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# Vibration and Flutter Flight Testing

By

M. O. W. Wolfe

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# Vibration and Flutter Flight Testing

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M. O. W. Wolfe

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## SUMMARY

A review is made of the techniques that have been developed or are being developed in the United Kingdom for flight vibration testing and flight flutter testing aircraft. This includes a description of the instrumentation used for recording the Vibrational response, and a comparative assessment of the various methods used for exciting the aircraft in flight flutter tests.

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## 1 Introduction

The expansion of our knowledge of the flutter of aircraft has not kept pace with the rapid changes in aircraft design and the considerable increases in speed that have followed the introduction of the gas turbine engine. In particular the extent of our knowledge of the aerodynamic forces involved in flutter is at present inadequate for the satisfactory prediction of the flutter characteristics of an aircraft at high air speeds from data provided by pre-flight experimental and theoretical investigation. In view of our limited resources for research on flutter and the continuous advances in aircraft performance this situation is not likely to change materially for some considerable time. Consequently, despite experiments and calculations carried out at all stages of a prototype development prior to flight, the possibility of flutter being encountered, particularly flutter involving the control surfaces, cannot be ruled out. The increases in aircraft speed have not only enhanced the likelihood of flutter occurring but have also led to an increase in the level of aerodynamic excitation due to buffeting and Mach number effects. Moreover, a condition of low damping due to a near approach to a critical flutter condition can considerably augment the response of the structure to aerodynamic forces.

It is therefore realised in the United Kingdom that elaborate and accurate techniques of Flight Vibration Testing*, and in certain circumstances Flight Flutter Testing** are of very great importance as means of obtaining the essential data on vibration and flutter characteristics necessary for the clearance of prototype aircraft. At the present time, in view of the practical difficulty of installing the necessary equipment and conducting comprehensive Flight Flutter Tests on all prototypes, our policy is to ask for a comprehensive Flight Flutter Testing programme only in those cases where marginal stabilities have been predicted by pre-flight investigations. In all other cases we are proposing, as a minimum requirement, to make the installation of multi-channel vibration measurement equipment and a programme of flight vibration tests mandatory for one prototype of all new Service aircraft.

## 2 Instrumentation for Vibration Measurement in Flight

### 2.1 The General Measurement Problem

The essential information required for the diagnosis of a vibratory condition on an aircraft is the frequency and mode of the oscillation involved. To resolve an aircraft mode from measurements made in flight it is necessary to know the linear translation amplitude ratios between a certain minimum number of points on the structure and their phase relationships for the frequencies concerned, and corresponding data for the angular displacements between certain parallel planes in the structure including the control surfaces and tabs. The modes of the main structure and lifting surfaces can usually be resolved adequately by using linear translation transducers deployed at appropriate points on the structure. For example, in the case of a wing the pickups are deployed chordwise in spanwise pairs, each pair comprising one transducer on the main and one on the rear spar.

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* By Flight Vibration Testing is meant the measurement of the vibration frequencies of an aircraft and their associated modes in flight without deliberate artificial excitation of the aircraft

** By Flight Flutter Testing is meant a technique of testing involving artificial excitation of the aircraft in flight with the object of obtaining the damping in its modes of vibration.

This arrangement is usually found to be satisfactory for resolving the rotational and vertical translational components of motion. An important analytical difficulty arises, however, with this method of measurement when a phase difference exists between the translational and rotational components of motion.

The difficulty may be illustrated by reference to the diagram in Fig. 1(a) which shows a chord section of a wing which is assumed to have out of phase motions of rotation and vertical translation. These motions are referred to a spanwise axis passing through O, which for simplicity is assumed to be equidistant from the points A and B at which transducers measuring vertical translation are placed. Referring to the vector diagram of Fig. 1(b), the amplitude of the translational component of wing motion is assumed to be C and the amplitude of rotational motion $\theta$, and the phase difference between them $\alpha$. The rotational motion produces additional translational motions $\ell \tan \theta$, where $\ell$ is the distance of O from A and B. These components are shown as x and -x on the vector diagram. The translational amplitudes a and b measured at A and B are therefore the vector sums of C and x, and C and -x respectively, and have some phase difference $\beta$ depending on the values of A, $\theta$ and $\alpha$.

Where there is no noticeable phase difference, the usual method of determining the components of motion from the readings of linear translation transducers disposed in this manner is to take half the sum of a and b as being the translational component, and half their difference as being the rotational component. However if the rotational component is small compared to the translational component, it will be clear from a consideration of the vector diagram shown in Fig. 1(c) that a very small phase difference between the measurements at a and b does not necessarily imply a correspondingly small phase difference between the components of the motion. In fact, on a conventional multi-channel record, particularly if it contains random transient frequencies due to aerodynamic disturbances, a large phase difference between the components of motion may not only be difficult to resolve but may not actually be noticed.

To overcome this difficulty a non-seismic rotation sensitive transducer has been developed in this country particularly for control surface and tab measurements where the detection and measurement of phase differences in the motion are most important from the flutter aspect.

## 2.2 Instrumentation

A considerable amount of work has been done in this country in recent years on the instrumentation problem. There are three main aspects of this problem namely, the development of suitable transducers, the development of suitable amplifiers and finally the analysis problem. The latter is not strictly an instrumentation problem only, but it arises because of the increasing difficulty of analysing conventional multi-channel trace records, and the desirability of recording the information in a manner which would permit the data to be dealt with directly from the records by computational machines.

Several different types of transducers are in current use for vibration measurement. The one which has undergone the greatest development and which is found to be the most useful for flight vibration and flutter measurements is the Lan Elec Inductance Accelerometer[1]. This is similar in principle to the corresponding American Miller instrument but is in many respects a better transducer. In particular the Miller instrument has been found to be unsuitable for high altitude applications because of leakage of damping fluid. The Lan Elec accelerometer incorporates a differential pressure compensating device and does not suffer from this defect.

The main advantages of the inductance accelerometer for this work are that the instrument itself is quite small and can be used in the range from 0 to 100 c.p.s. without integration, and from 2 to 100 c.p.s. with integration. It can also be used satisfactorily in manoeuvres involving applied g, conditions for which certain other types of instrument are unsuitable.

## 2.3 Amplifiers

Two types of amplifier are tending to become standard for flight vibration testing, one a straightforward A.C. amplifier with single integration for use with generator type transducers, and the other a carrier type of amplifier with double integration for use with inductance accelerometer type transducers. In both cases one of the major problems of development has been miniaturisation because of the installation problem on small fighter type aircraft. Examples of the lastest type of equipment are shown in the photograph, Fig.2. Both types of amplifier are interchangeable. The integration characteristics for the carrier type amplifier are shown in Fig.3[2].

## 2.4 Recorders

The multi-channel mirror galvanometer type of recorder has been found to be the most suitable for flight vibration testing. Here also the question of miniaturisation is important, and miniature multi-channel recorders are being developed in this country. The analysis problem is intimately associated with that of recorder design. The conventional multi-channel trace record is, in some cases, no longer a satisfactory method of presentation for analysis purposes because of the complexity of the vibrations encountered on high speed aircraft. For this reason multi-channel play-back recorders of the photographic and magnetic tape type are being developed to enable subsequent anlyses to be made by means of electronic wave analysers.

