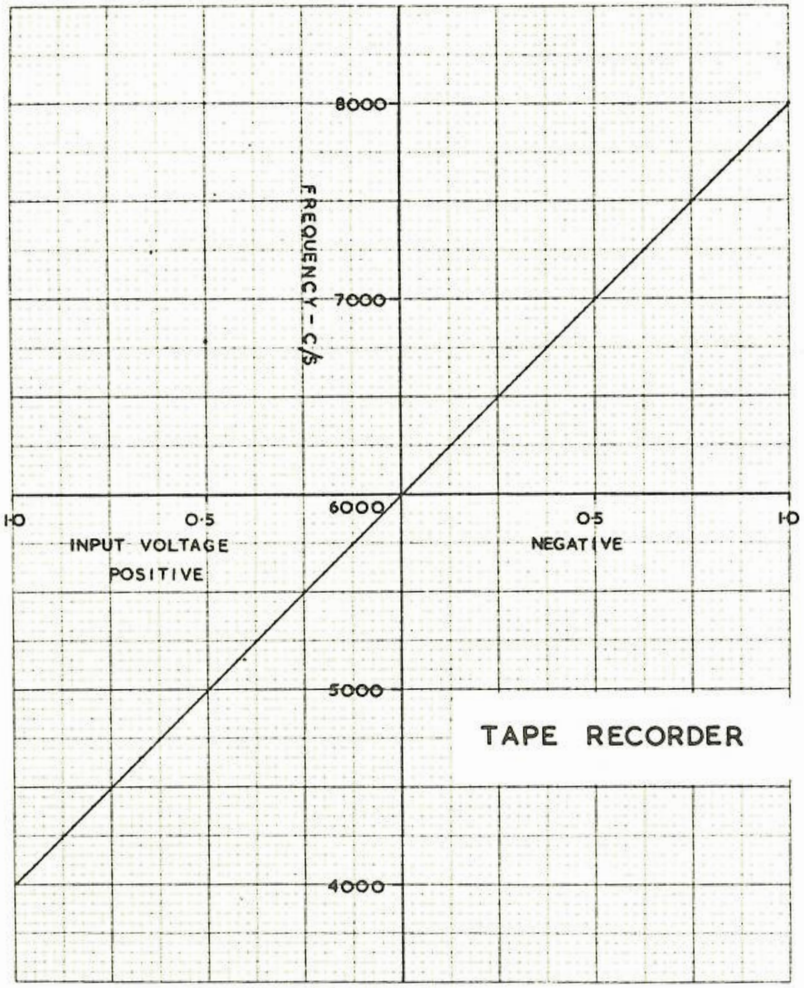
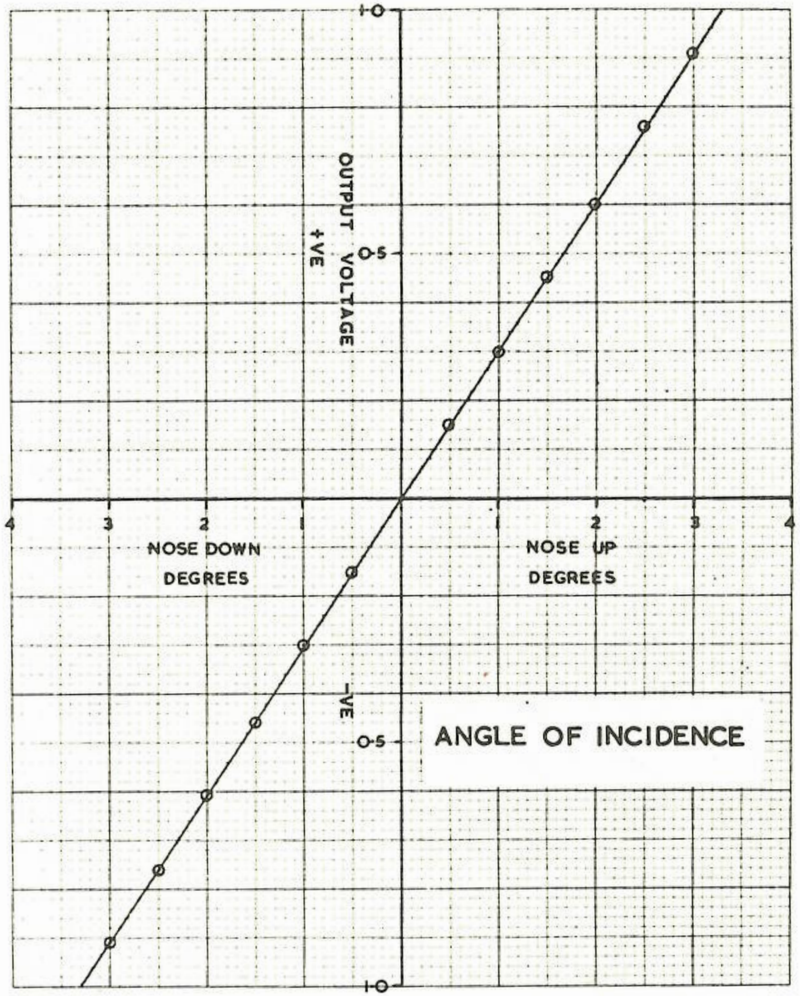


FIG. 11. BASIC TRANSDUCER LOCATIONS.

