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on

Aeroelastic Test Methods

Experimental Techniques

by

G. Piazzoli

NORTH ATLANTIC TREATY ORGANIZATION

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AEROELASTIC TEST METHODS

Experimental Techniques

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G.Piazzoli

Office National d'Etudes et de
Recherches Aerospatiales
Chatillon-sous-Bagneux, France

This report is sponsored by the Structures and Materials Panel of AGARD as an up-dating revision of the Article "Flight Flutter Tests" by M.O.W.WOLFE and W.T.KIRKBY, published in 1961 in the AGARD Manual on Aeroelasticity, Volume IV, Chapter 10.

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FOREWORD

This report has been prepared for the purpose of up-dating and replacing the article on Flight Flutter Tests by M.O.W. WOLFE and W.T.KIRKBY, published in 1961 as Chapter 10 of Volume IV of the Manual on Aeroelasticity. It was originaly intended to be printed in a loose-leaf form, to fit into the hard cover binder of the Manual. This loose-leaf form has been recently given up and the forthcoming revisions and additions to the Manual on Aeroelasticity will be printed in the standard format of AGARD reports.

The original manuscript in French of this article by G.PIAZZOLI, was completed in October 1969 and received by the Structures and Materials Panel. The technical difficulties encountered in the translation and preparation of the manuscript delayed the printing to the Fall of 1970.

A.J.BARRETT
Chairman, Structures and Materials Panel

CONTENTS

NOTATION

L	displacement
V	speed
Γ	acceleration
f, N	frequency
ω	excitation frequency
$t\ \tau$	time
$[\mu]$	generalised mass matrix
$[\beta]$	generalised damping matrix
$[\gamma]$	generalised stiffness matrix
A	amplitude
F	force
$[F]$	generalised force matrix or column
i, k	indices
$q(t)$	modal function
$L(P,t)$	natural shape
P, P_e, P_m	general point, excitation point, measurement point
λ	damping coefficient
$\alpha\ \beta$	reduced damping
ψ	phase angles
$Z(j\omega)$	complex admittance
$T(j\omega)$	transfer function
$D(t)$	indicial response
$E(t)$	random process
$R(\tau)$	correlation function
$\phi(\omega)$	spectral density
S	symbolic variable
$\mathcal{R}, \mathcal{J}$	real and imaginary part of
θ	temperature

INDEX OF TERMS

AEROELASTIC TEST	- A test aimed at verifying the dynamic behaviour of an elastic mechanical system in aerodynamic flow conditions.
FLUTTER	- Dynamic instability that may affect an aeroelastic system.
CONSERVATIVE SYSTEM	- A fictitious system without internal damping, associated with a real system, where the sum of the potential and kinetic energies remains constant in the absence of external forces.
DISSIPATIVE SYSTEM	- A viscous system where energy dissipates with time.
MODE SHAPE	- A spatial function defining the displacements assumed by the set of points of a system that has departed from equilibrium at an instant t.
MODE	- A function associated with each mode shape and characterising its evolution with time.
BASE	- The generalised coordinates within which the motion of a system is described.
APPROPRIATION	- The distribution of discrete exterior forces on a dissipative system, such that the work of these forces compensates at each point, and for each vibration cycle, the work of the damping forces.

1. INTRODUCTION

1.1 General

The object of this Chapter is to present a general survey of the methods of investigating the dynamic stability of aircraft structures - in flight - which are used at present in the various countries with aeronautical interests.

Since the end of World War II, the importance of the role played by this field of study has asserted itself progressively. Nowadays, series of vibratory tests are an integral part of the flight programme evolved for any important prototype development and - in the case of the supersonic transport aircraft - the time allotted to them amounts to nearly ten per cent of the total time allowed for development and Certificate of Airworthiness approval.

At the same time, novel practical techniques have developed in the past ten years - both in the field of excitation and that of analysis - and it becomes necessary to make a critical survey of their respective capabilities and of the specific conditions of their use.

A close interdependence relates the aeroelastic test to other methods of investigation available to the structural specialists in order to achieve predicition and control of the flutter phenomenon: ground vibration tests, theoretical or experimental knowledge of aerodynamic coefficients, calculation of critical speeds. These various approaches to the same physical situation, which is known to be difficult to apprehend with accuracy, must be pursued with knowledge and understanding of the problems encountered within each specific area in order to formulate a reliable diagnosis. The flight vibration test certainly has the advantage of not being burdened by a number of restrictive hypotheses which are inherent in the formulation of a mathematical "model"; but, on the other hand, interpretation of the results is often difficult, owing to aerodynamic coupling between structural modes and to the random "noise" generated by flow turbulence.

In any case, the preparatory phase of a flight vibration test must be supported by a survey of the structural mode shapes on the ground and knowledge of the calculations of the critical flutter speeds. The methods developed must ensure uniformity of definition and representation in the treatment of the structure by theoretical and experimental means, so that the comparison of their results may be direct and fruitful.

Although aeroelastic tests are favoured more and more by aircraft constructors, on account of the practical results that they provide, their implementation does not constitute, in itself, a panacea. When they are separated from the general background to which they belong, or conducted by means of insufficiently proved techniques, such tests may even result in misleading guarantees of safety.

1.2 Objectives of Aeroelastic Tests

1.2.1 The main purpose of aeroelastic tests is to maintain the structural integrity of a prototype while its flight range is being progressively extended.

Any elastic system associated with an energy supply is subject to dynamic instability[1], and for an aircraft in flight, the energy is provided by the propulsion systems which maintain the relative airflow around the structure; the instability phenomenon is then known as "flutter".

Knowledge of certain physical data expressing the balance of energy transfer between the flow and the structure provides a procedure for investigating the state of the aeroelastic system. Thus, if, during any vibratory cycle, resulting from a perturbation of the system steady state, the energy loss due to damping is greater than the energy gain, the influence of the perturbation vanishes with time and the system is stable. In the opposite case, any perturbation, however small, creates divergent oscillations which very rapidly produce failure of the structure: the system is unstable. When the energy loss and the energy gain are equal, the system is in an auto-oscillation state and the corresponding aerodynamic speed is called the critical flutter speed.

The dynamic viscosity rate (or damping) relative to a vibration sequence (positive, negative or zero) constitutes a criterion of these three states. The study of its evolution in the sub-critical range with reference to the flow characteristics (dynamic pressure, Mach number) gives warning of an eventual trend toward instability and an indication of the hardness of the phenomenon. The evolution of the vibratory resonance frequency is also a significant factor, as this parameter provides information to the specialist on the internal energy transfer processes, through coupling, within the system.

1.2.2 For each prototype, before its first flight, curves of the evolution of these two parameters are computed. Although there remain problems of satisfactory prediction of critical flutter speeds in the subsonic range as well, it is the appearance of transonic and supersonic aircraft which has placed particular emphasis on the development of aeroelastic tests, in particular because of

(i) uncertainties in the values to be assigned to the unsteady aerodynamic coefficients in the lower transonic range, more specifically for wings of small aspect ratio and large angles of sweep, with control surfaces extending over most of the span;

(ii) the large structural flexibility of supersonic transport aircraft, with delta wings, for which the elastic characteristics vary considerably, depending on fuel load distribution and kinetic heating at high Mach numbers;

(iii) new structural solutions: all-moving stabilisers with a rotational degree of freedom, locked by servo-control or variable sweepback wings, involving a new type of aerodynamic interaction between lifting surfaces.

The data furnished by flight vibration tests provide a final control of the prediction accuracy of computations, which depends on a great number of experiments conducted, in particular, in wind tunnels with models. It is extremely useful for the specialist on unsteady aerodynamics to have - in detail - full-scale experimental curves and to compare them with the computed curves. Even in the absence of a critical speed, a comparison of their values, and of their inflections, permits a more accurate evaluation of the correctness of the chosen coupling processes and of the validity of the unsteady coefficients that were introduced and may thus be adjusted.

In this respect, aeroelastic tests are an aid to research on unsteady aerodynamics.

1.2.3 On the other hand, calculations are not made for all the elastic configurations assumed by an aircraft during a flight mission, corresponding, for example, to changes in fuel system contents. It is not certain that the study of limiting configurations which is generally undertaken (empty, full) is sufficient to ensure safety.

Furthermore, certain effects which define the basic structural behaviour are not simulated in the ground vibration tests: for instance, lifting surface load factors and fuselage pressurisation. Representation of the structure, under flight conditions, may then be inaccurate if non-linear effects are ignored.

Aeroelastic tests are thus complementary to the computational programme required for certification of a production aircraft, for all configurations corresponding to the mission profile of its type.

1.2.4 Finally, knowledge of the structural dynamic transfer function is needed by the constructors' design and development department in order to evaluate the behaviour of the aircraft under turbulent conditions and its fatigue life.

1.3 Theoretical aspects

1.3.1 Ground representation of the structure

The elastic behaviour of a continuous mechanical system may be described within a configuration space of n degrees of freedom, n being a finite number for a limited band of frequency.

A degree of freedom of k^{th} order is characterised by
- a space function or "natural shape" $L_k(P)$
P (x,y,z) being a general point of the system.
- a time function or "natural mode" $q_k(t)$
- It is possible to conceive an idealised model, without internal damping called the "associated conservative" of a real system. The free vibrations of such a system are governed by the matrix equation of n^{th} order.

$$[\mu][\ddot{q}] + \quad \cdot \quad \cdot \quad \cdot \quad + [\gamma][q] = 0 \qquad (1)$$

The vibration mode shapes of this model are the natural mode shapes - the envelope at an instant "t" of all the points of the system vibrating in phase (or π out of phase); the mass and stiffness matrices are diagonal. The system representation base is "orthogonal" and the n degrees of freedom are uncoupled.

- In practice, all structures have internal damping and for an aircraft the structural damping rate, although small, is not negligible. The system then becomes a passive dissipative system.

The purpose of ground vibration tests is to determine the modal characteristics of the equations of motion: μ_k , γ_k and the natural shape L_k, by subjecting the structure to a forced excitation.

The general equation, including the second term, is written as follows:

$$\lceil\mu\rfloor[\ddot{q}]+[\beta][\dot{q}]+\lceil\gamma\rfloor[q]=[F] \tag{2}$$

F being the column of <u>real</u>, <u>generalised</u> external forces.

It is assumed that the matrix $[\beta]$ may be considered as a diagonal matrix (the so-called Basile hypothesis): $\lceil\beta\rfloor$.

The problem of <u>appropriation</u> arises; to appropriate is to ensure a suitable spacial distribution of the point forces applied to each shape considered, such as to balance exactly the damping energy loss - within each strucutral area. Provided that appropriate distributed forces are applied (intensity and phase), the matrix equation (2) may be reduced to a set of equations, each of which represents a degree of freedom in an orthogonal base.

The resulting model scheme then serves as a basis for computing the critical speed.

1.3.2 Flight representation of the structure

In flight, owing to the relative airflow, the aeroelastic system becomes an <u>active dissipative system</u> admitting of unstable solutions.

The general equation, with a forced excitation, becomes

$$\lceil\mu\rfloor[\ddot{q}]+\left\{[\beta]+[b]V\right\}[\dot{q}]+\left\{\lceil\gamma\rfloor+[c]V^{2}\right\}[q]=[F] \tag{3}$$

$[b]$ and $[c]$ being the matrices of the aerodynamic terms, which are functions of Mach number.

The overall stiffness and viscosity matrices are no longer diagonal and, through the action of the cross-terms of the matrices , the development of equation (3) leads to couplings between the orthogonal modes measured on the ground. The base for representation of the system becomes <u>complex</u>; in this base the concept of "<u>natural mode</u>" may be maintained, but with a complex representation.

It is, therefore, impossible to isolate a "<u>natural mode" in flight</u>, for the whole frequency spectrum, with a <u>real</u> force distribution. But experiments are concerned only with the evolution, with reference to speed (or Mach number), of the overall damping rate (structural and aerodynamic) and of the natural frequency relative to each flight mode. These parameters may be obtained by considering only a restricted range around each natural frequency and may be continuously observed at all points on the structure selected as being significant for measurement.

The concept of appropriation - in its precise meaning as applied to ground tests - is no longer valid and must be replaced by the broader concept of optimisation of the work put into each flight mode by the excitation forces.

1.4 Flight Test Preparation

Lengthy and detailed flight test preparations are required, on which the quality of results obtained depends.

1.4.1 General

Preparation starts with a survey of the designer's computed mode shapes; this survey provides guidance for the initial stages of excitation definition and layout. Then, as soon as the prototype airframe is completed, these mode shapes are controlled experimentally, and their modal characteristics are measured accurately during the ground vibration tests. These are performed systematically for any large aircraft.

