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Part I. A Description of the Excitation and Recording Equipment used for Flight Flutter Tests on a *Meteor* 8

By P. D. R. LUSCOMBE, B.Sc., A.F.R.Ae.S.

Part II. Comparative Flight Flutter Tests using the 'Decaying Oscillation' and 'Amplitude Response' Techniques

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Summary. A description is given of the installation of a single linear inertia exciter and multichannel recording equipment which was fitted to a *Meteor* aircraft for use in the development of flight flutter test techniques. The installation was designed so that either amplitude response or damping measurements could be made. Typical records and results are illustrated and the accuracy and capabilities of the equipment are assessed.

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1. *Introduction.* The need for flight flutter testing of prototype aircraft was first generally appreciated in this country in the period following the 1939–45 war when a serious number of flutter incidents occurred on different types of aircraft that were being developed to operate in the high subsonic and transonic regions. Although some of these incidents could have been anticipated by more thorough theoretical prediction using the data then available, nevertheless it became evident that the data used in relation to the aerodynamic derivatives were not reliable, particularly in the transonic region and for aircraft having unconventional planforms. Accordingly, it was decided that flight flutter tests should be made in cases when the predictions showed marginal flutter clearance or where there were reasons to suspect the accuracy of the data used in the calculations.

Aircraft vibrations, and accidents, have been ascribed to flutter since as long ago as 1916[1, 2] but the earliest systematic flight flutter tests known were the German flight resonance tests[3] which were started in 1935, when flutter involving fuselage lateral bending and rudder rotation of the Ju.87 was investigated and cured. The flight resonance tests utilised von Schlippe's proposed amplitude response technique, and research into improved apparatus and flight techniques was started in 1936, using a Ju.52/3 as the test vehicle. Several methods of excitation were tried, recording apparatus was developed, and finally, the efficacy of the technique was demonstrated by increasing the speed of the aircraft until it fluttered at a speed which had been predicted at lower speeds by the flight resonance tests. A further five German aircraft were cleared for flutter by means of similar tests by 1940. In the U.S.A. the Glenn Martin Company did some simple tests in 1937[4] on their

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* Part I previously issued as R.A.E. Tech. Note No. Structures 252—A.R.C. 21,056. Part II previously issued as R.A.E. Report No. Structures 248—A.R.C. 21,158.

Model 156 *Russian Clipper*, relying on gust excitation to obtain transient amplitudes of a control surface. As this was not satisfactory a mechanism was devised to deflect, and then suddenly release a control surface. This technique was used successfully to predict a rudder flutter condition and to clear the modified aircraft. Subsequent tests were made on the XPBM-1, of 1939, using a linear force rotating inertia exciter in the leading edge of one wing at 75 per cent semi-span. Amplitude response measurements were made, and damping was calculated from the amplitude response and power input data. A review of British experience of flight flutter test techniques and associated equipment was made at a symposium[5] on the general flutter problem, held at the Royal Aircraft Establishment in January, 1953. It was evident at that time that a considerable development of flight flutter testing techniques was required before tests of this kind could be regarded as reliable methods of establishing the flutter characteristics of an aircraft.

A programme of work was commenced, therefore, at R.A.E. to obtain general experience of flight flutter testing, using current experimental techniques, and to develop new techniques and associated equipment. One of the aircraft chosen as a convenient 'test bed' for this work was a *Meteor* 8, because it was of conventional metal construction, had a good record of safety and serviceability, and, since it was of medium size, there was no undue difficulty in installing items of experimental equipment.

This Report is limited to a detailed description of the installation of a linear force rotating inertia exciter and its associated control gear, together with the vibration recording equipment, which were used for the first series of tests on the *Meteor*. In these tests, general experience of flight flutter testing was obtained and a comparison of two existing techniques was made. A comparative assessment of the two techniques investigated will be made in a separate paper. In addition to describing the installation, the general capabilities of the equipment are illustrated by typical records and results, and the quality of the results is discussed.

2. *Vibration Recording Equipment.*

2.1. *General.* Conventional flight vibration recording equipment was used. The vibration waveforms at a selected number of points on the aircraft structure and control surfaces were recorded on a multichannel galvanometer recorder so that amplitudes, frequencies and approximate phase relationships at the selected points could be measured. The amplifiers and the recorder time base were switched on before take-off, to give as long a warming up period as possible before recording commenced. The recorder was operated automatically by the exciter speed control unit, which is described later in Section 3.4.

2.2. *Equipment Used.* Thirty variable inductance acceleration transducers of the type IT1-22[6], aligned so as to measure vertical vibrations, were fixed at the various positions on the aircraft shown in Fig. 1, so that vibration modes of vertical bending of the wing, fuselage and tail plane, wing and tail-plane torsion, and aileron and elevator rotation could be measured.

As there were insufficient channels available to record simultaneously the vibrations of all of the transducers, batches of twelve were selected. For each flight a group was chosen, and the transducers connected to a Miller type CD-2 fifteen channel, double integrating, carrier wave amplifier, which was mounted in the port gun bay, whilst its power pack was mounted in the ammunition bay behind the cockpit, as shown in Figs. 1, 2 and 3.

The signals from the appropriate twelve amplifier channels were recorded in a Miller type W sixteen channel galvanometer oscillograph which was mounted in the radio bay, in the position shown in Fig. 1. On most flights the acceleration signals from the transducers were integrated twice in order to obtain displacement records, but occasional flights were made in which acceleration records were taken with 2 to 3*g* on the aircraft, as a check on the relative phase relationships between the individual transducers of the particular array in use.

As a completely independent check on the possible malfunctioning of the main electronic amplifying equipment, two Sperry generator type velocity transducers were fitted, each close to an acceleration transducer, one in the starboard wing tip and one in the rear fuselage, as shown in Fig. 1. The outputs from these Sperry transducers were fed through simple, non-amplifying, resistance-capacitance integrating circuits directly into two channels of the Miller recorder.

To assist pilots in judging maximum amplitudes when attempting to obtain decaying oscillation records, an indication of the amplitude of vibration was displayed in the cockpit on a rectifying micro-ammeter. The meter was fed with the output of an amplifier channel connected to the rear-most transducer in the fuselage (Transducer No. 8, shown in Fig. 1).

In order to indicate on the record the instant at which the exciter was switched off, one of the recorder galvanometers was shunted, through a resistance, across the exciter motor armature.

2.3. *Calibration.* Before installation in the aircraft the transducers were calibrated by subjecting them to oscillation at known amplitudes and frequencies on a Sperry vibrating table. All the amplifier channels were adjusted to give the same overall magnification prior to calibration, to facilitate the use of any transducer with any amplifier.

A portable calibrator which gave a similar signal to that of a transducer oscillating at about 10 c.p.s. was used to supply a standard input, so that it was possible to retrim the gain of the amplifiers at frequent intervals without the inconvenience of removing them from the aircraft to the laboratory. Galvanometer sensitivities were compared by feeding each in turn with the output from the calibrator amplified by one particular amplifier channel. Having thus separated the effects of amplifiers and galvanometers the transducers were all calibrated over a range of frequencies, and magnification against frequency curves were obtained for each transducer. Check calibrations at different amplitudes were made for a few of the transducers, but no significant differences were found, so it was therefore assumed that all were linear with amplitude within their operating limits. At the annual survey of the aircraft the opportunity was taken of removing the vibration recording equipment for recalibration, when only small variations from the earlier calibration were noted.

It was realised, as work went on, that, ideally, a calibration signal should be switched on to every channel at the beginning or end of each record, if short term changes in amplifier gain during flight were to be measured. However, considerable modification to the existing equipment would have been required, and excessive delay to the flight programme would have resulted. The signals from the velocity transducers were relied upon, therefore, to indicate any marked change in response of the electronics as a whole.

Even with built-in calibration on all channels, regular trimming of the amplifiers to a standard overall magnification would still be advisable, provided that this practice was not liable to harm the particular type of amplifier in use.

3. *Excitation Equipment.* 3.1. *General.* A linear rotating inertia exciter was mounted in the nose of the aircraft and driven by a d.c. motor. The speed of the motor was controlled by a modified Ward-Leonard circuit incorporating an engine driven generator on the port engine of the aircraft.

Automatic control gear in the Ward-Leonard circuit caused the exciter to sweep through the frequency range of about 5 to a maximum of 15 c.p.s. with a preset frequency-time relationship which could be varied. Once the appropriate flight condition had been established, the whole sequence, including the operation of the recording equipment, was initiated by one master switch. The rotation of the exciter could be stopped very rapidly at any point in the frequency range, if so desired.

3.2. *Exciter Assembly.* A standard R.A.E. 10 lb in. linear exciter was driven by a 5 h.p. d.c. motor through a 7·5:1 reduction gear. The three components of the unit were mounted on a steel plate which was attached to the tubular structure which supported the nose wheel, as shown in Fig. 4. The force produced by this exciter varied with the square of the frequency and the level of this force could be preselected by varying the out of balance mass on the rotors. Any one of the nine values shown in Fig. 5 could be chosen, up to the maximum of 10 lb in. moment. The power required to accelerate the exciter through the frequency range was approximately 1 h.p. the major part of which was dissipated in frictional losses. The reserve of power available was found to be very valuable in providing regenerative breaking torque when a rapid cut-off of the excitation force was required.

3.3. *Power Supply.* Power for the motor was supplied from the aircraft port generator, which was disconnected from the aircraft bus bars, and reconnected to the exciter motor in the form of Ward-Leonard circuit shown in Fig. 6. In addition to the usual protection against electrical faults an 'over-speed' control was embodied in the circuit which would break the exciter motor armature supply automatically if the voltage should become sufficient to drive the exciter at more than about 20 c.p.s. An 'emergency stop' circuit was incorporated so that the pilot could stop the exciter in about one revolution, by pressing a button, which interrupted the armature supply current, and at the same time short circuited the armature, so applying powerful electrodynamic braking.

3.4. *Speed Control.* The exciter frequency was controlled by varying the current to the generator field. This was done by rheostatic variation of the current through the coil of a carbon-pile regulator, which in turn controlled the current through the generator field. Stability was achieved by negative feedback from the motor armature supply, as the control rheostat and regulator coil were shunted across it near the motor.

The rheostat was operated automatically to ensure that the pattern of sweeping through the frequency range should be the same from flight to flight. For simplicity of manufacture the resistance was wound toroidally round half the circumference of an annular core. To obtain a wide variation of the exciter frequency–time relationship, the resistance was mounted so that the centre of the core could be placed at any desired eccentricity to the contact arm spindle. A general view of the control unit is shown in Fig. 7, and two typical frequency-time curves are shown in Fig. 8. The unit was mounted on an existing multi-speed gear box, and driven through a reduction gear by a high-speed 24 volt d.c. motor. Three cams were mounted on the contact-arm spindle to operate micro-switches, one of which controlled the power supply to the motor driving the rheostat-brush spindle, the second switched the recorder on and off, and the third operated the main supply relay for the exciter motor armature. The cams and switches are visible in Fig. 7, and the electrical circuit of the control unit is shown in Fig. 9. The operating switches for the exciter, together with the power pack and recorder standby switch were grouped on a panel in the cockpit, as seen in Fig. 10, and the emergency stop button was placed on the throttle.

Provided that the contact arm was not rotated too quickly, the speed of rotation of the exciter was very nearly proportional to the resistance selected by the brush at any instant.