A twelve channel photographic type, operating on the variable area trace principle has been in use at the R.A.E. for some time in conjunction with a Muirhead Pamedra Wave Analyser. It was employed, for example, on the Comet I accident investigation for the recording and analysis of the complex high frequency panel vibration excited by jet efflux effects.

The main advantages of this technique are that it enables the amplitudes of component frequencies in a complex wave form to be determined accurately, and for a particular frequency, for example a flutter frequency involving motion of main surfaces and controls, it makes possible the measurement of phase difference between the motions of different parts of the structure where the motions are complex.

## 3 Flight Vibration Testing

Most of the flight vibration testing carried out in this country is done on prototype aircraft during the flight development phase. During the early stages the object is to detect and measure vibrations when they arise with a view to establishing the cause and providing the data to effect a cure in severe cases. At a later stage tests are necessary to show that the aircraft meets specification requirements in respect of permissible vibration levels.

Aircraft vibration may be classified into two broad categories:-

(1) forced vibration, e.g. mechanical vibration and buffeting in which the main agents are the excitation and the resonance properties of the structure,

(2) vibration characterised by a poorly damped mode, resulting in high vibrational response under moderate excitation.

The vibrations under group (1) are those associated with a definite source of excitation and of which the significant features are the magnitudes of the exciting forces and their frequency relationships to the natural frequencies of the aircraft. The primary object of flight vibration testing in these cases is to identify the source of the excitation and the nature of the aircraft's response so that curative measures involving either reduction or elimination of the source, or detuning to avoid resonance may be undertaken.

The vibrations under group (2) will in general be appreciably influenced by air speed because the damping in a mode is usually critically dependent on the air speed. In the extreme, a mode may become negatively damped, when flutter occurs as a self excited oscillation. The object of the tests in relation to the possibility of these vibrations is to obtain some indication of the possible existence of any poorly damped modes, together with some quantitative measure of the damping and its variation with air speed. For this purpose a technique of Flight Flutter Testing involving deliberate excitation of the aircraft is required.

In general it is not possible to foresee with certainty ab initio to what extent each of the foregoing effects is going to contribute to the vibrations of a particular prototype aircraft, and to cater for all eventualities would involve equipping all prototype aircraft with exciting equipment for exhaustive flight flutter testing, in addition to the measurement equipment. It is felt therefore that the more practical approach is to do flight vibration tests over the whole performance range on one prototype of each new type, attempting to assess the damping in significant modes by simple methods where these are applicable, for example by control jerking and by flights in bumpy conditions, in all cases where marginal stabilities have not been predicted by theory. In other cases exhaustive flight flutter tests are required.

## 4 Typical Flight Programme for Flight Vibration Tests

At moderate speeds and Mach numbers tests are made by increasing the aircraft speed by reasonably small increments (about 20 knots I.A.S.) and recording at each speed. In suitable cases, and where necessary, each cockpit control is jerked in turn, records being taken at each jerk. Ideally the records should be examined after each test before proceeding to the next higher air speed; however at low speeds, and particularly where no instabilities are suspected, this procedure would be unnecessarily restrictive and in practice recordings of several air speeds are made in one flight. If no severe vibration is encountered this procedure is continued throughout the performance range of the aircraft; at high speeds, however, the records are analysed after each 20 knot increment before proceeding to the next, and in the transonic region where rapid changes in the aerodynamic coefficients are likely to be encountered, tests are made at small increments of Mach number, for example increments of 0.02M in the range from 0.8 to 0.9 and increments of 0.01M in the range from 0.9 to 1.1 analysing the records after each increment.

There is always a possibility that unforeseen severe vibrations may arise during a flight covering several airspeed increments without necessarily being observed by the pilot. On large aircraft monitoring devices are provided for the flight observers to guard against this occurrence, and on single seater aircraft it is recommended practice to provide a monitoring device for the pilot to provide him with information on the motions of the control surfaces.

With regard to buffeting, the effects of increasing $C_L$ at a given Mach number may be important. This aspect is investigated by straightforward measurements at increments of $C_L$ at a particular Mach number.

### 4.1 Limitations of Control Jerking

Control jerking as a means of applying a sudden force to an aircraft to excite transient responses with the object of determining the damping in the modes excited has certain limitations. In many cases lack of high frequency response of the control system will not permit the application of a sharp jerk to the control surface. This may impose a low upper limit on the frequency of the modes that can be excited. The technique is therefore used with some discretion because of the possibility of significant modes being overlooked. Its chief virtue, in cases where it can usefully be employed, is its simplicity. Typical examples of stick jerk records taken on a high speed aircraft from which values of damping have been deduced are shown in Fig.4.

### 4.2 Special Problems of Forced Vibration

Certain particular problems of localised severe forced vibrations sometimes arise which require special treatment, examples are buffeting caused by open bomb bays, panel vibrations excited by jet efflux effects and vibrations originating from propeller disturbances. In the first example it is usually necessary to augment the structure vibration measurements by measurements of the fluctuating pressures in, and in the vicinity of, the bomb bay, in order to diagnose the mechanism of the disturbance. In the second example, very severe panel vibrations leading to fatigue failures have been known to occur caused by jet efflux effects. These are characterised by high frequencies and "white" excitation spectra. For this problem acceleration transducers of the Piezo electric type and very sensitive fluctuating pressure transducers capable of covering a frequency range from 0 to 10 Kc/sec are required. In the third example, where severe propeller order aircraft vibration occurs the problem is usually one of determining the mechanism of the energy transfer; whether, for example, the forces are being transmitted mechanically through the engine mountings, or whether they are being transmitted aerodynamically in the form of pressure waves emanating from the propeller blades. Here again it may be necessary to employ fluctuating pressure transducers.

## 5 Flight Flutter Testing

### 5.1 General Techniques

A considerable amount of work has been done on the development of flight flutter testing techniques in this country in the last four years.

The techniques employed may be classified broadly into the following categories, the "continuously forced oscillation" technique and the "decaying oscillation" technique. The former is characterised by a continuous sinusoidal excitation of the aircraft structure or controls by means of a mechanical or some other form of exciter. The excitation frequency is slowly increased from zero over a pre-determined range and the vibration response of the aircraft is recorded by means of multi-channel vibration measuring instruments. This process is repeated at suitable increasing increments of air speed or Mach number, and the amplitude speed responses in the significant modes are deduced from the measurements; an approach to a critical flutter condition being indicated by an increase in amplitude response with air speed.

In the "decaying oscillation" technique either a sudden force is applied to the aircraft, or a sinusoidal force at a fixed frequency is suddenly removed, and the subsequent transient responses of the aircraft structure are measured. The overall dampings in the modes concerned are then deduced from the time rates of decay of the ensuing transient oscillations; the process being repeated at increasing increments of air speed. An approach to a critical flutter condition is indicated by the damping approaching zero. Stick jerking is a crude form of this technique.