The model shapes which are very varied, may be divided into two categories:

(a) The so-called "structural" mode shapes, (bending, torsion) which involve mainly the fixed components of the aircraft and affect

- either one particular surface
- or the whole aircraft, through the medium of the fuselage.

(b) The so-called "control-surface" mode shapes, where the control surface motion predominates.

The control surfaces' role has various aspects - from the aeroelastic point of view - that must be clearly distinguished. On the one hand, the control surfaces contribute to the vibratory representation of the fixed structural components, of which they are geometrical extensions; their dynamic behaviour depends on the degree of balance and on their attachments to the main surfaces. On the other hand, they have specific degrees of freedom (rotation around the hinge) due to elasticity in the linkage. Furthermore, control surfaces are subject to particular distortions (bending, torsion), but in a frequency range generally higher than that of flutter.

Control surfaces are often used as a mean of dynamic excitation of the structure, which is an extension of their legitimate role, in quasi-static stability and handling tests. But an artificial manipulation of control surfaces in order to excite structural modes is often not permissible.

In practice, the local flow is disturbed and the disturbance progresses upstream of the hinge; in the transonic range ($M < 1$) the position of the foot of the shock-wave varies with the control angle. The aerodynamic excitation forces that are applied then become a function of the structural response and are not constant. Finally, certain modes are very unsatisfactorily excited by the control surfaces, on account both of symmetrical and anti-symmetrical characteristics and of the spanwise location of these surfaces.

1.4.2 Distribution of Excitation Points

It is advisable to plan a distribution of excitation over the whole structure and, taking into account the fact that it is extremely difficult to modify it afterwards, there must be excitation points additional to the number required in ground vibration tests.

The points of application of the excitation forces should be selected so as to optimise - for each flight configuration, as far as possible - the work input, that is, they should be located within areas where the amplitude of vibration will remain the largest. The problem encountered here is that flight modes are complex, and that nodal lines vary owing to the effect of coupling terms that modify the aerodynamic stiffness distribution.

Flexibility in number and distribution of the excitation forces must therefore be maintained by means of a matrix programming chart.

1.4.3 Criteria for the Definition of an Excitation Installation

To sum up the previous remarks, three general criteria will be formulated in order to define the value of an excitation array:

(i) Functional independence of the Excitation forces with respect to the structural response;

(ii) Negligible modification by the experimental equipment of the elastic characteristics of the system considered (masses, stiffness, number of degrees of freedom);

(iii) Flexibility in the number and distribution of the excitation forces, according to the evolution of the flight modes.

2. HARMONIC EXCITATION METHOD

2.1 Principle

This method consists in studying the forced structural response to an harmonic force distribution, sinusoidal forces being generally selected:

$$F = \sum_i F_i \quad R\left(e^{j\omega_i t}\right) \quad i = 1 \ldots n \tag{4}$$

The excitation frequency of this distribution is itself a function of time.

$$\omega_i = K(t)\,\omega_0 \tag{5}$$

Note: (i) The excitation force distribution is a real distribution although the flight mode representation base is complex, for the sake of safety; in fact, "quadrature" force application would be equivalent to a stiffness modification of the system considered.

(ii) The harmonic method therefore appears as an extension in flight of the structural ground test method. It should be kept in mind, however, that certain characteristic flight responses are modified considerably compared to ground responses.

- Thus a flight mode may be interpreted only within a narrow range around the resonance frequency.
- The resonance frequency no longer corresponds to the phase quadrature of the response in relation to excitation.
- Even when the work of the excitation forces is optimised for a mode shape, an equiphased response of the various structural points is no longer obtained at resonance.

(iii) As a result, what significance may be attached to the interpretation of the admittance curve?

Various experiments have been conducted, both on analogue computers and on aircraft [2,3]. They show that each flight mode is a linear combination of orthogonal ground modes. The frequency and damping behaviour extracted from the response curves is in agreement with the calculated data until near the critical speed - provided that one no longer considers a global mode representation obtained by summing the various point responses (as in G.R.T), but treats each point response separately.

2.2 Conditions of Use

The harmonic excitation method is an excellent method because it allows an aeroelastic system to be explored under conditions providing both

(a) a stable vortex state downstream of the trailing edge, in agreement with the hypothesis used in the computation of the unsteady coefficients;

(b) excellent accuracy for the spectral investigation of response.

2.2.1 Effect of Time Spent on Frequency Spectrum Exploration

When an elastic system, at rest, is subjected to an harmonic excitation F, the response L of a point of the system is described, during the course of time, by the superposition of two functions,

$$L = L_T + L_S \tag{6}$$

where L_T is the transient response which, in a particular system, depends on the initial excitation conditions and decays with time.

L_S is the forced response which alone remains when L_T has decayed to zero.

For a second-order system (one degree of freedom) the general solution has the form

$$L \doteq C_{exp}\Big[\Big[\Big\{-\lambda + j\sqrt{1-\lambda^2}\Big\}\omega_1 t\Big] + \frac{F}{1-(\omega/\omega^*)^2 + 2j\lambda(\omega/\omega^*)} \tag{7}$$

ω^* being the natural frequency of the system.

The second term on the right hand side of equation (7) represents the steady response L_S. The non-dimensional ratio L_S/F is called the complex frequency response curve or complex admittance of the structure. Its examination and the accurate interpretation of the system state that it furnishes are the specific objectives of the harmonic method. When the response parameter considered is the displacement speed, the velocity vector locus is a circle in the complex plane [4]. When the system has several degrees of freedom, the locus is a combination of circular sectors, located spectrally around each of the resonances and interconnected by arcs, the shapes of which depend on the nature and intensity of the coupling coefficients. The study of these coupling processes is essential for the precise determination of modal evolution in the subcritical range.

In practice, a definite spectral area must be explored for a finite period of time, and then a law of evolution must be assumed, which may be either a discrete or a continuous time function. The transient response therefore always exists and the time spent on a sweep of the area is a compromise between practical flight test requirements and the data accuracy resulting from steady state analysis.

It is generally agreed that for the damping ratios encountered in flight and the frequency ranges considered, the time spent on each sweep of the area may be about one minute (or more) if the steady response is desired.

On the contrary, if the excitation application time is extremely short - that is, if the structural response is comparable with the indicial response - only the transient state L_T need be considered, and the study of the free vibrations of the system may be performed just as well using other techniques (cf. Section 3).

It must be strongly emphasised, however, that considerable problems may arise in the analysis when the rate of sweep is selected in such a way that the two states are superimposed in roughly equal proportions, particularly in the case of strong couplings between neighbouring modes, with a low ratio signal/noise.

2.2.2 The Effect of "Background Noise"

The "background noise" on an aircraft structure in flight is due to its environment, in the broadest sense.

There are three main sources of this noise:

(a) Internal sources within the aircraft propulsion system.

(b) External sources, related to the interaction between structure and air flow, such as separation, vortices, and shock-waves.

(c) External sources independent of the aircraft such as atmospheric turbulence.

While it is relatively easy to suppress, by filtering, the effects due to the sources (a) and sometimes (b) when they belong to a frequency range quite distinct from that of the structural modes involved in flutter (this is not always true for control surfaces), the turbulence effect (c) influences a large number of structural modes with variable intensity.

$$\text{Let} \quad \rho(\omega) = \left| \frac{\text{harmonic excitation response}}{\text{turbulent excitation response}} \right|$$

This ratio ρ is a real stumbling block in practical analysis.

FIGURE 1

In practice, the response of a structural mode is, for each frequency, the resultant of two vectors:

- the first, $\vec{V}(\omega)$, is a "determinate" vector; its extremity describes the theoretical admittance curve of the system
- the second, $\vec{v}(\omega)$, is a vector of which the instantaneous amplitude and phase are random. It is the response of the same mode to the generalised gust forces. The result is a blurring of the experimental curve with respect to the theoretical locus and the repercussions affect both the pattern of the curve and the apparent frequency distribution.

Good weather conditions are desirable, of course, for vibration tests. Provided that $|V| / |v| \gg 1$ smoothing of the local distortions of the curve permits an accurate interpretation.

But the spectral density of turbulence is particularly high at the low frequencies corresponding to the first fundamental modes of the main surface (wing, stabiliser and fin bending) and to the overall aircraft deformation (vertical bending, fuselage torsion). The work of the harmonic forces, by contrast, is restricted by the performance and engineering of the exciter, in the same frequency ranges, and by the restricted number of exciters that may be placed on the aircraft.

What procedure should therefore be followed in order to preserve an accurate interpretation when the ratio ρ for a particular mode, decreases and becomes very unfavourable?

There appear to be two solutions: Either

(i) to suppress the harmonic excitation and to use only the random-process analysis techniques described in Section 4, or

(ii) to maintain the harmonic excitation and to sweep the frequency spectrum at an extremely low rate.

In fact, the turbulent random process is a symmetrical process in which the first moment of distribution (or mean) is zero. This characteristic is expressed by the relation

$$\frac{1}{T}\int_0^T v(t)\, e^{j\omega t}\, dt \longrightarrow 0 \quad \text{for } T \longrightarrow \infty \tag{8}$$

When the sweep rate is very low it is permissible, in the analysis, to balance the response by significant time constants while maintaining a state close to the steady state. Thus the effect of turbulence, even if not cancelled, may at least be minimised and the case $|V|/|W| \gg 1$ restored.

2.3 Experimental Techniques

Experimental techniques have developed and improved as the technology progressed.

2.3.1 Excitation Systems

The following are excitation systems, that have been or still are in use:

- Excitation by means of out-of-balance weights (inertial)

  An electric motor rotates two eccentric masses in opposite directions with the same frequency ω. A sinusoidal force, increasing as the square of ω, is applied in the plane of symmetry of the two masses.

- Excitation through the main control surfaces, the trim controls or the tabs (aerodynamic)

  An electric signal emitted by a sinusoidal generator is fed into the control valve of the position control actuators. The oscillation in the relative wind induces unsteady forces, the resultant of which exerts a moment about the hinge. The intensity of the force is a function of speed, Mach number and frequency, according to the actuator transfer function.

- Excitation by means of an auxiliary flap (aerodynamic)

  A flap, oscillating about an axis located at the quarter-chord point is installed at a wing tip and is actuated by a motor-cam system. The mean aerodynamic incidence setting varies with the Mach number.

  The value of such an arrangement is that it provides appreciable forces, of aerodynamic origin, at the very low structure frequencies affecting flexible wing aircraft ($N < 2$ Hz).

- Excitation produced by an auxiliary actuator coupled to weights (inertial)

  A small auxiliary actuator with a large pass-band (0-50Hz) produces angular oscillation ϕ of a mass having a moment of inertia I about its hinge axis. The force developed, $F = I\omega^2\phi$, becomes quite considerable for frequencies higher than 10 Hz. The whole apparatus is elongated and flat and can be housed inside thin tail units.

Each engineer specialising in aeroelastic tests must select the excitation system best suited to his problem. The user will appreciate to what extent neglect of any of the criteria defined in Section 1.4.3 may affect the validity of the data obtained.

2.3.2 Electrodynamic excitation

The use of airborne electrodynamic exciters has increased considerably during the last decade.

(a) Principle

The exciter is primarily composed of an active part (coil) subjected to a magnetic field that is perpendicular to the plane of the coil, produced by permanent magnets.

The force created within the coil, when a sinusoidal current passes through it, is governed by Laplace's law

$$F = H\,(m \times \ell)\,I \qquad (9)$$

where
H magnetic field intensity
m number of turns
ℓ length of a turn within the field
I electric current intensity.

The novelty of the airborne exciter lies in its type of suspension. In flight, a stable reference, from which the force is applied, is not available, as for a ground exciter. An artificial "seismic" platform is therefore created by elastically suspending the magnet block from the structure, using springs. The coil is linked rigidly to the structure.

The suspension frequency N^{*} is adjusted so as to be considerably lower than the lowest structural frequency N_{s1} (in practice, $N_{s1}/N^{*} > 3$ is used, so that the elastic restoring forces are negligible).

Thus, the additional degree of freedom provided by the magnet-spring system is uncoupled from the structural degree of freedom and the only additional mass involved in dynamically modifying the system considered is the mass of the coil, which is negligible.

(b) Advantages and disadvantages

The electrodynamic type of exciter has very varied uses, on all surfaces of the aircraft, provided that a specific case study is made of the overall dimensions and attachment to the structure.

Simultaneous operation of numerous distributed exciters is possible, with excellent synchronisation of their relative phases.