4. *The Flight Tests.* 4.1. *General.* A series of flights were made, first to check that the equipment was functioning satisfactorily, and then to investigate its suitability for use in connection with the 'amplitude response' and 'decaying oscillation' techniques of flight flutter testing. In the course of the flight tests, amplitude and damping measurements were taken for two modes of vibration of the aircraft: these modes had frequencies of approximately 7·9 c.p.s. and 10·8 c.p.s., being respectively the fundamental vertical bending mode of the wings and of the fuselage. Modes of vibration in flight at these two frequencies were plotted for fuselage vertical bending, and wing main spar symmetrical vertical bending. No attempt was made to obtain sufficient measurements to draw nodal lines.

4.2. *Amplitude Response Tests.* For these particular tests the exciter was controlled to sweep through the frequency range 5 to 13 c.p.s. in approximately 40 seconds, with the frequency-time relationship shown in Fig. 8. The flight technique was quite straightforward: the pilot selected Power Pack and Recorder 'ON' before take-off, and switches Nos. 1, 2 and 3, all visible in Fig. 10, were selected at any time during the climb to the required altitude. Having established the appropriate flight condition press-button No. 4 was operated, which initiated the excitation sweep and automatic recording sequence. For subsequent sweeps in the same flight it was necessary only to operate the press button, as the remainder of the switches were left on until the experiment had been completed.

Buffeting became noticeable on the records at speeds above 325 knots and Mach numbers above 0·7; it was presumed to be induced by breakaways and compressibility effects, and the severity increased with indicated speed and Mach number. The early test runs were made with the exciter set to give 2·8 lb in. out-of-balance and it was found that the ratio of forced amplitude to buffeting amplitudes became too small for accurate visual analysis for speeds above 350 knots. Test runs were made with increasing out-of-balance settings and it was found to be necessary to use the maximum setting in order to achieve a reasonable ratio of forced amplitude to buffeting amplitude at the high end of the aircraft performance range. Extracts from the records in the region of the 7·9 c.p.s. resonance and the 10·8 c.p.s. resonance, taken when the aircraft was flying at 150 knots are shown reduced in scale in Fig. 11. Corresponding records at 350 knots are shown in Fig. 12: it may be seen that the waveforms are somewhat irregular compared with those obtained at 150 knots.

4.3. *Decaying Oscillation Technique.* Several methods of obtaining decaying oscillation records were tried. The most effective method was found to be, to establish the required flight condition, then operate the equipment to perform an amplitude sweep, as described above, and note the maximum reading on the amplitude microammeter as each resonance was excited. The sweeping sequence was again initiated but this time the emergency stop button was pressed when the microammeter was reading approximately 80 per cent of the value previously noted for the appropriate resonance. This procedure was repeated for each resonance, as desired. The reason for operating the stop button before resonance was reached was to allow for the time delay caused by the several relays in the emergency stop circuit, which amounted to half a second between operating the button and the exciter being stopped. Decaying oscillation records for the 10·4 c.p.s. mode at 150 and 350 knots, obtained using the above technique, are shown in Fig. 13. It may be observed that the exponential decay at 350 knots has been seriously distorted by the background buffeting.

4.4. *Measurement of Modes of Vibration.* Measurements of the modes of vibration at 7·9 and 10·8 c.p.s. were made at several airspeeds between 150 and 300 knots. The changes in modal shapes were very small over this speed range and typical measured modes are shown in Figs. 14, 15; it should be mentioned that the wing bending mode was measured along the line of the front spar only and that no attempt was made to measure the associated wing torsion. The modes were plotted with all points assumed to be directly in or out of phase as no deviations from these phase relationships, beyond the possible errors in measurement, could be seen on the records.

5. *Results of Flight Tests.* The quality of the results obtained is discussed below in relation to the measurement of frequency, amplitude, damping and modal shapes.

5.1. *Frequency Measurements.* Resonant frequency was measured on the records by taking three or four cycles on either side of the maximum amplitude, and counting up the time base lines over those cycles. Provided that the waveform was nearly sinusoidal, and that the amplifier gain was chosen so as to give reasonably well defined peaks, it was not difficult to measure the time taken to within ± 0·005 secs at a recording paper speed of approximately 5 inches per second. This implied a maximum error in calculating frequency of about ± 1 per cent. Even if conditions were not ideal, this analysis error should not have been more than doubled provided that reasonable care was taken.

The variation of resonant frequency measured on different flights was negligible. When repeating a particular flight condition the worst mean deviation obtained was less than 1·4 per cent and over ten flights covering a speed range of 150 to 500 knots the mean deviation in resonant frequency of the 10·8 c.p.s. mode was slightly over 1 per cent.

5.2. *Amplitude Measurements.* The amplitude response records were analysed by the graphical enveloping technique[7], and record amplitudes were converted into airframe amplitudes by reference to the ground calibration of the instrumentation. Comparison of successive calibrations suggested that the overall magnification (*i.e.*, measured record amplitude ÷ transducer amplitude) was unlikely to vary more than about ± 5 per cent for the accelerometers, provided that the amplifier gains were adjusted regularly, but variation in magnification was less than ± 1 per cent for the velocity transducers. As the variation in calibration of the velocity transducers was so small, most of the amplitude response measurements were obtained from them, the accelerometers being used to obtain modal shapes. Measurements of maximum response for the 10·8 c.p.s. flight modes are shown plotted against airspeed in Fig. 16, the smooth line being drawn approximately through the mean of the observations at each airspeed. Some indication of the trend and magnitude of the scatter of these measurements may be seen in Fig. 17, which shows the mean deviation expressed as a percentage of the mean amplitude, for each airspeed at which more than one record was taken. The mean deviation varied between 1·25 per cent and 15·8 per cent in no obviously definite manner, but a line drawn through the points by the method of least squares indicated a definite increase in scatter with increase in airspeed. In seeking an explanation for the scatter four possibilities were considered:

(*a*) Changes in equipment sensitivity.
(*b*) Errors in establishing required flight conditions.
(*c*) Inaccurate analysis.
(*d*) Day to day changes in the aircraft response.

It is unlikely that possibilities (*a*) and (*b*) applied in this case. Considering first the possible changes in the sensitivity of the equipment; the same order of scatter was obtained on two basically different types of measuring equipment, both of which showed no variations in calibration which could have been significant in relation to the above errors. Again, considering possible errors in establishing the flight conditions with sufficient accuracy, the pilot could readily hold the speed to within ± 5 knots of the desired condition and, on the steepest part of the amplitude response curve, this margin of error would only account for ± 2 per cent variation in amplitude. Other tests showed no appreciable change in amplitude response with the altitude changed from 10,000 to 5,000 ft therefore it is most unlikely that errors in altitude setting would account for any of the scatter.

There is little doubt that inaccurate analysis (*c*) could explain, at least in part, the somewhat greater scatter apparent at high speeds than at low speeds. At 150 knots the waveforms were almost purely sinusoidal, as seen in Fig. 10, and the analytical errors would not exceed those in the analysis during ground calibration tests. However, as the highest speeds were approached, the analytical difficulties became greater due to the superimposed buffeting and undoubtedly the analytical accuracy was reduced.

The scatter evident at the low speeds cannot therefore be explained by the foregoing considerations and it appears that day to day changes in the aircraft response (*d*) do occur. On each flight during the flight flutter tests the exciter was operated at 150 knots and at three other successively higher speeds. As the tests proceeded the highest speed in each flight was progressively increased, so that in several flights an amplitude response measurement at a particular speed was made at two or three different stages in the flight, *i.e.*, at several different fuel load and airframe temperature levels. In an attempt to find out if this was causing some of the scatter a flight was made in which the exciter was operated under the same flight conditions (300 knots, 10,000 ft) at five min intervals. If fuel load and airframe temperature were affecting the response a definite amplitude trend should have been apparent. However, the results, as seen in Fig. 18, show no definite trend, as the 'best lines' through the points are nearly parallel with the abscissa, rising very slightly with time of flight. As the mean deviation of the wing-tip amplitudes was 7·5 per cent of their mean, and that of the rear fuselage amplitudes was 5·9 per cent the flight seems to have been typical, as the amount of scatter was that usually observed, so it appears that fuel load and airframe temperature had no significant effect on the amplitude response of the *Meteor*. Therefore part of the observed scatter of the amplitude response results appear to be due to unexplained day to day variations in the aircraft response.

5.3. *Damping Measurements.* The values of damping were obtained from the decaying oscillation records using a graphical enveloping technique; the Naperian logarithms of the amplitudes of successive amplitudes were plotted against the number of cycles to give, ideally, a straight line, and the damping was deduced from the slope of that line. In cases where the correct slope was in doubt due to the scatter of the points, the method of least squares was used to obtain the slope. The errors associated with calibration of the instrumentation, and subsequent possible changes in overall sensitivity, were of less significance in relation to damping measurements than in relation to amplitude response measurements. In the former case, only changes of sensitivity occurring during the duration of a decaying oscillation record could effect the accuracy of the result. As the oscillations decayed in no more than two seconds it is most unlikely that significant changes of sensitivity could occur in so short a time interval.

Measurements of damping for the 10·8 c.p.s. mode are plotted against airspeed in Fig. 19. Several repeat measurements were taken at airspeeds above 250 knots and, although the number of repeats at each airspeed was not constant, it is evident that the scatter was increasing as the higher speeds were approached. Fig. 20 shows the mean deviation of measured damping coefficients from the mean at each airspeed, and it is obvious that the scatter was increasing markedly with airspeed. Following the lines of the discussion of the amplitude response measurements in Section 5.1 above, there is little doubt that the major part of the apparent scatter occurring at the higher airspeeds is due to errors in analysis. It will be noticed that the mean deviation of the damping measurements far exceeds that of the amplitude response measurements at the higher airspeeds, when background buffeting was present. Under these conditions the analysis of decaying oscillation records is fundamentally much less accurate than the analysis of amplitude response records. In analysing the latter type of record it may be assumed that the amplitudes in the region of the resonance peak are changing sufficiently slowly to be averaged without introducing serious errors, provided that the rate of frequency sweep through the resonance is relatively low: in the analysis of the decaying oscillation records no correspondingly simple averaging method can be employed. The use of the method of least squares in the analysis of the damping measurements, as mentioned above, was not considered to be very satisfactory. It is assumed in this method that each point is liable to be in error to the same degree. In the presence of background buffeting this will not be the case since, in general, the smaller the amplitude of the decaying waveform the greater will be the percentage error. The method was used, however, because the author was not aware at that time of a more satisfactory method.

5.4. *Modes of Vibration.* The quality of the amplitude measurements which were used in plotting the flight modes has been discussed in Section 5.1 above. It is believed that the errors in determining the phase relationships between different measuring points did not exceed ± 10 deg at the low airspeeds and very approximately ± 45 deg at high airspeeds when buffeting was present. Errors, associated with the behaviour of the integrating circuits in the electronic equipment, might occur but would not be likely to exceed ± 5 deg. It is probable that the greater part of the total error was caused by analytical difficulties. Because of this uncertainty phase angles were approximated to the nearest 90 deg when modes were plotted.

5.5. *Electronic Methods of Analysis.* To alleviate analysis difficulties, flight vibration records made on transparent film have been analysed electronically by a 'play back' technique which is being developed at R.A.E., but there has been no opportunity as yet to try to analyse the type of records obtained in flight flutter testing. It appears probable that a frequency response curve could be obtained from a frequency sweep record by suitable manipulation of the apparatus. If this can be done reasonably quickly it will alleviate much of the analysis difficulty. Similar analysis of decaying oscillations is not possible directly, as the high 'Q' characteristic of the analyser prevents it from 'following' normal aircraft decaying oscillations. However, the Mazet technique[8] is being tried, using tape recording, in which a decaying oscillation is played in reverse into the analyser, where unwanted frequencies are filtered off, and the 'purified' waveform is re-recorded, to be analysed by a graphical method.