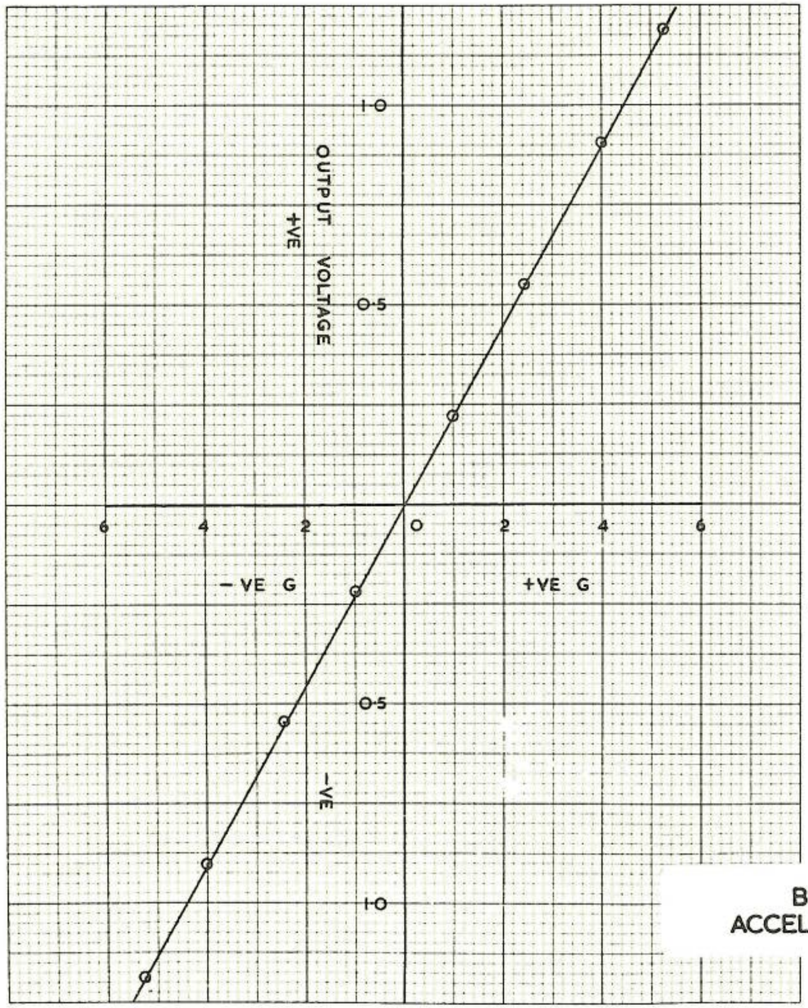


GRAPH 1

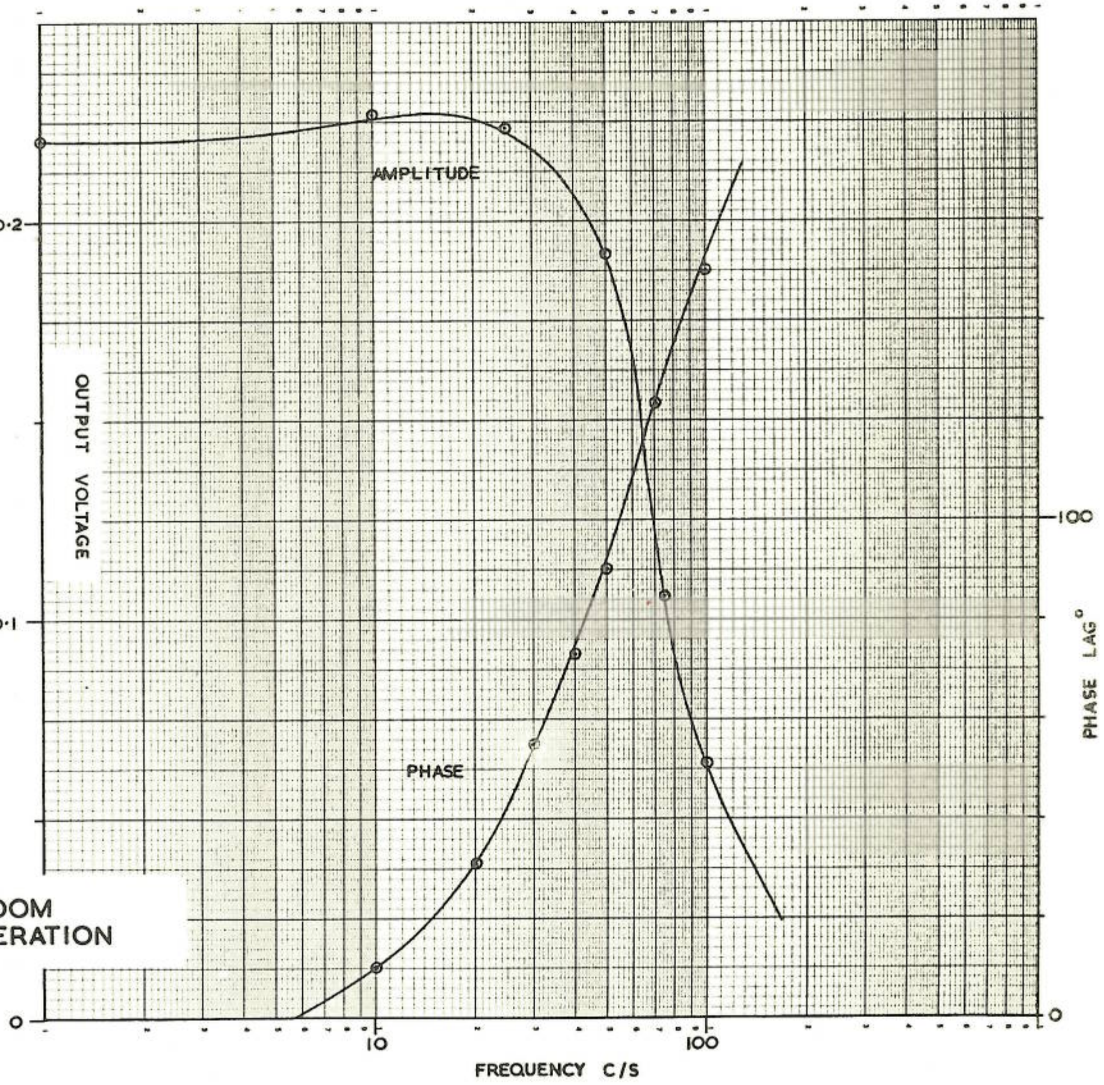


GRAPH 2

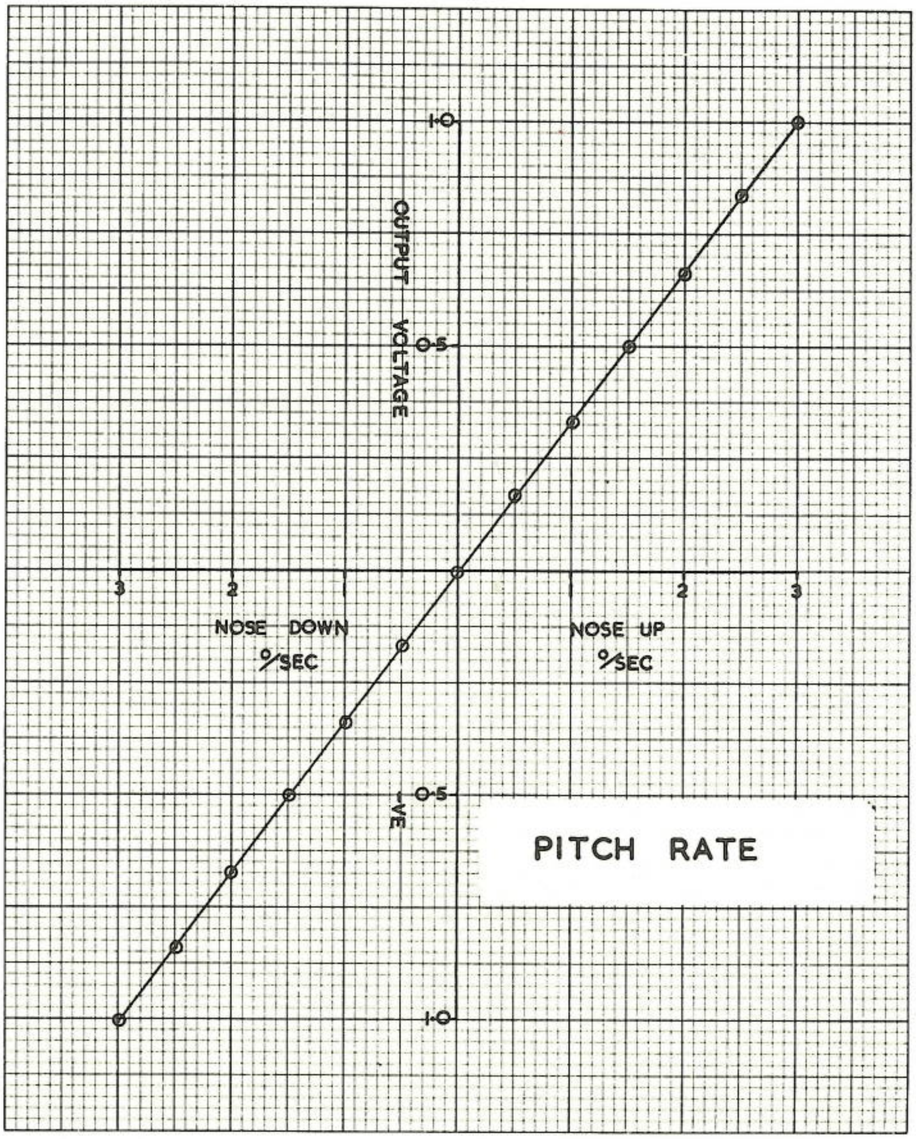
BOOM
ACCELERATION



GRAPH 3