The decaying oscillation technique is the more informative of the two, because it not only yields information on the approach to flutter but also gives the values of the relative dampings in the modes concerned over the whole of the air speed range.

Quantitative information on damping cannot easily be derived from the amplitude/frequency curves in the continuously forced oscillation technique. Apart from consideration of flutter prediction a knowledge of the damping in flight modes of vibration is becoming important for other aspects of aircraft vibration, for example in the buffeting problem and in the fatigue problem where the influence of damping on the response of the aircraft to gusts may be significant.

In both techniques the analysis of the flight records becomes difficult when buffeting occurs because the artificially induced oscillations cannot easily be distinguished from those arising from the buffeting. Since buffeting occurs on most high speed aircraft at the upper end of the Mach number and speed ranges the analysis problem is a very relevant one.

It has been found that in buffeting conditions, the degree of experimental scatter of amplitude values at the same flight conditions for several repeat amplitude air speed curves using the continuous oscillation technique has been rather less than the corresponding scatter of damping values for the transient technique. This difference is believed to be almost entirely due to the analytical difficulties referred to.

In comparing the relative merits of these techniques, an important aspect of the continuous oscillation technique should be mentioned. It is a difficulty which arises when the amplitude/air speed curves are derived from a study of the recordings from transducers placed at different positions on an aircraft. Normally the transducer positions chosen are at extremeties such as tail plane and wing tips, and in the control surfaces. It has been found that in certain cases the amplitude/air speed curves for different transducer positions do not always exhibit the same trends with air speed, this being due presumably, to changes in the flight mode of vibration, for example, movement of the zones of minimum amplitude. This difficulty can give rise to some degree of ambiguity in flutter testing, and makes it necessary to record the trends at several transducer positions to minimise the danger of overlooking an important case.

This particular difficulty does not arise in the decaying oscillation technique, because the rates of decay for a given mode must be the same at different points in the structure for a particular flight condition. Analytical difficulties may arise, however, with this technique when two or more transients are excited decaying at different rates.

It has been found that the best technique appears to be a combination of the two methods. A variable frequency exciter is used to locate the amplitude peaks in the frequency range, and a decay record is then obtained by cutting off the excitation as rapidly as possible when tuned to the peak. Both the amplitude response and the damping can then be watched as the air-speed is increased. Even if buffeting is encountered, making the damping estimates less reliable, some guidance can still be obtained from the amplitude responses at different parts of the structure and in the control surfaces.

## 5.2 Methods of Excitation

### 5.2.1 General

The two main types of excitation are: firstly those in which a sinusoidal force of variable frequency is applied to the aircraft structure or controls, and secondly those in which an impulse, or series of impulses are applied. In this country the last type is only used when installation difficulties and time preclude the use of the former type.

### 5.2.2 Single Inertia Exciter

In this technique a single inertia exciter of the rotating out-of-balance weight type is attached to the structure, usually either at the nose or in the rear fuselage of the aircraft. A typical such installation is shown in the nose of a Meteor aircraft in Fig.5. Where necessary, provision is made for lateral as well as vertical excitation by providing two exciters operating in the appropriate planes and incorporating clutching arrangements so that either may be used singly. On single seater aircraft it is usual to employ an automatic frequency sweeping device for the exciter, and the pilot is provided with a visual indication of amplitude and an overriding control of the frequency to permit him to tune to each amplitude peak if necessary On larger aircraft a manual frequency control is normally used.

To enable the decaying oscillation technique to be employed, and to provide the pilot with a rapid means of stopping the excitation, as a safety precaution, two methods of rapid exciter cut-off have been developed. One method employs the principle of regenerative braking, where the exciter is driven by an electric motor, and the other involves the use of a specially designed inertia exciter in which the out-of-balance effect may be cancelled with great rapidity by mechanical means. In a particular design the cancellation can be effected in half of a cycle.

In particular cases symmetric and antisymmetric bending modes of wings and tail units have been excited satisfactorily with this technique. Asymmetric modes have been excited with exciters placed in the wing tip or tail-plane tip.

### 5.2.3 Phased Inertia Exciters

Certain flight modes of vibration may be difficult, or indeed impossible to excite with an exciter placed at a single point in the structure, for example a wing torsional mode. Consequently, a method of driving two or more identical inertia exciters by means of phased D.C.

electric motors suitable for use on ordinary aircraft D.C. electrical supplies has been developed, and at present works satisfactorily in the laboratory. A flight version is at present being installed on a Meteor aircraft.

### 5.2.4 Electrodynamic Excitation of Control Circuits

A method of applying a sinusoidal force to a control circuit by means of a moving coil electrical vibrator has been developed and used in flight. This method has shown promising results, although it is probably only applicable to aircraft having either pure servo tab, or spring tab controls. The advantages of this system are that both the force amplitude and the frequency can be controlled independently in flight, and the force may be removed instantaneously. A further advantage is that the vibrator may be used as a regenerative brake thereby increasing the damping in the control circuit. The vibrator unit as installed in the rudder tab circuit on a Lancaster aircraft fitted with pure servo tab controls is shown in the photograph, Fig.6.

### 5.2.5 Stick Jerking

This method of exciting the aircraft control surfaces is still used on some aircraft with manual or power assisted controls, but only when better methods are not practicable. It is normally only successful in exciting the fundamental frequencies of the aircraft structure. It is of little value on aircraft fitted with fully powered controls. An example of records of transients obtained from stick jerks on the elevator controls of a fighter aircraft at increasing air speeds is shown in Fig.4, a fall in damping with air speed is clearly indicated in this case.

### 5.2.6 Rocket Excitation

The shortcomings of the stick jerk technique combined with the difficulty of installing equipment for continuous excitation on small very high speed aircraft, particularly supersonic aircraft with thin wing sections, has led to the development of a rocket excitation technique. In this technique small rockets are attached to appropriate parts of the aircraft structure and used to provide a thrust of an impulsive nature to excite transient oscillations of the aircraft. One type of rocket unit, known as a "Bonker", is cylindrical in shape, of $1\frac{3}{4}$ inches diameter and $4^5/8$ inches overall length, its thrust is 200 lb and duration 50 milliseconds. A thrust time curve for this unit is shown in Fig.7. The duration can be varied by modifying the explosive charge. Standard times for this unit are 75, 50 and 25 milliseconds. A smaller unit is at present under development. This unit is $\frac{7}{8}$ inches diameter, and of lengths 6, 4 and $2\frac{1}{2}$ inches depending on the corresponding duration times of 50, 25 and 12.5 milliseconds. Its mean thrust is 200 lb, and for ease of installation in thin section wings, tail planes or fins, the thrust axis may be arranged to be normal to the longitudinal axis of the unit.

The units are fired electrically and one great advantage of this technique is that several units deployed at different parts of the aircraft structure can be fired either simultaneously, or in a pre-arranged time sequence appropriate to the frequency and the mode being investigated. In this way some degree of selectivity may be achieved and unwanted modes suppressed.

This technique has been used with success for flutter investigations of prototype aircraft.