The size of the excitation force is independent, to a large extent of the outside physical parameters, such as test frequency, speed and Mach number of the aircraft.

The force applied is constant during a frequency sweep.

Finally, the excitation cut-off is instantaneous and the short-circuited coil becomes the source of Foucault currents that damp parasitic oscillations.

On the other hand, the electrodynamic exciter system must be planned well in advance, for example, the attachment points, and the electrical power required is considerable.

(c) Illustration of an excitation and measurement sequence

An example of this system is the forced excitation sequence of the "Concorde" supersonic transport.

. BLOCK DIAGRAM (FIGURE 2)

Two-Phase generator

Having a stability greater than 5 x 10^{-5}, the two-phase generator releases two sinusoidal signals that are used both to control the excitation (phase) and in the later response analysis (phase and quadrature). Removable control units, pre-adjusted on the ground, display the central frequency of each of the various modes to be investigated (24 modes are planned). Around this central frequency a swing of ± 15% is ensured, with a linear evolution rate for the period.

Pre-display panel

This is in the form of a matrix of order 24 (modes) by 19 (exciters).

It allows optimisation, for each mode, of phase (0 or π) and intensity (6 values from 0 to maximum) of the force distribution on the structure.

A general force control permits overall adjustment of the excitation level without affecting the values selected for optimisation.

Control Console

The control console is the nerve center of the system, where the test sequences are initiated and controlled, using the following devices:

- a mode selection board
- a sweep duration selector = 30 sec., 1min., 2min., 3min.,
- safety indicators" overheating, cut-outs

An aircraft silhouette diagram presents the displays and safety indicators visually.

Amplifier rack

The power amplifiers are arranged in sets of four into separate sub-systems fed by the 208 V - 400 Hz board network. The transistor boxes are fixed on a hollow base cooled by ducted water circulation. The water is pumped from a tank where it is maintained at the temperature of melting ice.

An operational endurance of one hour is guaranteed.

The current produced by each amplifier is kept constant - whatever the motional impedance may be - by a strong counter-reaction.

The maximum current is 25 A

Exciters

Nineteen exciters of four different types are located in various parts of the aircraft:

FIGURE 3

wing exciters		F max = 400 N
fin exciters		F max = 200 N
fuselage exciters	vertical	F max = 800 N
	horizontal	F max = 800 N

A section of the wing exciter diagram is shown in Figure 4. A hermetically -sealed cowl for protection against fuel vapours is enviaged.

FIGURE 4

The excitation system operatores without appreciable loss of performance at the limiting environmental conditions of the aircraft flight range, in particular at $\theta = +400^\circ K$.

2.4 Analysis

2.4.1 Analysis of the structural response at various points obtained from accelerometers is based on the interpretation of the complex admittance curve relative to the steady state.

The two generator references ($\sin \omega_i t$, $\cos \omega_i t$) and the responses are recorded on magnetic tape for later analysis.

In order to obtain the Fourier coefficients a multiplier system is used which performs the following operations:

$$\left.\begin{array}{l}\sin \omega t \times V \cos (\omega t + \phi) \\ \cos \omega t \times V \cos (\omega t + \phi)\end{array}\right\} \qquad (10)$$

After filtering of the harmonic 2ω by integration, these products furnish the two real and imaginary coefficients of the complex admittance curve for the frequency ω ,

$$\left.\begin{array}{l}V \sin \phi \\ V \cos \phi\end{array}\right\} \qquad (11)$$

ϕ being the phase angle between the excitation and the response.

2.4.2 The admittance curve is recorded automatically by a table (X, Y) where the input signals are $V \sin \phi$ and $V \cos \phi$.

The frequency values are indicated by "gaps" in the diagram produced by the electromagnetic control of the recording stylus and this frequency is recorded by a decade oscillator controlling a high speed printing machine (an absolute accuracy 0.01 Hz must be achieved).

The curve thus defined has "intrinsically" all the elements required for interpretation of the system dynamic characteristics.

FIGURE 5

FIGURE 6

The out-of-phase with respect to the main reference axes results from two causes in flight:

(a) the vibration sensing system (accelerometers)

(b) coupling between natural modes,

but this does not affect the interpretation as it may be considered steady in the frequency range explored.

The phase resonance frequency is defined by

$$\max \frac{d\overset{\frown}{s}}{d\eta} \equiv \max \frac{d\bar{s}}{d\eta} \qquad (12)$$

where $\eta = N/N^*$
$\overset{\frown}{s}$: length of arc
$\bar{s}$: length of corresponding chord

The principal axis being re-set on this point, the principal diameter may be plotted and the reduced damping rate is determined from the values of the points (N_1, N_2) where this diameter intersects the circle.

$$\alpha = |\Delta\eta| = |\Delta N / N^*| \qquad (13)$$

where $$|\Delta N| = \begin{cases} |N_1 - N^*| \\ \text{or } |N_2 - N^*| \end{cases}$$

Where there is coupling between two neighbouring modes, the damping may also be obtained, within a narrower zone around the phase resonance, by the relation

$$\alpha = \frac{1}{\eta} \; \frac{1}{d(\mathrm{cotg}\,\phi)/d\eta} \qquad (14)$$

3. IMPULSE EXCITATION METHOD

3.1 Principle

This method consists in submitting the structure to a very short excitation function or pulse, resulting in its departure from equilibrium, and in exploring the free vibration state resulting from this pulse.[9]

The displacement of any structural point is given by

$$L(P,t) = \sum_{i=1}^{\ell} \sum_{k=1}^{n} L_{ki}(P)\, q_{ki}(t) \qquad (15)$$

If the structure is defined in terms of its natural modes, relation (15) becomes

$$L(P,t) = \sum_{k=1}^{n} L_k(P)\, q_K(t) \qquad (16)$$

where $L_k(P)$ defines the normalised mode shape

$$q_k(t) = e^{-\lambda_k t} \sin(\omega_k t + \varphi_k)$$

modal function associated with each mode shape.

Knowing the natural mode shape and its modal characteristics, it is possible to study by symbolic transform, the transfer impedance I to a pulse (orthogonal base).

$$I(P_e, P_m, S) = \sum_k \frac{L_k(P_e)\; L_k(P_m)}{\mu_k S^2 + \beta_k S + \delta_k} \qquad (17)$$

P_e being the excitation point,
P_m being the measurement point.

If the pulse has the form of a Dirac distribution $\delta(t)$, the structural response is the indicial response, and the value of the acceleration recorded at the point P_m is

$$\Gamma(P_m, t) = \sum_k \frac{L_k(P_e)\, L_k(P_m)}{\mu_k}\, \omega_k\, e^{-\lambda_k t} \sin\left(\omega_k t + \varphi_k\right) \tag{18}$$

The Dirac excitation promotes high frequencies.

If the pulse has a rectangular form (or trapezoidal in a practical case), the acceleration at the point P_m is:

$$\Gamma(P_m, t) = \sum_k \frac{L_k(P_e)\, L_k(P_m)}{\mu_k}\, M_k\, e^{-\lambda_k t} \sin\left(\omega_k t + \varphi_k\right) \tag{19}$$

The function Mk, called the "adaptation function", is calculated for each type of pulse.

FIGURE 7

NOTE:

(i) The energy imparted to the structure by "rectangular" pulse is concentrated within a chosen frequency band, which depends on the duration of the pulse. This characteristic is of value in practice because it allows <u>selection</u> of certain modes.

(ii) The acceleration assumed by each mode, at the end of the pulse ($t= \varepsilon$) depends only on the modal parameter μ_k (generalised mass) and not on the damping β_K.

Assuming that the mode shape does not vary noticeably in flight, the measured acceleration will be of the same order of magnitude as on the ground. This characteristic makes it possible <u>a priori</u>, if some flight records are available, to adjust and distribute the pulses so that the relation

ρ = (effective signal/background noise) is in agreement with an accurate analysis of the transient state (in practice $\rho > 5$).

(iii) It is also advisable to check by calculation that the shear force at the point of application of the pulse and the root bending moments are not too high.

3.2 Conditions of Use

The percussion method is attractive a priori. In fact:

- <u>its implementation is easy:</u> the impulse generators are small and cheap, and they may be installed in relatively thin surfaces.
- <u>the time allotted to each impulse sequence is extremely short</u>: (a few seconds, taking into account current values of damping in aircraft structures). The limiting region where aircraft parameters vary very rapidly (dive) may be explored easily.
- <u>the impulsive excitation of control surfaces does not affect their natural dynamic characteristics</u>:

However, the pulse method has a number of disadvantages which, in certain cases, restrict its use.

- <u>the pulse is not selective:</u> the structural response is a linear combination of modes that must then be separated during analysis.
- the pulse <u>repetition capability</u> is restricted;
- accurate synchronisation of impulses applied simultaneously at various points is difficult; there can be a scatter of as much as ten milliseconds in firing delays;
- finally, <u>thermal problems arise.</u> The mechanical and thermodynamic properties of current powders(Ballistite, Plastolite) are affected by temperature:

Used cold ($\theta < -20^{\circ}C$) the powders become brittle

Used hot ($\theta > 60^{\circ}C$) they soften.

In both cases, the combustion surfaces and, of course, the performance, are affected which may result, under certain limiting conditions, in the explosion of the casing. Heat protection is therefore required.

To sum up, the impulse method can be applied with advantage in tests of high-speed aircraft (fighters, interceptors) and for control surfaces.

3.3 Experimental techniques

The development of explosive-charged impulse systems with a thrust of 60 DN to 600 DN and combustion times from 10 ms to 50 ms is required to cover all current cases.

FIGURE 8

An impulse system is essentially composed of

- a cylindrical external body forming the combustion chamber;
- a flange which provides a base for the combustion chamber, with a radial groove for the ignition fuse;
- a choke constituting a divergent which is identical for all cartridges types;
- a cartridge case, characterising the type of impulse to be communicated to the structure; this case contains:

    the primary ignition charge (black powder)

    the powder charge

    the support gird for the charge, the nozzle and the throat (with variable diameter according to type)

    the jettisonable mounted seal, which ensures the initial pressurisation of the chamber

These impulse systems provide a thrust curve of ± 10% accuracy in the temperature range - 20° C to + 60° C. They are not affected by a prolonged sojourn in a humid environment.

Special impulse systems, having an elongated, flat shape with a 90° cranked nozzle, are also planned for thin surfaces (tails, stabilisers).

3.4 Analysis

A high-speed, accurate analysis of the structural response to a pulse has been the major problem of this method for a long time. At present, an automatic analogue arrangement provides separation of the various modes combined in the response:

Survey of the Underlying Theory [10]

With reversal of the raw signal $f(t)$ (for instance, accelerometer response)

$$f(t) = f(-t) \quad \text{for} \quad t \leqslant 0$$
$$f(t) = 0 \quad \text{for} \quad t > 0 \qquad (20)$$

After passing through a selective filter, governed by a second-order equation $\ddot{r} + 2\Omega\beta\dot{r} + \Omega_0^2 r = 0$
the response at time t is

$$r(t) = \int_{-\infty}^{0} f(\tau)\, e^{-\lambda(t-\tau)} [\cos \Omega(t-\tau) + j \sin \Omega(t-\tau)]\, d\tau \qquad (21)$$

where $\lambda = \omega/\beta$ and $\Omega = \sqrt{(\Omega_0^2 - \beta^2)}$

Assuming $\tau = U$

and $U - j\Omega = S$

the response at time t=0 is

$$r(0) = -\int_{0}^{\infty} f(U)\, e^{-SU}\, dU \qquad (22)$$

The frequency response curve is no other than the Laplace transform of the input signal. This transform is very near to the Fourier transform for the usual filter dampings. The peaks of this curve match the various mode amplitude resonances.

When the filter is blocked at the resonance frequency of one of the modes (ω_k) with damping α_k, the filtered signal amplitude at the time t=0 is

$$A_k \max = \frac{1}{2\omega_k(\lambda+\alpha_k)} \tag{23}$$

The attenuation coefficient of a neighbouring mode, with an output amplitude A_H, when the block is at the resonance frequency W_K, is given by

$$\rho = \frac{A_H}{A_k} = A_H\left[2\omega_k(\lambda+\alpha_k)\right] \tag{24}$$

with $2\omega_k(\lambda+\alpha_k) \ll 1$

This attenuation coefficient is often insufficient with a single filter. In practice, two identical filters in series are used, which results in increasing the filter exit overshoot to its square, and the damping coefficient then becomes

$$\rho = \frac{A_H}{A_k} = A_H \times \left[4\omega_k^2(\lambda+\alpha_k)^2\right] \tag{25}$$

The apparatus

An automatic system is used.