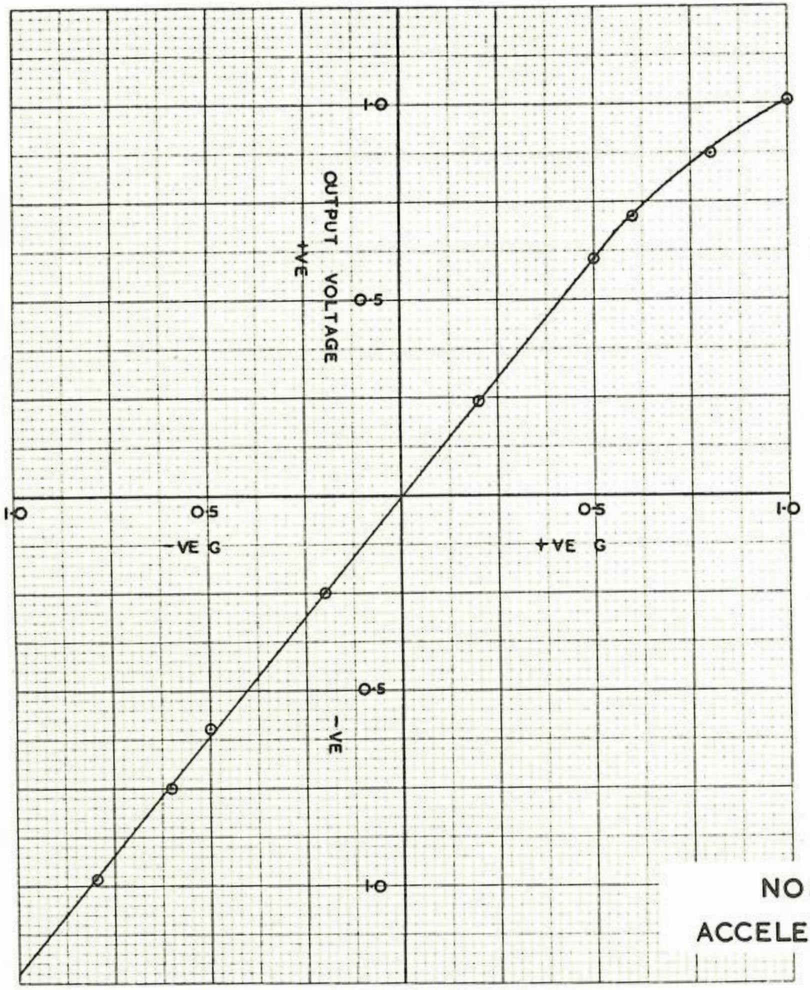
GRAPH 4



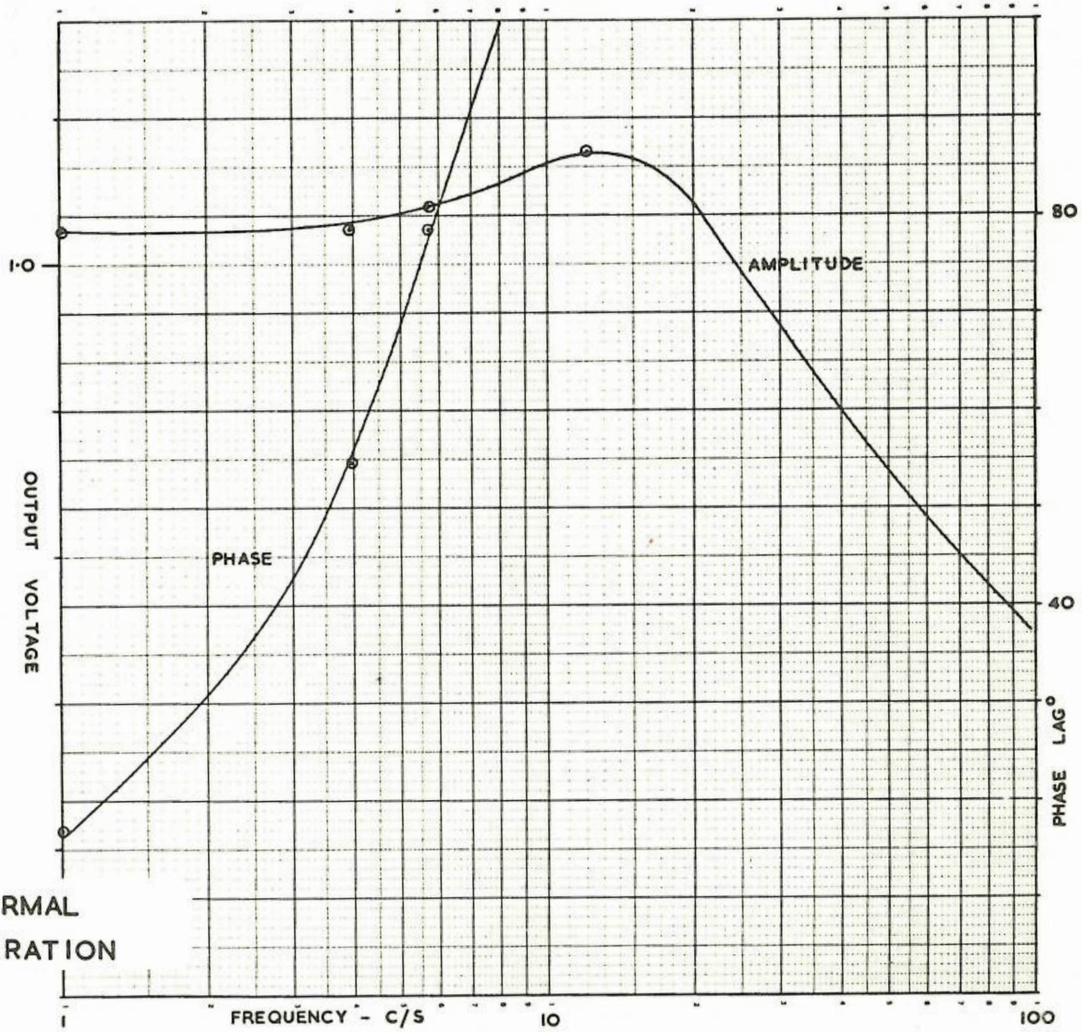
1·0
OUTPUT VOLTAGE
0·5
3
2
1
1
2
3
NOSE DOWN
°/SEC
NOSE UP
°/SEC
0·5
-VE
1·0
PITCH RATE