On one aircraft a flight flutter test was made on a mode involving tail plane antisymmetric yawing motion at 8 c.p.s. Rockets were fitted at each tail plane tip, firing fore and aft respectively. In this particular case the tail plane was mounted approximately half way up the fin and some degree of fin torsion was involved in the motion. Satisfactory damping/air speed curves were obtained up to the speed at which compressibility buffeting amplitudes became large in relation to the amplitudes excited by the rockets.

In cases such as the foregoing the excitation can be made more effective by firing a second pair of rockets mounted in the same positions as the first pair but arranged to fire in the opposite directions after a time interval equal to half a period of the appropriate oscillation. For this purpose the duration of the rockets must not be greater than half a period of the oscillation.

## 5.3 General Remarks on Technique

One of the difficulties of employing the mechanical inertia type of exciter is that these units are very inefficient at low frequencies. Methods involving the oscillation of a control surface tab overcome this difficulty since they exploit comparatively large aerodynamic forces arising from small applied hinge moments; however this method is limited in scope. An extension of the technique is to employ an auxiliary control surface installed solely for the purpose of excitation. This has never been attempted in this country, but a unit has been designed and is being manufactured with a view to examining the possibilities of the technique. Clearly, such a surface must be irreversible, and the backlash in the system should be as small as possible to avoid any possibility of flutter occurring involving the auxiliary control surface itself. In a particular case this aspect would have to be thoroughly explored.

Another method of producing comparatively large sinusoidal forces at low frequencies which is at present being investigated at the R.A.E. is the use of a rotating rocket nozzle. This involves the use of liquid propellants which are burnt in a combustion chamber, the products of combustion being expanded through a nozzle which is rotated by means of a speed controlled electric motor. In this way the full thrust of the rocket may be applied to produce sinusoidal forces down to zero frequency.

## 5.4 Associated Theoretical Work

It is the policy in this country to carry out comprehensive theoretical calculations, and in some cases wind tunnel model experiments, to determine the flutter characteristics of an aircraft before embarking on flight flutter tests. In particular, advantage is taken of the rapidity with which amplitude/air speed curves can be deduced for modes involving several degrees of freedom on electronic analogue computers.

It is of considerable value in a flight test to have some foreknowledge of the probable shape of the amplitude/air speed, or damping/air speed curves particularly when conditions of low damping are being approached. In fact the theoretical calculations and the flight tests are now regarded as complimentary aspects of the investigation as a whole with "feed back" of information from both sides. In particular, the flight flutter tests may be expected to provide some check on the validity of the aerodynamic derivatives used in the calculations and the number of important degrees of freedom involved in a particular flight mode.

The extent to which good correlation may be achieved between the results of flight tests and calculations is exemplified in the curves shown in Fig. 8. These curves show the calculated amplitude/air speed curves for an aircraft on which a series of flight flutter tests was carried out for a mode of vibration involving primarily elevator rotation and tailplane bending, compared with the curve obtained from the tests. In this case the continuous oscillation technique was employed, and single inertia exciters were installed in the nose of the aircraft for vertical excitation, and in the fin for lateral excitation.

## 5.5 Conclusions

It is considered that, in cases where the equipment can be installed in the aircraft, the continuous excitation method employed to obtain values of damping and amplitude response with air speed for the major amplitude peaks is the best technique of those at present available. Phased inertia exciters provide a further refinement to this technique. In other cases the rocket excitation technique provides the best alternative.

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| No. | Author | Title, etc. |
|---|---|---|
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| 2 | E.T. de la Perelle | An Integrating Amplifier for Instrumentation<br>R.A.E. Tech. Note No. INSTN.144 |

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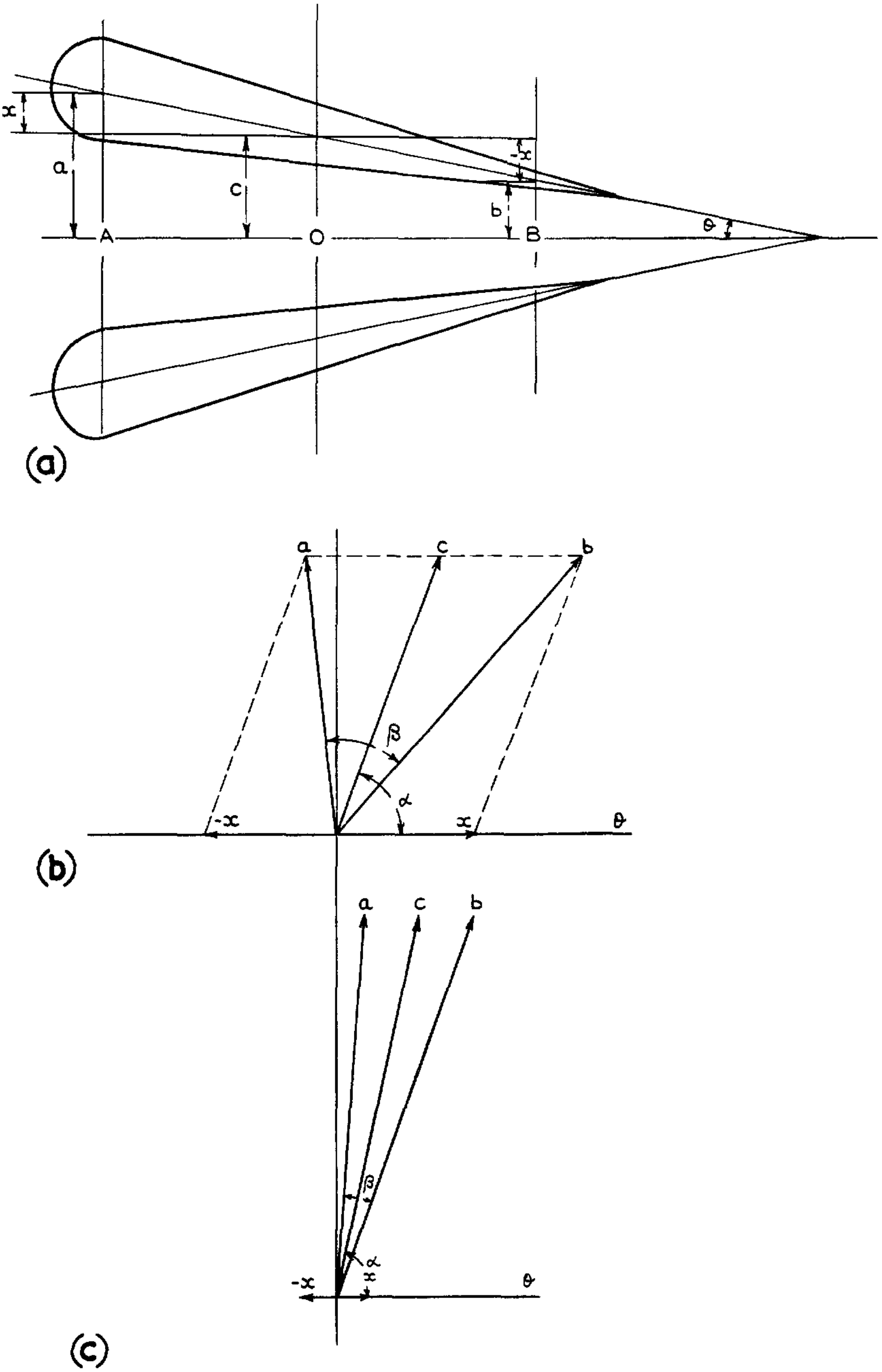

FIG. 1 (a - c) ANALYSIS OF PHASE DIFFERENCE BETWEEN TRANSLATIONAL AND ROTATIONAL COMPONENTS OF WING MOTION.