6. *Safety Precautions.* 6.1. *General.* In view of the satisfactory history of the *Meteor* 8 in relation to flutter, it was considered to be most unlikely that a dangerously large oscillation would be induced except, possibly, as a secondary effect following for example, the failure from fatigue of a massbalance weight attachment. To cater for this possibility, an emergency stop for the exciter (*see* Section 3.3 above) was fitted to the throttle control, and in addition, the standard ejection seat was replaced by a fully automatic seat to give the pilot the best possible chance of making a successful escape, if the resultant oscillation were divergent.

6.2. *Strength Considerations.* In the event of serious overspeeding of the exciter, dangerously high loads might be imposed on the aircraft structure; to minimise the risk of this occurring, an automatic overspeed cut-off circuit was incorporated in the electrical supply to the exciter motor in addition to the pilot's emergency stop for the exciter.

7. *Conclusions.* The excitation and recording equipment fitted to the aircraft functioned satisfactorily and is suitable for use in connection with both the amplitude response and decaying oscillation techniques.

Considerable scatter was evident in the amplitude and damping measurements at the higher airspeeds when buffeting was present. It is thought that the major part of the scatter arose from analytical difficulties. It is believed that this scatter may be considerably reduced by the application of electronic analytical methods in both cases.

Phase relationships between the oscillations of the various parts of the aircraft were measured with sufficient accuracy to obtain a general indication of the nature of the modes of vibration in flight, but the measurements were not sufficiently accurate to determine, for example, the energy input from the exciter to the aircraft structure.

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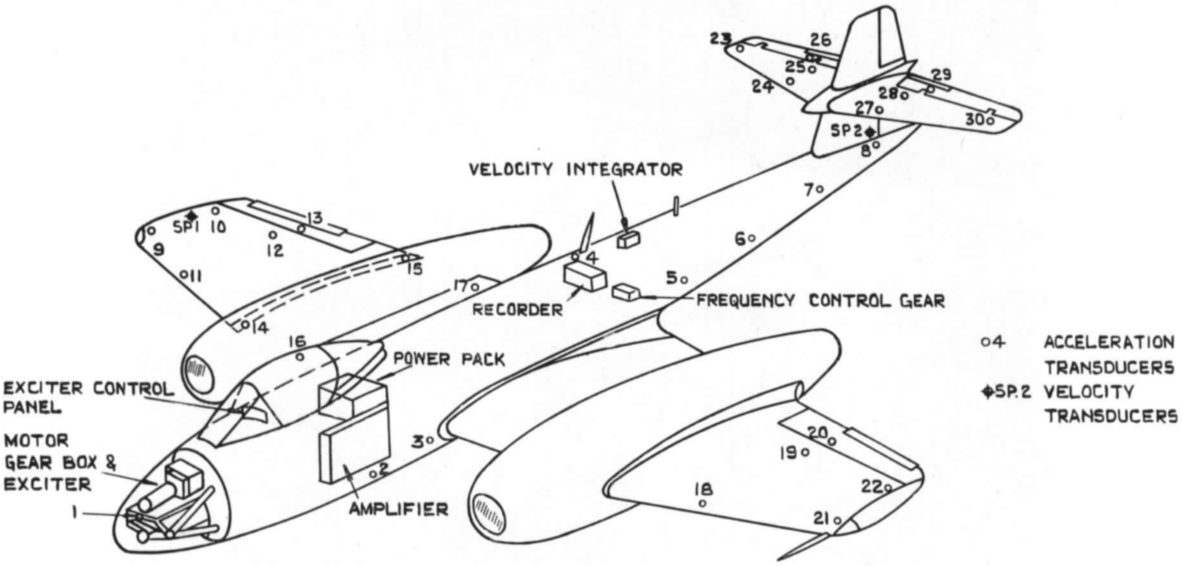


FIG. 1. Layout of experimental equipment in WK 878.

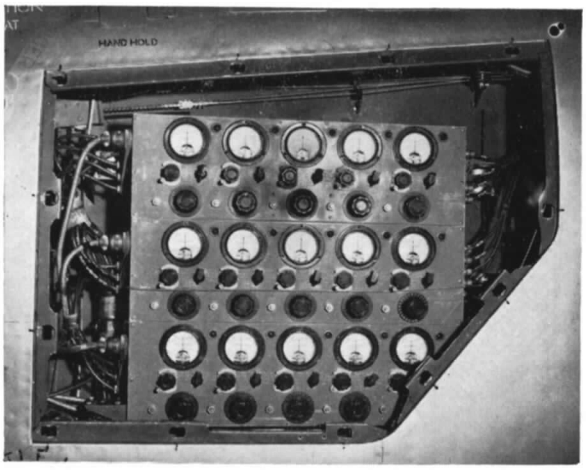


FIG. 2. Installation of amplifier.

FIG. 3. Installation of power pack.

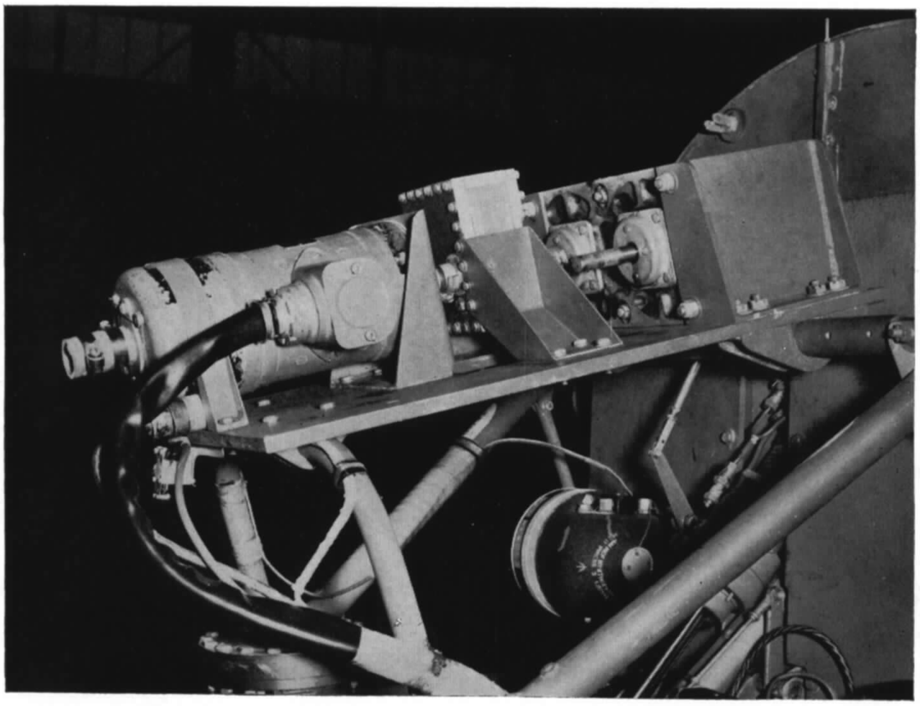


FIG. 4. Installation of motor, gear-box and exciter.

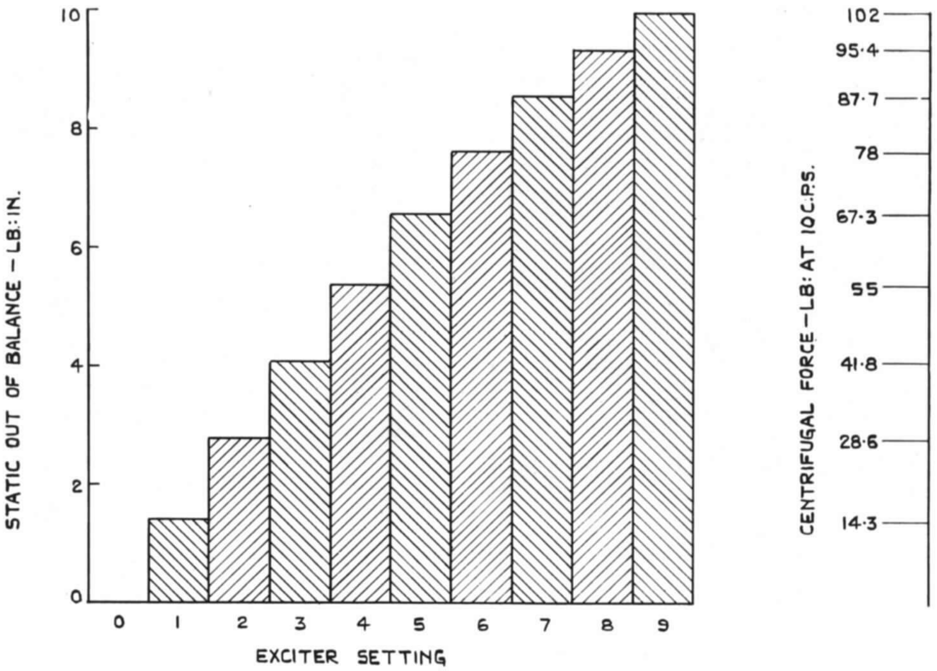


FIG. 5. Characteristics of R.A.E. 10 lb in. linear inertia exciter.

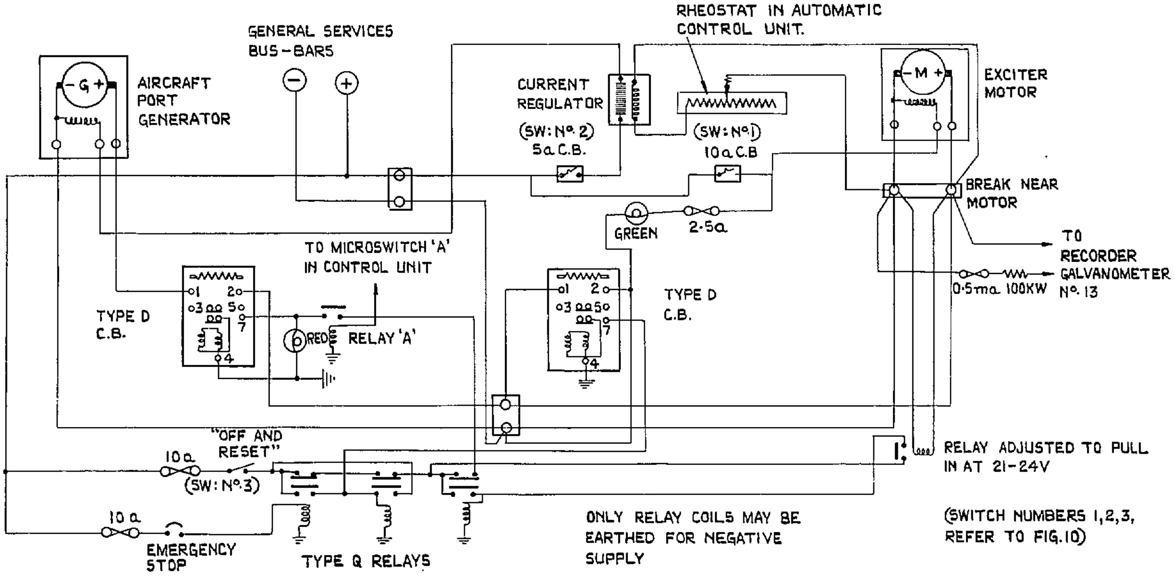


FIG. 6. Supply and control circuit for exciter motor in *Meteor* WK 878.