GRAPH 5

NORMAL
ACCELERATION

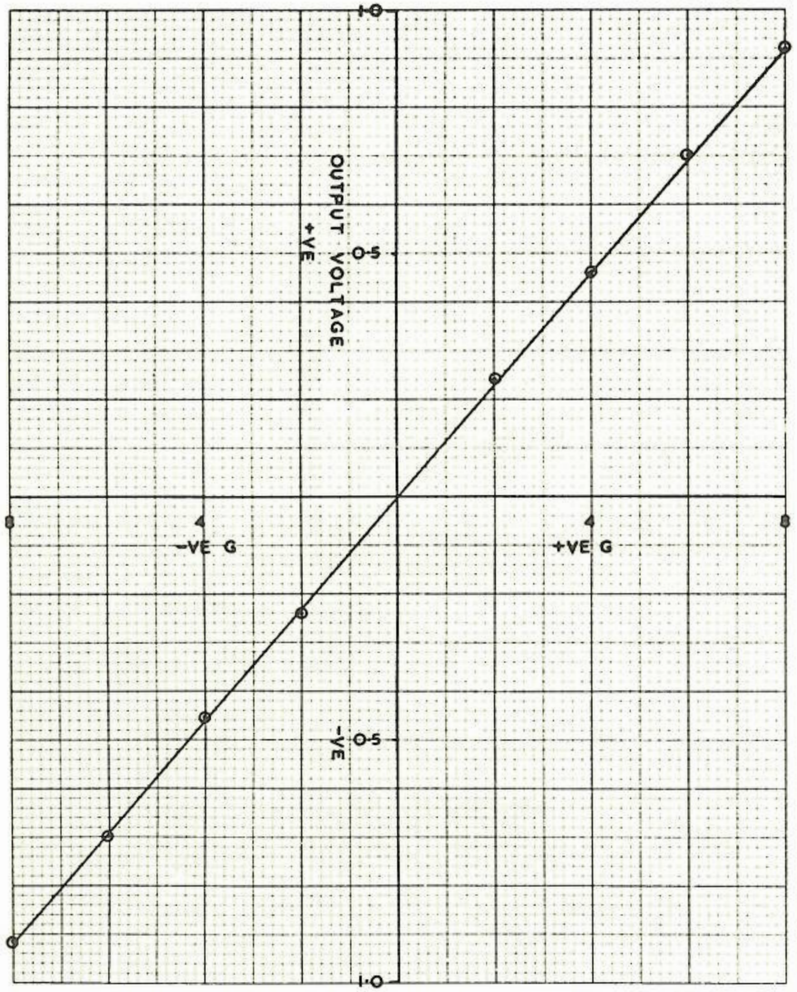


GRAPH 6

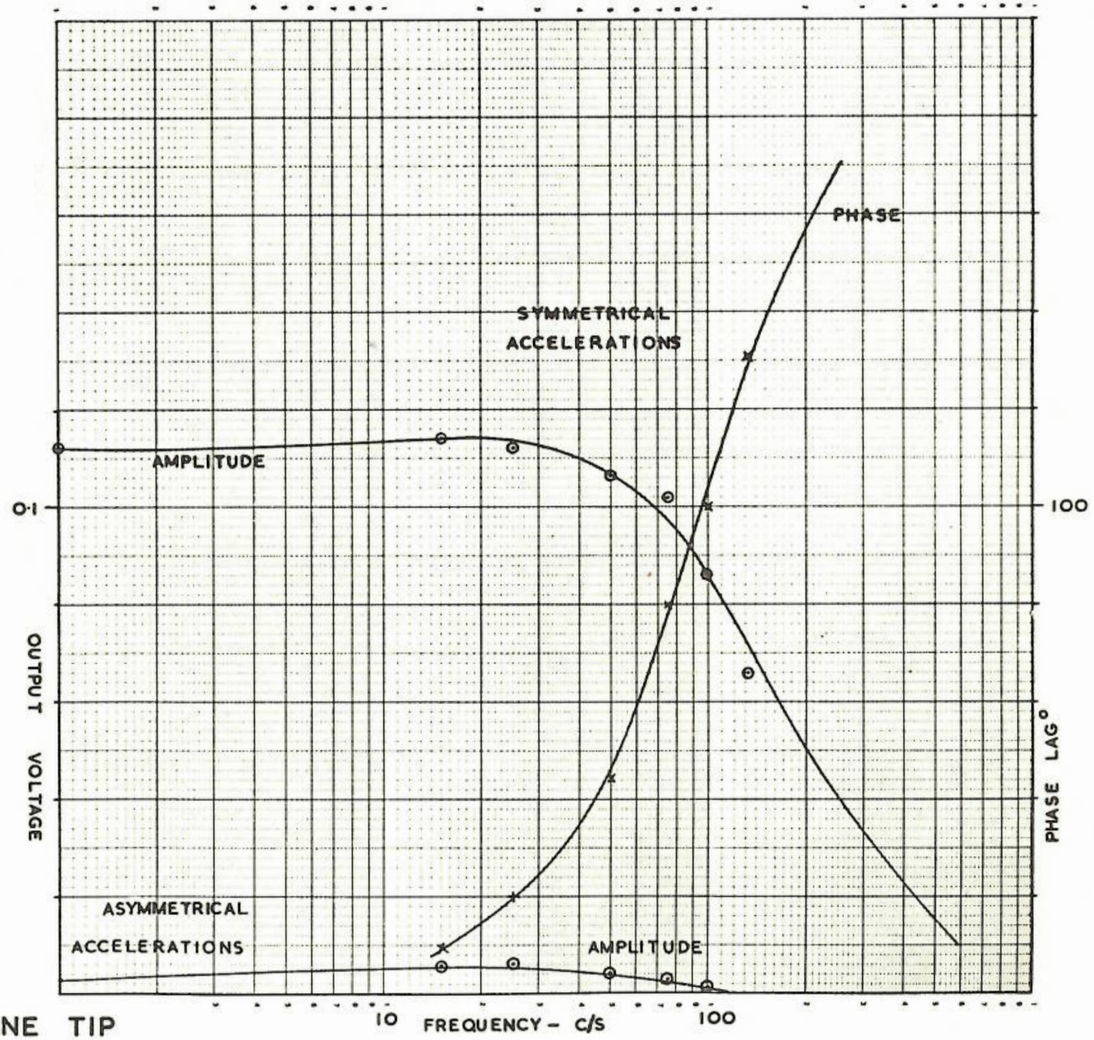


GRAPH 7

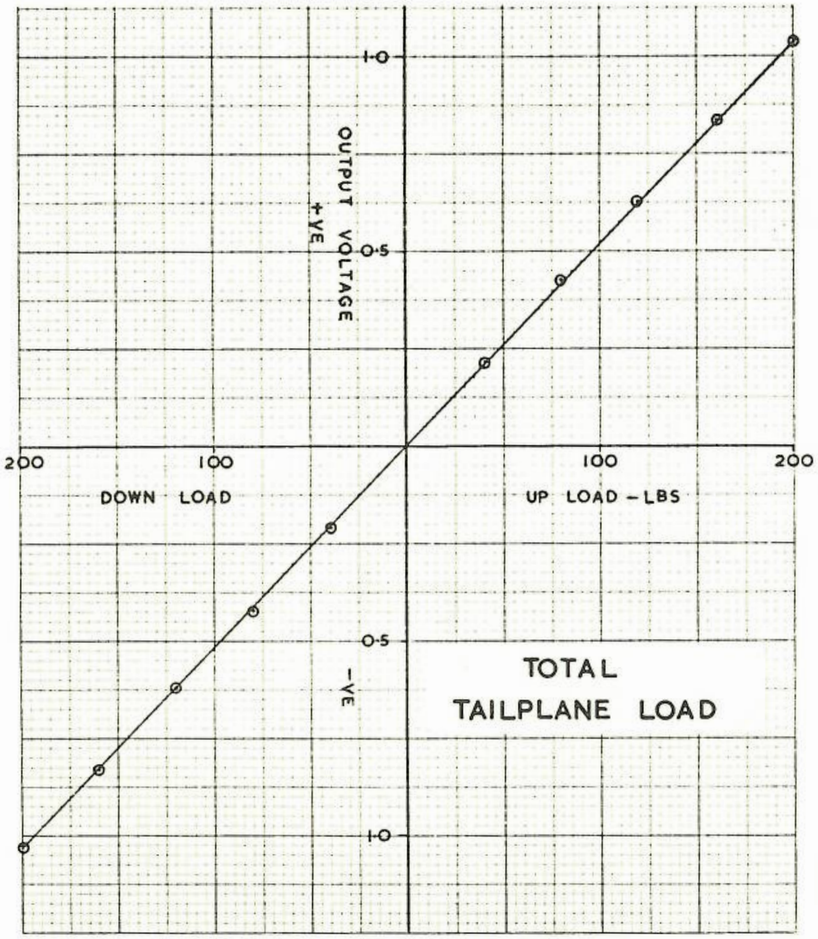
TAILPLANE TIP
ACCELERATION