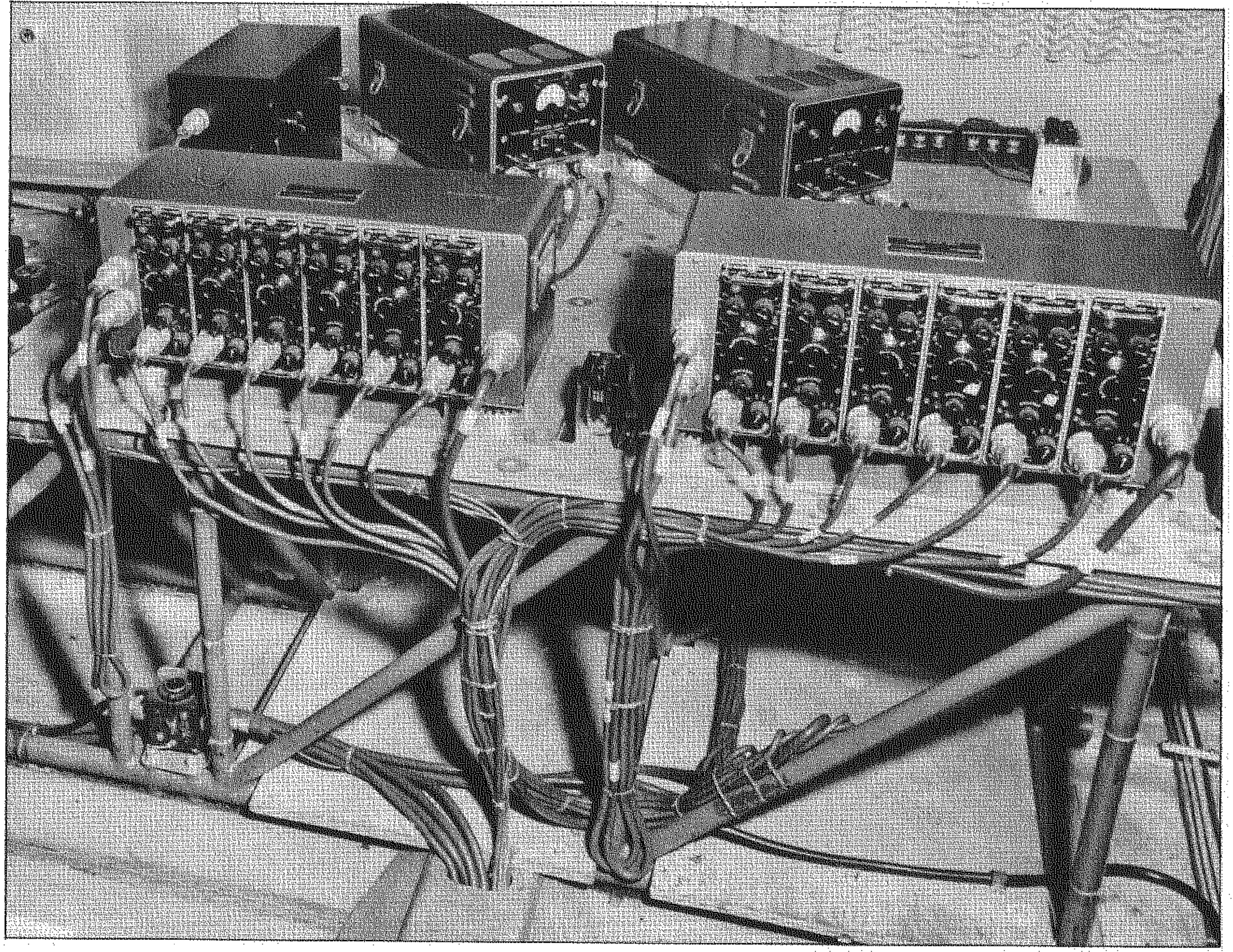

FIG.2. DOUBLE INTEGRATING MULTI-CHANNEL AMPLIFIERS AND RECORDERS

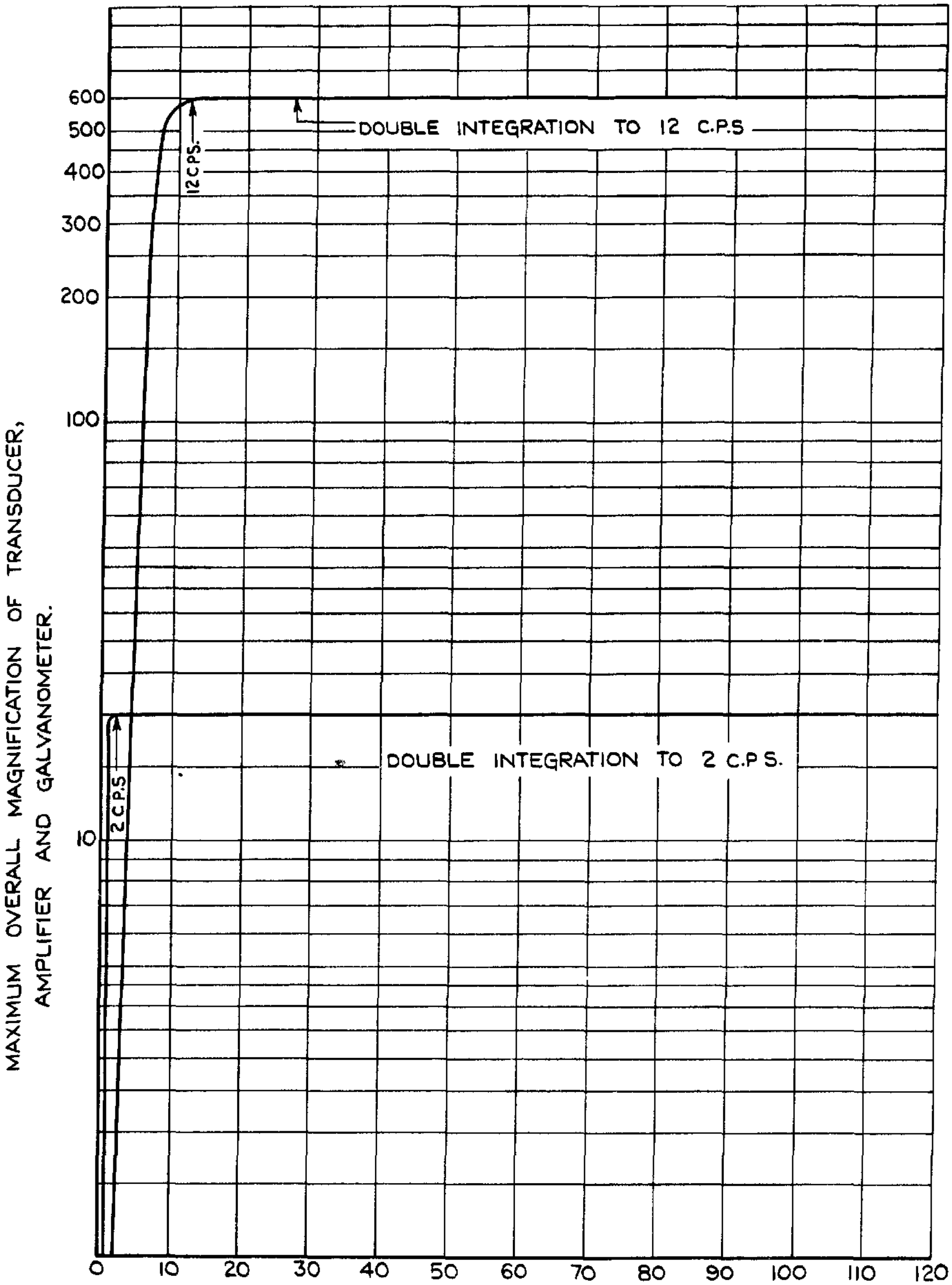

FIG. 3. PERFORMANCE CURVES FOR TYPE IT. I - 6 AMPLIFIERS.