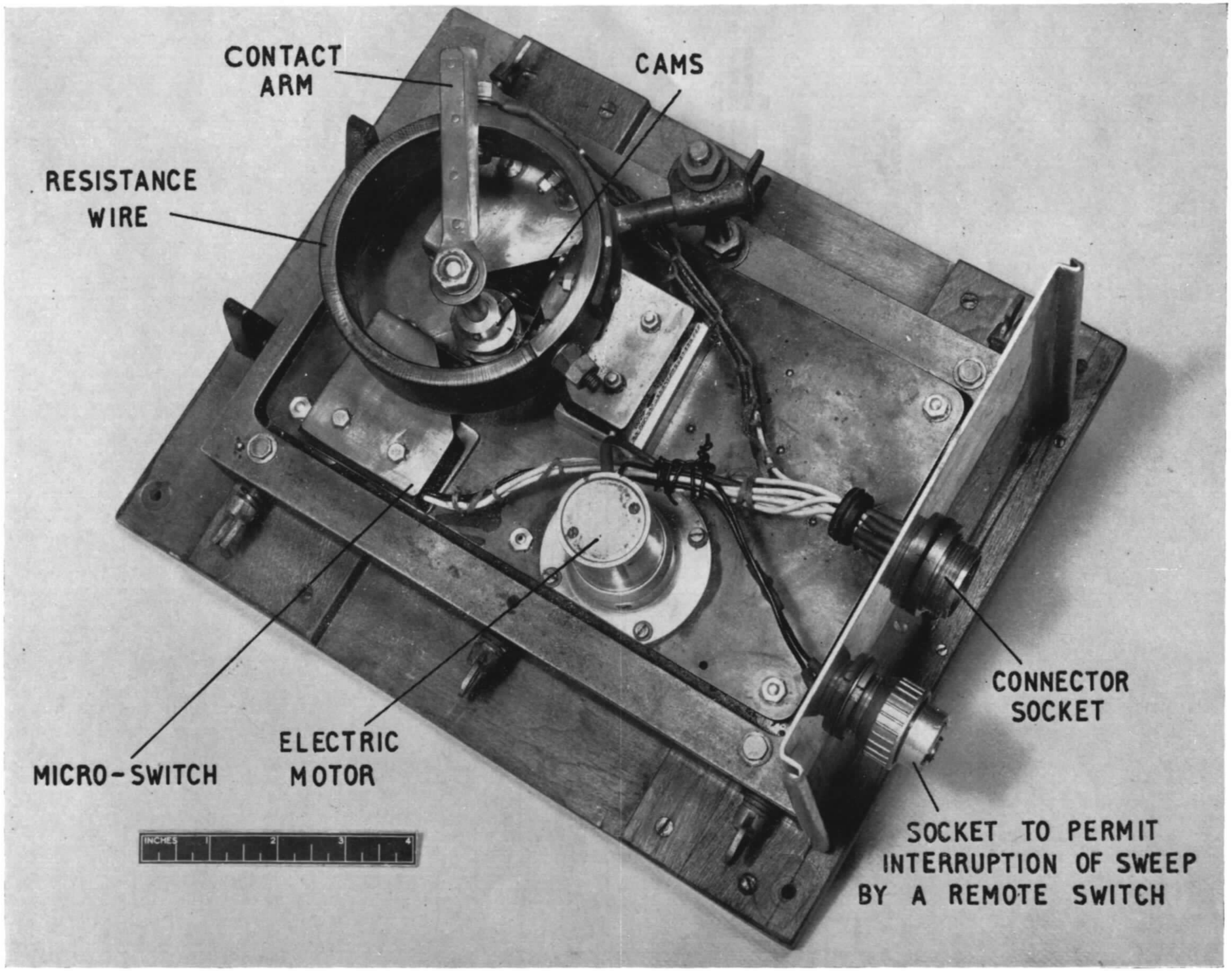


FIG. 7. Automatic control unit.

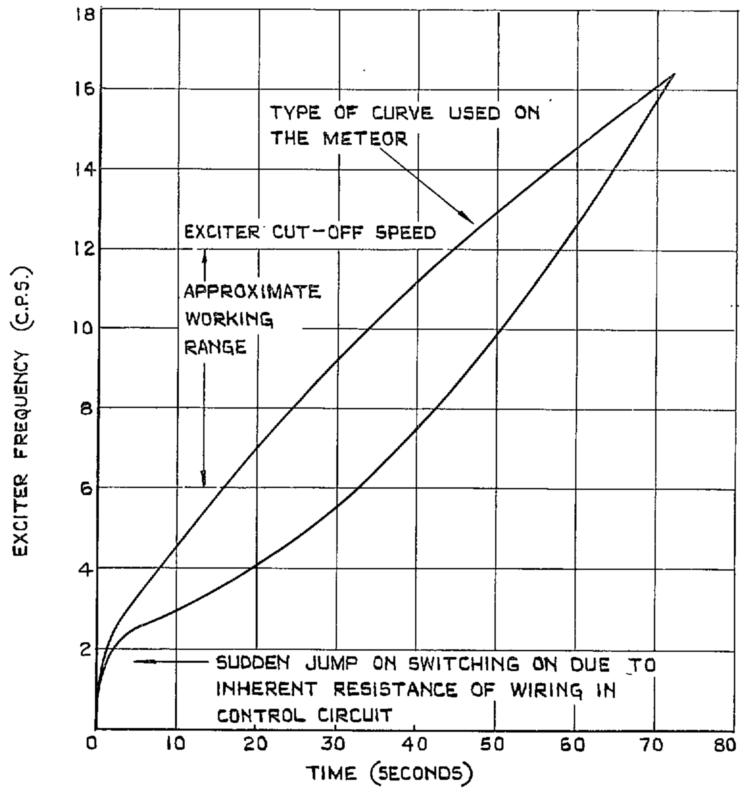


FIG. 8. Two typical patterns of variation of exciter speed with time.

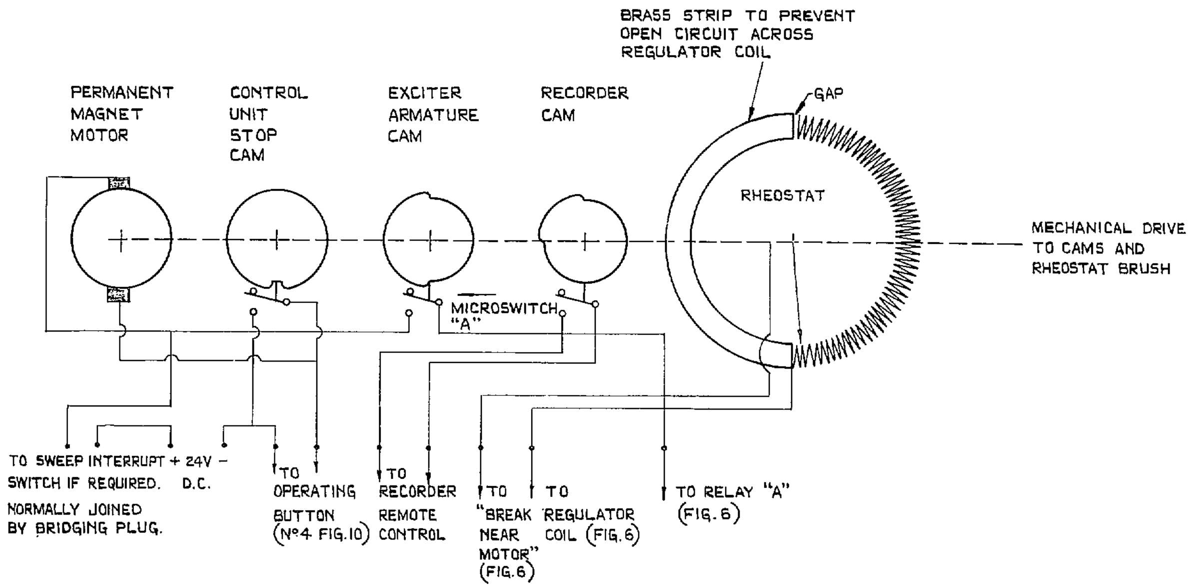


FIG. 9. Automatic frequency control unit circuit.

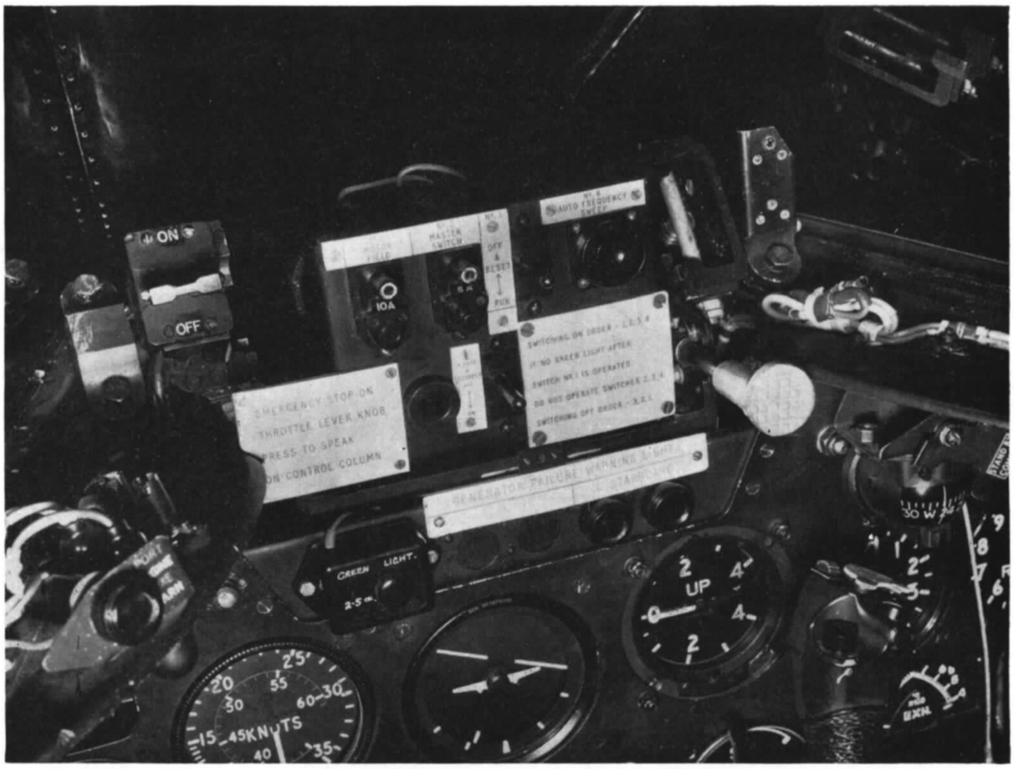


FIG. 10. Pilot's switches for experimental equipment.

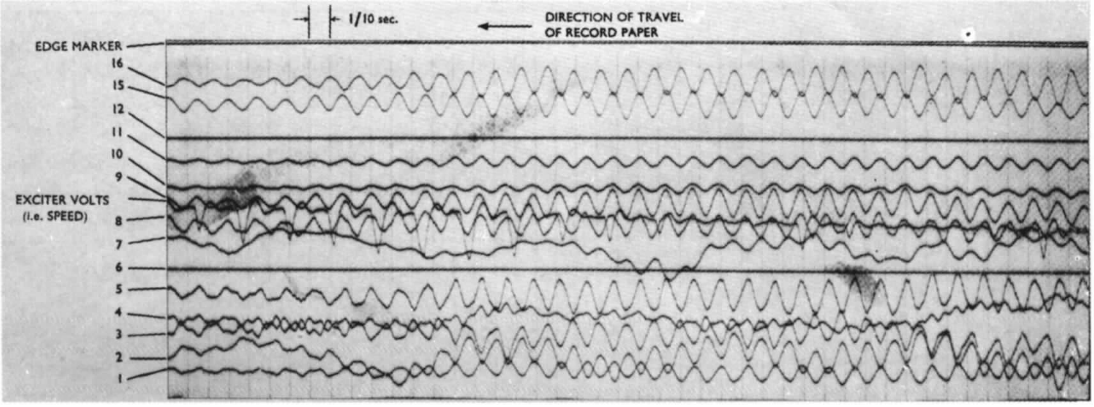


FIG. 11a. 7·7 c.p.s. resonance at 150 knots, 10 lb in. exciter moment.