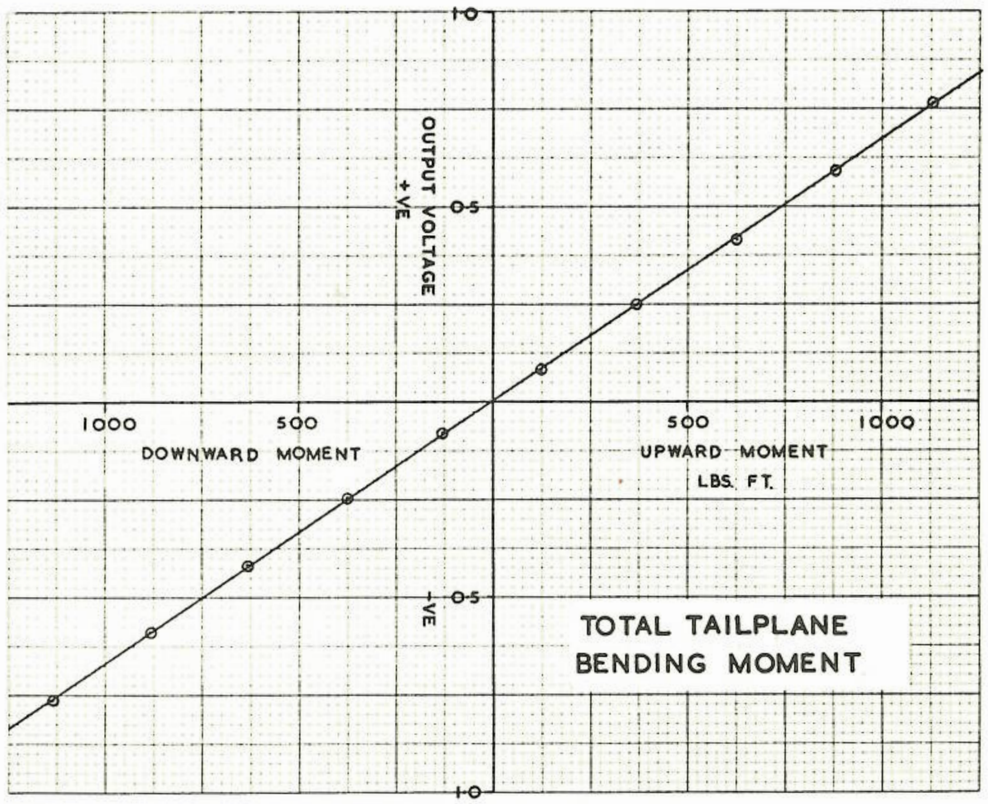
GRAPH 8



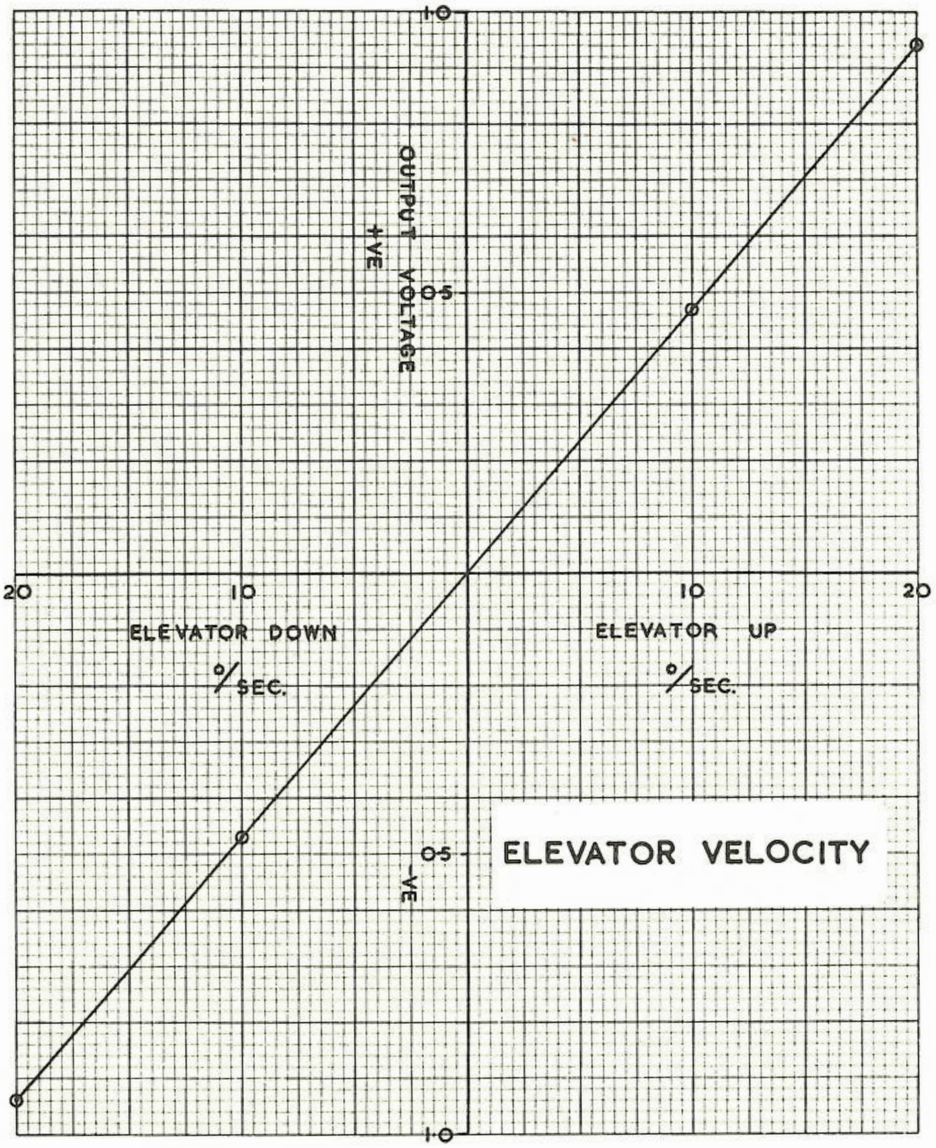
GRAPH 9



GRAPH 10

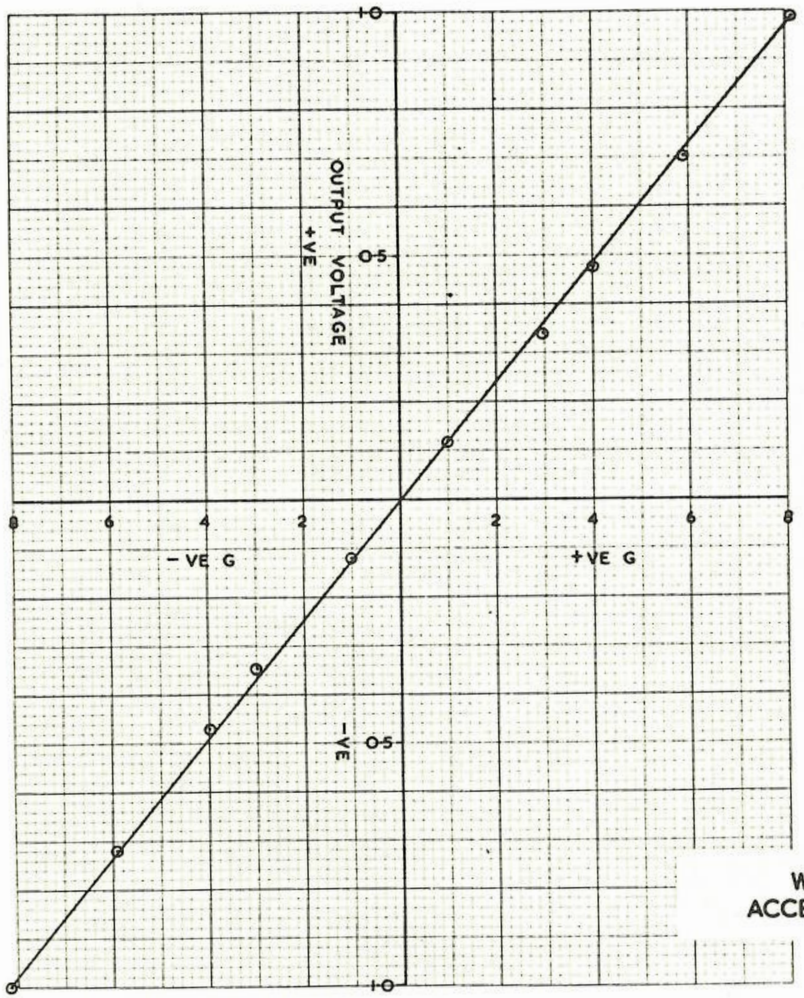


GRAPH 11

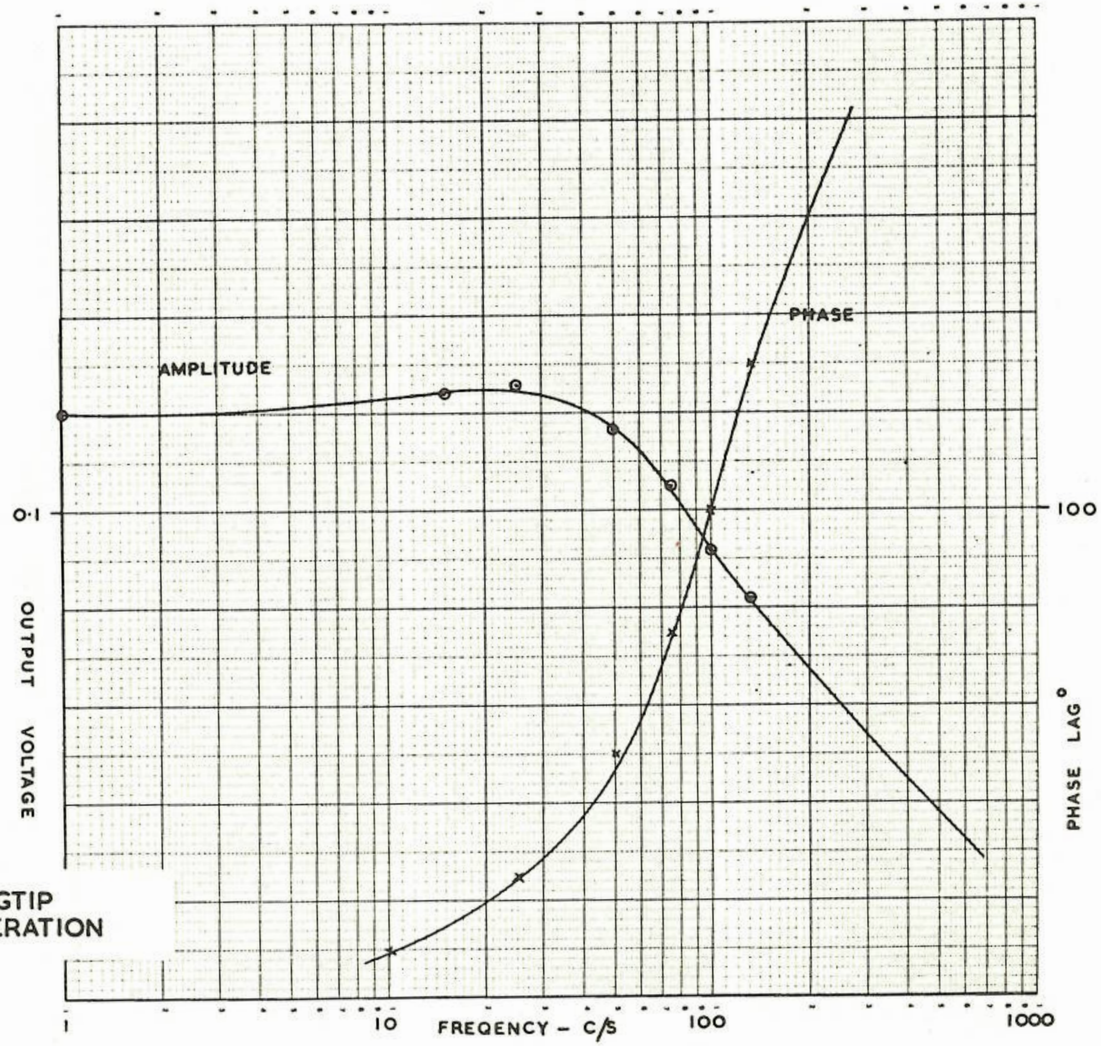

1·0
0·5
OUTPUT VOLTAGE
+VE