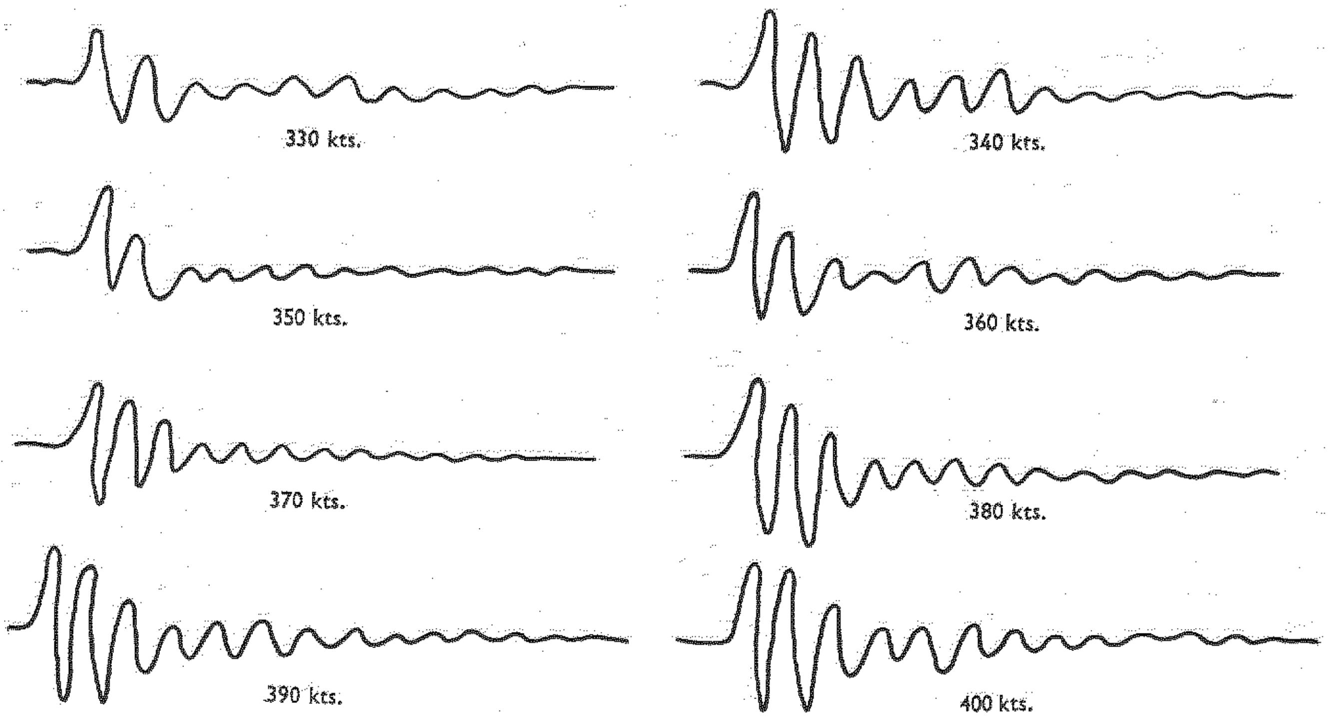

FIG.4. WAVEFORMS OBTAINED FROM STICK JERK TEST ON A JET FIGHTER AIRCRAFT

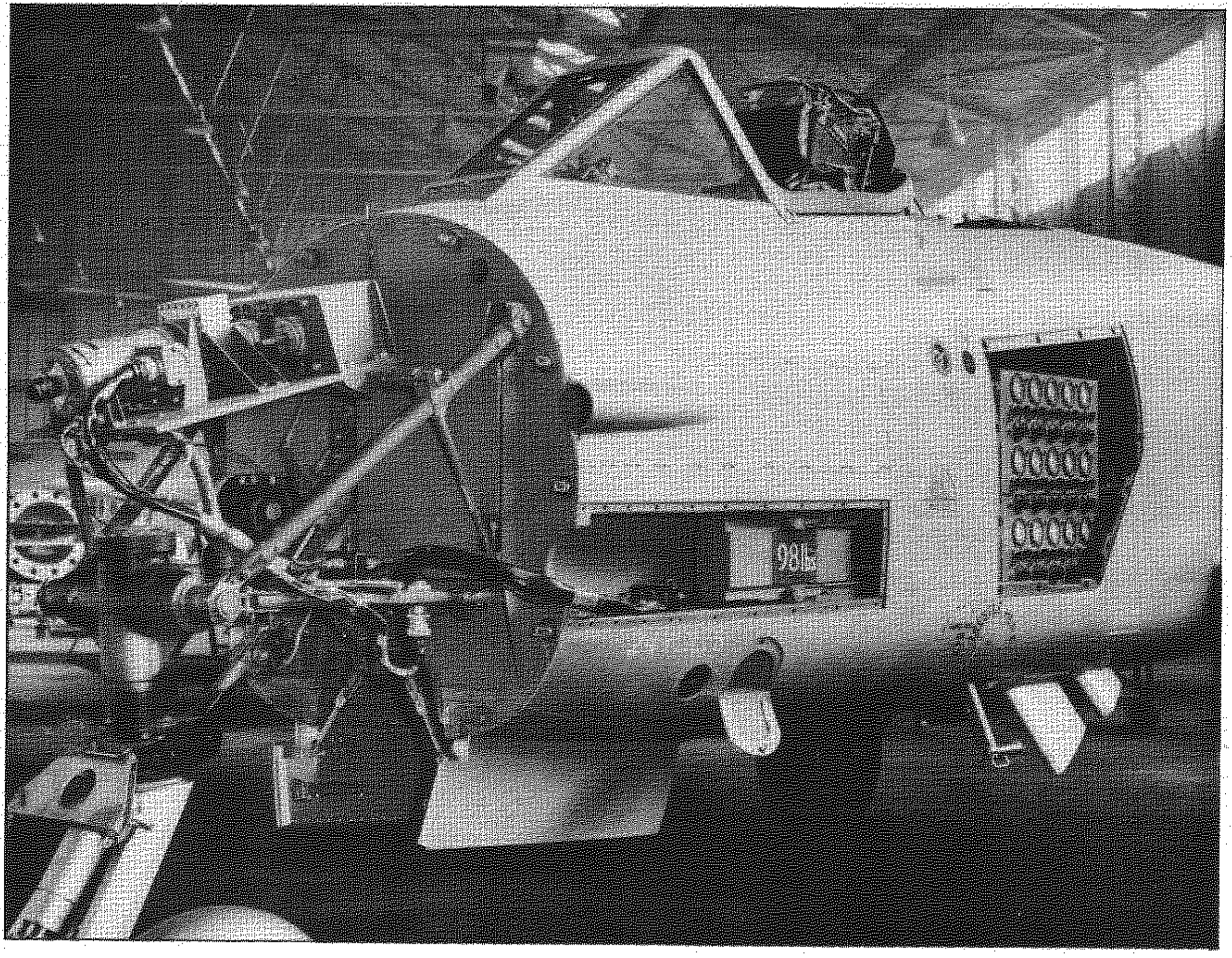

FIG.5. SINGLE INERTIA EXCITER INSTALLED IN THE NOSE OF A METEOR AIRCRAFT

