C.P. No. 48
12796
A.R.C. Technical Report

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Data on Flight Loads obtained with Miller Recording Equipment, with particular reference to Test Flights in Lancaster PD.119

By

Anne Burns, B.A.

LONDON: HIS MAJESTY'S STATIONERY OFFICE
1951
Price 6s. 0d. net.

C.P. No.48

Report No. Structures 50

September, 1949

ROYAL AIRCRAFT ESTABLISHMENT

Data on Flight Loads obtained with Miller Recording Equipment, with Particular Reference to Test Flights in Lancaster PD.119

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SUMMARY

A technique is presented for using Miller recording equipment to obtain statistical data on flight loads. The technique includes modifying the equipment and taking sample records of the flight loads.

Considerable labour is required to extract statistical data from the records, and Miller recording equipment should only be used until more suitable equipment has been developed.

LIST OF CONTENTS

LIST OF APPENDICES

LIST OF ILLUSTRATIONS

1 Introduction

In 1946 the Mechanics Committee A.R.C. noted the scarcity of flight load statistics and recommended the immediate collection of statistical data[1,2]. Until more suitable equipment should become available a multi-channel recording oscillograph was to be used, the equipment to be operated by a trained observer over standard airline routes.

In 1947 some trial flights were made in a Lancaster. The purpose of the flights was to develop a technique of measurement using Miller multi-channel oscillograph recording equipment.

An account of these test flights and of the technique developed is given in this report. The technique includes modifications to the equipment, and methods of calibration and sampling for use in flight. The analysis of the records is also discussed.

2 Equipment and installation

A brief account of the Miller recording equipment and of the accelerometer and strain gauge pick-ups is given in Appendix I; further details are to be found in a paper by Bennett, Richards and Voss[3]. In order to carry out the present work it was necessary to make a number of modifications to the equipment both before and during the flight tests. The purpose of these modifications was to render equipment normally used to measure accelerations up to ± 12g over short periods of time suitable for measurement of small strains and accelerations (normally less than ± 1g) over a long period of time. A list of the modifications is given in Appendix I.

Notes on the installation of the Miller equipment and of the accelerometer and strain gauge pick-ups are also given in Appendix I. Particular care was taken to waterproof the strain gauges in order to reduce drift as much as possible, but because of the long periods of time over which strains were recorded, drift produced appreciable errors.

3 Description of flight tests

Eighteen flight tests were made. Most of them were made to test the modifications to the equipment and, owing to a long period of unserviceability of the aircraft, only a short time was available for the development of a suitable technique. The details are given in Appendix II, a summary of which is given below.

The first six flight tests were concerned with the elimination of faults due to the use of a much slower speed for the recording paper than the standard, ($\frac{1}{4}$ inch/second instead of 5 inch/second), and with the adaptation of Statham type accelerometers for use with Miller recording equipment. The seventh flight was of long duration ($3\frac{1}{2}$ hours) and the records showed considerable drift in the mean values of the accelerations and strains. The eighth to fifteenth flights were concerned with the testing of further modifications made to the Statham accelerometers and with the use of a faster speed (1 inch/second) for the recording paper. Analysis of the records obtained in these flights showed an unsatisfactory amount of drift and variation in sensitivity. It was at this stage that the aircraft became unserviceable for three months and only three more flight tests could be fitted in. Of these the sixteenth flight was short and made to test the functioning of the equipment after the long period of unserviceability, and the last two flights were a $3\frac{1}{2}$ hours flight to study the calibration of the strain gauges and a $6\frac{1}{2}$ hour cross-country flight to make a final check on the complete unit. The drift and variation of sensitivity still remained appreciable and special measures for determining the sensitivity in flight and correcting for drift in the analysis are described in Appendices III and V.

4 Technique of recording flight loads

4.1 Calibration of pick-ups and recording equipment

The Lancaster test flights showed that reliable results could not be obtained if laboratory calibrations made prior to the test flights were used to interpret the measurements made in flight. For this reason methods of calibrating both equipment and pick-ups in flight were devised. A detailed description of the methods is given in Appendix III.

4.2 Limitation on the frequency of loads to be measured

Williams[1] has divided repeated loads into three types:-

(i) Very large loads of the order of half the ultimate load produced by exceptionally rough air conditions.

(ii) Smaller loads that are constantly but intermittently met under slightly bumpy air conditions.

(iii) Still smaller loads produced by resonance of the structure under the forcing frequencies of engine or airscrew.

In the trial tests on the Lancaster attention was focussed on the development of a technique for measuring loads of the second type. The accelerations associated with the third type although large produce little load in the main wing structure because of their high frequency. These accelerations were eliminated from the records since they would have obscured them. The absence of any measurable high frequency variation in the records of strain in the main spars confirms the smallness of the loads in the main wing structure associated with the high frequency accelerations. Electrical damping was used to cut out the high frequency accelerations. The amount of damping finally selected gave 95% of full response at 10 c.p.s. Above this frequency the response fell off rapidly, about 33% of full response being obtained at 30 c.p.s.

4.3 Technique of sampling

In recording accelerations and strains in a series of flights designed to provide statistical data on flight loads, it is necessary, if the recording is not to be continuous, to decide at what times during the flight records are to be taken. The early trials on the Lancaster showed that the speed of the recording paper could not be sufficiently reduced to make continuous recording a practical proposition, (except for a very small number of flying hours). For this reason it was necessary to resort to a sampling procedure. Such a procedure has the disadvantage of introducing a greater margin of error in estimating the frequency of occurrence of high loads which only occur infrequently. However, little accuracy is lost in estimating the lower and more frequently occurring loads and it is probable that, even if recording was not limited to samples, the records would still require sampling during analysis[4].

During the test flights it became clear that the variation in the magnitude of the repeated loads along the flight path tended to lie in the same range for considerable periods of time making it possible for the experienced observer to vary the frequency of sampling with the severity of the loads encountered. In this way a limited amount of recording paper could be used more efficiently, and statistical data on the frequency of occurrence of the higher loads could be obtained with a smaller margin of error than if the frequency of sampling were kept constant.

Suggested frequencies of sampling and a list of the observations to be logged at the time of sampling are given in Appendix IV.

5 Analysis of the records

Miller records of acceleration and strain in flight contain a great deal of information, but not in a statistical form, and considerable labour is involved in extracting such information from the records. The statistical data contained in the records can be classified under two headings:-

(i) Data particular to the aircraft in which the measurements are taken showing the effect of flexibility on the distribution of the loads induced in the structure: (this does not include the effect of flexibility on the external air loads and hence on the induced internal loads).

(ii) Data of a more general application on the magnitude and frequency of the gusts and other loads encountered.

Of these, (ii) are probably the more important and form the usual objective of measuring loads encountered in flight[5,6,7]. Information under heading (i) can be obtained directly from the strains and accelerations measured at various stations on the aircraft (see Fig.7), but that under heading (ii) must be derived from the measured response of the aircraft. Methods of determining the acceleration of the centre of gravity of the aircraft for the purpose of estimating the magnitude of the equivalent gusts encountered by the aircraft are described in Appendix V.

Whether statistical information is required under headings (i) or (ii) it is necessary to make a count of strains and accelerations according to a scheme of classification. The form and scope of the count adopted for a particular series of flights depends on the type of data required and the effort available for analysing the records. If special equipment is built the form in which the count is made may be partly determined by the operations which it can conveniently be designed to perform. For the purpose of framing fatigue tests in the laboratory a useful form of count is that in which the peaks are counted in bands and classified according to the range between each peak and its adjacent troughs. In analysing a large number of records the labour involved in counting peaks and ranges is very great, and it may be found necessary to restrict the full count to a limited number of representative records, counting only peaks for the remaining records.

An account of the preliminary work necessary before making a count (e.g. the determination of the scale of deflection and position of the base line) and a detailed description of methods of counting, including a description of a 'grid analyser' designed to assist in analysing the records, are given in Appendices V and VI.

6 Conclusions

Flight tests in a Lancaster show that Miller equipment can be modified to record strains and accelerations from which statistical data on flight loads can be obtained. The use of Miller equipment involves special techniques for calibrating the equipment in flight, eliminating unwanted accelerations associated with engine vibrations, and limiting the amount of recording paper by a sampling procedure in which the frequency of sampling is adjusted to the degree of turbulence encountered.

From the records of strain and acceleration thus obtained statistical data on the magnitude and frequency of the applied gusts and manoeuvre loads and on the distribution of the internal loads can be extracted. A useful form in which to present the information is that of a count of peak accelerations or strains classified in bands and according to the associated range between each peak and its adjacent troughs. An analysis in this form involves considerable labour. A simpler method consists of counting peaks (or thresholds crossed) classified only according to magnitude. It is an advantage if this simple count can be correlated with the more complicated count since alone it does not provide all the information necessary for framing fatigue tests in the laboratory.

The use of Miller equipment to obtain statistical information on flight loads is to be regarded as an interim measure until more suitable equipment has been developed.