20
10
10
20
ELEVATOR DOWN
°/SEC.
ELEVATOR UP
°/SEC.
0·5
-VE
1·0
ELEVATOR VELOCITY

GRAPH 12

WINGTIP
ACCELERATION

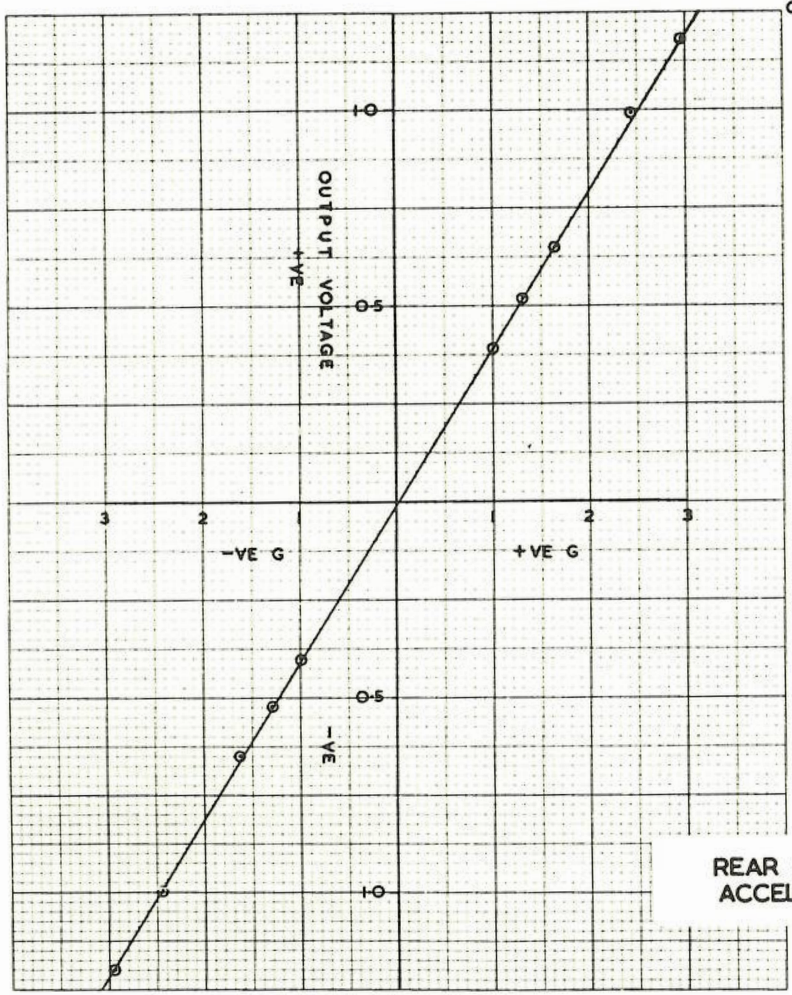


GRAPH 13

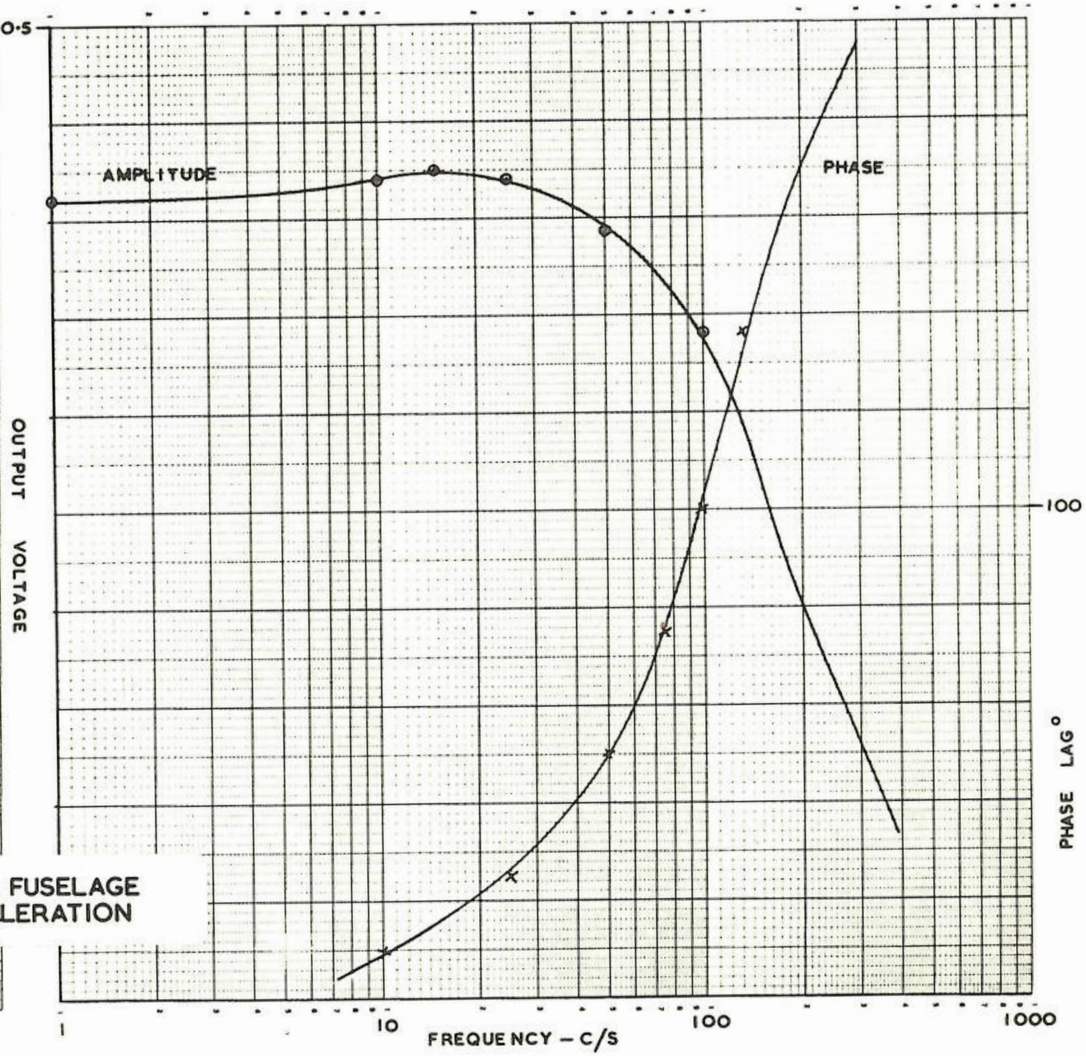


GRAPH 14