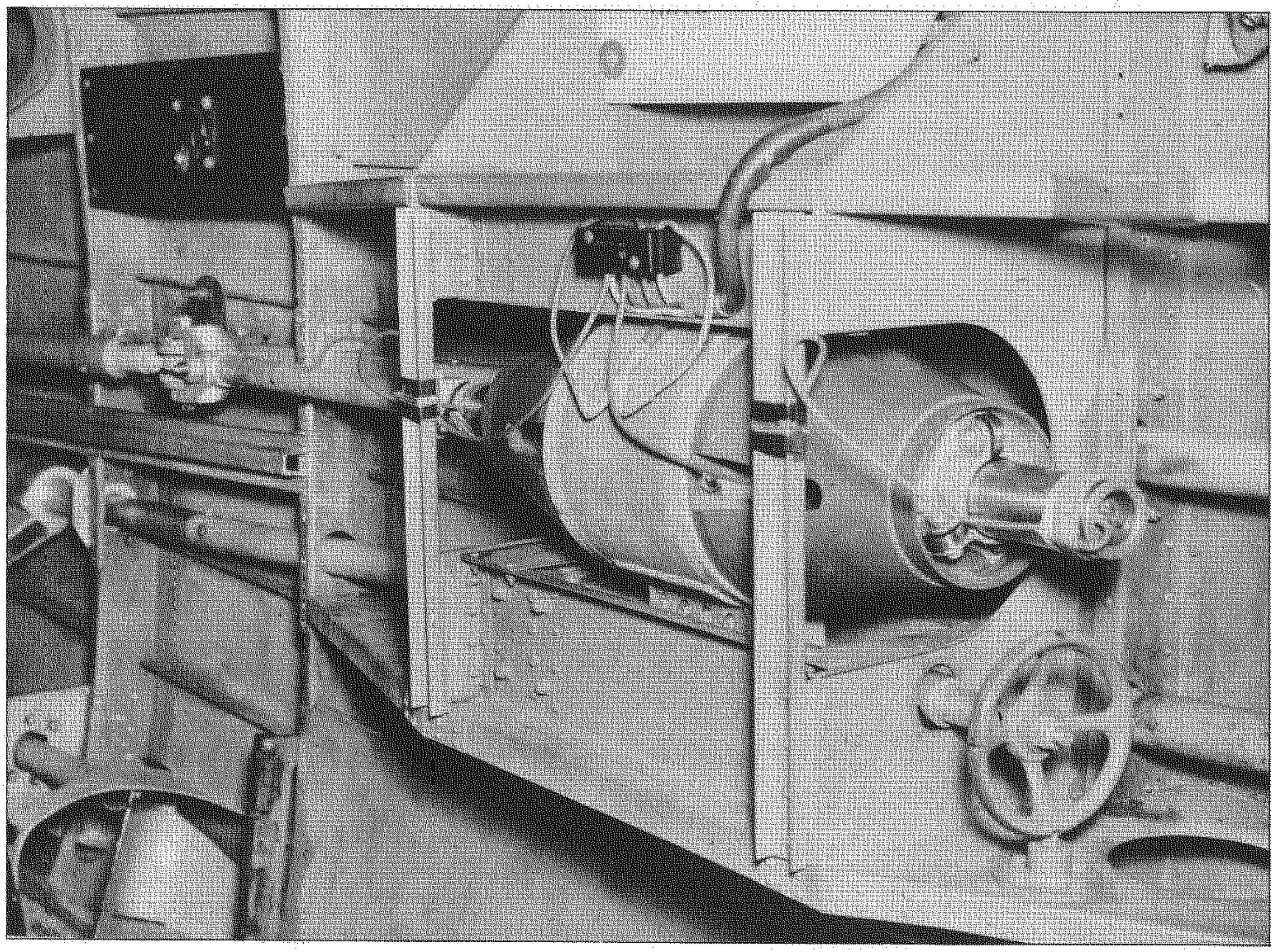

FIG.6. ELECTRODYNAMIC EXCITER INSTALLED IN A PURE SERVO TAB LANCASTER AIRCRAFT FOR THE EXCITATION OF THE RUDDER TAB CONTROL CIRCUIT