BLOCK DIAGRAM, FIGURE 9

- The analysis includes several preliminary steps:

COPYING AND FREEZING (FIGURE 10)

The transient signal, considered to be effectively damped after a time τ, is copied on to a magnetic "disc" rotating with a period T ($T > \tau$).

A contact between the disc-plate and a revolving arm synchronises the sweeping of an oscilloscope with the rotation of the disc. The signal then appears frozen on the tube.

REVERSAL AND CUT-OFF (FIGURE 11)

The rotational direction is reversed. A second contact serves to short circuit the signal at any point marked on the oscilloscope tube. The pulse zone is thus suppressed (allowing a safety margin) which is a requirement for an accurate analysis.

A timed relay re-establishes the signal at an appropriate point.

A parasitic free response of the filter is also suppressed and only the forced excitation response remains.

- Automatic filter for variable-frequency analysis

The two series mounted filtering circuits have a dynamic overshoot of fifty. The step-by-step progress of the filter, driven by the disc, occurs at each revolution.

By capacity variation, the filter has eight frequency ranges, from 2 to 500 Hz. Each range provides one hundred discrete analysis points.

- Spectrum graph - Determination of the damping

The output intensity of the filtered circuits after their passage through a peak voltmeter is plotted on a recording table that provides the curve $A = f(\omega)$, characterising the frequency response curve (Figure 12). After examination of this curve, and for each resonance ω_i, the decrement α_i is obtained by logarithmic plotting of the typical points of the filtered signal envelope.

The whole sequence of these operations is rapid, the rotational speed of the disc being one per second. The complete analysis of a signal within the range 2 to 100 Hz takes no more than ten minutes.

FIGURE 12

4. RANDOM EXCITATION METHOD

The two methods previously described, harmonic and impulse excitation, are the methods currently applied in prototype ground-vibration tests.

However, they require an installation that depends on contingencies that may be embarrassing: a large power supply for the electrodynamic excitations, and prohibitive local shear forces for the impulsive excitation of modes with large generalised masses.

The very low frequency excitation characterising the fundamental modes of large transport aircraft also raises difficult technological problems.

4.1 Random processes

4.1.1 Natural random process = turbulence

Natural atmospheric turbulence is a random process with a particularly high spectral density at low frequencies. It, therefore, seems to be of the greatest interest to attempt to use the natural power supply provided by turbulence in order to achieve structural mode excitation. The requirements for the application of this method will now be reviewed.

- First of all, some turbulence must exist and it is known that the time-space location of this phenomenon is itself very"random";
- the method of dealing with random mechanisms is a statistical method; the sample to be analysed must therefore correspond to a sufficiently long steady flight (in practice it will last minutes). Dive tests are therefore excluded.
- turbulence does not ensure an appropriate excitation of all aircraft modes. Low frequency modes generally present an appreciable response (wing fundamental bending, fuselage torsion ...), whereas the other modes are excited relatively less well, or not at all, because the work done by the generalised gust force on a natural mode shape may be zero when "averaged", taking into account the geometrical location of nodal lines.

  Strictly speaking, the exploitation of a structural response to the natural turbulence field can furnish only a transfer function of the aircraft to the gusts.

  A structural mode capable of flutter at a certain speed may not be noticeably excited in the sub-critical speed.

  This method is therefore restricted to achieving certain specific objectives:

  - extension of harmonic excitation for very low frequencies;
  - study of a specific mode which computation has shown to present a risk of flutter, when it is known that it is sufficiently excited in turbulence;
  - knowledge of structural mode dynamic overshoots for application to fatigue problems.

4.1.2 Programmed Artificial random process

Another method consists in programming an artificial random process (generally "white noise") on a magnetic tape and applying random excitation forces at various points of the structure, using appropriate excitations.

This procedure provides operational flexibility since, on the one hand, the use of electronic filters allows the correct adjustment of the energy levels in spectral frequency bands, and, on the other hand, the relative out-of-phase (0 or π) of the various excitation forces may be achieved by a reverser which allows one at least to select the symmetrical and anti-symmetrical modes.

4.2 Analysis

Methods of analysis of the structural response to a random excitation are based on the fundamental relations of statistical mechanics.

We shall describe four distinct methods: the first one, called the "spectral densities" method, is a theoretical method which is seldom applicable; the other three are operational methods.[11,12]

4.2.1 "Spectral Densities" Method

If a linear system is excited by a random process E(t), which is entirely defined by its second-order moment, with a spectral density $\phi(\omega)$, its output spectral density is

$$\phi_{out}(\omega) = \left[\left|T(j\omega)\right|\right]^2 \phi_{inp}(\omega) \tag{26}$$

$T(j\omega)$ being the system transfer function.

This relation makes it possible to obtain the transfer function, point by point, since spectral densities are scalar quantities.

$$T(j\omega) = \left\{ \frac{\phi_{out}(\omega)}{\phi_{inp}(\omega)} \right\}^{1/2} \tag{27}$$

FIGURE 13

A technique based on the measurement of the "sharpness of resonance" then provides the damping. $\alpha_i = \dfrac{\Delta\omega_i}{2\omega_i}$

Special case. If the input process is a white noise $\phi_{inp}(\omega) \equiv C^{te}, \forall_\omega$ the analysis of the response only is sufficient to determine the transfer function.

In practice, this method is difficult to apply to the precise determination of the damping, because current techniques for obtaining the spectral density - selective filtering or machine computation - do not provide sufficient resolution to account for the characteristics of a system with high overshoot; on the other hand, the "sharpness of resonance" technique is severaly restricted whenever two modes are appreciably coupled.

This procedure remains very valuable however from the safety viewpoint, when the response transmitted by telemetery is treated by an analyser which provides the spectral density <u>in real time</u>; a rough estimate of the order of magnitude of the dynamic overshoot warns of the approach of flutter.

4.2.2 Second Method: Determination of the indicial response based on the cross-correlation function

Assuming a linear system, with an indicial response D(t), excited by a random process E(t), its response S(t) is given by the Duhamel integral

$$S(t) = \int_{-\infty}^{+\infty} E(t-\eta)\, D(\eta)\, d\eta \tag{28}$$

and the cross-correlation function between the excitation and the response is

$$R_{I},o(\tau) = \lim_{T\to\infty} \frac{1}{2T}\int_{-T}^{+T} E(t)\cdot S(t+\tau)dt = \lim_{T\to\infty}\frac{1}{2T}\int_{-T}^{+T} E(t)\int_{-\infty}^{+\infty} E(t+\tau-\eta)D(\eta)\,d\eta\ \Delta t \tag{29}$$

$$= \int_{-\infty}^{+\infty} D(\eta)\left\{\lim_{T\to\infty}\frac{1}{2T}\int_{-T}^{+T} E(t)\cdot E(t+\tau-\eta)dt\right\} d\eta$$

The <u>autocorrelation function</u> of the excitation is

$$P(\tau-\eta) = \lim_{T\to\infty}\frac{1}{2T}\int_{-T}^{+T} E(t+\tau-\eta)\, E(t)\cdot dt \tag{30}$$

Consequently, the cross-correlation function assumes the form of the convolution product

$$R_{I,0}(\tau) = \int_{-\infty}^{+\infty} P(\tau-\eta)\, D(\eta)\, d\eta \tag{31}$$

1st case: Excitation by broad-band white noise

In this case, the excitation is not correlated and its autocorrelation assumes the form of a Dirac distribution $\delta(t)$.

The indicial response of the linear system has the general form

$$D(t) = \sum_k A_k\, e^{-\lambda_k t} \sin(\omega_k t + \varphi_k) \tag{32}$$

The cross-correlation function is expressed by

$$R_{I,o}(\tau) = \int_{-\infty}^{+\infty} \delta(t-\eta)\, D(\eta)\, d\eta = D(\tau) = \sum_k A_k e^{-\lambda_k t} \sin(\omega_k t + \varphi_k) \qquad (33)$$

and is just the indicial response of the system.

The analysis of this response may be performed by selective filtering of the various modes, which gives ω_k and λ_k.

2nd case: Excitation by atmospheric turbulence

Turbulence is a mechanism that has a monotonically decreasing correlation function $\rho(\tau)$ which cannot be represented by a Dirac distribution

FIGURE 14

It is shown that the cross-correlation function is then a linear combination of the autocorrelation function of the excitation $\rho(\tau)$ and the indicial response of the system

$$R_{inp \cdot out} = B\,\rho(\tau) + C e^{-\lambda_k t} \sin(\omega_k t + \varphi_k) \qquad (34)$$

In practice, the analysis requires determination of the cross-correlation function by an analogue followed by selective filtering.

NOTE: When there is only one mode in the response, the parameters ω and λ may be read directly from the graph of the function.

FIGURE 15

4.2.3 Third Method: Rejection method [12]

This method requires no accurate quantitative knowledge of the input function. It assumes only a qualitative characteristic of the spectral density $\phi(\omega)$, which must be monotonic. It will, therefore, apply particularly well to the response of any parameter (acceleration, bending moment) of an aircraft exposed to a natural turbulent excitation, since the input spectral density curve always shows a monotonically decreasing trend.

Principle

Assuming a one degree of freedom system, with an admittance $z(\alpha, j\omega)$, the general relation between the input and output spectral densities is expressed as

$$\phi_{out}(\omega) = [z(\alpha, j\omega)]^2 \cdot \phi_{inp}(\omega) \qquad (35)$$

The response is directed into an electronic circuit, with damping β and admittance Z^* $(\alpha, j\omega)$; the output will have the spectral density

$$\phi_{out}(\omega) = [Z(\alpha, j\omega)\, Z^*(\beta, j\omega)]^2 \phi_{inp}(\omega) \qquad (36)$$

If the circuit has an admittance curve which is the reverse of that of a second-order system, the following relation is obtained:

$$\text{if } \beta = \alpha,\; Z^*(\beta, j\omega)\, Z(\alpha, j\omega) \equiv 1 \text{ for all } \omega \qquad (37)$$

$$\text{and } \phi_{out}(\omega) \equiv \phi_{inp}(\omega) \qquad (38)$$

In other words, the procedure followed is the same as the operating procedure of a zero method.

The reduced mode damping α is the unknown value sought; the reduced damping β of the rejection filter is continuously variable.

If $\beta < \alpha$, at the system resonance frequency, the rejection is too great, and out(ω) will have a peak. For $\beta = \alpha$, ϕ out decreases monotonically as ϕ inp do.

These remarks may easily be extended to the case of several modes.

Equipment and test procedure

The operator - the rejection filter B - is placed into the computating process for the spectral density ahead of the actual analysis filter (D).

The filter is essentially composed of a double T-bridge incorporated into the direct channel of a counter-reactioned amplifier and shows, within a broad band around the central frequency, behaviour which is exactly the reverse of that of a second-order system ("rejection" circuit); the asymptotic behaviour is different and, for $\omega/\omega_i \gg 1$, the curve tends toward unity.

The damping and the frequency vary continuously within ranges corresponding to the usual values of structural modes.

FIGURE 16

There are three identical circuits, arranged in series and separately adjustable, and having a common output allowing the simultaneous rejection of three modes.

The rejection filter has two positions:

- An "out-of-circuit" position (B), with a transfer function which provides a first crude curve of the spectral density by means of the analysis filter. Inspection of this graph provides the resonance frequency ω_i.
- An "operational" position (C) for which are displayed the ω_i values and the assumed α_i, the order of magnitude of which may at least be estimated on the rough curve (E). Some points of the spectrum are revised for each resonance frequency and the adjacent frequency bands.

  After a few manipulations, guided by an examination of the "peaks" and "troughs" of the spectrum the accurate values may be adjusted, (F).

The convergence is rapid and the accuracy satisfactory for modes that are not too strongly coupled, since in the spectral density curve the modal overshoots are squared.

Delay in the analysis is considerably reduced by starting from the copy of the sample on a long magnetic "loop" (A) of which the playback is speeded up.

An example is given in FIGURE 17.

4.2.4 Fourth method: Counting the number of zero-crossings of the random variable [12]

Principle

This method is based on the use of the first Rice formula[13], and provides the mean number N_0 of zero-crossings in one direction of a stationary Gaussian process

$$N_0 = \left\{ \frac{\int_0^\infty f^2 \phi(f)\, df}{\int_0^\infty \phi(f)\, df} \right\}^{1/2}, \qquad f = \frac{\omega}{2\pi} \tag{39}$$

It may be extended to processes which are locally stationary and Gaussian, such as atmospheric turbulence.