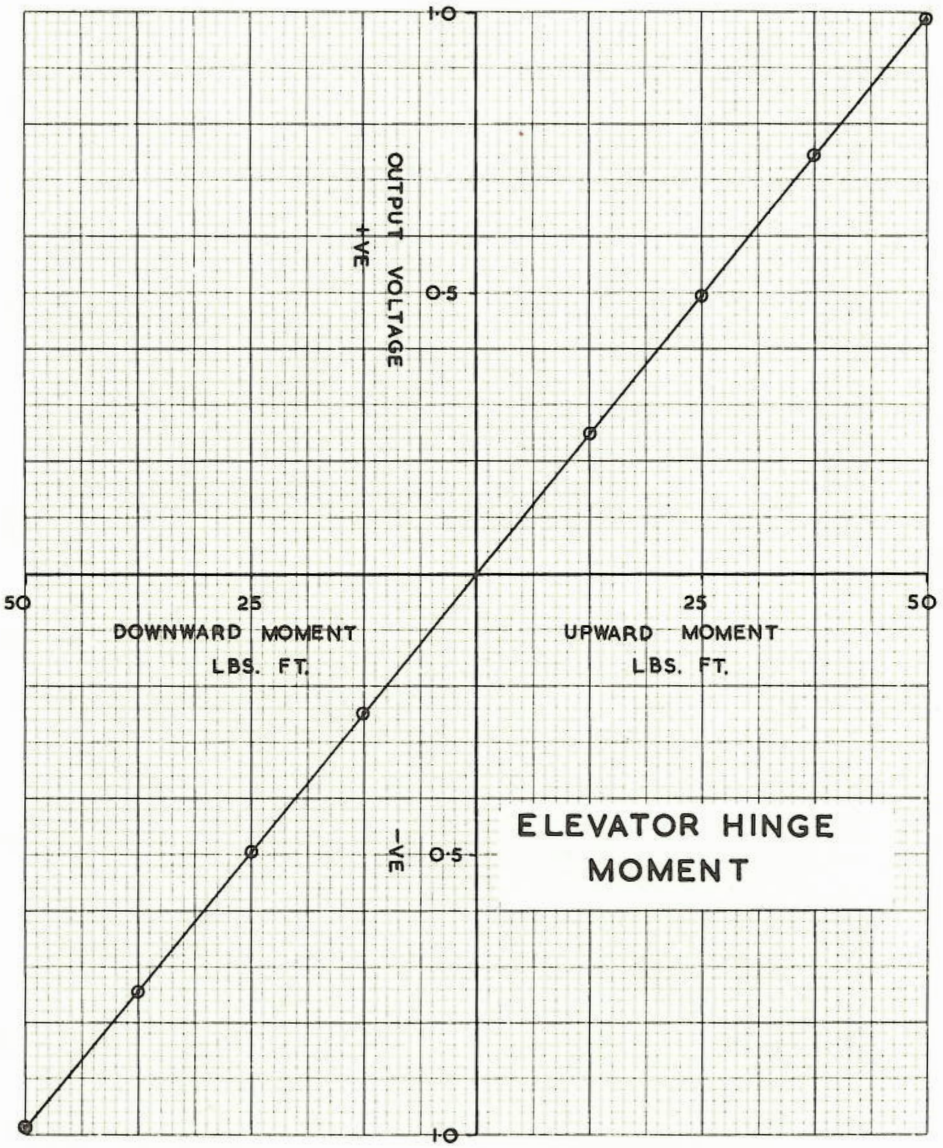
REAR FUSELAGE
ACCELERATION



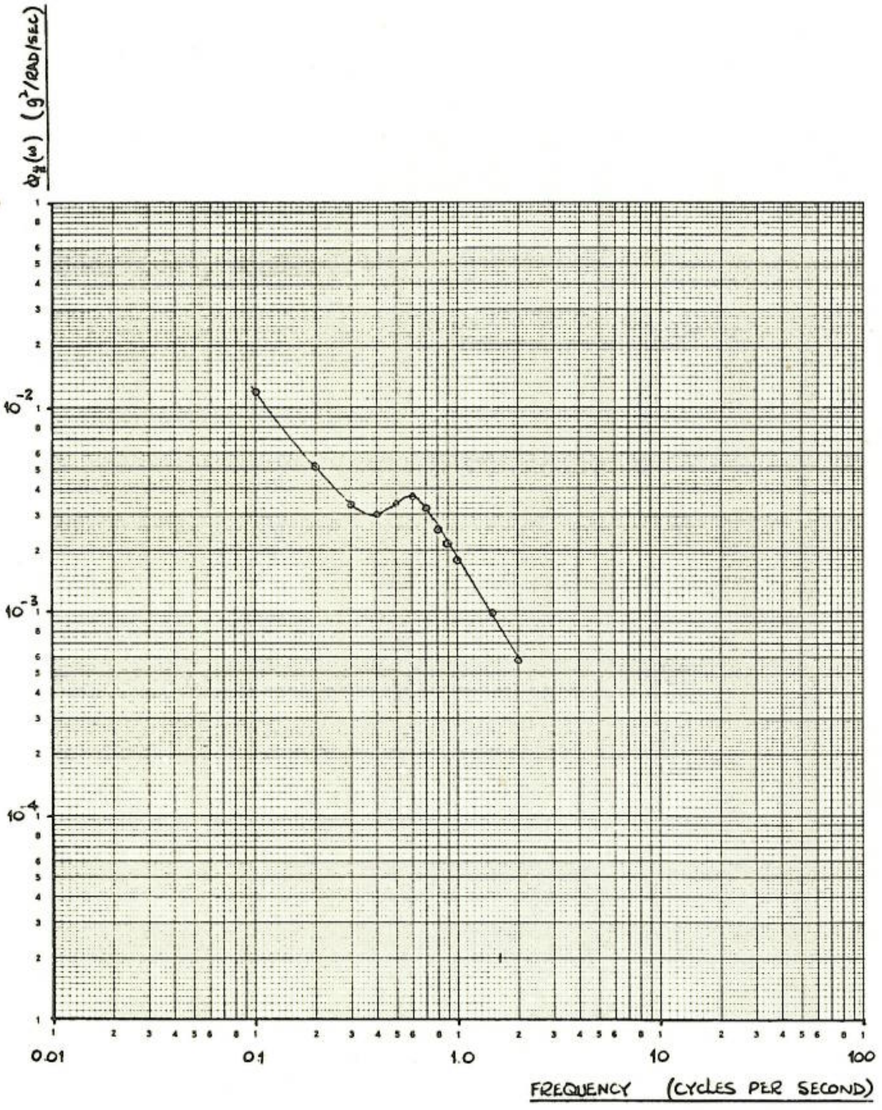
GRAPH 15



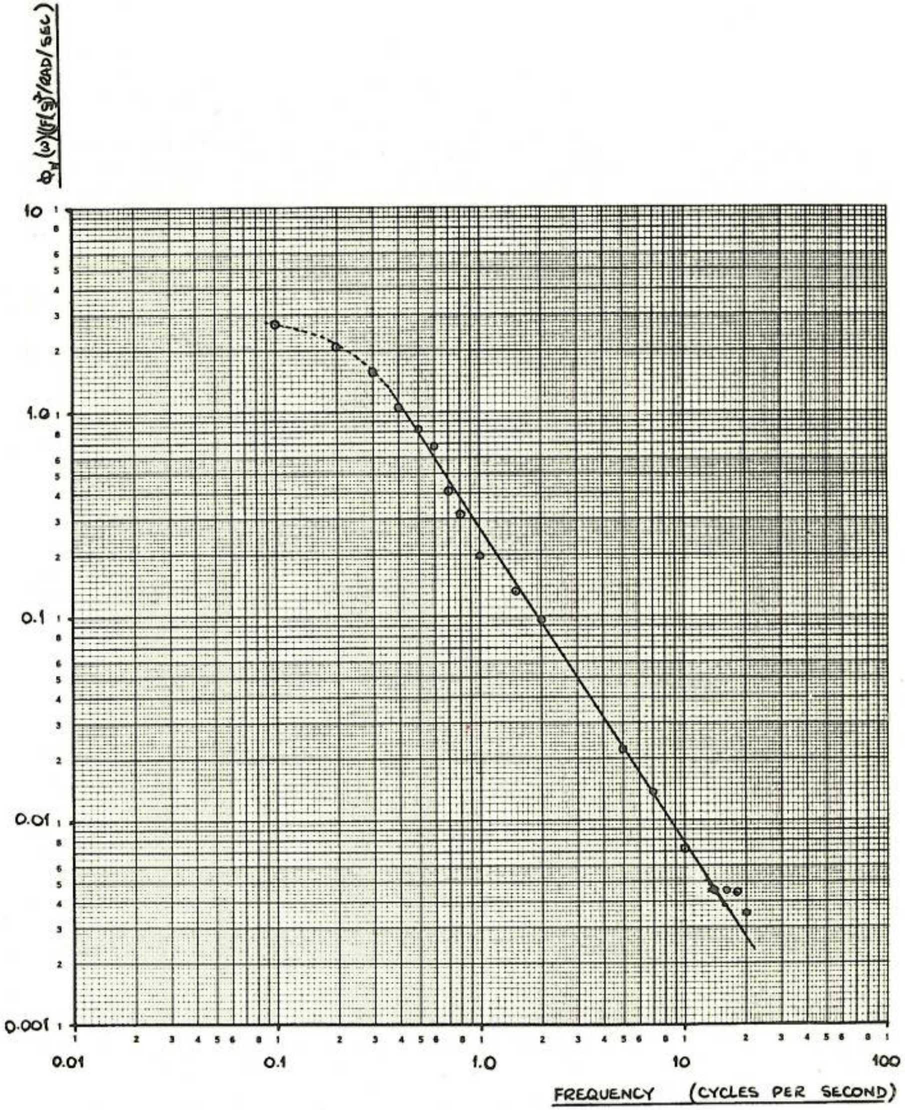
GRAPH 16


1·0
0·5
OUTPUT VOLTAGE
+VE
50
25