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APPENDIX I

Modification and Installation of Equipment

Description of equipment

(i) Miller recording equipment

For the benefit of readers unfamiliar with the Miller recording equipment the following brief description of the particular models used in the Lancaster tests is given:-

The equipment consists of two power packs, two six-channel amplifiers, Type C2, and one twelve-channel oscillograph, model H. The power packs provide the various low and high tension supplies required for the amplifiers, and also a closely regulated 10 volt 1000 c.p.s. supply for the pick-ups. The amplifiers contain pairs of bridge arms which with the pick-up arms form a complete A.C. bridge. Means for initially balancing the bridge and injecting a calibration signal (termed 'blipping') are provided. In the amplifiers the out-of-balance signals from the bridges are amplified, demodulated, filtered and again amplified. They are then fed into the Miller twelve-channel electromagnetic recorder. This recorder contains twelve D'Arsonval galvonometers each of which deflects a spot of light across a six inch wide photographic recording paper, the deflection being sensibly linear over a distance of ± 1½" for each of the 100 c.p.s. galvonometers used. When records are being taken the recording paper is driven at a fixed speed which can be varied in four steps from 5 to 20 inch/second. The recording paper is marked with a time scale by means of a slotted disc revolving in front of a lamp, the speed of the disc being determined by a synchronous motor controlled by a vibrating reed. A numbering device prints the number of the record at foot intervals. The amount of recording paper used is shown on a footage indicator, the maximum capacity of the spools being 200 feet. A means of visually observing the position of the twelve spots of light on the paper is provided. Both power packs and recorder are run off a 12 volt D.C. supply.

(ii) Acceleration pick-ups

Statham accelerometer. This is a resistance type accelerometer incorporating all four bridge arms in the accelerometer. It is designed to measure accelerations over the range ± 12g and has a natural frequency of 270 c.p.s.

Miller Accelerometer. This induction type accelerometer is designed for use with Miller recording equipment and contains only two bridge arms. It measures accelerations over a range of ± 12g and has a natural frequency of 180 c.p.s.

Modifications to equipment

Various modifications were necessary to adapt the standard Miller recording equipment described above for recording loads in flight. Some of these modifications were carried out before the flight tests and some during the course of the tests. Only brief mention will be made of modifications which have no bearing on the equipment in its final state.

Modifications prior to commencement of flight tests

(i) Addition of damping circuits

Provision was made for introducing between the signal and earth condensers of capacity varying from 0.001 μF to 0.1 μF in discrete steps. This damping was introduced before the final amplification stage and necessitated the use of ancillary gear which was arranged to plug into the amplifiers.

(ii) Slowing down of recording paper

A slower paper speed of $\frac{1}{4}$ inch/second was provided on the twelve-channel recorder. This was additional to the four standard speeds already available.

(iii) Modification to amplifiers to cut out the two bridge arms

This modification was necessary since the Statham accelerometers contained a complete bridge of four arms so that the two arms normally provided by the amplifier to complete the bridge were not required. Elimination of these two arms had the effect of also eliminating the calibrating device included in the amplifiers, and other means had to be provided whereby an electrical signal of known voltage could be injected into the recording equipment for calibration purposes. The whole of this modification was dropped later in favour of modification (vii) owing to various snags inherent in the arrangement.

Further modifications during flight tests

(iv) Alternative lamp brilliancies for $\frac{1}{4}$ inch/second paper speed

It was found necessary to alter the relative brilliancies of the galvonometer lamp and time marker lamp to obtain better definition of recording at slow speeds. A switch was provided for making this change.

(v) Change of slowest speed of recording

The additional slow speed was increased from $\frac{1}{4}$ inch/second to 1 inch/second for greater clarity of recording and to be able to distinguish frequencies up to 10 c.p.s.

(vi) Increase of intervals between time marks

The number of time marks was decreased from 100 a second to 5 a second to avoid obscuring the record. For this purpose a new disc was made with a single slot instead of 20 slots.

(vii) Modification to Statham accelerometers to cut out two arms

The original modification to the amplifiers to cut out two arms necessitated cutting out the potentiometer for initially balancing the bridge. The lack of zero adjustment was found to be extremely inconvenient and instead of cutting out the amplifier arms it was decided to modify the Statham accelerometers to operate on two arms only. This modification had the disadvantage of halving the sensitivity of the Statham accelerometers but despite this they still proved sufficiently sensitive.

Introduction of a 1000 c.p.s. galvonometer to give a datum line

It was found that the width of the recording paper varied and it was not sufficiently accurate to measure deflection of the traces from the edge of the paper. One of the twelve-channels was therefore used to give a datum line, a 1000 c.p.s. galvonometer being fitting for this purpose. (The 1000 c.p.s. galvonometer was less liable to small spurious effects due to acceleration than the 100 c.p.s. galvonometers used to measure accelerations and strains.)

Change in source of high tension supply for time marker

The high tension batteries originally fitted to provide a 240 volt D.C. supply for the time marker did not maintain this voltage satisfactorily and were replaced by a small power pack running off the same 12 volt accumulator as the twelve-channel recorder.

Substitution of Miller for Statham accelerometers

It was decided for purposes of comparison to fit Miller induction type accelerometers instead of Statham accelerometers at four stations. This change was made about half way through the test flights, but comparisons between the behaviour of the two types in flight were inconclusive. It was finally decided to use Statham accelerometers since laboratory tests showed that they possessed better characteristics when subjected to varying temperatures.

Pick-ups and Miller equipment finally selected

As has been described above various modifications and alterations were made before and during the course of the flight tests. Of the arrangements tried the following were the most promising:-

Accelerometers. Statham accelerometers modified to operate on two arms only.

Strain gauges. British Thermostat resistance strain gauges, 200 ohms and 1000 ohms, (this was the only make of resistance strain gauge tested on these flights).

Recording equipment. Standard Miller equipment consisting of 2 power packs, 2 six-channel amplifiers - Model C2, 1 twelve-channel recorder - Model H, with the following modifications:-

(1) Additional damping 0.01 μF before the final amplification stage.

(2) Additional film speed of 1 inch/second.

(3) Frequency of time marks reduced to 5 per second.

(4) Fitting of 1 1000 c.p.s. galvonometer in twelve-channel recorder - the other galvonometers to be 100 c.p.s.

(5) High tension supply for time marker from additional power pack running off a 12 volt accumulator. (The accumulator supplying the recorder can be used for this purpose.)

Power Supply. At least six 12 volt 40 amp hour accumulators are required for a six hour flight. An arrangement for charging spare accumulators during flight would be an advantage.

Installation of equipment

The installation of the equipment on the Lancaster was carried out as follows:-

Accelerometers. Statham resistance type accelerometers were fitted at eight stations:- three spaced along the port wing front spar, one on the port inner engine, one on the port outer engine, and three along the fuselage at the nose, front spar, and tail. The positions are shown in Fig.1. All accelerometers were attached by brackets or clamps to the most rigid part of the aircraft structure available. The accelerometers were connected to the recording equipment by four-cored metal-sheathed rubber-covered cables (supplied by the Miller Corporation). Connections to the accelerometer leads were made by terminal blocks.

Strain gauges. Strain measurements were taken at four positions along the wing spars: just outboard of the port inner engine on the front spar top boom, on the front and rear spar top boom in the fuselage and just outboard of the starboard inner engine on the front spar top boom, (see Fig.1). The gauges used were British Thermostat wire resistance gauges of resistance 200 ohms. The main gauge was attached to the flat of the T-boom so that it measured the longitudinal boom stress, and a matched dummy gauge (for temperature compensation) was attached at right angles to the main gauge. A spare gauge and dummy were similarly attached at every station as a precaution against failure of the first pair. The resistance of the spare gauges was 1000 ohms (British Thermostat). The gauges were stuck to the cleaned metal surfaces with Durofix and left to dry for 24 hours. After this period they were artificially dried out by maintaining a current of 60 milliamps through the gauge windings, the heat generated serving to dry out the fixative and any moisture present. Drying was continued until the leakage resistance to earth had been increased to a satisfactory level, (of the order of 50 megohms for a 100 volt potential between the gauge winding and earth). The gauges were then immediately waterproofed by painting with melted Dijell and covered with oiled silk. A final covering of polythene tape was added to prevent the Dijell being rubbed off. The gauges were connected to the recording equipment by means of four-cored metal-sheathed cables (quadramet 4): small lengths of duratube wire were used for the connections between the quadramet and the gauges, and all joins soldered, insulated and waterproofed with Dijell.

Miller recording equipment. This recording equipment was mounted in wooden trays attached to the navigator's table. A 2 inch thick rubber sheet was placed between the recorder and its tray as an anti-vibration mounting, and all the equipment was held down by elastic cords. The arrangement was such that the instrument dials on the power packs and amplifiers could be easily seen by the seated observer.

APPENDIX II

Diary of Test Flights and Progress

No. of test flight	Date	Purpose of flight	Faults detected	Modifications	Ground Tests	Remarks
1	4.6.47	General functioning of apparatus.	(a) Identification of channels not clear. (b) Absence of zero adjustment for Statham accelerometers unsatisfactory. (c) Paper fogged at slowest speed ($\frac{1}{4}$ inch/second). (d) Channels 8 and 11 not operating. (e) Readings of strain gauge 10 and accelerometer 3 inverted. (f) Severe high frequency vibration occurring in records of accelerometer 7. (g) Time mark obscure.	Manufacture of ancillary apparatus to overcome (a) and (b) started. Position of accelerometer 7 changes to obtain greater rigidity of mounting.	Laboratory tests put in hand to determine causes of (c) and (g).	Faults (d) and (e) traced to wiring of filter box. Idea of having continuous zero adjustment for accelerometers abandoned (11.6.47).
2	9.6.47	"	(a) No identification numbers on records. (b) High frequency vibration on channel 8. (c) Identification and calibration of accelerometer channels still unsatisfactory.		Alignment test made on recorder - results satisfactory (16.6.47).	A sheet of paper fixed to the time marker disc to cut out a number of the slots improved the clarity of the time marks.
3	17.6.47	"	(a) Power pack failure just before flight.	Switch provided to change relative power of recording and timing lamps.	Channel sensitivities adjusted to give more equal amplification. (16.6.47).	Trouble in power pack thought to be caused by over-heating.

