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Wind Tunnel Flutter Tests at Subsonic Speeds on a Half-Wing with a Fan Engine Nacelle

by

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WIND TUNNEL FLUTTER TESTS AT SUBSONIC SPEEDS ON A HALF-WING WITH A FAN ENGINE NACELLE

by

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G. B. Hutton

SUMMARY

Flutter tests have been made on a half-wing model with a fan-engine nacelle attached by a pylon at an inboard section. The model was nominally rigid and flexibilities in pitch and roll were introduced at the root. Measurements were made of the flutter characteristics of the model at Mach numbers of 0.6 and 0.8 over a range of dynamic pressures using three different methods of analysis. The nacelle was replaced by a narrow 'pencil' of equivalent inertia in order to assess the effects on the flutter characteristics of the aerodynamic forces on the nacelle. It is shown that these forces modify significantly the aeroelastic behaviour of the wing-nacelle system. The tests were made in conjunction with the Office National d'Etudes et de Recherches Aérospatiales, and were part of a larger investigation which included static and oscillatory pressure measurements on the wing.

* Replaces RAE Technical Report 74130 - ARC 35955

CONTENTS

1 INTRODUCTION

Two current developments in subsonic aircraft design, namely the increasing use of large fan engines slung under the wing, and the adoption of supercritcal flow wings (that is to say wings designed to take advantage of substantial regions of supersonic flow) have posed problems for the aeroelastics engineer. The problems arise mainly from lack of data on the oscillatory aerodynamic forces associated with these developments. A recent investigation, made jointly by the Royal Aircraft Establishment and the Office National d'Etudes et de Recherches Aérospatiales, has enabled both these problem areas to be explored, albeit to a limited extent; the purpose of this Report is to present the results obtained from part of this investigation. The part that is dealt with here concerns the subcritical flutter response behaviour of a model wing, and the aerodynamic effect of a large fan engine nacelle on this behaviour. Although the wing was designed for an operational condition in which there is some degree of supercritical flow, it was not possible, for reasons that are given in the report, to carry out the flutter tests with the wing in this flow condition. The tests were, in fact, made with zero wing root rolling moment and low lift coefficients; transonic flow occurred over the wing, but the large area of supersonic flow which is a characteristic of 'supercritical' wings was not developed.

The influence of the aerodynamic forces associated with a large fan engine was investigated by testing the model in two configurations, first with a model engine nacelle mounted on a pylon under the wing, then with the nacelle replaced by a slim body of equivalent inertia.

The tests were made at Mach numbers of 0.6 and 0.8, and the subcritical response characteristics were determined from analysis of the response of the model to turbulence in the airflow. ONERA and RAE used different methods of analysis, so that it was possible to compare these methods under identical test conditions.

Although limited measurements of oscillatory pressure distributions over the wing were made earlier for the lift condition of the flutter tests, these measurements have not yet been used in flutter calculations. The flutter test results are therefore compared with calculations based on linear aerodynamic theory; they were made to check that the theoretical flutter behaviour of the wing was comparable with the actual behaviour during test.

The results of the test programme show that the aerodynamic forces associated with a large fan engine nacelle can have a significant influence on the flutter characteristics of the wing. For the particular configuration tested, in which the nacelle was rigidly attached to the wing, the principal effect of the nacelle aerodynamic forces is to reduce the flutter speed.

This effect is confirmed by the calculations, although it is evident that flutter calculations based on linear aerodynamic theory have not given close agreement with measured modal characteristics, the measurements indicating higher flutter speeds than were calculated. However, more valid comparisons of measurement and calculation will have to await the inclusion of measured aerodynamic forces in the calculations.

The comparison of three different methods of analysing the response of the model to obtain modal characteristics showed that, in general, the differences were small, although there was rather larger scatter of the results from one of the methods than from the other two.

The overall conclusion that can be drawn from the programme is that both the 'supercritical' wing and the large fan engine nacelle can have a significant influence on wing flutter, and in neither case can the aerodynamic forces peculiar to these design features be ignored. It is considered essential, therefore, to follow up the preliminary work which has now been done with more detailed aerodynamic investigations.

2 OUTLINE OF PROGRAMME

The programme of work that has been undertaken is one of several research programmes in aeroelasticity that have been tackled jointly by RAE and ONERA in recent years. In the initial discussions that led to the present programme there were two main objectives:

(i) to acquire knowledge of the unsteady aerodynamic forces associated with a wing with some degree of supercritical flow, and

(ii) to acquire similar information for a wing with a large fan engine nacelle attached.