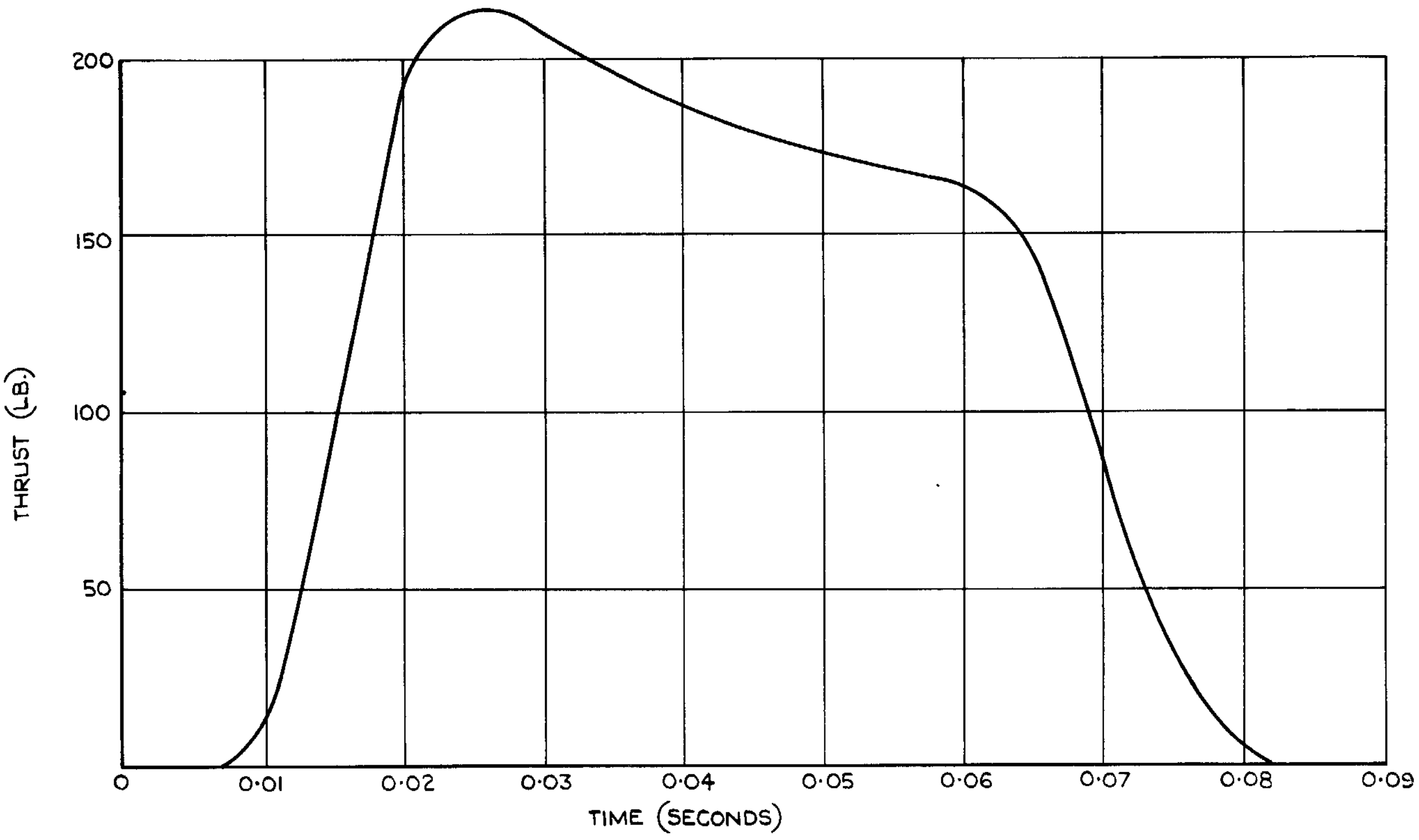

FIG. 7. THRUST - TIME CURVE FOR ROCKET IMPULSE UNIT.

NOTE:- THE SAFETY MARGINS REFER TO AIRSPEEDS FOR CRITICAL FLUTTER CONDITIONS AND ARE RELATED TO DIFFERENT AMOUNTS OF ELEVATOR MASS BALANCE.

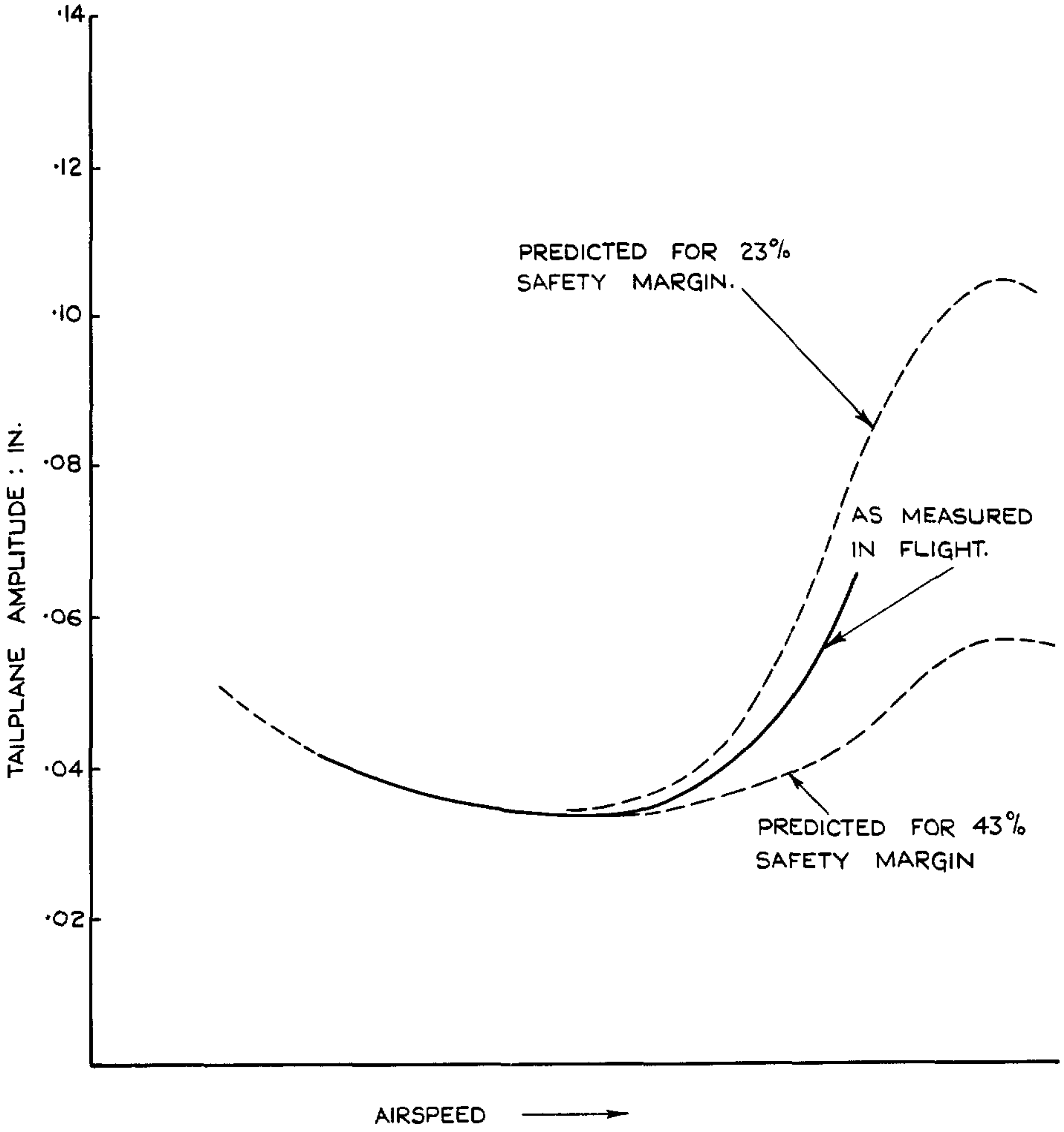

FIG. 8. COMPARISON OF AMPLITUDE RESPONSE CURVES MEASURED IN A FLIGHT FLUTTER TEST WITH PREDICTED VALUES.

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