No. of test flight	Date	Purpose of flight	Faults detected	Modifications	Ground Tests	Remarks
4	20.6.47	Determination of amount of electrical damping required. Investigation into the amount of vibration excited at different speeds.	(a) Failure of accumulators. (b) Damping appears to be inconsistent. (c) Microphony test shows small spurious signals on some channels.		Check of resistance to earth of strain gauges. All resistances greater than 20 megohms.	
5	24.6.47	"	(a) Failure of power pack during flight. (b) Drift in accelerometer mean levels.	Manufacture of extra gear wheels to give paper speed of 1 inch/second put in hand.		An attempt to use heavy damping to give smooth level flight readings to be used as a datum for the strain gauge readings was unsuccessful.
6	26.6.47	Study of strain gauge levels on the ground and in the air.	(a) Flight abandoned owing to jamming of recording paper.	A 1000 c.p.s. galvonometer fitted on channel 7 to give datum line.		
7	26.6.47	$3\frac{1}{2}$ hour flight to study drift in mean levels during flight.	(a) Failure of channels 7 and 11. (b) Perforation causing jamming of recording paper. (c) Drift observed on some accelerometer channels - especially between take-off and first level flight reading.	Galvonometer zero adjustments locked with Durofix.		Drift thought to be due to shift of galvonometer zero.

APPENDIX II (Contd.)

No. of test flight	Date	Purpose of flight	Faults detected	Modifications	Ground Tests	Remarks
8	27.6.47	General functioning of apparatus.	(a) Failure of power pack.	4 Statham accelerometers replaced by 4 Miller accelerometers. Position of accelerometer 2 moved nearer that of fundamental node on front spar. Statham accelerometers modified to read on two arms only.		Loss of one amplifier and power pack owing to low priority of work (3.7.47). Work continues on 6 channels only.
9	15.7.47	General functioning of apparatus.	(a) Adjustments in sensitivity required.	New timing mark disc fitted with one slot instead of twenty New gear wheels fitted to give paper speed of 1 inch/second.		
10	15.7.47	Measurements in severe turbulence.				Large cumulus cloud available but pilot did not consider it safe to make deep penetrations.
11	16.7.47	Trials of new paper speed (1 inch/second).				

No. of test flight	Date	Purpose of flight	Faults detected	Modifications	Ground tests	Remarks
12	17.7.47	Determination of natural modes of vibration.				
13	18.7.47	Developments of methods of calibration in heavy pull-outs and under negative 'g'.	(a) Irregularity of time marks. (b) Drift in accelerometer levels. (c) Amplifier trouble on channels 1 and 3.			Attempts were made to bounce the aircraft heavily on the runway in order to determine modes of vibration.
14	28.7.47	Investigation into the variation of levels with air speed.	(a) Trouble with fixing of apparatus at negative 'g'.			
15	29.7.47	"		One 40 cycle galvonometer fitted for trial. New power pack for time-marker installed.	Gauge resistance to earth satisfactory (30.7.47). Irregularity of time marks and lack of numbering found to be due to faulty power supply for time-marker. Temperature tests on Miller and Statham accelerometers showed better results for Statham accelerometers. Attempt made to estimate effect of filling fuel tanks on strain in main spars.	40 cycle galvonometer unsatisfactory owing to vibration trouble. In order to have as many channels as possible working for test flights, a new amplifier and three more galvonometers fitted (one a new type galvonometer made in U.K.). Two channels still incomplete.

APPENDIX II (Contd.)

No. of test flight	Date	Purpose of flight	Faults detected	Modifications	Ground Tests	Remarks
16	28.10.47	Preliminary flight to determine sensitivity settings on new amplifier.	(a) High frequency vibration on two channels of new amplifier. (b) U.K. galvonometer reading inverted.			
17	29.10.47	$3\frac{1}{2}$ hours continuous landings and take-offs for study of strain gauge calibration levels.				
18	30.10.47	$6\frac{1}{2}$ hours cross-country flight to try out methods of sampling, calibration etc.				This flight was intended as a dress rehearsal for the final project.

APPENDIX III

Calibration of pick-ups and recording equipment

A number of detailed calibration tests are made in the laboratory prior to flight tests to check the linearity and frequency response of pick-ups and recording equipment. Calibration figures obtained in laboratory tests, however, cannot be relied upon to remain constant during a series of flight tests and it is desirable to have some means of making a spot check of the sensitivities without a detailed exploration. Methods for making a simple check during flight are now described: the sensitivities of the pick-ups are in all cases considered in conjunction with those of the recording equipment and when methods of calibrating a pick-up are described the appropriate recording channel is included with the pick-up.

Calibration of accelerometers by inversion

The most direct way of checking the calibration of the accelerometers is by inversion, i.e. by applying in effect a decremental acceleration of 2g. Records are taken at a suitable sensitivity with the accelerometers the right-way-up and up-side-down. In the case of Miller accelerometers mounted on a heavy metal base or clamp, the base as well as the accelerometer must be inverted since the induction of the coils is affected by the surrounding metal, (errors up to 10% can be obtained if this precaution is omitted).

The method of inversion is generally only practicable in the case of the accelerometer in the mid fuselage. This or any other accessible accelerometer is termed the 'master accelerometer' and the sensitivities of other accelerometers are determined relative to that of the master accelerometer by comparing simultaneous records obtained during manoeuvres in which a reasonably equal acceleration is imposed on the whole aircraft.

Calibration of accelerometers by pull-outs

The best manoeuvre for calibrating accelerometers is a slow pull-out. It should be carried out in smooth air if possible. (Calibrations can be obtained from pull-outs made in rough air but the results cannot be analysed so accurately). The procedure is as follows:- the aircraft is put into a shallow dive and pulled out slowly until the required acceleration is recorded on a Kollsman or other visual accelerometer. The maximum acceleration is maintained for a second or two and then the aircraft is brought back slowly to the straight and level attitude and original cruising speed. The object of carrying out the manoeuvre slowly is to reduce the accelerations in pitch in order to obtain sensibly the same normal acceleration at every part of the aircraft. The following records are taken:- before the pull-out a record of the accelerometer signals during straight and level flight at fixed airspeed and engine settings, with blips in numerical order on each channel to check amplifier and recorder sensitivities and to identify the traces. A record is next taken of the complete pull-out followed by a check record during straight and level flight.

The records are analysed by plotting the readings for each accelerometer against the master accelerometer reading at the same instant of time: the result should be a straight line with very little scatter.

When it is not possible to perform pull-outs (e.g. in an airliner carrying passengers) a sustained turn can be substituted for the pull-out.

Calibrations made by the above methods are finally expressed in terms of deflection per unit acceleration, the scales of deflection appropriate to each flight being used in the analysis of the records obtained in that flight.

Calibration of strain gauges by pull-outs

The sensitivity of the strain gauges cannot be relied upon to remain constant and a check of sensitivity is strongly advisable each flight. There is no perfect calibration method for strain gauges but a method which has much to recommend it is that of calibrating in flight by means of a rapidly performed standardised pull-out. The aircraft is first flown straight and level at fixed airspeed and engine settings: it is then put into a shallow dive again at fixed airspeed and engine settings and when conditions are steady the control column is pulled hard back until 2g is read on the Kollsman or visual accelerometer. The control column is then pushed quickly forward again and the aircraft returned to straight and level flight at the original airspeed and engine settings. The manoeuvre should if possible be carried out in smooth air; if done in rough air the records will be more difficult to analyse and will give less reliable results. Records with blips on all channels in numerical order are taken during the straight and level flights and during the pull-out. The airspeed should be noted during the pull-out. The object of pulling-out as quickly as possible is to ensure that the extra air loading on the wing is applied before the airspeed has time to fall off. If it is allowed to fall off the distribution of air load on the wing will change and different strain gauge readings will be obtained at the same normal acceleration going in and coming out of the pull-out. An example of this effect is given in Fig.2, which shows a plot of calibration readings obtained in two slow pull-outs of about ten seconds duration. The differneces in slope are probably due to the pull-outs being made at different airspeeds and fuel loads, and the narrow loops are caused by the airspeed falling off during the pull-outs.