Assuming that the response of the structure of admittance $z(\alpha, jf)$ is directed into a selective filter with admittance $z'(\beta, jf)$ the mean number of zeros per second of the resulting process will be

$$N_0^* = \left\{ \frac{\int_0^\infty f^2 |z'(\beta, jf)\, z(\alpha, jf)|^2 \phi_{inp}(f)\, df}{\int_0^\infty |z'(\beta, jf)\, z(\alpha, jf)|^2 \phi_{inp}(f)\, df} \right\}^{1/2} \tag{40}$$

If successive measurements of N_0^* are taken, for various values of the frequency, in the neighbourhood of f_i - the resonance frequency of one structural mode - it can be shown that α and β are connected by the relation

$$\alpha = \beta \, \frac{\delta N_0^* / \delta f}{1 - \delta N_0^* / \delta f} \tag{41}$$

Measurement of $\delta N_0 / \delta f$ gives the solution of the problem since β is known. This method requires no trial and error.

Apparatus

The apparatus consists of a counter meter of "level crossing" type and a band filter.

In order to separate two neighbouring modes, it is sufficient to take a highly selective filter.

5. CONCLUSION

Several methods - and, for each method, various techniques for applying it - are thus available to the specialist interested in aeroelastic test procedures. Particular considerations in each case will guide his individual choice: weight, overall dimensions, electrical power of the installation, nature and frequency of the modes to be surveyed, means of analysis. In order to perform a test on a large aircraft, it is sometimes profitable to apply simultaneously two methods - for instance, the harmonic and the pulse methods; the first is better adapted to the excitation of fixed parts of the structure, and the second is more adaptable for the excitation of control surfaces.

It is interesting to say a few words on the use of accessory techniques, such as telemetry. Without doubt, the transmission by telemetry of some significant signals is a great advantage in respect of safety; close observation on the ground of the structural response makes it possible to stop a test when a certain margin on the variation of a parameter determined a priori, is no longer maintained. But the systematic and particularly the exclusive use, of telemetry for a vibratory test is not advisable. Experience shows that it is often difficult to meet simultaneously the requirements associated with the restricted range of the transmitters and those which result from the investigation of geographical regions of weaker turbulence, especially for a high-speed aircraft flying in steady level flight - at low or medium altitude.

The test procedure governing the exploration of the flight range of a prototype must also be considered. In general, with a prototype, a restricted flight range is cleared, using as a basis the result of computations for the subsonic range.

The exploration of dangerous areas that may be affected by critical speeds inaccurately predicted by computation, must be done step by step, with adequate time allocated to deliberation of successive steps.

Also even in the case where an automatic, advanced analysis system is available, which operates in real time, it is hazardous to cover several points of the flight range during the same flight, except in a few very simple individual cases.

The application of a test sequence includes two phases:

A first phase, purely experimental, which includes the actual implementation of the excitation and the analysis by means of techniques which, other things being equal, should be selected so as to extract the parameter values with the least delay.

A second phase, which is for reflection, consists in data exploitation, i.e.:

- collection of all data and the critical survey of their validity;
- following the behaviour of flight modes and the study of coupling mechanisms;
- review of experimental curve trends.

A coherent interpretation is a prerequisite for the preparation and realisation of the next step. This difficult phase, of great importance in its effects, can only be accomplished if there is no severe time limitation.

It must be acknowledged that a vibration test programme engages an aircraft for a relatively long time. But it is only at such a cost that the aeroelastic test really provides an effective operational procedure, for actually ensuring the integrity of a prototype, and not simply an elaborate demonstration of structural vibrations in flight, without any real guarantee of safety.

REFERENCES

1. MAZET, R. — Mecanique Vibratoire. Gauthier Villars. Paris 1955

2. BROADBENT, E.G.; HARTLEY, E. Violet — Vectorial Analysis of Flight Flutter Test Results. RAE Technical Note Structures 233, 1958

3. COUPRY, G. — Determination des Formes en Vol d'un Avion. Communication a l'Association Technique Maritime et Aeronautique, 1960

4. KENNEDY, Charles C.; PANCU, C.D.P. — The Use of Vectors in Vibration Measurement and Analysis. Journal of the Aeronautical Sciences, Vol. 14, 1947.

5. PIAZZOLI, G. — Quelques Aspects de l'Evolution des Techniques d'Essai Aeroelastiques. Recherche Aeronautique, No. 117, Mars-Avril 1967.

6. De VRIES, C. — Quelques Points Particuliers de la Technique d'Excitation en Vol par Vibrations Harmoniques. Recherche Aeronautique No. 74, 1960

7. BOISSEAU, J. — Les Excitateurs a Bobine Plate pour les Essais de Vibrations des Structures. Recherche Aeronautique No. 94, 1963

8. PIAZZOLI, G. — Appareillage d'Essais de Vibration en Vol de l'Avion Concorde. Recherche Aeronautique No. 120, 1967.

9. COUPRY, G. et al. — Etude de l'Amortissement des Vibrations en Vol par Percussions sur les Surfaces Portantes. Recherche Aeronautique, No. 47, 1955.

10. COUPRY, G. — Auscultation d'une Structure par Percussion. Communication a l'Association Technique Maritime et Aeronautique, June 1957.

11. COUPRY, G.; PIAZZOLI, G. — Problemes du Vol en Atmosphere Turbulente. Recherche Aeronautique No. 111, 1966.

12. COUPRY, G.; PIAZZOLI, G. — Utilisation de la Turbulence comme Source d'Excitation lors d'Essais en Vol de Flottement. Fifth International Congress of the Aeronautical Sciences. London, September 1966.

13. RICE, S.O. — Mathematical Analysis of Random Noise. Bell Systems Technical Journal, Vol. XXIII, No. 3, 1944 and Vol. XXIV, No. 1, 1945.

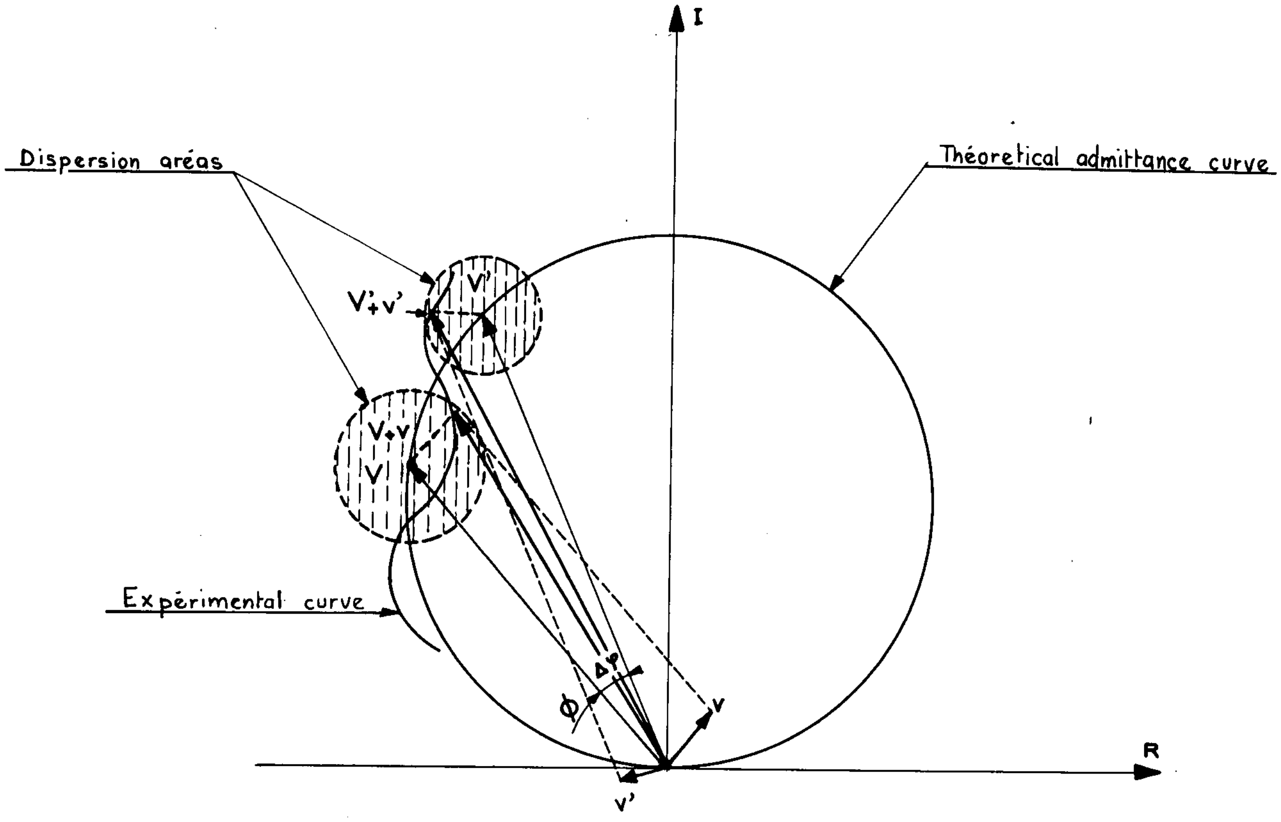
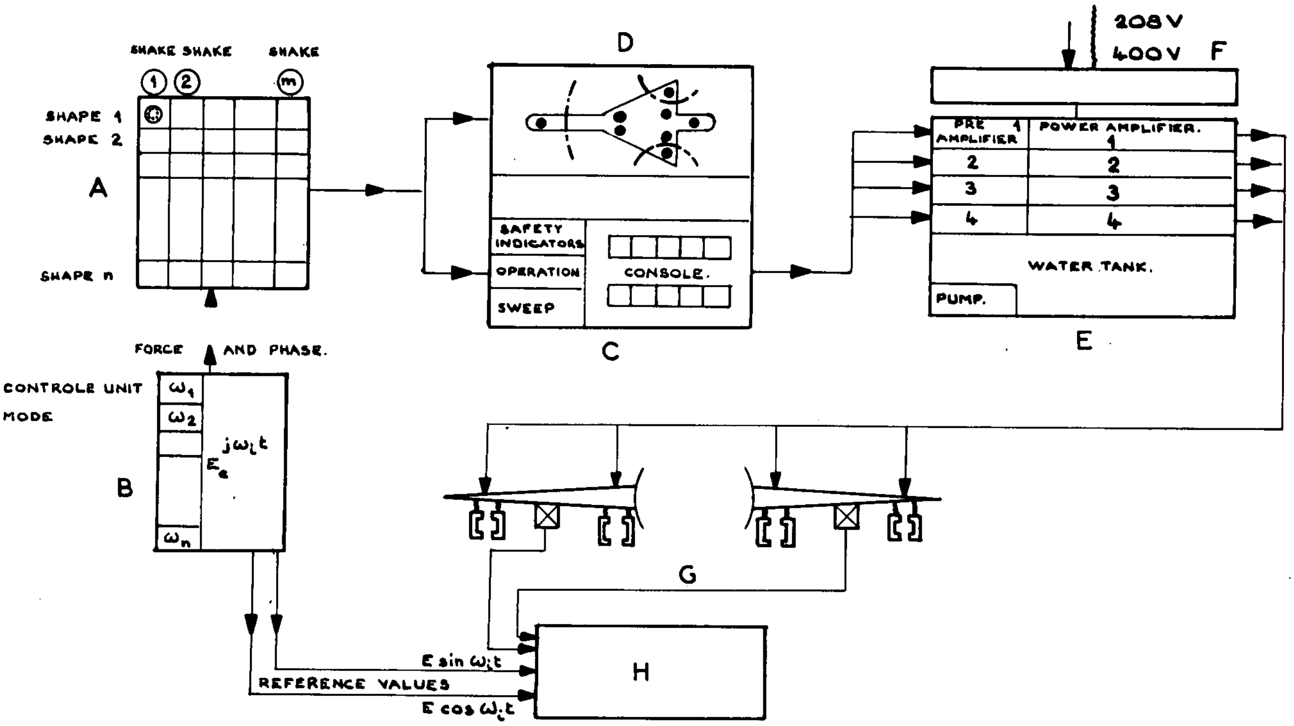


Fig. 1 Effect of noise on the admittance curve



A - Pré - display panel
B - Two - phase générator
C - Control panel
D - Aircraft control profile
E - Amplifying unit
F - Stabilized power supply
G - Accéléromelers
H - Magnétophone (14 tracks)