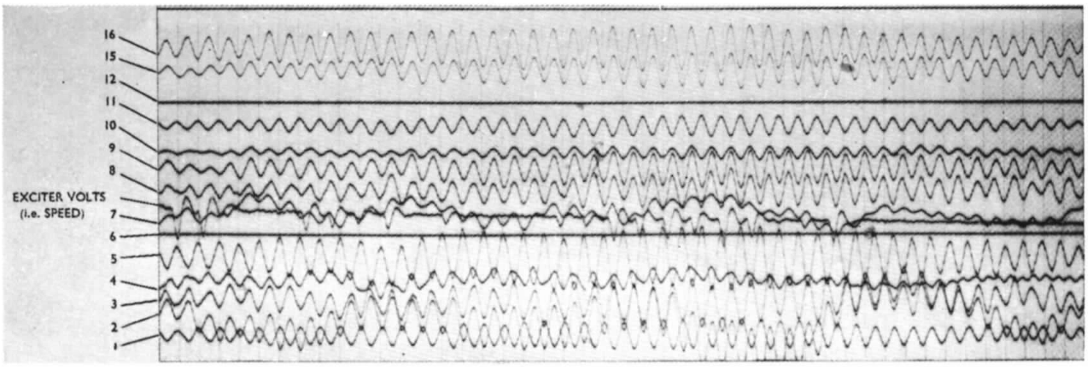


FIG. 11b. 10·4 c.p.s. resonance at 150 knots, 10 lb in. exciter moment.

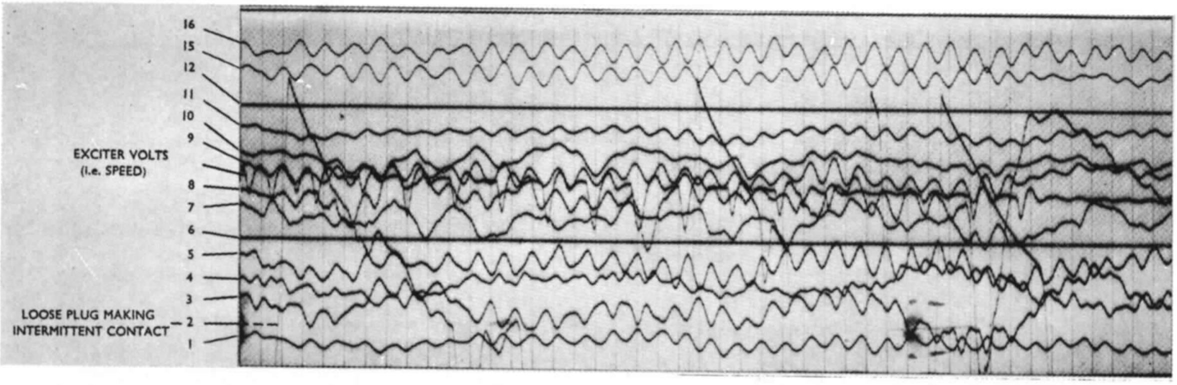


FIG. 12a. 8·2 c.p.s. resonance at 350 knots, 10 lb in. exciter moment.

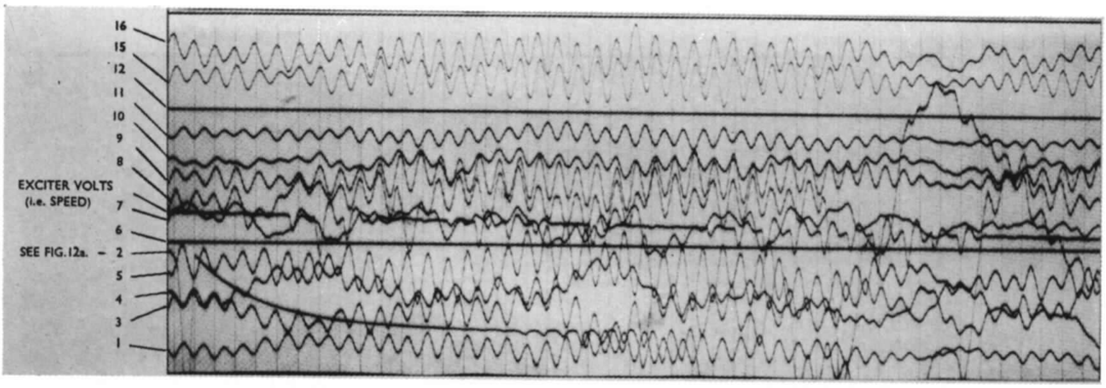


FIG. 12b. 10·7 c.p.s. resonance at 350 knots, 10 lb in. exciter moment.

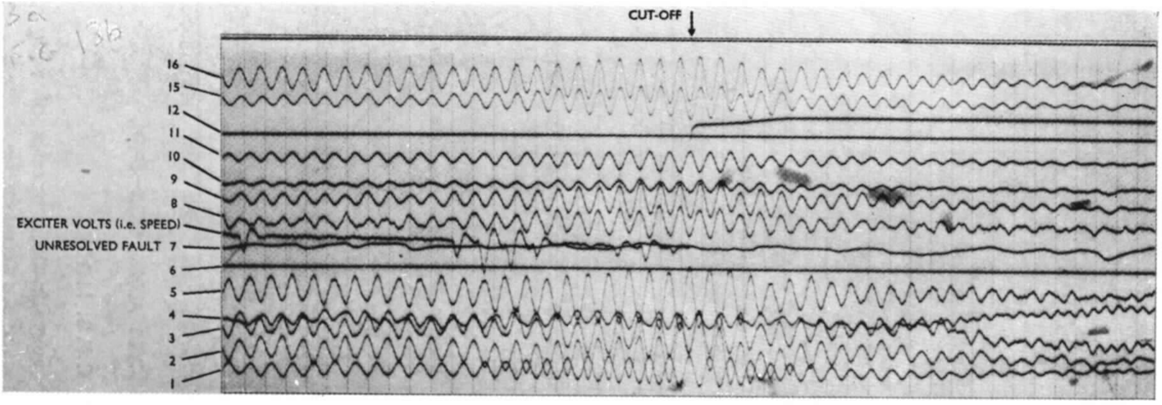


FIG. 13a. Cut-off from 10·4 c.p.s. at 150 knots, 10 lb in. exciter moment.

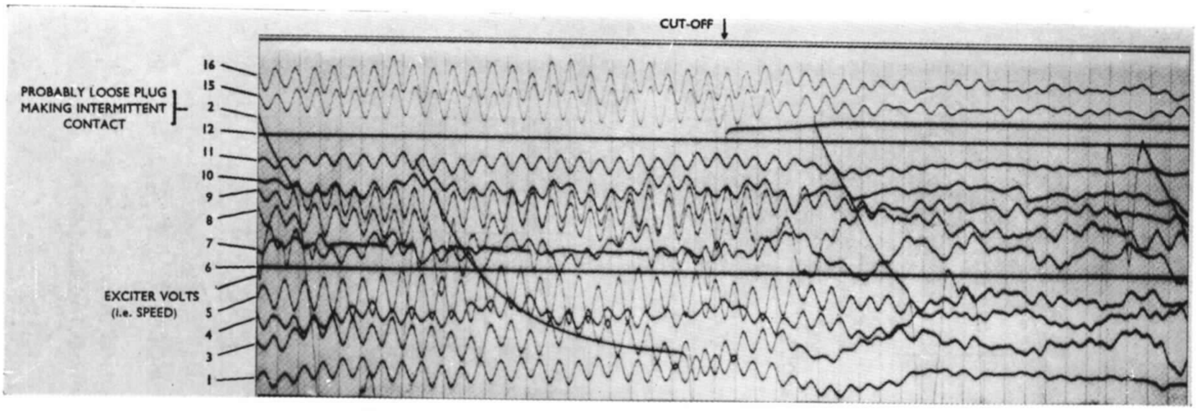
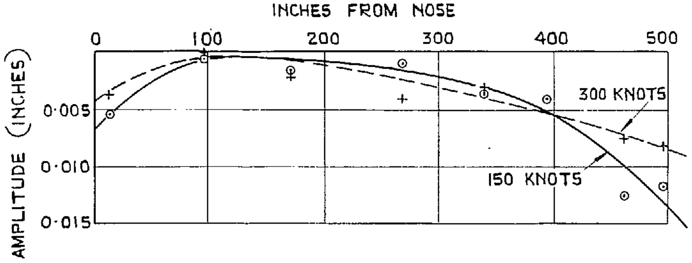
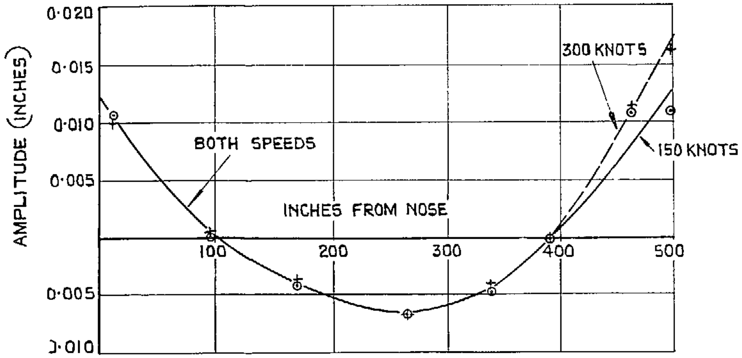


FIG. 13b. Cut-off from 10·7 c.p.s. at 350 knots, 10 lb in. exciter moment.

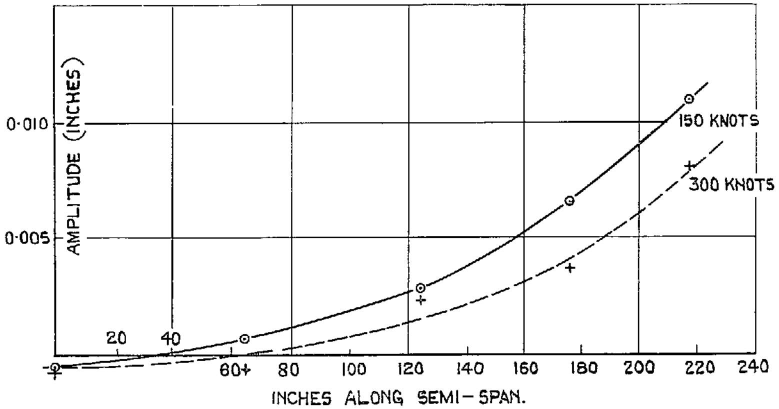


(a) 7·9 C.P.S. MODE.

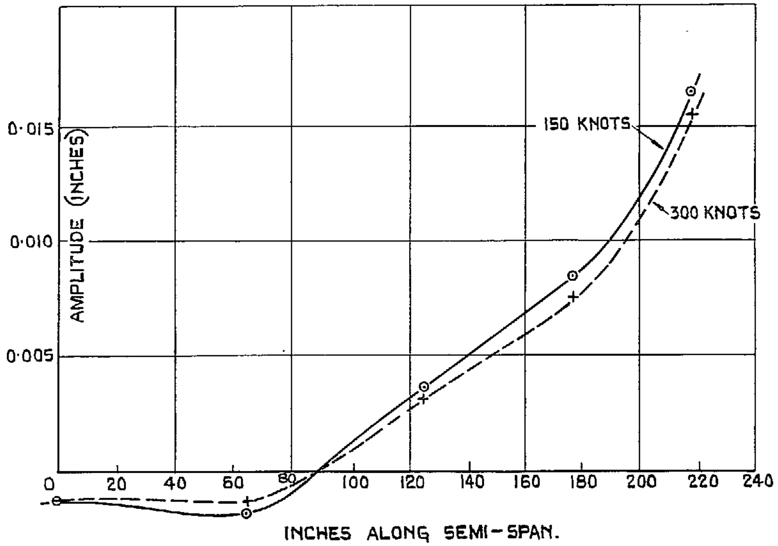


(b) 10·8 C.P.S. MODE.