Whilst it would clearly be possible to plan a very comprehensive programme to achieve each of these objectives, it was the intention, at the outset, to limit the programme so that all the experimental work could be undertaken during a single series of tests requiring 80 to 100 hours of wind tunnel use. This restraint was necessary for several reasons, which are not pertinent to this Report, but the restraint is mentioned because it affected the planning of the programme, and accounted for some of the omissions that will be mentioned later.

It was decided to use one model to investigate both supercritical and fan engine nacelle aerodynamic effects. Practical considerations led to the use of a rigid, half-wing model with flexibilities in pitch and roll introduced at the root. The model was based on a design for the wing of an aircraft intended to cruise at a Mach number of 0.84 and with lift coefficients in the range 0.3-0.4. In these conditions a moderate degree of supercritical flow is developed. A fan engine nacelle was mounted on a pylon under the wing.

The first part of the programme was concerned with measurements of unsteady pressures on the wing when the wing was oscillated sinusoidally about a sweptback pitch axis[1]. The steady lift forces generated on the wing at cruise incidence, and at other incidences that were investigated, were so large that it was essential to support the tip of the wing on the pitch axis.

The second part of the programme was an investigation of the subcritical response characteristics of the model when the wing was allowed freedom in roll about the root in addition to the pitch freedom of the earlier pressure measurements. Although it had been intended initially that the subcritical flutter tests should be made for the same conditions of wing incidence as the pressure measurements, it proved impossible to realise this intention because the bending moment developed on the wing was too great for the structure to support. As a result, the subcritical flutter tests were made with the wing in a near zero-lift condition. In this condition the flow was not supercritical and the pressure measurements referred to above do not apply. Accordingly, an additional set of pressure measurements was made for the zero-lift condition and these yielded aerodynamic data appropriate to the flutter tests. It can be seen, therefore, that the pressure measurements in supercritical flow conditions are not complementary to the flutter tests and that the latter cannot be used as a guide to the effect of supercritical flow on flutter behaviour.

The subcritical flutter characteristics were obtained, both with and without the nacelle, at each of two Mach numbers as a function of tunnel stagnation pressure. An unexpected feature of the tests was that the level of tunnel turbulence at the higher values of stagnation pressure produced very large responses in the wing; extensive testing in these conditions was considered to be hazardous. The perforated walls of the tunnel were sealed between sections 1.5m upstream and 1.5m downstream of the model in an attempt to reduce the excitation level. This modification was found to have an effect on the sub-critical behaviour of the model at M = 0.8, but the limited availability of the tunnel prevented fuller investigation of the effects in all model configurations. It was desirable to show the effect of the modification over the range of tunnel pressures where tests could be made safely with the wall perforations open. The tests could then be extended to higher pressures with the perforations sealed, and the two sets of data used to derive the 'perforations open' results at the higher pressures. In fact, in only one case was this procedure not followed, and this was at M = 0.8 without the nacelle on the wing.

It should be mentioned that the pre-test flutter calculations were made by ONERA in order to find a position on the wing at which mass-balance could be attached so that (a) the critical flutter condition lay within the tunnel performance range and (b) the rate of change of modal damping with tunnel pressure near the flutter condition was as rapid as possible. The calculations were made using linear aerodynamic theory, which, although clearly inappropriate to the particular configuration, was considered adequate for the purpose of mass-balancing the model. A method for computing the aerodynamic forces on the nacelle has been developed at ONERA[2] and these forces were included in the flutter calculations. No allowance was made for any aerodynamic effect of the supporting pylon. The measurement of more appropriate aerodynamic forces in the test programme now enables more realistic flutter calculations to be undertaken. However, these calculations have not yet been made, and in this Report the results of the earlier calculations are given.

3 MODEL, RIG DESIGN AND CONSTRUCTION

3.1 Wing and support rig

The wing planform is shown in Fig.1. The section profile was cambered and twisted along the span. At M = 0.8 the wing root incidence for zero wing root bending moment was -2.6°. The wing was built of aluminium alloy, and was designed so that its natural frequencies were as high as possible. A housing was fitted at the wing tip to carry the mass-balance determined from the pre-test calculations (see section 2).