Fig. 2 Block diagram

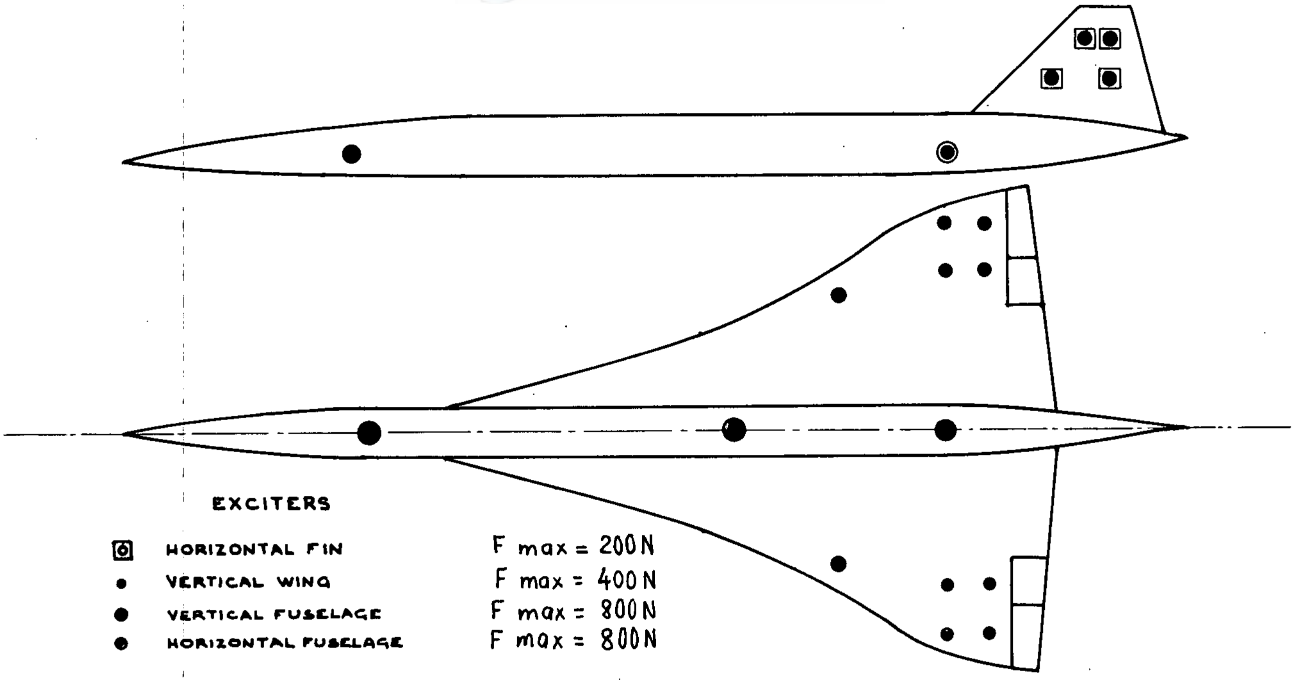
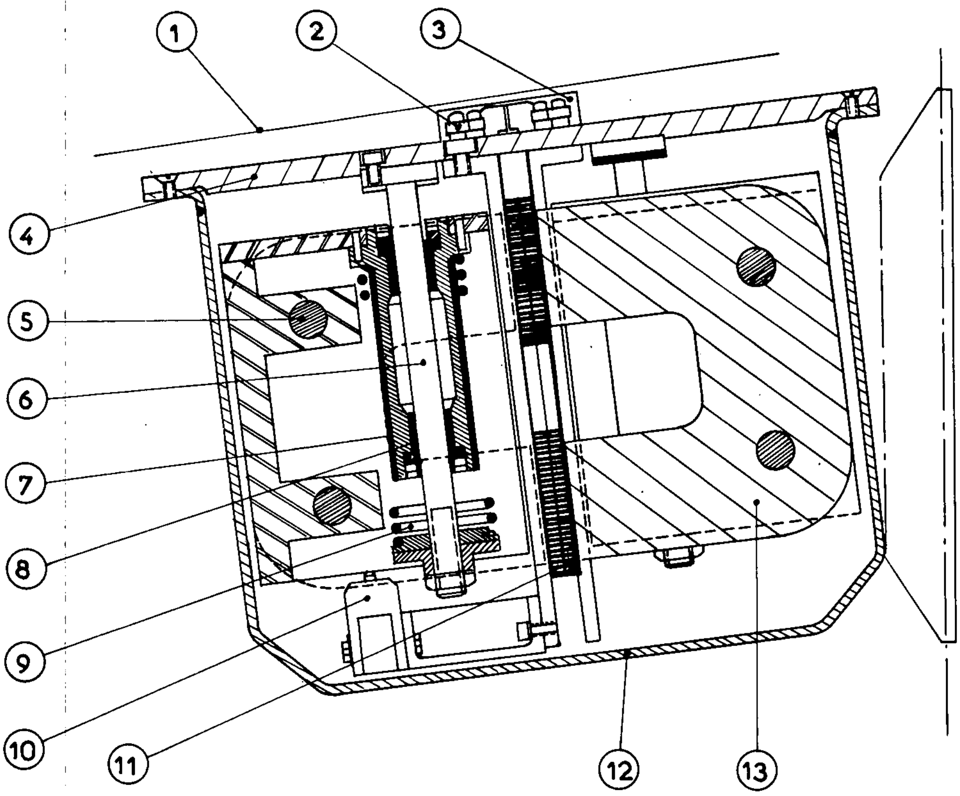


Fig.3 S.S.T Concorde 001. Location of exciters



1 Aircraft skin
2 Sealed passage
3 Silastène protection
4 Mounting base
5 Threaded rod
6 Guiding rod
7 Shock - absorbing
8 Metafram ring
9 Spring
10 High température microswitch
11 High température coil
12 Sealed fairing
13 Magnet

Fig.4 Wing exciter (Transverse section)

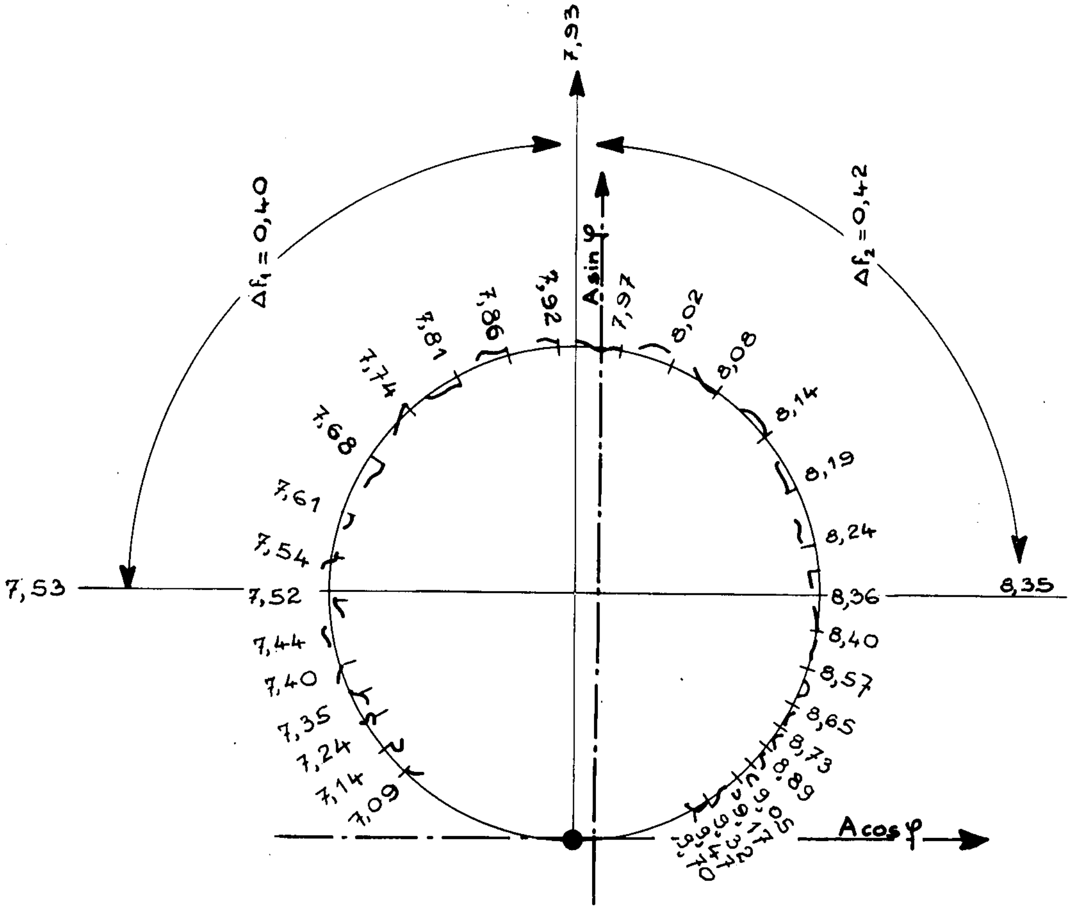


Fig.5 C160 "Transall". Wing bending (Fournodes)