Calibration of strain gauges from difference in ground and flight readings

For strain gauges in the wing a calibration may be obtained from the difference in wing loading when the aircraft is stationary on the ground and flying straight and level. The chief drawback to this method is that a certain time is bound to elapse between the ground and flight readings during which the strain gauge signals may drift owing to heating and instability effects in the equipment. It is then impossible to distinguish between the change in signal due to increased wing loading and that due to drift. In calibrations made at the beginning of flight the error due to drift may be reduced by switching on the electrical equipment $\frac{1}{2}$ to 1 hour before flight in order to allow it to attain a steady temperature. The calibration procedure is then as follows:- records on the ground are taken first with the engines off and then with the engines ticking over at fixed r.p.m. and the aircraft facing into wind. The records should show blips on all strain gauge channels in numerical order and the spots from the strain gauges should be displaced to allow room for deflection when the aircraft becomes airborne. As soon as the aircraft is airborne and the air conditions are smooth a record is taken in straight and level flight at fixed airspeed and engine settings with blips on all strain gauge channels. If smooth air is not quickly obtainable a record is taken while the aircraft is still climbing at a fixed rate of climb and airspeed. Taking the record immediately the aircraft is airborne while still climbing reduces the time in which drift is occurring but may make the records harder to analyse owing to the turbulence often encountered at low altitudes.

Errors in the ground readings are introduced by static friction (this causes the wing to take up a position other than its equilibrium position) and by ground level winds. Nevertheless reasonably reliable results can be obtained, (see Fig.3 which shows repeated ground and flight readings taken over a period of 2 hours, the errors being within ± 6%). It may be necessary to allow for the effect of the consumption of fuel load in this method of calibration: for example, in the case of the Lancaster the arrangement of the fuel tanks in the wing is such that the difference between the wing root bending moment on the ground and in level flight is approximately 30% less with wing tanks empty than with wing tanks full.

The strain calibrations are used to determine scales of deflection for each flight to be used in analysing the records.

APPENDIX IV

Technique for taking sample records in flight

If the recorder is run continuously for a long series of flights, the amount of recording paper used will be difficult to handle and will require a very large number of man-hours to analyse, (with continuous recording at 1 inch/second, over $5\frac{1}{2}$ miles of film are used in 100 flying hours). For occasional flights continuous recording can be used but it is more economical in paper, and the amount of film to be developed and analysed is more easily handled, if a system of sampling in the air is adopted.

Recommended method of sampling

The observer takes sample records of fixed duration at regular intervals of time. The records are taken for the whole of the flight from the time of raising to that of lowering the undercarriage. A suitable duration for the sample is 24 seconds. At a film speed of 1 inch/second this gives a length of 24 inches, which is a convenient length for analysis. (24 inches is also the length of record at which the recorder shuts itself off automatically.) The frequency of sampling is varied according to the severity of the turbulence encountered. In smooth flying conditions (accelerations at the wing tip less than 0.1g) the samples are widely spaced working up to nearly continuous recording when rapid changes in the severity of the turbulence are encountered; for example, when flying in and out of cumulus cloud tops with smooth air in between. In most cases five rates of recording are sufficient, 1 sample every $\frac{1}{2}$ hour for smooth air, 1 every $\frac{1}{4}$ hour for very slight turbulence, 1 every 5 minutes for slight turbulence, 1 every $2\frac{1}{2}$ minutes for slight and moderate turbulence and 1 every minute for occasional large gusts or rapidly changing conditions. In deciding the frequencies of sampling consideration should be given to the man-hours available for analysing the records.

This method of sampling requires a reliable and experienced observer since he has to decide which frequency of sampling is appropriate for the weather conditions and when to reload the camera in order not to interfere with the sampling; he must also keep a careful log during the flight. The log should include for each record:-

(1) Time of recording

(2) Indicated airspeed

(3) Altitude

(4) Outside temperature

(5) Rate of climb or descent, rate of turn if any

(6) Type and amount of cloud

(7) Position of aircraft relative to cloud

(8) Observer's comments on turbulence

(9) Pilot's comments on turbulence

(10) Whether aircraft is flown manually or on auto-pilot

(11) Changes made to recording equipment, e.g. change of accumulators, readjustment of spots on screen, or change of sensitivity settings.

The all-up weight of the aircraft should also be noted for each flight and the fuel contents of the tanks at the beginning and end of, and occasionally during, the flight.

Alternative method of sampling

The observer takes records of 24 seconds duration every 2½ minutes of flight. At this frequency of sampling about 300 feet of recording paper is used in nine hours at a speed of 1 inch/second. When the observer is certain that the turbulence is too slight to record, that particular record can be omitted.

APPENDIX V

Analysis of the Records

PART I

Determination of the acceleration of the centre of gravity of the aircraft

Although Miller equipment, used in conjunction with accelerometer and strain gauge pick-ups, does not provide direct information on the magnitude and frequency of the gusts encountered, useful data on equivalent gusts can be derived from the measurements of acceleration obtained. In particular the velocity of an equivalent gust, based on the assumption of a standard gust gradient, can be derived from the normal acceleration of the centre of gravity of the aircraft - (by the centre of gravity is meant the mathematical centre of gravity and not the so-called position of the centre of gravity on the aircraft frame). The advantage of analysing the records in terms of equivalent gusts is that the information obtained has a direct application to other aircraft.

The normal acceleration of the aircraft centre of gravity is not measured directly since the accelerations measured at various stations in the aircraft contain not only components of the rigid body accelerations of the aircraft but also components of acceleration due to structural oscillations excited by the gust loading. The normal acceleration of the centre of gravity may be determined from the measurements at a particular station either by removing the oscillatory part of the acceleration by eye, or by combining traces in certain proportions to eliminate the oscillatory accelerations[8]. This procedure is not always satisfactory since the rate of build-up and die-down of the acceleration of the aircraft centre of gravity is often comparable with that of the oscillatory acceleration (especially that of the fundamental mode) making it difficult to separate the two. In such cases reference to other traces may help to determine how much of a particular acceleration is due to a natural oscillation of the structure. A more direct method is to install two accelerometers in series, one on each wing at nodal points of the troublesome mode, thence obtaining a trace free of oscillation in that mode (two accelerometers are necessary in order to eliminate roll). This method may not completely eliminate the mode at all times during the flight owing to movement of the mode with the consumable loads.

PART II

Methods of counting

Determination of scales and base lines. The records obtained for the measurement of loads in flight consist of a number of sample records of 24 seconds duration, (or whatever duration of sample has been chosen). Each sample record shows eleven traces, the deflections of which represent variation of strain or acceleration at particular stations in the aircraft. The records also provide a datum line from which to measure the deflection of the traces. To interpret the records in terms of acceleration and strain it is necessary to know the scale of deflection and the position of a base line representing a known acceleration or strain for each trace. The scale of deflection is determined by the procedure for calibration described in Appendix III. The position of the base line is determined as follows:-

On each sample record the position of the mean line through each trace is estimated and its distance from the datum line plotted against the time of recording. The position of the mean line can be obtained with the aid of the grid analyser described in Appendix VI, or determined by an integrating mechanism. A number of points denoting the position of the mean line on each sample record are obtained (see Figs. 4 and 5). The value of acceleration or strain represented by the mean line is usually very near the value of the acceleration or strain in steady flight at normal cruising speed. It may, however, differ slightly from this value owing to inaccuracies in its determination, or because the record was taken when the aircraft was accelerating in a slight turn or pull-out, or flying at a speed different from the normal cruising speed. Such differences cause irregularities in the variation of mean line position and these can be faired out to give an estimate of the base line position corresponding to straight and level flight at constant speed.

The variation during flight in the position of the base line for the acceleration traces is due to drift caused by imperfections in the equipment (e.g. inadequate temperature compensation, regulation of voltage supplied, effects of moisture, etc.). It may in future be possible to reduce this drift to negligible proportions but at the present time it is necessary to adopt a method of analysis which takes account of this effect. Drift also occurs in the strain gauge records but in this case the variation in the position of the mean line during flight is not solely caused by defects in the equipment, but is partly due to variation in strain caused by changes in disposable load. If the two effects are separated the drift due to defects in the equipment is still large enough to necessitate the determination of a base line position for individual records.

The value of acceleration in straight and level flight - i.e. 1g - is an obvious choice for the base line from which to measure the variation in acceleration. For the strain trace the choice of base line is not so straight forward since there are two possibilities, a base line representing a constant strain can be used, or one corresponding to a constant condition of flight - i.e straight and level flight at cruising speed. In some aircraft and for some positions of strain gauge the change in strain due to consumption of fuel is negligible so that the base line corresponding to the constant condition of flight does represent the same strain throughout the flight. In the other cases in which the two base lines are not identical a choice must be made. For methods of counting which include peaks and ranges either base line can be used, whereas for simpler methods of counting, involving only peaks or thresholds crossed, an uncorrected straight and level flight base line will probably have to be used.

Frequency restriction

In recording accelerations, electric means are used to partially cut out high frequency vibrations, and only accelerations of which the frequency lies below a certain value are recorded within the required degree of accuracy. Before analysing the records, the high frequency vibrations which remain in the records, should be faired out.

Amplitude restriction

In order to count the crossings of threshold values or occurrences of peaks it is necessary to decide how far the trace must fall back below a particular peak or threshold value in order that the next occurrence of that peak or threshold crossing can qualify for another count.