Fig. 14a and b. Two vertical bending modes of fuselage vibration measured at two airspeeds.



(a) 7·9 C.P.S. MODE.



(b) 10·8 C.P.S. MODE.

Fig. 15a and b. Two symmetrical modes of wing vibration measured at two airspeeds.

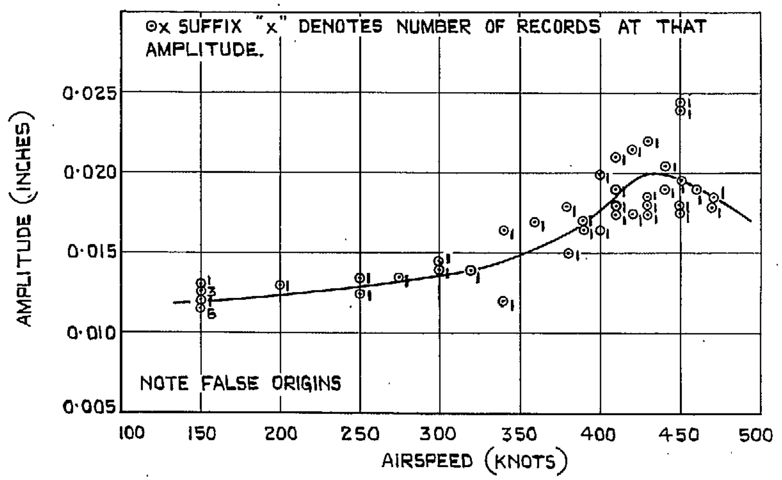


FIG. 16. Amplitude response curve from tail cone transducer for 10·8 c.p.s. resonance.

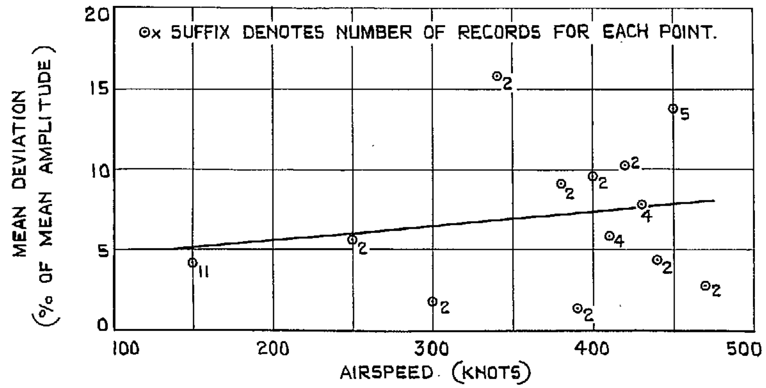


FIG. 17. The effect of airspeed on the scatter of resonant amplitudes measured at the tail cone in the 10·8 c.p.s. mode.

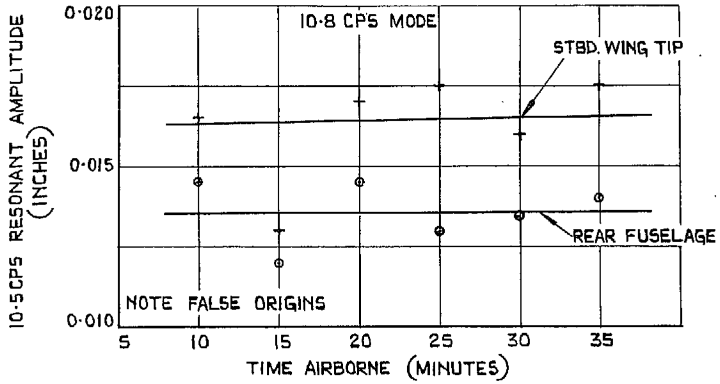


FIG. 18. Variation of aircraft response at 300 knots during a typical flight.

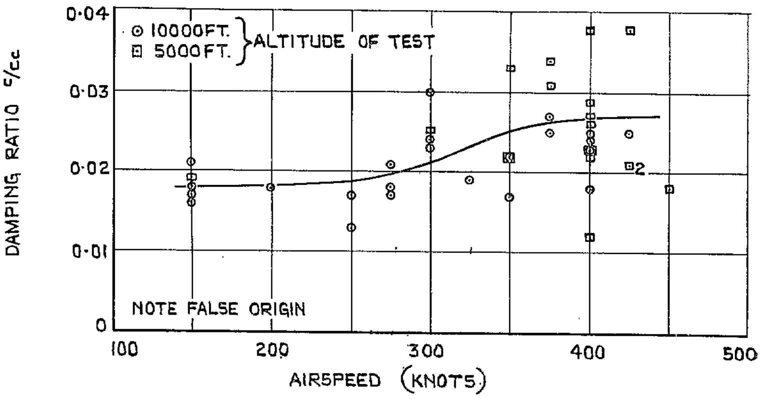


FIG. 19. Damping ratios obtained from decay records of the 10·8 c.p.s. mode

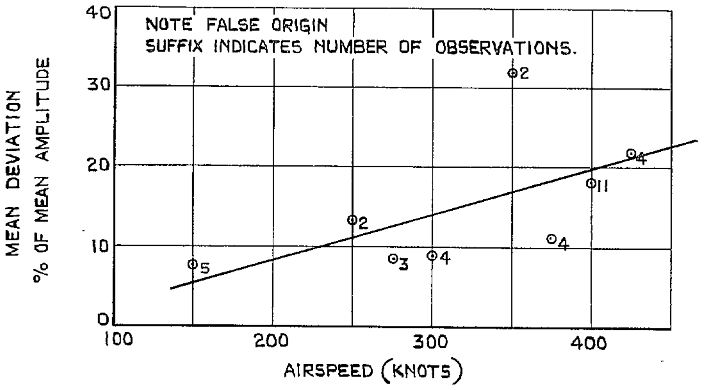


FIG. 20. The effect of airspeed on the scatter of damping measurements in the 10·8 c.p.s. mode.

Part II. Comparative Flight Flutter Tests using the 'Decaying Oscillation' and 'Amplitude Response' Techniques

By W. T. KIRKBY and P. D. R. LUSCOMBE

Summary. Two techniques of flight flutter testing have been evolved; the 'amplitude response' technique, in which a variable frequency sinusoidal force is applied to the aircraft, and its response observed at increments of airspeed, and the 'decaying oscillation' technique in which the transient responses in the modes under consideration are observed over a similar series of airspeeds.

A series of experiments is described which were made on a *Meteor* aircraft to compare these techniques. Typical records and results are illustrated and their significance is discussed.

It is considered that the results obtained from the decaying oscillation technique are more valuable than those obtained from the amplitude response technique. However, in the presence of buffeting, analytical difficulties may make it desirable to use a technique in which both methods are combined.

---

1. *Introduction.* Two techniques for flight flutter testing are at present being used; one is known as the 'continuously forced oscillation', or 'amplitude response' technique, and the other as the 'decaying oscillation' technique. In both cases an indication of approach to a critical flutter speed is obtained by observing the stability trends of the aircraft modes of oscillation in flight as the airspeed is increased. In the amplitude response technique a sinusoidal force of variable frequency is applied to the aircraft structure and the amplitude response in the appropriate modes is measured as the airspeed is increased. For the range of damping values of interest in flight flutter testing, the maximum forced amplitude on resonance in a mode is approximately inversely proportional to the relative damping ratio for that mode, and hence the variation in amplitude response for a particular mode with increasing airspeed gives an indication of the variation in relative damping ratio. No absolute values of damping ratio are obtained in this technique and the stability trend is inferred from the assumption that the damping changes, as air speed is increased, are inversely proportional to the resonant amplitudes in the relevant modes. In the decaying oscillation technique, absolute values of the stability are obtained by exciting the relevant modes and allowing the amplitudes to decay freely to zero; the values of damping, which are a direct measure of the stability, are deduced from the rates of decay and therefore the stability trend can be established positively.

The amplitude response technique originated in Germany in 1935 and was advocated primarily by von Schlippe[1]. It is known to have been applied there subsequently, with success, on several prototype aircraft. It was first applied in the United States in 1939 and in this country in 1953. The decaying oscillation technique was proposed in Russia in 1936 in a paper by Grossman[2], but no reference has been found to any subsequent application of the method which may have been made in Russia, nor does it appear to have come into general use elsewhere until 1943.

A programme of experimental research and development work on flight flutter test techniques and associated equipment was commenced in this country in 1953 and, as the work progressed, it became apparent that a direct comparison of the application of the two techniques to the same aircraft would provide valuable information with which to assess their relative merits. All the information that was available at that time had been obtained from individual applications of each technique to different aircraft, which was not felt to be a sound basis for direct comparison.

Accordingly, an aircraft was instrumented with equipment which could be used to apply both techniques consecutively in any flight: the amplitude response and the damping associated with two flight modes was investigated over the performance range of the aircraft. The results obtained with the two techniques are given in this report.

2. *Aircraft Instrumentation.* The tests were made on a *Meteor* 8 aircraft, which is a twin-engined single-seat fighter of conventional semi-monocoque stressed skin construction: the general configuration of the aircraft may be seen in Fig. 1. The excitation and recording equipment, which is outlined below, is described in detail in Ref. 3.

2.1. *Excitation Equipment.* A linear inertia exciter (10 lb in. out-of-balance) was fitted in the nose of the aircraft (*see* Fig. 1) with the forcing axis vertical. By means of the associated controlling equipment a continuous sweep was made automatically through a selected frequency range, so that amplitude response measurements could be obtained. Also, the pilot could stop the exciter very rapidly at any point in the frequency range, in order to obtain decaying oscillation records. The frequency range covered, the time of sweep, and the frequency-time relationship could be pre-set independently before flight. For the tests described in this Report, a sweep rate was chosen such that errors in peak amplitudes would not exceed 5 per cent, and errors in apparent resonant frequencies would not exceed 1 per cent.

2.2. *Recording Equipment.* Multichannel vibration recording equipment was used to measure the vertical vibration amplitudes on the aircraft structure and controls at thirty-two positions (*see* Fig. 1). Thirty inductance accelerometers and two velocity transducers were fitted. Signals from any group of twelve accelerometers, selected before flight, were fed, *via* integrating amplifiers, together with the integrated signals from the two velocity transducers, to a fifteen channel galvanometer recorder. To enable the instant of cut-off of the excitation to be related to the vibration waveforms, a signal from the excitation equipment was recorded on one channel. The section of typical record shown in Fig. 2a was recorded during a continuous excitation sweep through a resonance at 10·5 c.p.s. A corresponding record in which the excitation was cut-off on the resonant condition in order to obtain the decaying oscillation is shown in Fig. 2b.

3. *Scope of Tests.* In making the comparison, the stability trends of two flight modes were measured, firstly using the amplitude response technique and, secondly, using the decaying oscillation technique for each mode. The modes concerned were both symmetrical vertical bending modes, one being at approximately 8 c.p.s. and the other at approximately 10·5 c.p.s.: the modal shapes, as measured in flight at 150 knots, are shown in Fig. 3. Previous work[3] had shown that there were large differences in the stability trends for these two modes although no critical flutter condition was encountered in the aircraft performance range.