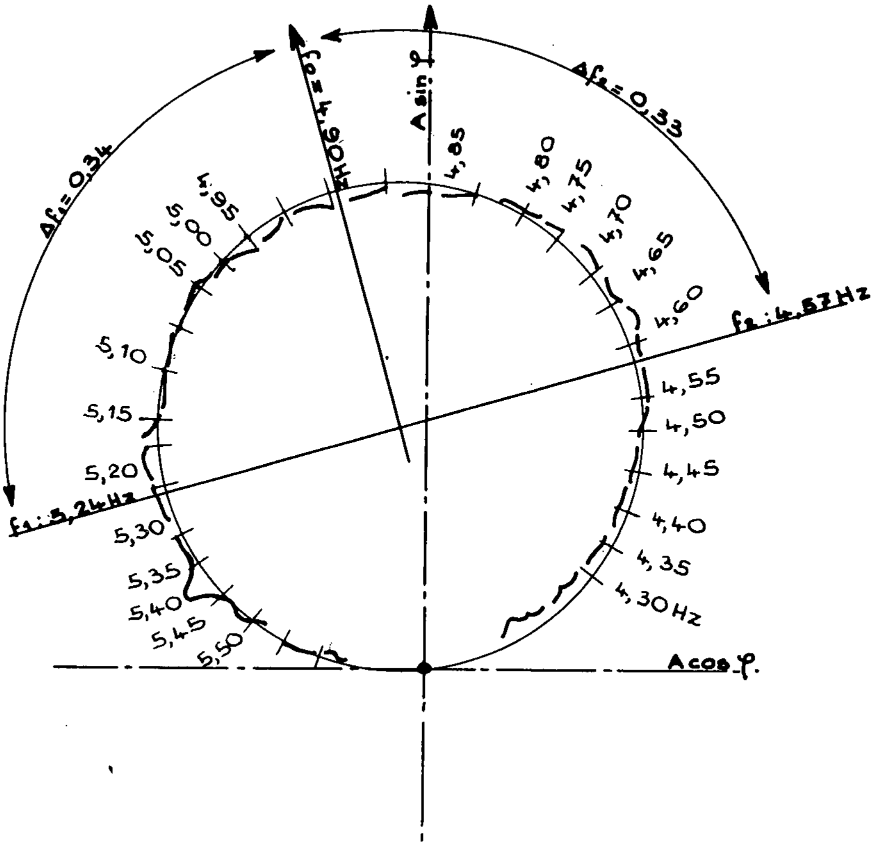


Fig.6 S.S.T Concorde 001. Fin bending

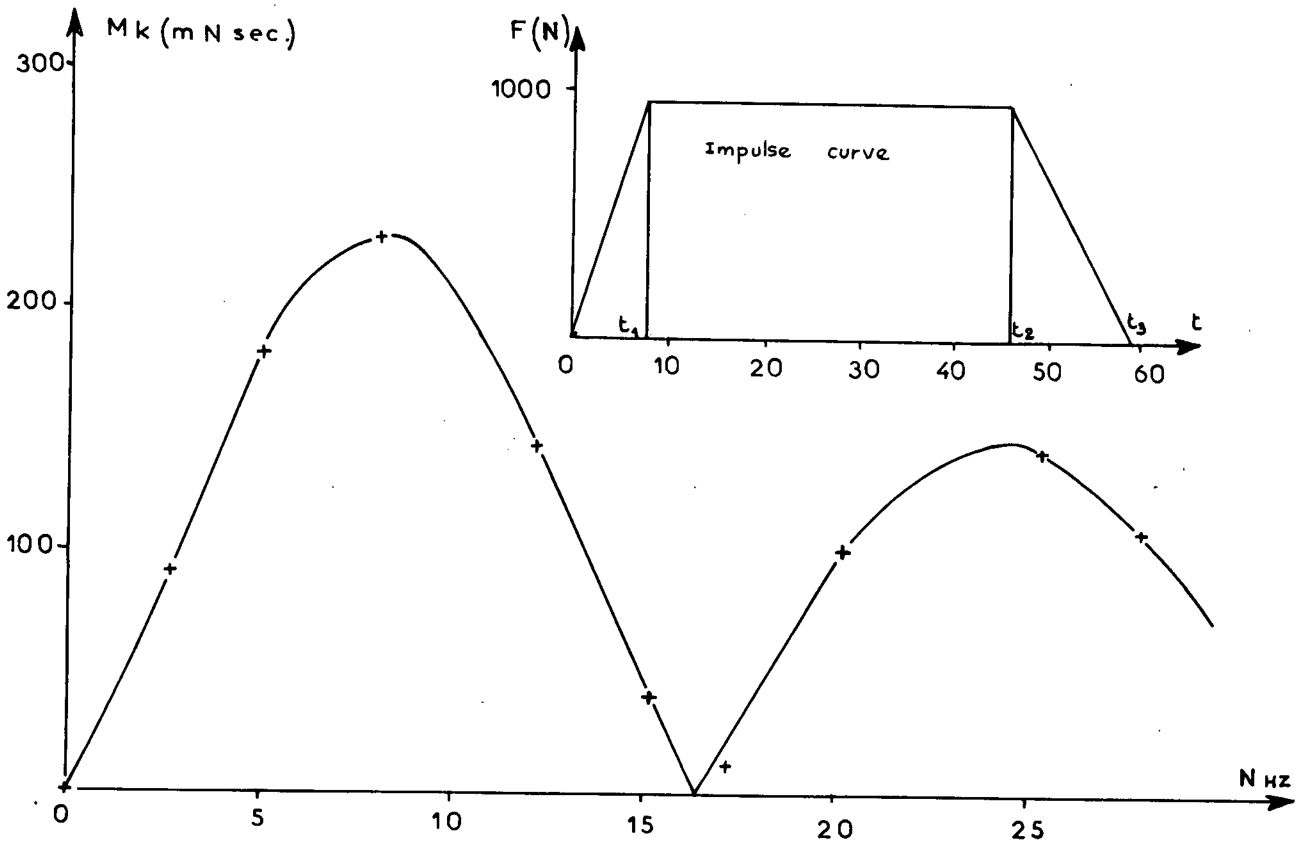


Fig.7 Adaptation function

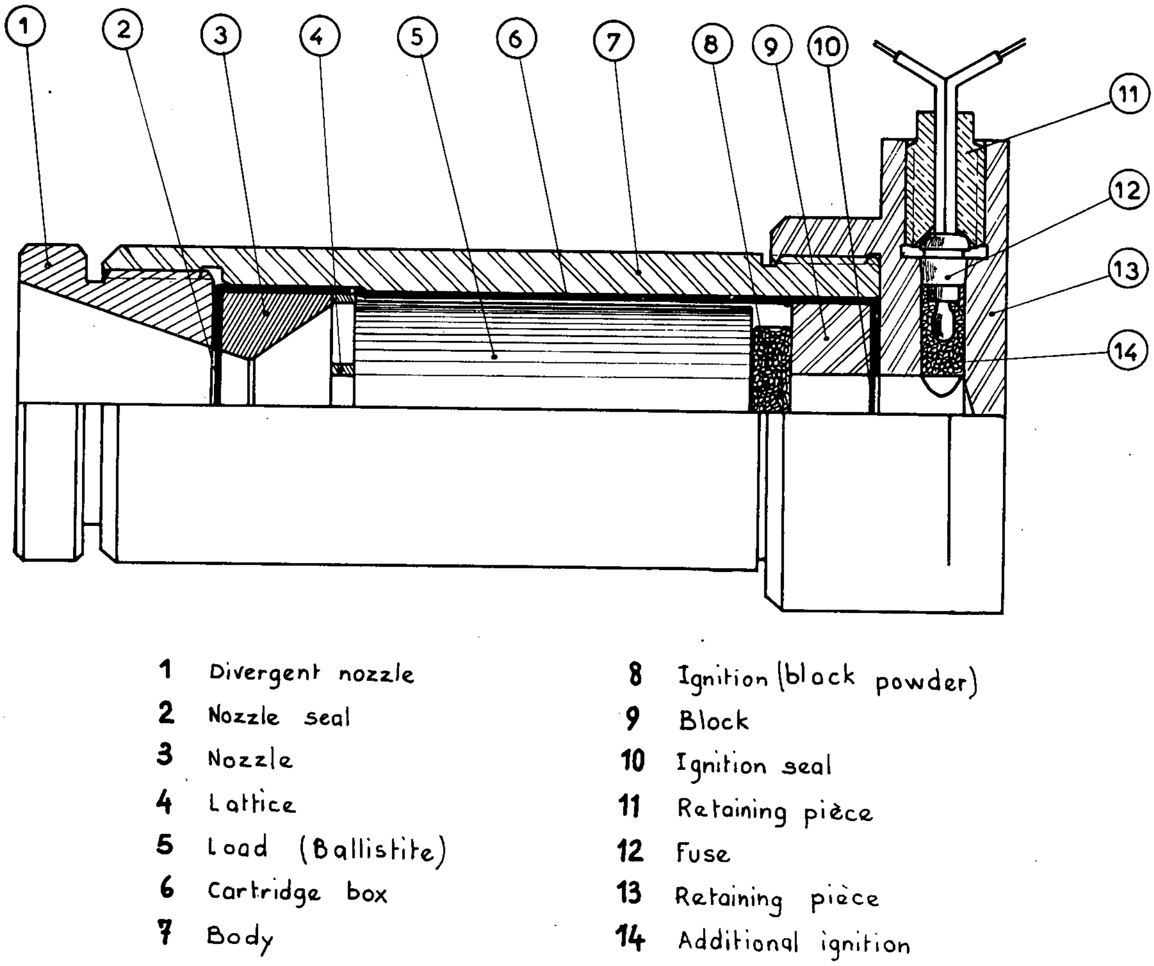


Fig.8 Cartridge-loaded "bonker" (A661)

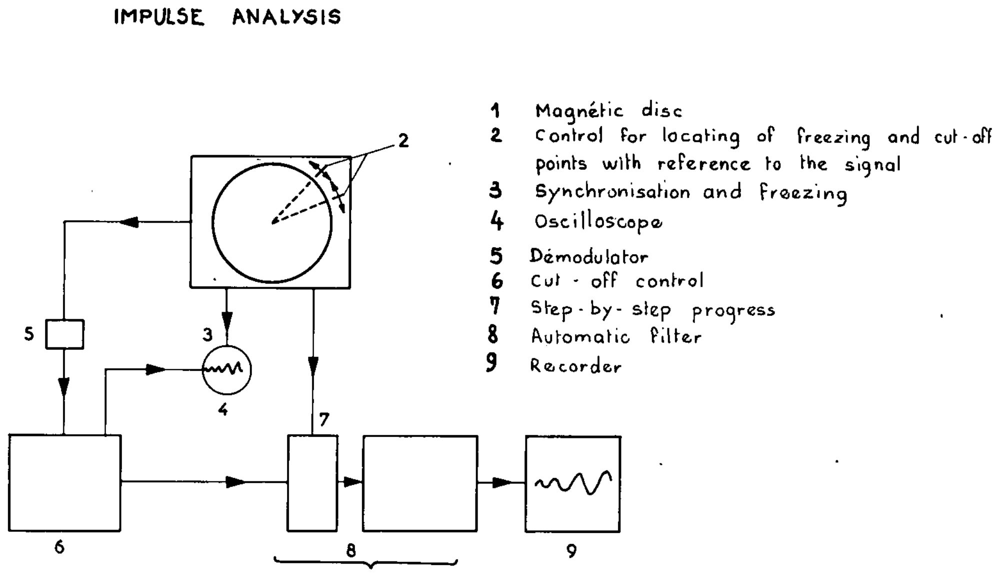


Fig. 9 Automatic system (block diagram)