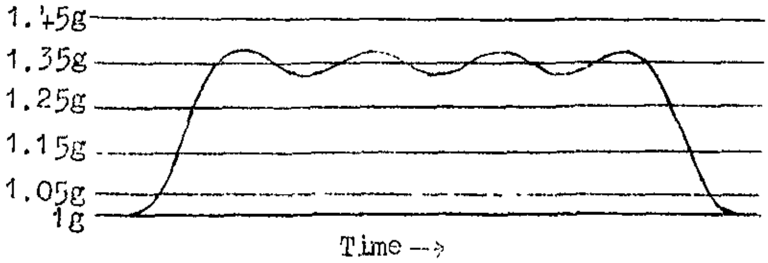


Diagram (a)

For example, counting the peaks of diagram (a) it is necessary to decide whether four peaks are to be counted in the 1.35g to 1.45g band or only one. For the purpose of setting up fatigue tests in the laboratory a count of one would give a better indication of the loads to be applied. A count of one in the case shown in diagram (b) would however be misleading. In this case it is apparent that the number of peaks counted in the 1.35g to 1.45g band depends largely on the variation in amplitude which the observer decides to neglect.

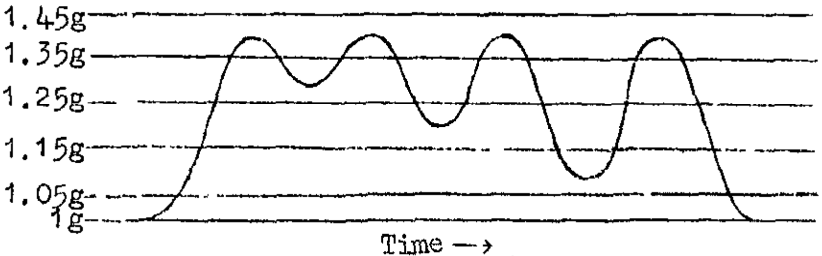


Diagram (b)

Two lines of approach are possible in deciding what variation to neglect. In one all variations which do not reduce the trace to an arbitrary value are neglected - for example, it is stipulated that the trace must return to the 1g level flight value in between each count, (this is the method advocated by Hooke[9]); alternatively the variation to be neglected can be fixed relative to the threshold crossed or magnitude of the peak; for example, it is stipulated that the trace must cross into an adjacent band between counts. If a method of counting is adopted which takes account of peaks and ranges of variation the variation in amplitude to be neglected is decided relative to the peak in the light of the degree of accuracy required, but for methods of counting which include no account of the range the variation neglected has a more radical significance.

Recommended method of counting

(a) Counting of maxima and minima and associated range

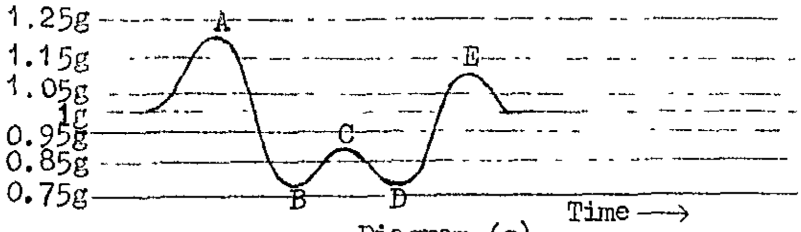


Diagram (c)

A count is made of each maximum and minimum and of the associated range, that is the gap between the maximum and minimum being counted and the following minimum or maximum. In diagram (c) the following maxima and minima and associated ranges are counted.

Maximum or minimum	Range
A	AB
B	BC
C	CD
D	DE

The maximum or minimum and its associated range are classified according to the acceleration band in which they occur and the magnitude of the range can be conveniently expressed in terms of the band width. The count can be made in a tabular form such as that shown in diagram (d).

Maximum or minimum acceleration or strain

		0.7g	0.8g	0.9g	1g	1.1g	1.2g	1.3g
Range of acceleration or strain	-0.4g							
	-0.3g							
	-0.2g							
	-0.1g							
	+0.1g							
	+0.2g							
	+0.3g							
	+0.4g							

Diagram (d)

A decision must be taken as to the minimum associated range to be counted.

Alternative methods of counting

(b) Counting of maxima and minima

All maxima and minima are counted and classified according to the band in which they occur unless the value between adjacent maxima and minima is less than a pre-determined minimum - or alternatively, unless the adjacent maximum or minimum occurs in the same band.

(c) Counting of peaks

Peaks (i.e. maxima and minima concave to the base line) are counted and classified according to the band in which they occur. The count obtained will depend on the variation between turning points deemed negligible. If peaks less than a certain magnitude are not counted there is a 'dead area' on either side of the base line.

(d) Counting of thresholds crossed

A count is made of the number of times the trace exceeds certain threshold values. The count obtained will depend on the 'fall-off' below the threshold value deemed necessary for a re-cross of the threshold to constitute another count.

APPENDIX VI

A Grid Analyser Designed to Assist in the Analysis of Records

The grid analyser shown in Fig.6 consists of a thin perspex plate with a slight inset on the underside in which is mounted an adjustable grid of nylon wires. The grid spacing can be adjusted to any required scale by revolving the arms to which the wires are attached. Two scales at either end of the grid provide a means of readily determining the spacing between wires.

The instrument is designed to assist in two operations:-

(1) in the determination of the position of a mean line through each trace,

(2) in the counting of peaks, thresholds crossed and amplitudes between peaks.

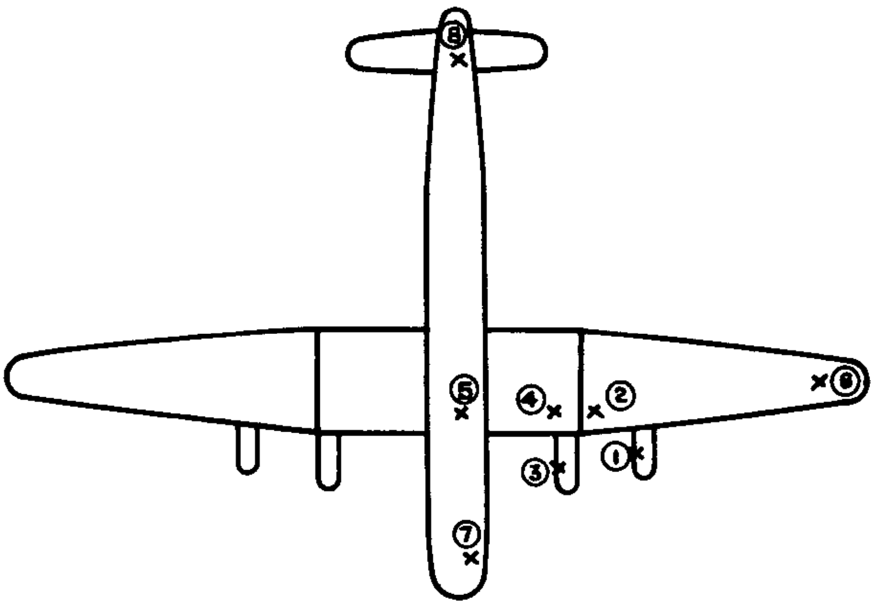
For the first operation only the central zero wire is required. The position of the grid analyser on the record is adjusted until the zero wire is judged to lie in a mean position across the trace; the distance of this mean position from the datum line is then read directly on the grid scale.

To count peaks and thresholds crossed the grid is adjusted so that the spacing between wires represents a suitable width of band and the grid is then positioned on the record with the zero wire lying in the corrected mean line position (see Appendix V). A count of peaks or thresholds crossed can then be readily made by looking along the bands, and the range between adjacent peaks estimated by counting the wires crossed.

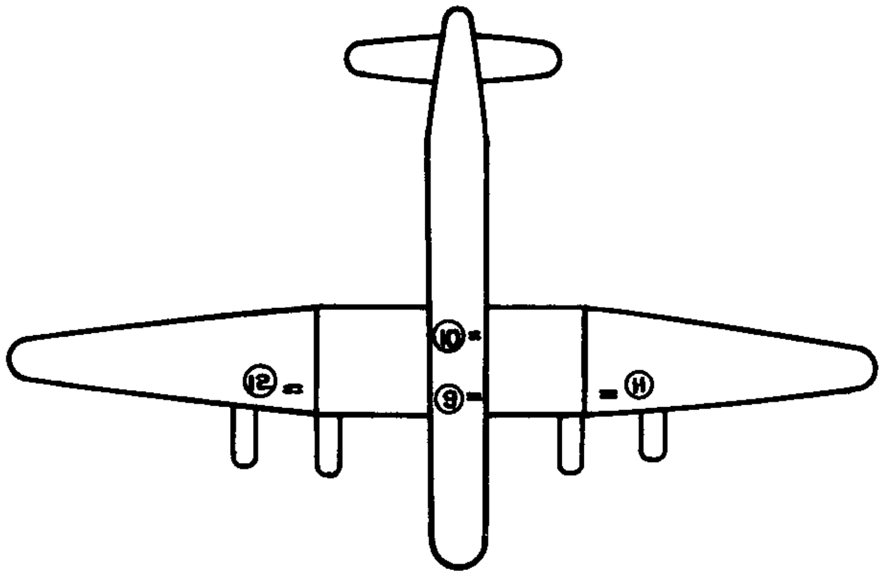
TABLE I

Sensitivity of accelerometers 1, 2, 3, 4 and 6 relative to 5 - determined from measurements taken in pull-outs

Accelerometer Number	Relative Sensitivity										
	15th July				18th July				29th July		
	First pull-out	Second pull-out	Third pull-out	Fourth pull-out	First pull-out	Second pull-out	Third pull-out	Fourth pull-out	First pull-out	Second pull-out	Third pull-out
1	0.79	0.81	0.82	0.82	0.83	0.85	0.83	0.86	-	1.02	-
2	0.89	0.91	0.91	0.90	1.03	1.01	0.97	0.97	1.19	1.08	-
3	0.83	0.85	0.84	0.83	0.88	0.84	0.85	0.85	1.06	1.09	1.07
4	1.23	1.25	1.25	1.25	1.35	1.30	1.29	1.29	1.62	1.56	1.66
6	0.93	0.96	0.96	0.96	1.05	1.04	1.01	1.01	-	-	-



(a) ACCELEROMETER POSITIONS



(b) STRAIN GAUGE POSITIONS.