The root of the wing was attached to a combined torsion and cantilever spring system which was, in turn, attached to a turntable in the wall of the wind tunnel.

3.2 Engine nacelle and equivalent inertia

The model nacelle was a simple representation of the external shape of a fan engine, with a central duct designed to ensure a flow pattern at the intake that was approximately representative of a full scale engine. No fan or engine was fitted in the nacelle. Fig.1 shows the spanwise position of the nacelle and Figs.2 and 3 illustrate the nacelle mounted on the wing pylon. When tests were made without the nacelle, a 'pencil' of equivalent inertia was attached to the pylon as shown in Fig.4. The inertia of the nacelle and pencil were equivalent in the sense that both items had the same mass and pitching and rolling moments of inertia about the wing.

4 INSTRUMENTATION AND ANALYSIS

4.1 Motion transducers

Two strain gauge bridges, sensitive to roll and pitch of the wing, were attached to the root support spring system. These gauges provided the response signals which were subsequently analysed by the methods described in section 4.3.

4.2 Excitation

The model was excited in the wind-on tests by turbulence in the airflow. Measurements of the tunnel noise spectrum given by Mabey[3] show no sharp peaks between 20 and 600 Hz at $M = 0.6$ and 0.8. Over the frequency range of interest (28-60 Hz) the spectrum appears almost flat.

An electro-mechanical exciter, attached to the wing root, was used to excite the model for measurements of frequency and damping in still air.

4.3 Analysis

4.3.1 ONERA procedures

The first method of analysis used by ONERA was to obtain the spectral density of samples of the output of the response transducers. A Federal Scientific spectrum analyser was used, sampling for each record, 2000 voltage levels at 2.5ms intervals. The modulus of the square root of the power spectral density was displayed on a viewing screen in the analyser, and subsequently drawn on an x-y plotter. The natural frequencies and dampings of the component modes were obtained from the spectral density plots by graphical analysis. This involved identifying the frequencies at which peaks occurred, and measuring the bandwidth of the peaks. A typical spectral density plot is shown in Fig.5.

A second method of analysis which was applied by ONERA was based on a method by Cole[4] - the so-called Random Decrement method. The whole response record for each test condition was digitised at equal intervals of about 1 ms. A computer was programmed to form the Random Decrement signature by searching the record for a portion where the signal crossed a reference voltage level. The next five hundred samples formed one of the sections of record on which the Random Decrement signature was based. The number of sections averaged to produce the Random Decrement signature varied between four hundred and eight hundred; the number of sections taken with the signal having, initially, a positive slope was the same as the number starting with a negative slope. When the sections were added together, the resultant function (the Random Decrement signature) was very similar to the one-sided autocorrelogram of the response of the system. The addition was made by a computer and a typical presentation of the Random Decrement signature is shown in Fig.6. A computer programme was developed by ONERA to analyse this function; the programme calculates the frequencies and damping ratios of up to three modes of vibrations.

4.3.2 RAE procedure

The RAE method of analysis was to obtain the power spectral densities of a number of samples of the outputs of the response transducers. A Hewlett Packard Fourier Analyser was used, sampling 2024 voltage levels at 2.5ms intervals. The analyser processed each set of samples whilst taking in the following set, averaging the power spectral densities from all the sets (usually between ten and twenty). The autocorrelogram of the averaged power spectral density was then formed. The subsequent analysis followed that used by Newman and others[5] and consisted of three stages;

(i) truncation of the autocorrelogram to remove 'noise' at the higher values of lag time,

(ii) weighting the truncated autocorrelogram with an exponential decay

and (iii) taking the Fourier transform of the one-sided autocorrelogram after it had been subjected to stages (i) and (ii).

The resulting function was analysed[6] by the Fourier analyser (which has a general purpose computing capacity) to give the model frequencies and fractions of critical damping, following which the damping values were corrected to allow for the exponential weighting.

4.3.3 Checks on analysis systems

It has been mentioned above that the function displayed by the spectrum analyser (Fig.5) was the square root of the modulus of the function displayed by the Fourier analyser (Fig.7a). The operation of the two analysers was checked during the course of the experiment by manipulating the power spectrum function obtained by the Fourier analyser to give a display (Fig.7b) which was directly comparable with that of the spectrum analyser.