The stability measurements were made at a series of airspeeds over the range of 150 to 470 knots. The airspeed was increased by 50 knot increments at first, but after 250 knots was reached the increments were reduced successively until 380 knots was reached, after which 10 knot increments were used. The range 150 to 420 knots was covered at 10,000 ft, 420 knots being the limiting speed of the aircraft at this altitude. It was therefore necessary to reduce the altitude to 5,000 ft for the remainder of the range. A number of repeat observations were taken in the above speed range at this lower altitude and the amplitudes measured could not be distinguished from those at 10,000 ft. In each flight three increments of airspeed were covered; at each increment the two techniques were applied consecutively, with the minimum delay between each run to ensure that both the flight conditions and the aircraft state should be virtually identical. A reference record was taken at 150 knots on each flight and also the increments of airspeed on each successive flight were overlapped by two increments, to give a check on the repeatability of the measurements.

The flight technique, briefly described below, is discussed in detail in Ref. 3. After trimming the aircraft into straight and level flight at the required speed and altitude, the pilot started the excitation equipment, and the exciter ran through the preset frequency range, the recorder operating automatically at the appropriate time. A meter in the cockpit gave an indication of vibration amplitude, and the pilot noted maximum readings at each resonance. When the exciter stopped on completion of this frequency sweep, a 180 deg turn was made onto a reciprocal course, so as to remain in the same general air conditions, and the exciter was run again. As the appropriate amplitude meter reading was approached, the pilot operated the 'emergency stop' system, which stopped the exciter very quickly, thus a record was obtained of a decaying oscillation. This technique was repeated at each increment of airspeed for each desired frequency. The pilot often had some difficulty in finding smooth enough air to obtain good records, and occasionally considerable distances were flown in search of satisfactory conditions.

4. *The Test Results.* 4.1. *The Curves of Amplitude Response and Damping.* The variation in amplitude response with airspeed at two different positions on the aircraft structure is shown for the 8 c.p.s. and 10·5 c.p.s. resonances in the curves of Figs. 4a and 5a. Corresponding curves showing the damping values measured in decaying oscillations at these resonances are also shown in Figs. 4b and 5b; in these cases the readings obtained at the two positions on the aircraft structure showed no different trends, outside the range of scatter, consequently one curve only is shown for each mode. Graphical analytical methods were used (*see* Ref. 3) in measuring the amplitude and damping values from the records. Buffeting first became noticeable, superimposed on the records, at 300 to 325 knots and increased in severity with increase in airspeed. Because of this, there was a corresponding increase in the difficulty of making an accurate analysis of the records at the higher airspeeds. The points plotted in all cases are the arithmetic mean of a number of measurements at each condition: the numbers of measurements from which the averages were taken are shown adjacent to each point.

4.2. *Amplitude Response Measurements.* The results obtained for the 8 c.p.s. mode at both positions in the aircraft (*see* Fig. 4a) show that the amplitudes which were excited were steadily decreasing as the airspeed was increased, which indicates a corresponding increase in the stability of that flight mode.

The results obtained for the 10·5 c.p.s. mode, shown in Fig. 5a, are not so straightforward, as the measurements which were taken at the starboard wing tip show, in general, a decrease of amplitude with increase of airspeed, which apparently indicates an increase in the stability, whereas the amplitudes measured in the rear fuselage rose by approximately 70 per cent between 150 and 440 knots and indicate a progressive reduction in stability up to this speed. Between 440 and 470 knots the stability trend at the rear fuselage position was reversed but the mean amplitudes at 470 knots were still some 50 per cent higher than those at 150 knots. In view of the conflicting evidence obtained from the measurements at the two points on the structure it is clearly impossible to decide from this evidence alone how the stability of the mode was, in fact, changing with variation in airspeed. Frazer and Jones published a paper[4] in 1938 in which they showed, from theoretical considerations, that such ambiguities could arise in applying the amplitude response technique: the measurements in relation to the 10·5 c.p.s. mode provide a striking example of this difficulty arising in practice.

Considerable scatter of the amplitude measurements became evident where repeat readings were made at each flight condition. The mean deviation varied considerably between zero and nearly 16 per cent, as shown in Fig. 6, but the 'best lines' drawn for the tail-cone and the wing-tip results both indicate an increase in scatter with increasing airspeed. It is thought that day to day variations in the aircraft response accounted for much of the scatter, and that the increased scatter evident at the higher speeds was associated with analytical difficulties caused by the presence of buffeting responses on the records. Recent developments may eventually alleviate this problem. Variable area trace recordings of aircraft vibrations in flight have been obtained, using a modified I.T.3–1 recorder, and subsequently analysed by electronic means by playing back the record. Although continuous excitation records are a rather different problem, due to their varying frequency, it is probable that a frequency-amplitude spectrum could be obtained with the existing apparatus, by suitable manipulation of the analyser; this has not been attempted yet, as the special recorder has not been available for such tests. Magnetic tape recording apparatus may also provide a convenient means of obtaining suitable records for electronic analysis.

The phase-amplitude plotting technique suggested by Kennedy and Pancu[5] has been used in Ground Resonance Testing, and it is possible that it may supersede the simple amplitude response technique if suitable recording and analysis apparatus can be devised in order to apply it to flight measurements[6] with sufficient accuracy.

4.3. *Measurements of Damping.* The damping measurements for both the 8·0 c.p.s. and 10·5 c.p.s. modes show that in each case the damping, which is a direct measure of the stability was increasing as the airspeed was increased. (*See* Fig. 4b, 5b). In the case of the 8 c.p.s. mode the rise was comparatively rapid—the damping increasing by 150 per cent between 150 and 300 knots; for the 10·5 c.p.s. mode the rise was more gradual giving approximately 50 per cent increase between 150 and 450 knots. In both cases there was good agreement between the values of damping measured both at the wing tip and the tail unit. The scatter, when repeat readings were made at each flight condition, was more severe than the corresponding scatter for the amplitude response measurements, the mean deviation increasing from 7½ per cent at 150 knots to 22 per cent at 450 knots. At speeds above 450 knots it became virtually impossible to analyse the records because of the superimposed buffeting.

The analysis of decaying oscillation records may be facilitated in the future by electronic methods of filtering off unwanted signals[7], using tape recording techniques. Experiments are going on at present at R.A.E. to evaluate the method using existing ground based apparatus.

5. *Summarised Comparison of the Results using the Two Methods.* To facilitate comparison of the two methods the more important features of the results obtained in each case are summarised below:

(1) Damping measurements yield a parameter, the damping coefficient (C/C_c), the value of which is not dependent on the part of the aircraft at which it is measured. The magnitude of the damping coefficient indicates the degree of dynamic stability of the aircraft in the mode concerned and its variation with airspeed indicates the stability trend, and thus the proximity of a critical flutter speed.

(2) Amplitude response measurements alone cannot give a precise indication of the stability trend, as the responses at different points on the aircraft may be affected by changes in 'modal' shape with airspeed, giving differing amplitude response trends at the various points. However, some general indication of the stability trend can be obtained by considering together the responses at a number of points on the aircraft, although no absolute value of the stability can be deduced from these differing responses.

(3) In both methods accurate graphical analysis of the results becomes difficult when buffeting is superimposed on the forced or transient oscillations, but it appears that under such adverse conditions the amplitude response measurements are less difficult to analyse, and exhibit less scatter in the results.

6. *Conclusions.* 6.1. Provided that flight conditions are sufficiently good to allow reasonably 'clean' decaying oscillation records to be obtained, the decaying oscillation technique will provide an unambiguous indication of the trend of the flutter stability of the aircraft, irrespective of the points of measurement, whereas when using the amplitude response technique, measurements must be taken at several points on the aircraft structure because the results obtained at a single point can be misleading. However, under adverse buffeting conditions, when analysis becomes difficult, the amplitude response technique will produce more accurate results than the decaying oscillation method.

6.2. If a specific flutter investigation is to be undertaken on an aircraft prototype it therefore seems desirable to operate both methods together. This may be done in the same way that the comparative records were obtained during the experiments described above. Then, if analysis of decay records becomes impossible at any particular flight condition, appropriate amplitude response results will be available, and may be used as a basis on which to extend measurements to the higher airspeeds using this technique alone.

6.3. If electronic methods eventually provide reliable analyses for both types of record, a technique providing reliable damping coefficients would undoubtedly be preferable to a simple amplitude response technique. This may rely on decaying oscillation methods, or may be a perfected phase-amplitude plot technique.

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Ref. No.	*Author*	*Title, etc.*
1	B. Von Schlippe	Zur Frage der selbsterregten Flügelschwingungen. (Ermittlung der kritischen Geschwindigkeit durch Flugschwingungsversuche). Luftfahrtforschung, Bd. 13. No. 2. 1936.
2	E. P. Grossman	Flutter. U.S.A.F. Tech. Report No. F-TS-1225-IA. May, 1949.
3	P. D. R. Luscombe	A description of the excitation and recording equipment used for Flight Flutter Tests on a *Meteor* 8. Part I of this R. & M.
4	R. A. Frazer and W. P. Jones	Forced oscillations of aeroplanes, with special reference to von Schlippe's method of predicting critical speeds for flutter. A.R.C. R. & M. 1795. 1937.
5	Kennedy and Pancu	The use of Vectors in vibration measurement and analysis. *J. Ae. Sci.* No. 11. Vol. 14. p. 603. November, 1947.
6	E. G. Broadbent	Vectorial analysis of Flight Flutter Test results. A.R.C. R. & M. 3125. February, 1958.
7	R. Mazet	Some aspects of Ground and Flight Vibration Tests. O.N.E.R.A. Tech. Note (34), 1956, France. A.R.C. 19,410. April, 1957.

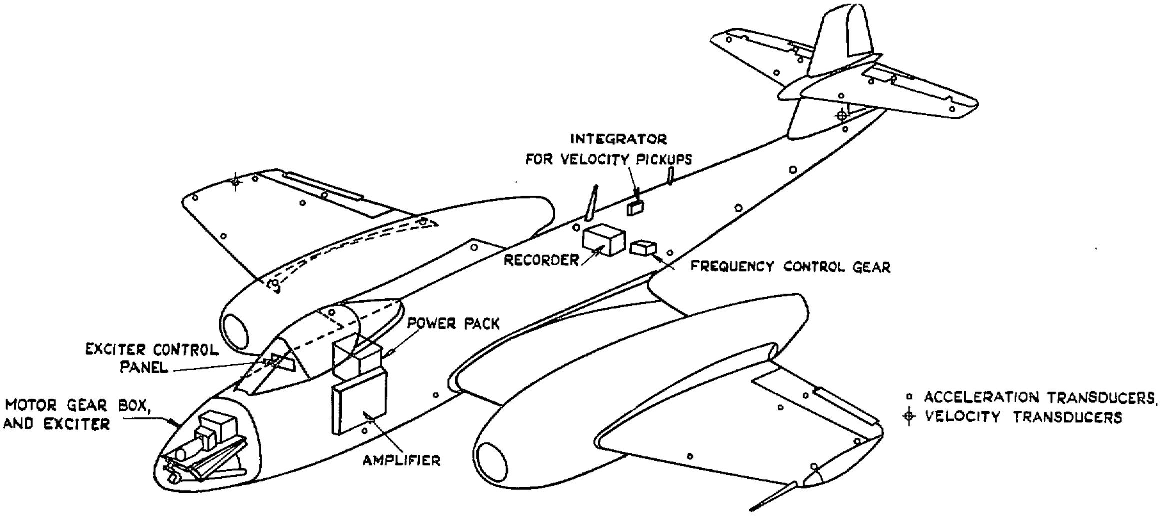


FIG. 1. General arrangement of flight flutter test equipment in *Meteor* aircraft WK 878.