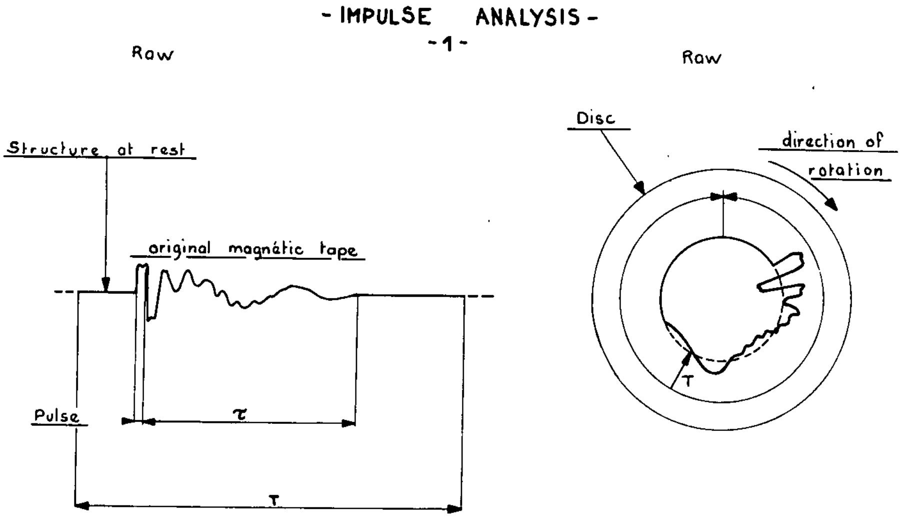


Fig. 10 Copying and freezing

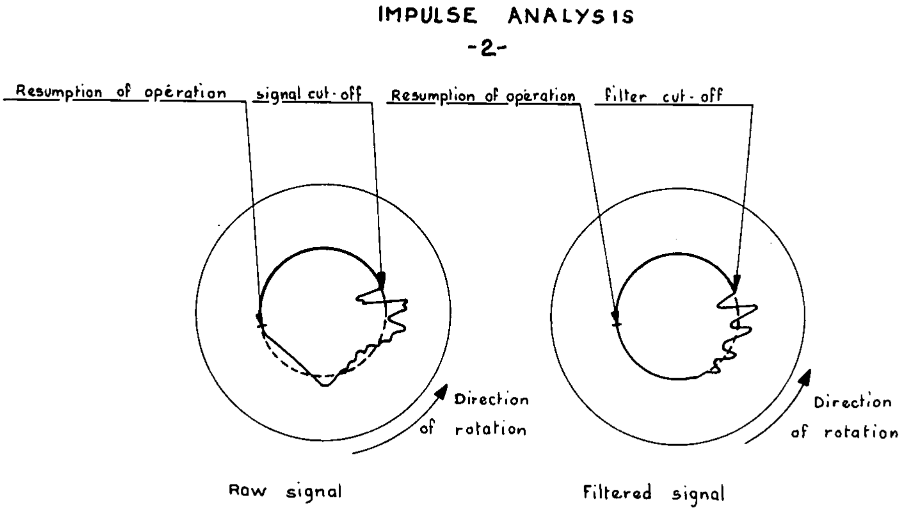


Fig. 11 Reversal and cut-off

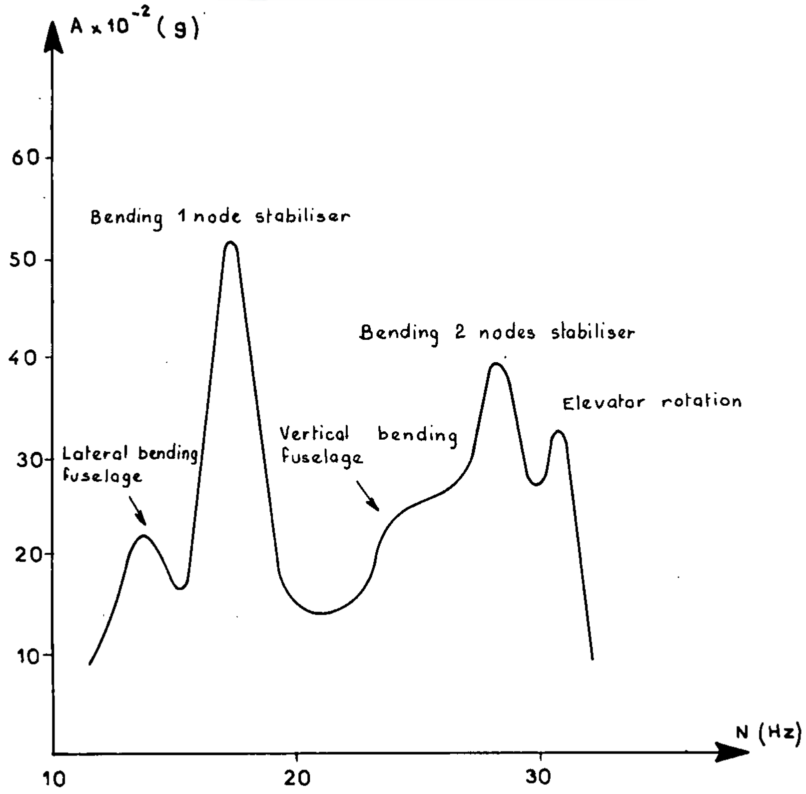


Fig.12 Response to a pulse in flight

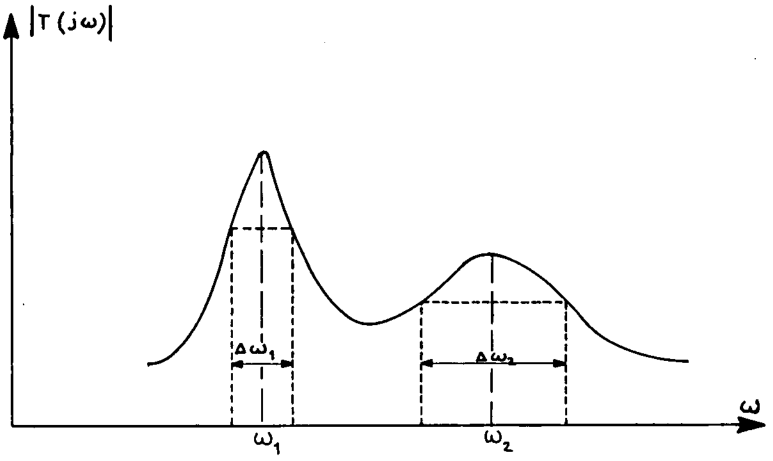


Fig.13 Measurement of damping from sharpness of resonance

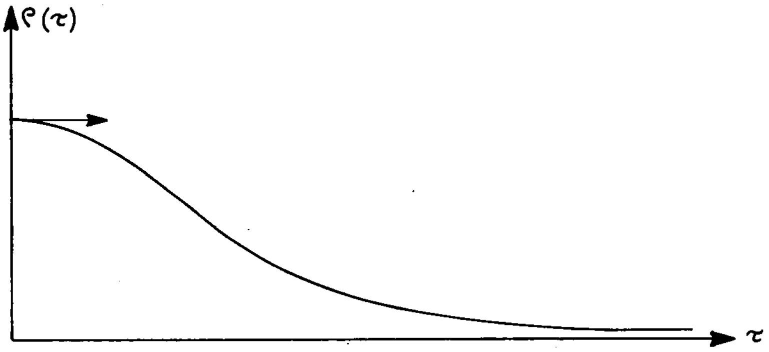


Fig.14 Autocorrelation function of turbulence

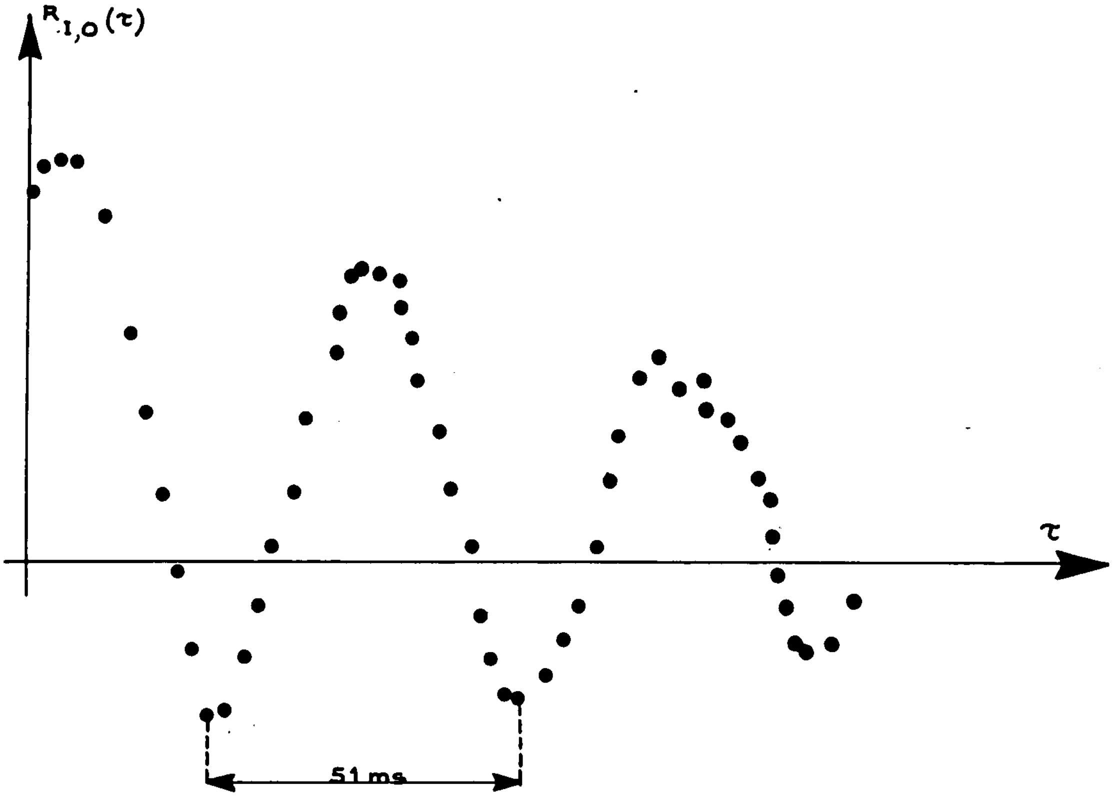
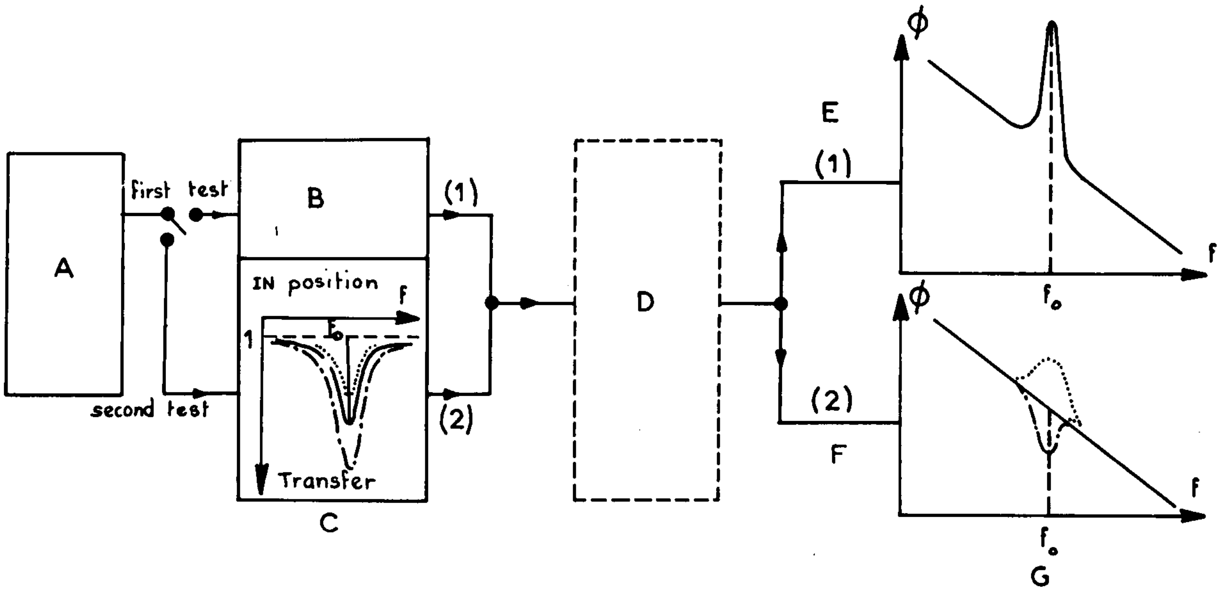


Fig.15 One degree of freedom response



A Long magnetic loop
B Out-of-circuit filter
C Rejection filter
D Analysis filter
E Rough curve of spectral density
F Spectral density after rejection

Fig.16 Block diagram

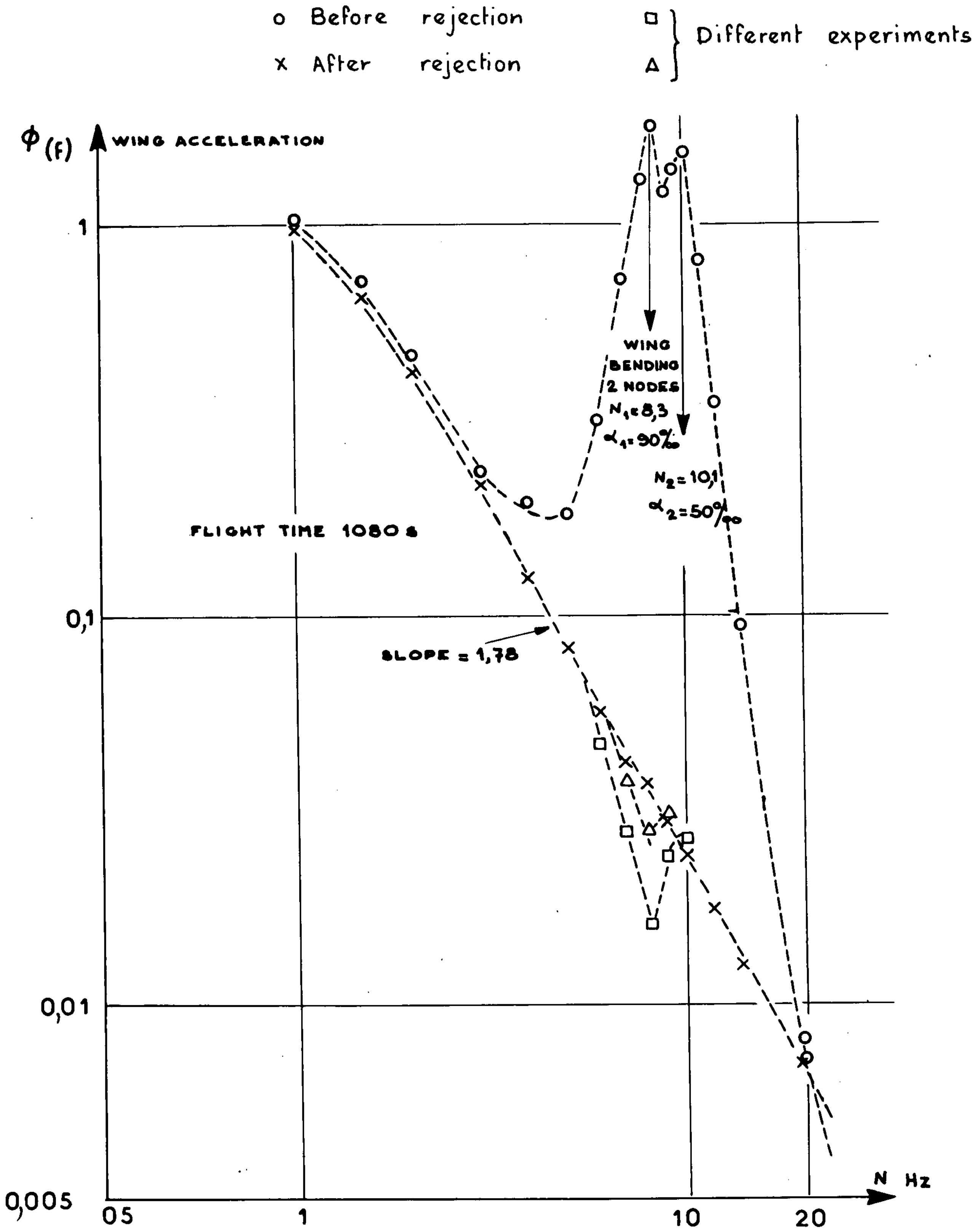


Fig. 17 Analysis of wing response in turbulence

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VOLUME III	PART III PREDICTION OF AEROELASTIC PHENOMENA
*VOLUME IV	PART IV EXPERIMENTAL METHODS
VOLUME V	PART V FACTUAL INFORMATION ON FLUTTER CHARACTERISTICS
VOLUME VI	PART VI COLLECTED TABLES AND GRAPHS

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October 1970

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G.Piazzoli
Published December 1970
36 pages

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