A check on the analyser procedure was made 'on-line' by displaying the transformed, one-sided autocorrelogram from the Fourier analyser as in-phase and in-quadrature frequency response diagrams - see Figs.7c and 7d - and as a vector response plot - see Fig.8. These diagrams were then analysed graphically to give resonance frequencies and dampings.

5 EXPERIMENTAL MEASUREMENTS

5.1 Still-air tests

Resonance tests were made on the model to obtain the natural frequencies and mode shapes for the first two modes (the roll and pitch modes) and to check whether any other modes existed below 100 Hz. The tests were made with the pencil and with the nacelle on the pylon. The natural frequencies were:-

Mode	With pencil	With nacelle
1 - 'roll'	30.74 Hz	30.73 Hz
2 - 'pitch'	46.56 Hz	46.59 Hz

Modal displacements were measured at the positions shown in Fig.1. The associated mode shapes are shown in Fig.9, from which it can be seen that there was some elastic distortion of the outboard structure of the wing in the pitch mode. There were no other modes in the frequency range up to 100 Hz.

Generalised moments of inertia about the pitch and roll axes were measured using the added mass technique, giving the following results:-

Mode	With pencil	With nacelle	Normalising point (Fig.1)
1 - 'roll'	0.371 kg m^2	0.380 kg m^2	53
2 - 'pitch'	1.6435 kg m^2	1.7760 kg m^2	11

5.2 Wind tunnel tests

5.2.1 M = 0.6

Figs.10 and 11 show the variation of model frequency and damping with tunnel stagnation pressure. The results are given for the tests with the pencil and with the nacelle. For each configuration, tests were made with the tunnel wall perforations partly sealed, and, at low stagnation pressures, with the perforations open. The results in Figs.10 and 11 were obtained from the Fourier analyser procedure described in section 4.3.2.

Fig.10 shows that there was a smooth change of frequency of both modes, mode 1 increasing and mode 2 decreasing in frequency as stagnation pressure was increased. Sealing the perforations had no significant effect on the frequencies but it is clear that the addition of the nacelle reduced the frequency of mode 2.

The damping values in Fig.11, which are complementary to the frequency values of Fig.10, show more scatter than the frequency values. Again it is reasonable to conclude that sealing the perforations had no significant effect on the damping. A comparison of the damping curves for mode 2, with the nacelle and pencil, shows that although flutter (i.e. zero damping) did not occur with either configuration, the damping values were lower with the nacelle attached. In both configurations the dampings were tending gradually to zero though tests with the nacelle were stopped at a pressure of 1.2 atmospheres because of the large response of the model. With the pencil attached, the tests were continued up to a pressure of 1.5 atmospheres.

5.2.2 M = 0.8

The test results given in Figs.12 and 13 for M = 0.8 correspond to those in Figs.10 and 11 for M = 0.6, except that the tests with the pencil attached were only made when the tunnel wall perforations were sealed.

The general trends in frequency (Fig.12) are the same as were observed for the lower Mach number (Fig.10), and, with the nacelle attached, sealing the perforations had little effect on frequency. The comparison is somewhat different for the damping values, however, (Fig.13) in that, with the nacelle attached, it is obvious that sealing the perforations raised the damping values of mode 2. Despite this, it can be deduced from both the damping and frequency values with the perforations open that the effects of the nacelle on the flutter characteristics were similar to but less marked than those observed at M = 0.6.

Figs.12 and 13 were obtained from analyses using the Fourier analyser. Figs.14 and 15 show the results for the same tests when the spectrum analyser was used and Figs.16 and 17 show the results when the Random Decrement method was used. Considering now the analyses made directly from the graphical output of the spectrum analyser and comparing Fig.12 with Fig.14 it can be seen that the only significant difference in the frequency measurement lies in the greater degree of scatter of the spectrum analyser results when the pencil was attached to the wing. It is not clear why the difference did not occur when the nacelle was attached. Comparison of Figs.13 and 15, for the damping values, suggests that the scatter of the spectrum analyser results for mode 2, with the nacelle attached, was large enough to mask the effects of sealing the perforations. The results of analyses made by the Random Decrement method are illustrated in Figs.16 and 17. Comparison of Fig.12 with Fig.16, and Fig.13 with Fig.17 shows that there is little to choose between results obtained with either the Fourier analyser method or the Random Decrement method. This measure of agreement was also observed in the results of tests at M = 0.6; these results have not therefore been included in this paper.