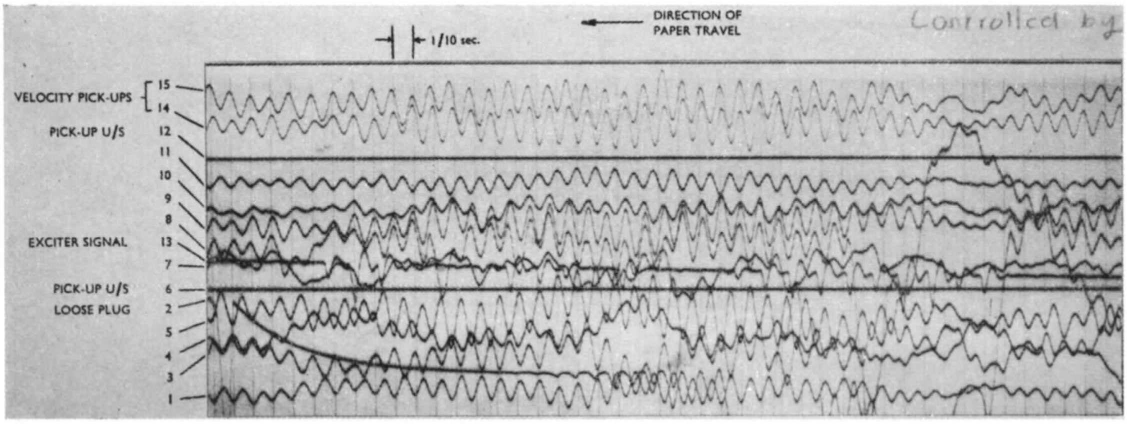


FIG. 2a. Sweep through 10·5 c.p.s. resonance at 350 knots.

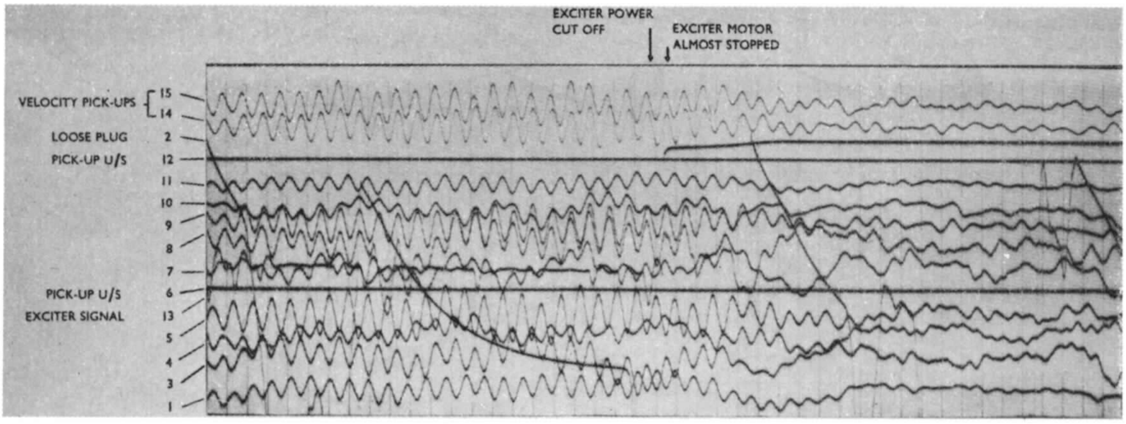
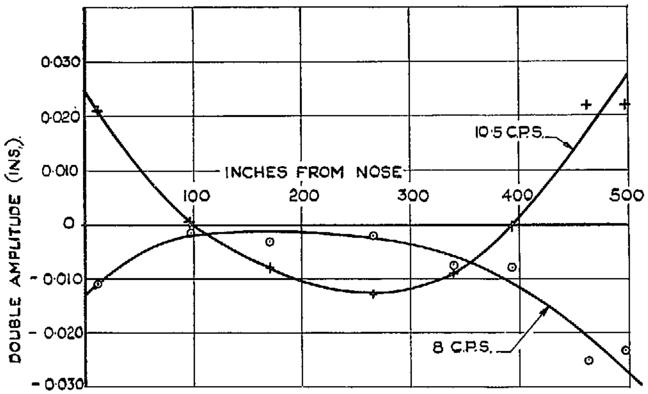
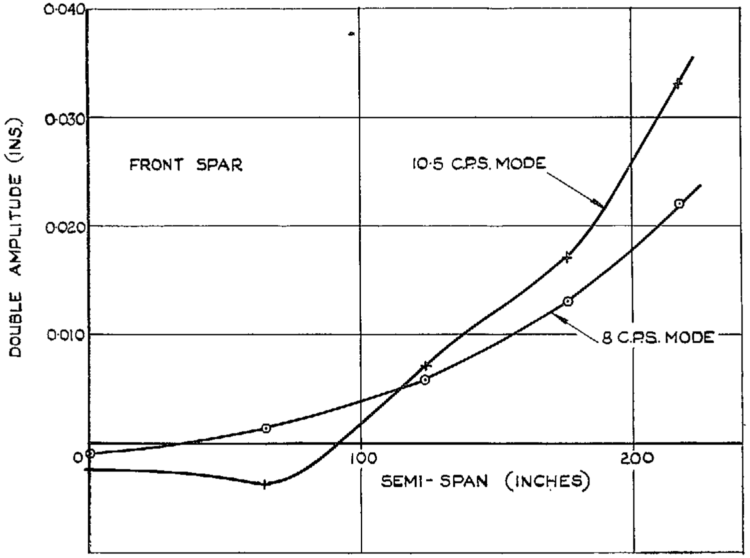


FIG. 2b. Decaying oscillation from 10·5 c.p.s. resonance at 350 knots.

FIG. 2. Sections of typical records.

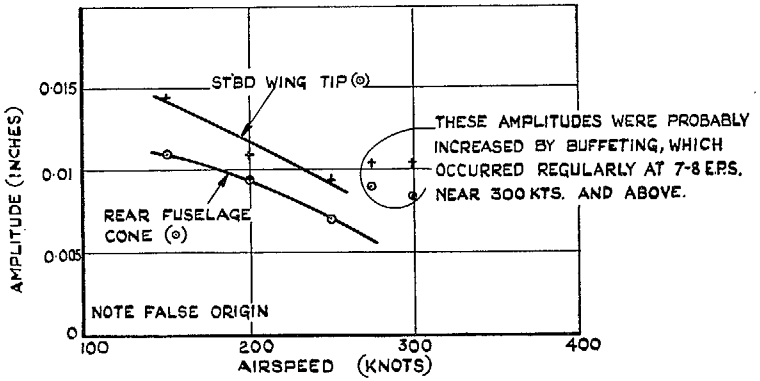


(a) FUSELAGE MODES AT 150 KTS

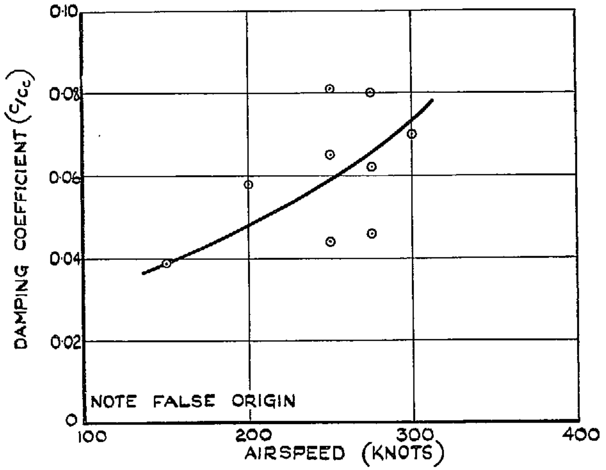


(b) SYMMETRIC WING MODES AT 150 KTS.

FIG. 3a and b. Typical vibration modes measured in flight.



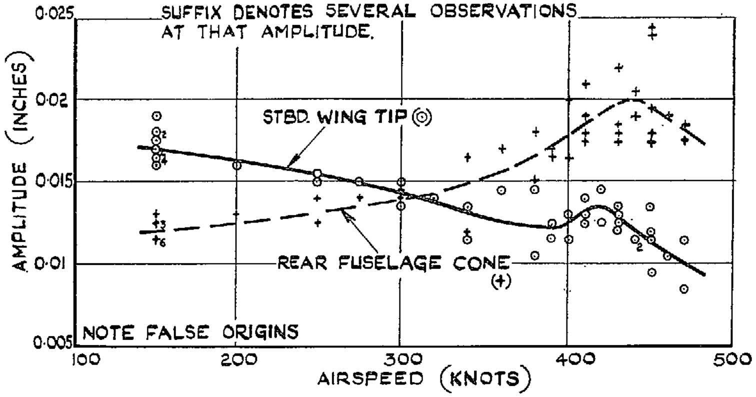
(a) AMPLITUDE RESPONSE OF 8 C.P.S. MODE.



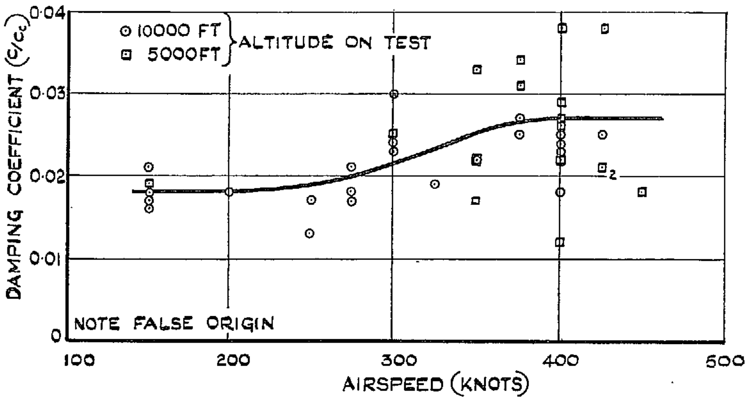
(b) RELATIVE DAMPING OF THE 8 C.P.S. MODE.

FIG. 4a and b. Comparison of variation in amplitude response and relative damping with airspeed in the 8 c.p.s. mode.

(83579) Wt. 87/1876 K.5 3/62 Hw.



(a) AMPLITUDE RESPONSE OF 10·5C.P.S. MODE



(b) RELATIVE DAMPING OF THE 10·5C.P.S. MODE.

FIG. 5a and b. Comparison of the variation in amplitude response and relative damping of the 10·5 c.p.s. mode.

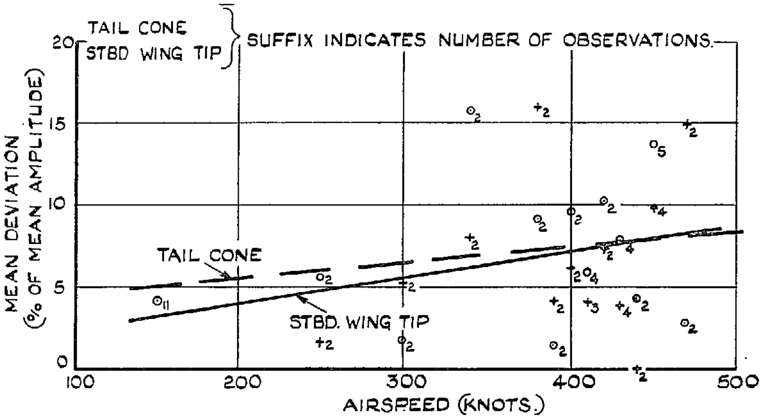


FIG. 6. Effect of airspeed on the scatter of resonant amplitudes measured in the 10·5 c.p.s. mode.

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