ACCELEROMETER POSITIONS.

① OUTER PORT ENGINE FRONT INNER FOOT

② FRONT SPAR FRONT FACE BETWEEN INNER & OUTER PORT ENGINES.

③ INNER PORT ENGINE FRONT INNER FOOT.

④ FRONT SPAR AFT FACE AT INNER PORT UNDERCARRIAGE CASTING

⑤ FRONT SPAR AFT FACE BOTTOM BOOM AT FUSELAGE CENTRE LINE.

⑥ FRONT SPAR AFT FACE NEAR WING TIP 18" INBOARD FROM AILERON END RIB.

⑦ FORWARD FACE OF MAIN BULKHEAD BETWEEN BOMB AIMER'S & PILOTS POSITIONS.

⑧ HEAVY FRAME JUST FORWARD OF TAIL TURRET.

STRAIN GAUGE POSITIONS

⑨ FRONT SPAR TOP BOOM AFT FACE NEAR CENTRE LINE OF AIRCRAFT

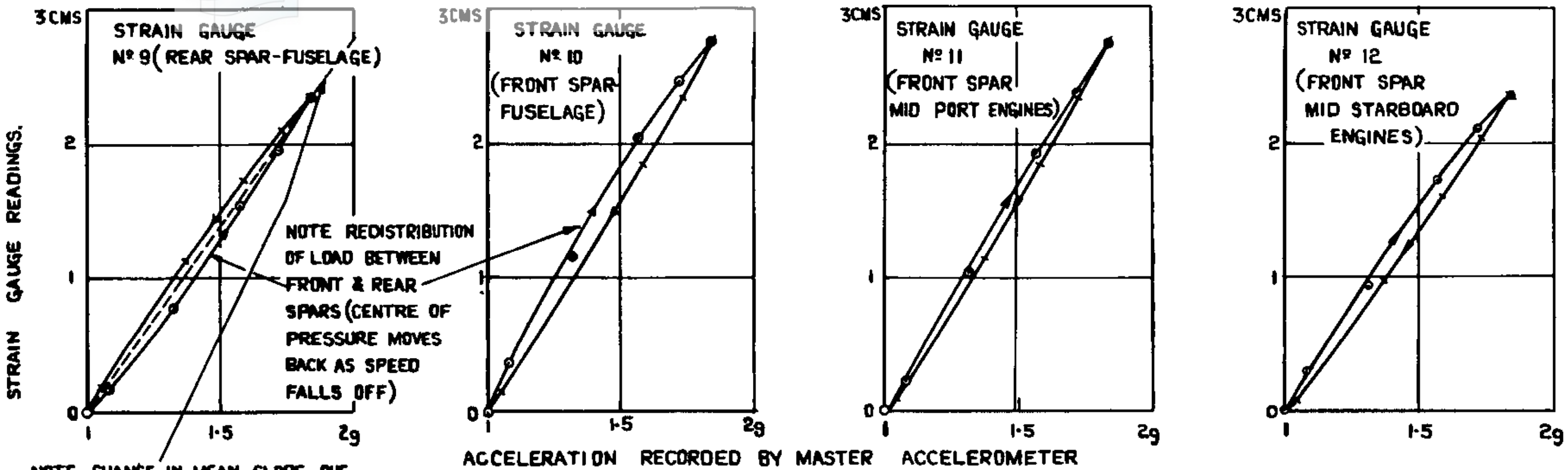
⑩ REAR SPAR LOWER BOOM FRONT FACE – 18" TO PORT OF CENTRELINE OF AIRCRAFT.

⑪ LOWER SPAR BOOM JUST OUTBOARD OF INNER ENGINE-PORT SIDE

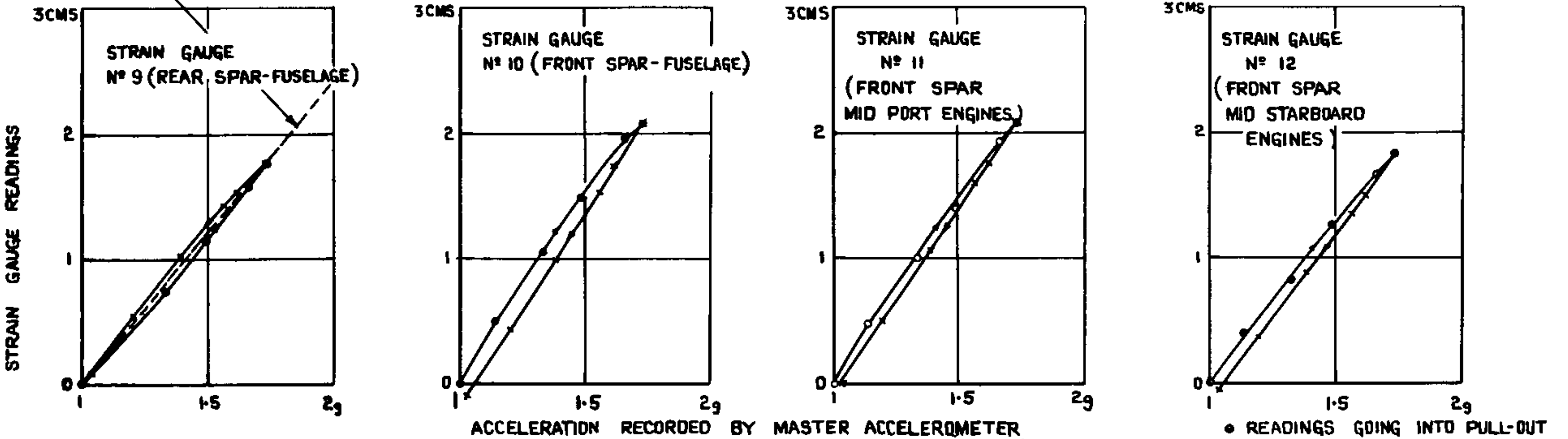
⑫ LOWER SPAR BOOM JUST OUTBOARD OF INNER ENGINE-STARBOARD SIDE.

FIG. I ACCELEROMETER & STRAIN GAUGE POSITIONS.