6 CALCULATIONS

The calculated flutter characteristics of the model have been plotted in Figs.10 to 17. It has been stated in section 2 that these calculations were made prior to the tests in order to determine a suitable test configuration, that linear aerodynamic theory was used, and that no aerodynamic allowance was made for the pencil or pylon. Measured modes and generalised inertias were used in the calculations.

Subcritically, the two modes approach each other in frequency as stagnation pressure is increased and as the flutter condition is approached the damping in mode 2, the pitch mode, falls. The rate of change of damping in mode 2 with stagnation pressure is such that the flutter would normally be called 'moderate' in character.

7 DISCUSSION

7.1 Comparison of analysis techniques

In general the differences in mean test results between the three methods of analysis were small; the methods themselves differed in their ability to handle response records where the component modes had either high or low values of damping.

Considering first the results obtained from the ONERA spectrum analyser, it can be seen (Figs.14 and 15) that there was a tendency for scatter to be greater than in the results obtained from the other two methods (Figs.10-13, 16 and 17). This is not surprising because analysis of the spectrum analyser output was made graphically and was effectively the method of analysing an amplitude response plot. With a mode that was heavily damped, it was difficult to obtain graphically from the spectrum analyser output an accurate value of damping from a 'wide' peak; this difficulty was accentuated when the modal frequency was close to that of another mode. Similarly, with a mode having low damping, the sharpness of the peak could result in measurement errors because the thickness of the graph line represented a significant proportion of the frequency bandwidth.

The second method used by ONERA - that of Random Decrement signatures - is suited primarily to continuous running wind tunnels; the time needed to gather sufficient data for the analysis would effectively preclude use of the method in all but the longest running of intermittent tunnels. Special purpose equipment is not needed for generating Random Decrement signatures; all that is required is a means of recording and digitising the signal. However, direct analysis of Random Decrement signatures for modal characteristics is at present a lengthly and complex process, and demands access to a large digital computer. The computer program devised by ONERA for this exercise was capable of handling three modes of oscillation. The results show decreased scatter when compared with those obtained from the spectrum analyser. The Random Decrement signature itself can give a clear indication of the onset of flutter. Moreover, there is no inherent limitation in the degree of resolution of frequency and damping ratio as there is in the other two methods described here because the degree of resolution is dependent only on the length of record and, unlike the other two methods, this length is limited only by the recording capacity and the run time. It was not possible to establish from this experiment whether the increased degree of resolution was of practical significance, though at levels of damping ratio of about one per cent the differences between results obtained by analysing the autocorrelogram and those obtained by the Random Decrement method were small.

The method of analysis adopted by RAE employed a Fourier analyser; the mode of handling the data is described in section 4.3.2. In general, the results obtained were very similar in character to those produced by ONERA using the Random Decrement method. The specialised computing capacity of the Fourier analyser enabled the Fourier transform of the one-sided autocorrelation function of a record to be calculated very quickly and presented as a vector plot. The general purpose computing capacity of the machine enabled analysis of the vector plots to be made more accurately than by graphical means; the process was also faster. Although the Fourier analyser is classed as a special purpose computer, it has considerable versatility. Thus it can, for example, be programmed to provide Random Decrement signatures.

7.2 Comparison of calculation with experiment

Figs.10-17 illustrate the calculated and measured values of modal frequency and damping ratio. At M = 0.6 the trends of the calculated values for the wing plus pencil do not follow measurements very closely; flutter does not occur within the tunnel operating range. When the nacelle is attached the calculations indicate that flutter should occur at a stagnation pressure of about 1.15 atmospheres; in the tests it was found that the system was stable at this condition, though flutter might occur at a higher stagnation pressure.

At M = 0.8 there is no experimental evidence of the onset of flutter, although the calculation indicates that it should occur when the stagnation pressure reaches 0.95 atmospheres for the wing without nacelle and when the stagnation pressure reaches 0.83 atmospheres for the wing with nacelle. Again, the trend of calculated values in the subcritical range does not agree with measurement very closely.

The extent to which these differences are the result of an unrealistic representation of the aerodynamic forces in the calculation will be demonstrated when calculations are made using measured unsteady pressures appropriate to these tests. Similarly, it is not yet possible to make any very satisfactory assessment of how well calculation predicts the changes in flutter behaviour which occur when the nacelle is attached although the changes in calculated characteristics are broadly similar to the changes in measured characteristics.