DOWNWARD MOMENT
LBS. FT.
25
50
UPWARD MOMENT
LBS. FT.
-VE
0·5
ELEVATOR HINGE
MOMENT
1·0

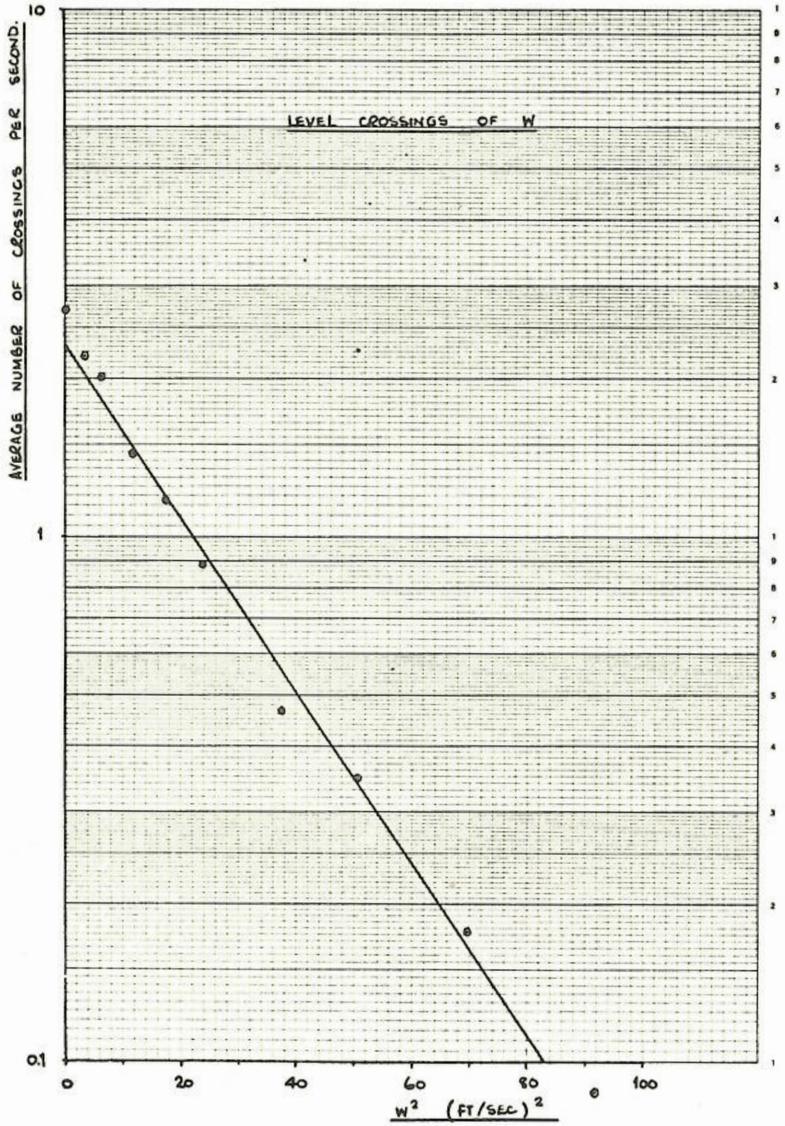
GRAPH 17



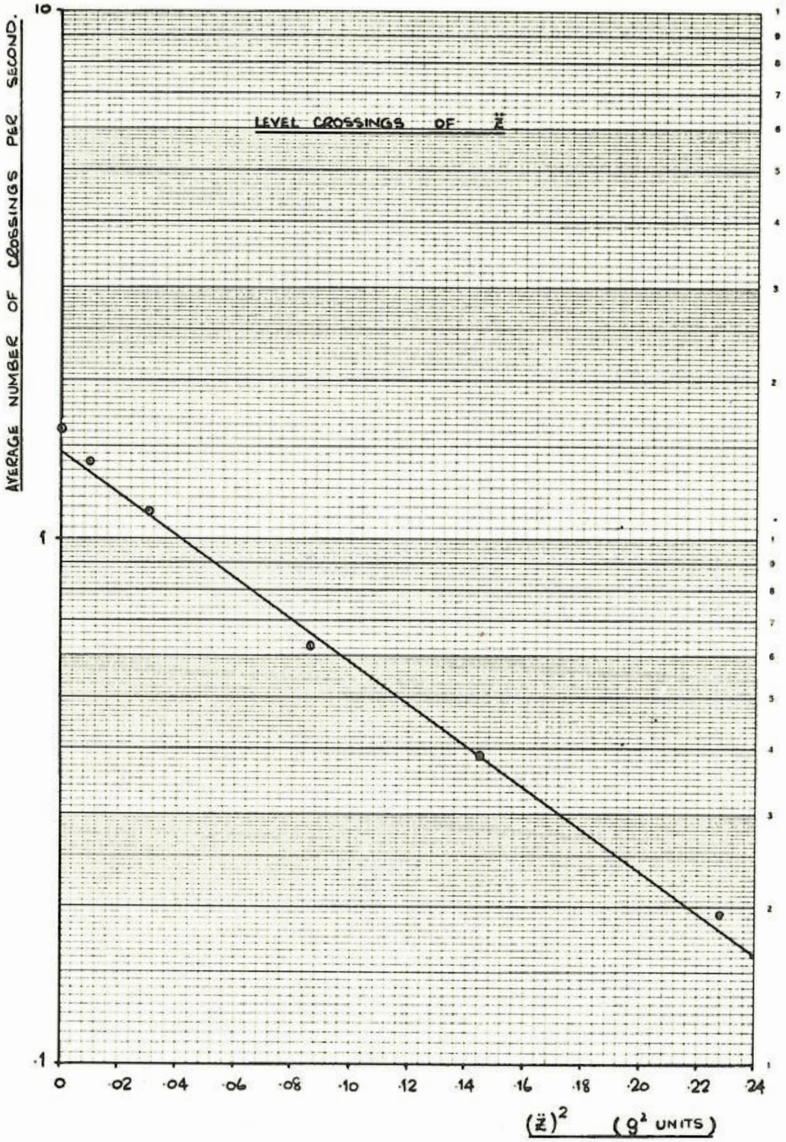
GRAPH 18



GRAPH 19



GRAPH 20



GRAPH 21