FIG. 2

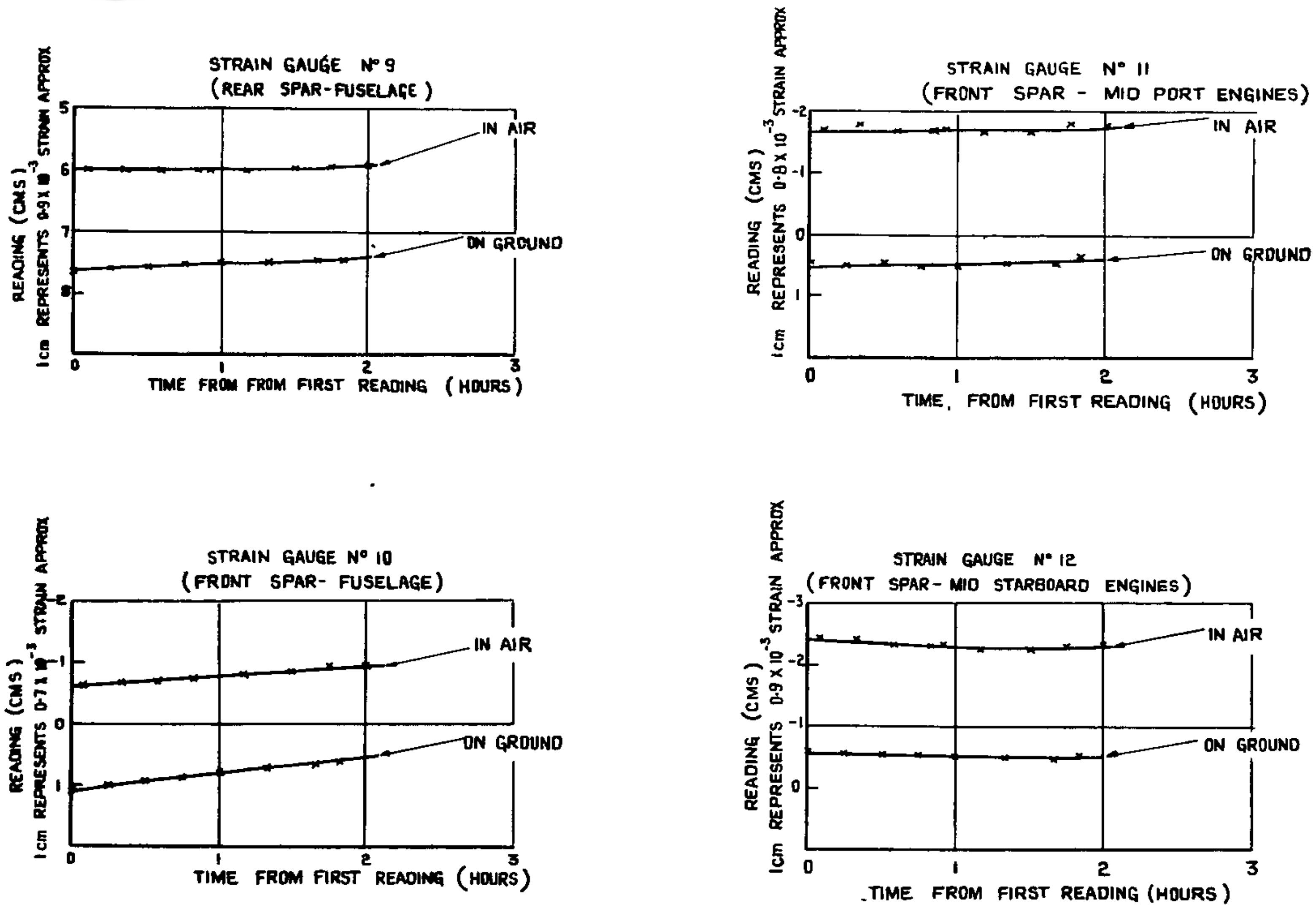


(a) PULL-OUT AT BEGINNING OF FLIGHT — WING TANKS FULL



(b) PULL-OUT AT END OF FLIGHT — WING TANKS ¼ FULL

FIG. 2 CALIBRATION CURVES FOR STRAIN GAUGES OBTAINED IN PULL-OUTS SHOWING LOOPS CAUSED BY LOSS OF SPEED & CHANGES IN SLOPE DUE TO FUEL CONSUMPTION



NOTE: THE DECREASE DURING FLIGHT OF CHANGE OF STRAIN AT FUSELAGE SPAR POSITIONS BETWEEN 'ON THE GROUND' AND 'IN AIR' IS PROBABLY DUE TO RELIEF OF FUEL LOAD

NOTE EQUIPMENT TURNED ON 50 MINS BEFORE 1ST READING

FIG. 3

FIG. 3 REPEATED GROUND AND LEVEL FLIGHT READINGS OBTAINED IN A TWO HOUR FLIGHT TO STUDY STRAIN GAUGE CALIBRATIONS.

FIG. 4

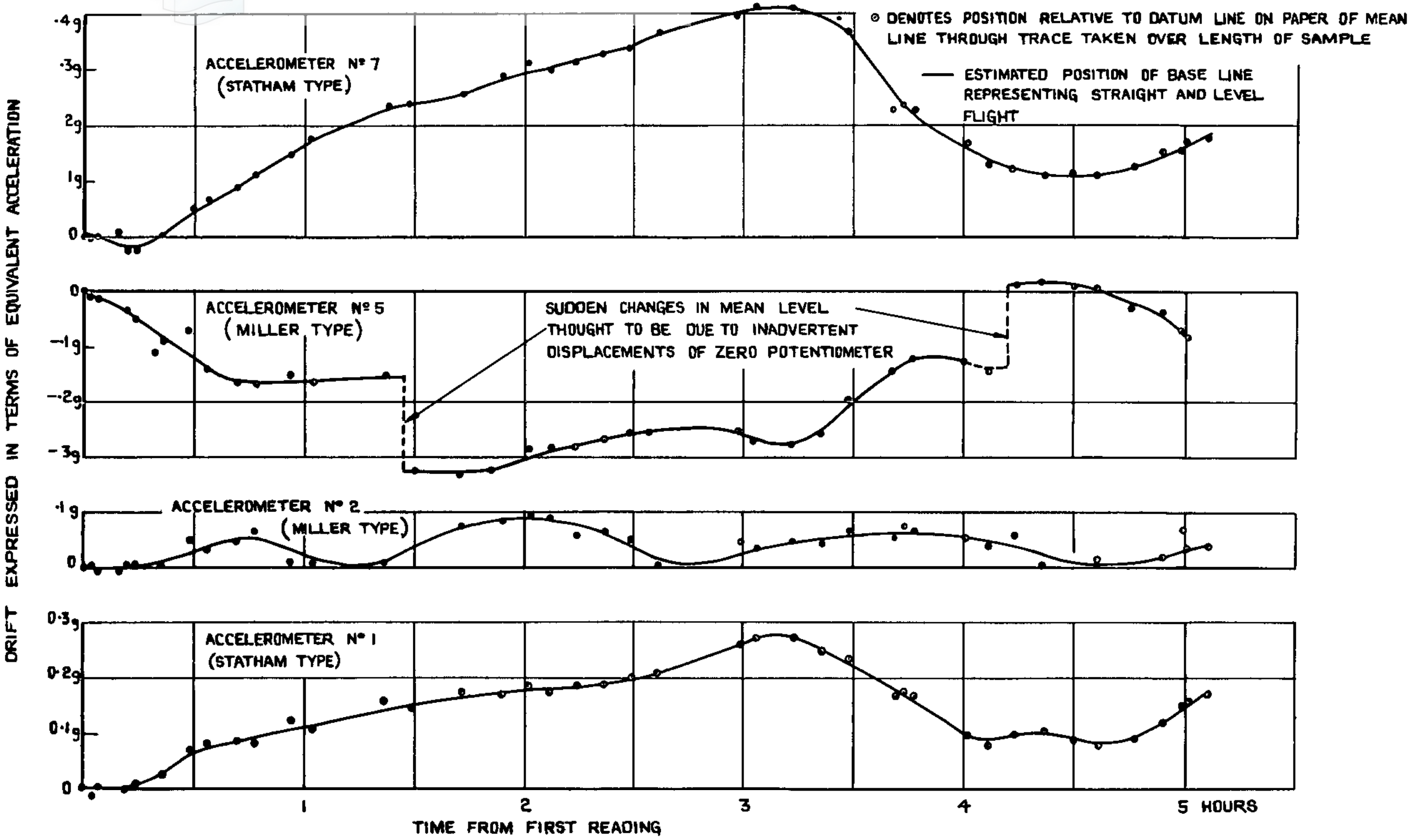


FIG. 4 DRIFT IN ACCELERATION MEAN LEVELS DURING FIVE HOURS FLIGHT.

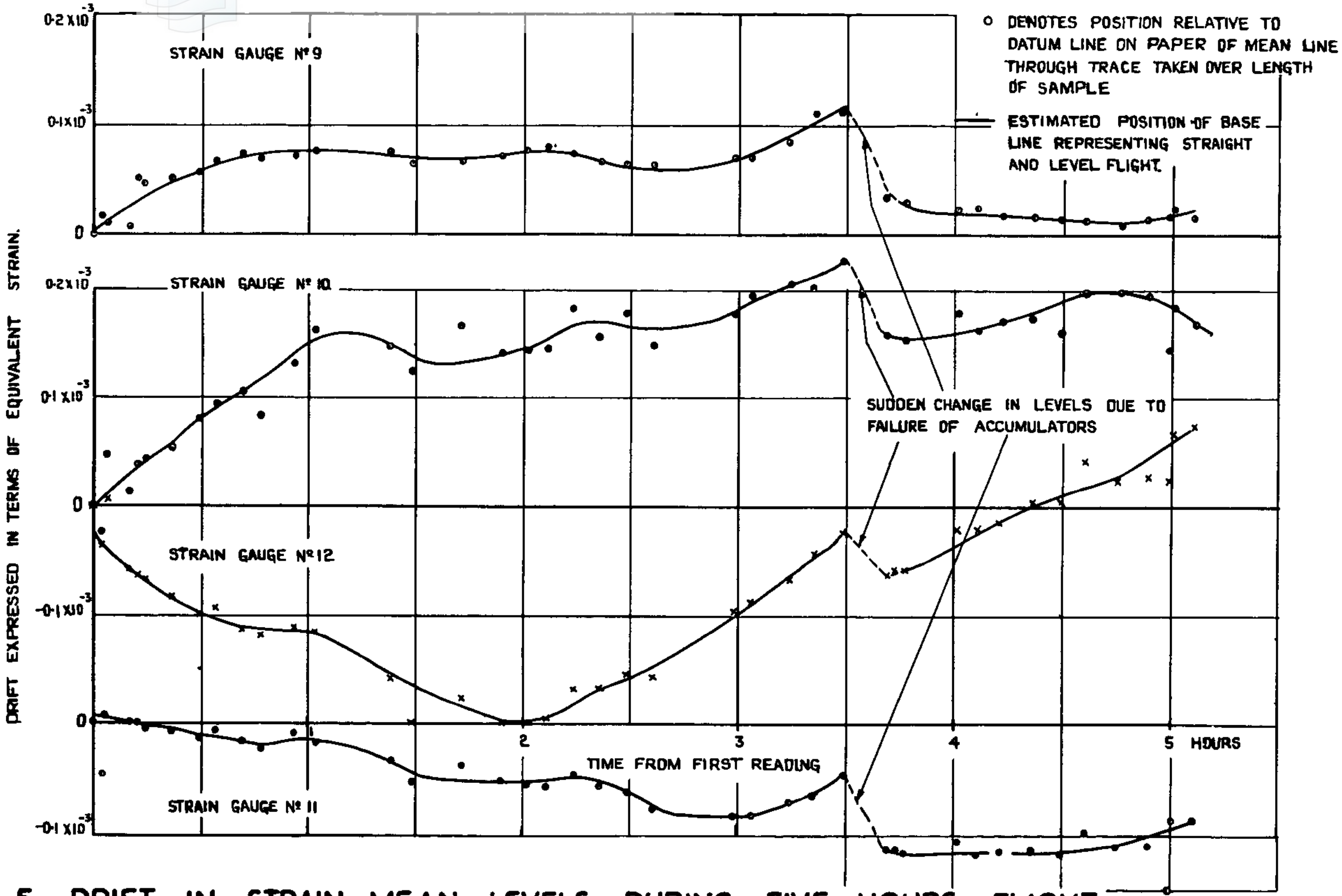


FIG. 5 DRIFT IN STRAIN MEAN LEVELS DURING FIVE HOURS FLIGHT.