7.3 Effect of tunnel wall conditions

It is possible to calculate the degree of unsteady interference on a model oscillating in a slotted wall tunnel[7] but no comparable analysis is yet available by which corrections can be made for tunnels with perforated walls. Figs.10 and 11 show that at M = 0.6 there are no noticeable changes in modal frequency and damping ratio resulting from sealing the perforations. At M = 0.8, however, although the modal frequencies are not affected (Fig.12), the damping in mode 2 is approximately doubled by sealing the perforations (Fig.13). No such increase is apparent in mode 1, although the high damping in this mode would make an increase more difficult to detect. The increased damping in mode 2 which occurs when the tunnel wall conditions are changed indicates that this flutter speed is also likely to be significantly higher.

7.4 Application of the Zimmerman formula

Zimmerman and Weissenberger[8] have shown that, for a binary system, a flutter margin function F can be defined such that F is dependent on values of modal frequency and damping ratio and decreases smoothly to zero at flutter. The use of this function often enables predictions of flutter speed to be obtained when prediction by extrapolation of measured modal damping is difficult. Thus, for example, in the present exercise, the very slow rate at which modal damping in the wing pitching mode changes as flutter is approached, i.e. the 'mildness' of the flutter, makes it extremely difficult to predict flutter speed from the measured damping values (see Figs.11, 13, 15 and 17). Another advantage of the Zimmerman type of presentation is that it permits an examination of the general trends of subcritical response as opposed to examinations of individual modal characteristics.

Figs.18 and 19 show the test results in the form of plots of values of flutter margin function F versus tunnel stagnation pressure p_t . It is evident from the results of the tests at $M = 0.6$ (Fig.18) that the effect of attaching the nacelle was to reduce flutter speed; the same tendency, though less marked, can be seen in the results of the tests at $M = 0.8$ (Fig.19). Whilst there is no obvious sign of tunnel unsteady interference effects at $M = 0.6$, changing tunnel wall conditions at $M = 0.8$ changed flutter behaviour; from tests with the nacelle attached it is clear that flutter speed was increased by sealing the perforations in the tunnel wall.

The values of F obtained from calculated values of modal frequency and damping ratio are also shown in Figs.18 and 19. At both Mach numbers calculation differs from theory; the calculated flutter speeds are all lower than those obtained by extrapolation of measurements.

8 CONCLUDING REMARKS

Flutter tests in the form of subcritical response measurements have been made at Mach Numbers of 0.6 and 0.8 on a half-wing model with root freedoms in roll and pitch. The wing was tested with and without a large nacelle, which was typical of a large fan engine, but which had no fan or core.

The model was excited by turbulence in the tunnel airflow and three methods of analysing the responses were applied. In one method the modal characteristics were obtained from the spectra of the responses; in the second they were obtained by using the Random Decrement method; in the third they were obtained from vector plots of the Fourier transform of the one-sided autocorrelation function of the response. The second method requires no specialised equipment and the degree of resolution of the frequency and damping ratio is not restricted but direct analysis of Random Decrement signatures is at present a complex and rather slow process. The third method when applied using a special-purpose computer has advantages in speed, accuracy and versatility.

The modal frequencies and damping ratios obtained by the three methods of of analysis showed that the model had very mild flutter; it was difficult to establish the flutter condition by extrapolating the measured modal damping curves. The flutter margin function of Zimmerman permitted examination of the general trends of flutter behaviour as opposed to examinations of individual modal characteristics.

The tests show that the aerodynamic effect of adding the nacelle was to reduce the flutter speed; the change in behaviour was much more marked at $M = 0.6$ than at $M = 0.8$. Changing the tunnel wall conditions by sealing the perforations altered modal behaviour at $M = 0.8$, in particular by increasing the modal damping in pitch.

At both Mach numbers the calculated flutter speeds of the wing without nacelle were lower than those obtained by extrapolating measurements; moreover, calculations of the subcritical response were also at variance with measurements. One possible reason for this was that calculations were based on assumed unsteady pressure distributions; closer agreement might be obtained if more realistic calculations were to be made using measured pressure distributions.

The lack of agreement between theory and experiment for tests on the wing without nacelle makes it impossible to draw a satisfactory comparison between theory and experiment for the tests made when the nacelle was added. However, observed changes in flutter behaviour were broadly similar to those predicted by theory.

Acknowledgments

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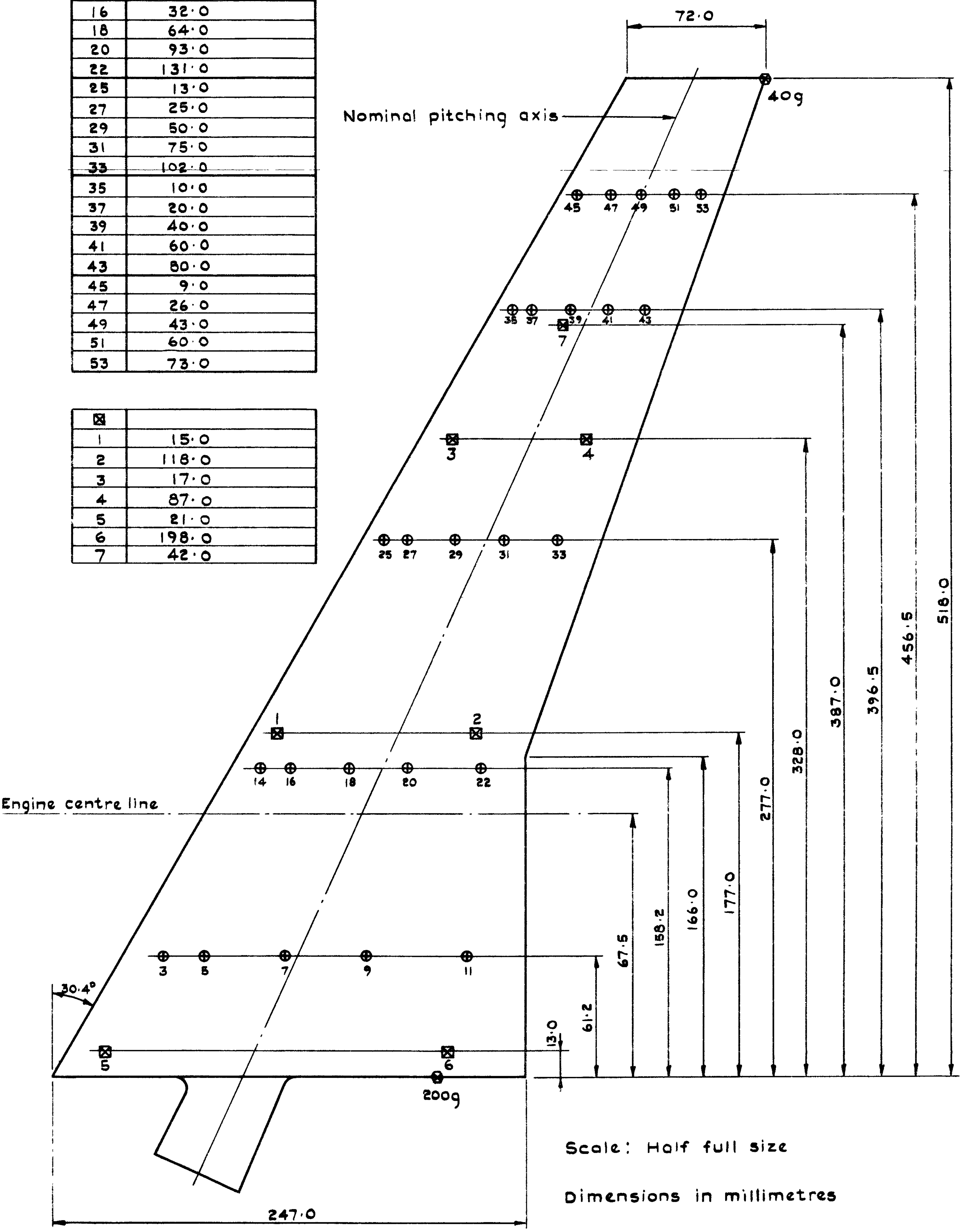
⊕ Position	Dist. from LE (mm)
3	22·0
5	43·0
7	85·0
9	127·0
11	180·0
14	16·0
16	32·0
18	64·0
20	93·0
22	131·0
25	13·0
27	25·0
29	50·0
31	75·0
33	102·0
35	10·0
37	20·0
39	40·0
41	60·0
43	80·0
45	9·0
47	26·0
49	43·0
51	60·0
53	73·0