FIG. 5

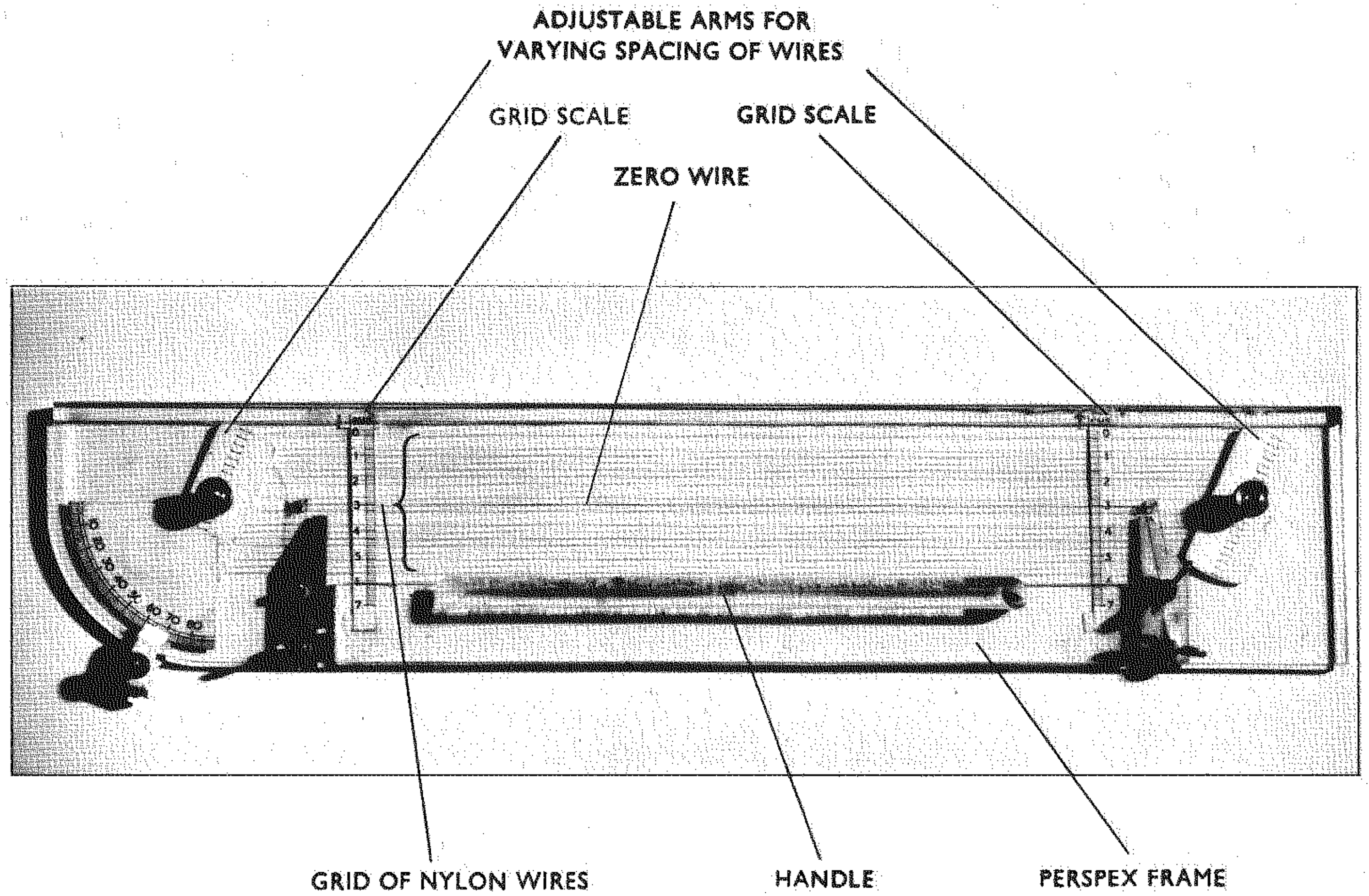


FIG.6. GRID ANALYSER FOR MILLER RECORDS

FIG. 7

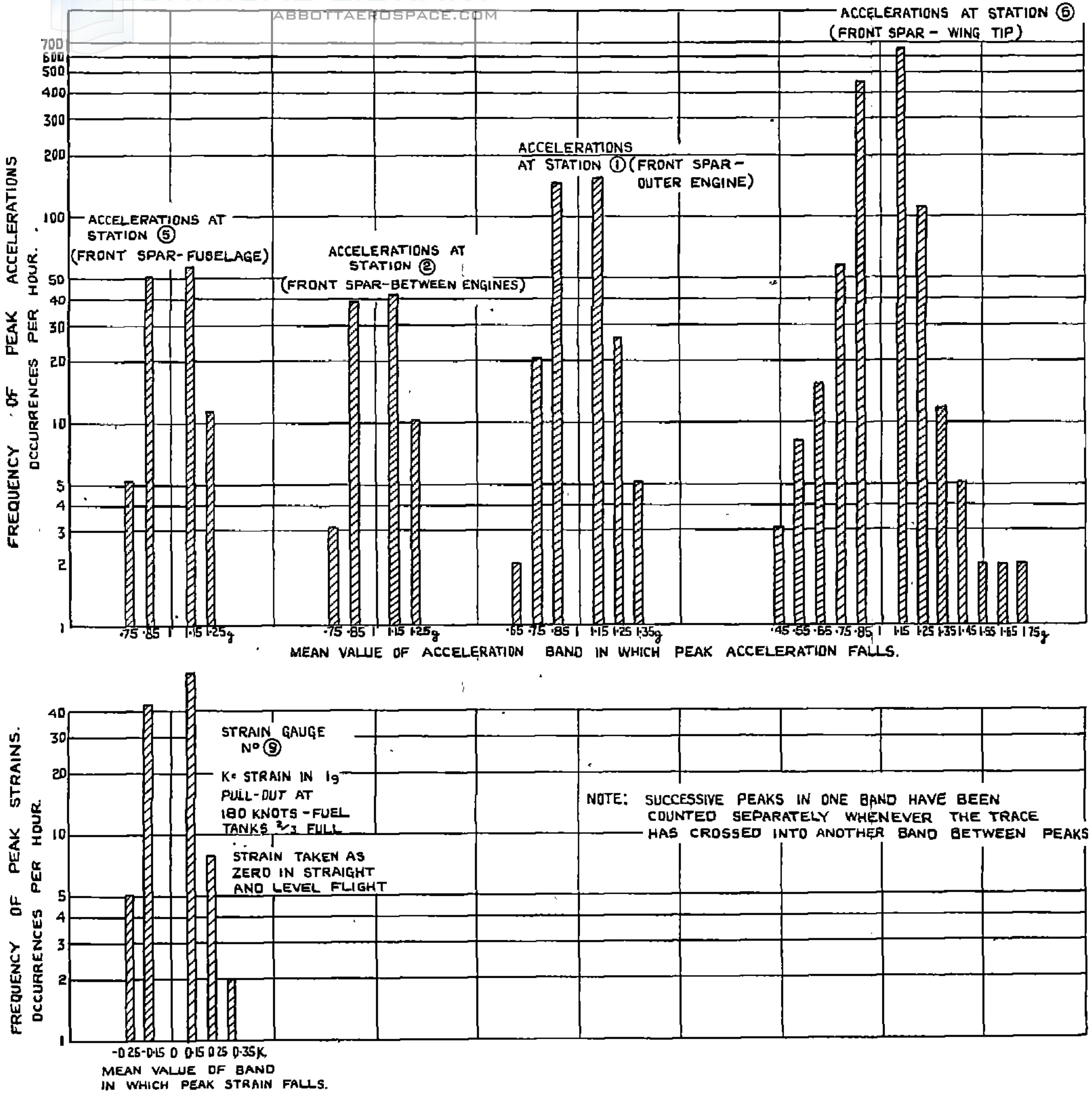


FIG. 7 HISTOGRAMS SHOWING FREQUENCY OF OCCURRENCE OF PEAK ACCELERATIONS & STRAINS AT VARIOUS STATIONS IN LANCASTER BASED ON A SIX HOUR CROSS-COUNTRY FLIGHT.

C.P. No. 48
12796
A.R.C. Technical Report

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