⊠	
1	15·0
2	118·0
3	17·0
4	87·0
5	21·0
6	198·0
7	42·0

⊠ Accelerometer positions

⊕ Points at which modal displacements where measured

⊗ Approximate position of added masses



Scale: Half full size

Dimensions in millimetres

Fig.1 Wing planform and instrumentation

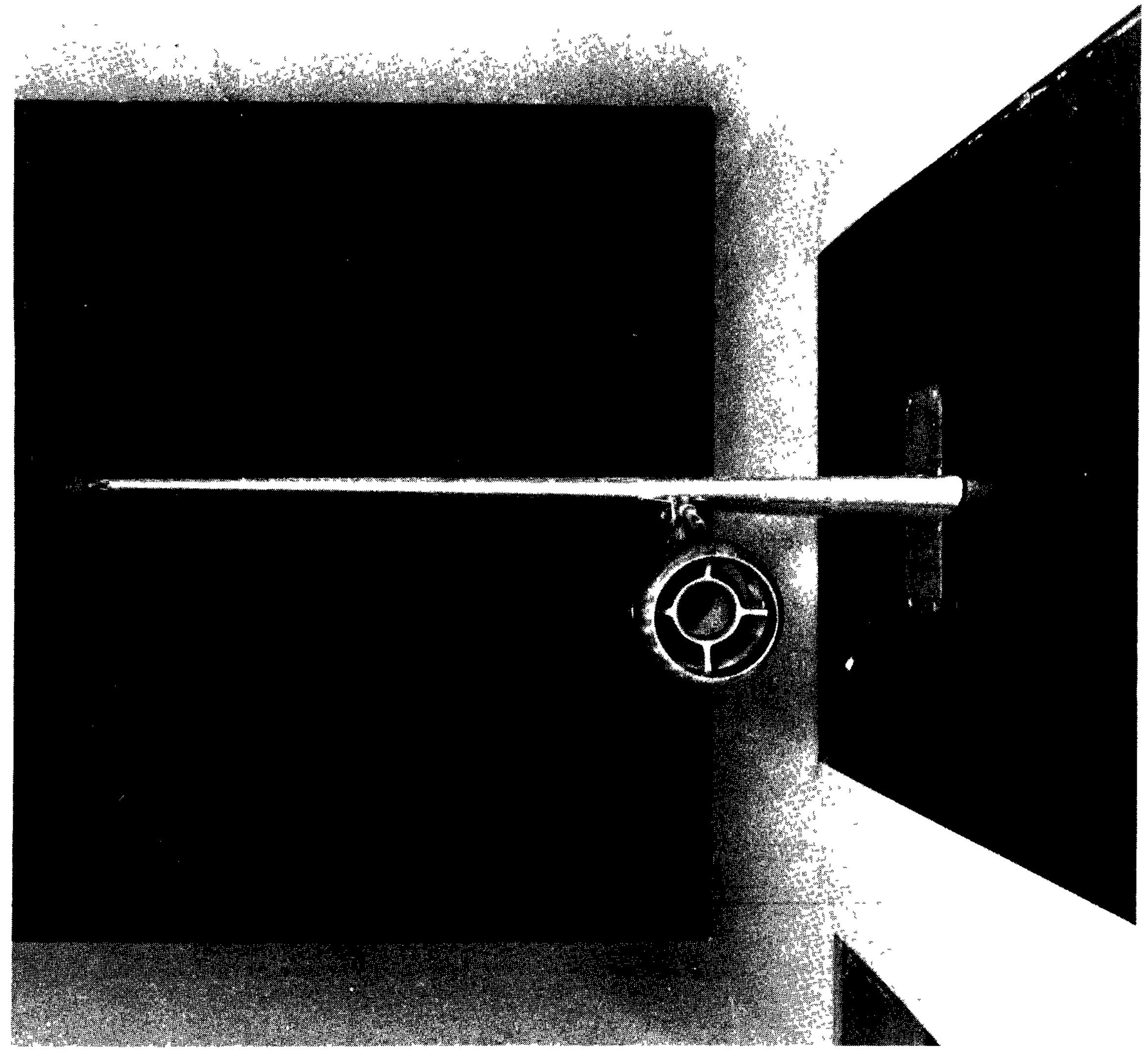


Fig.2 Wing with fan engine nacelle

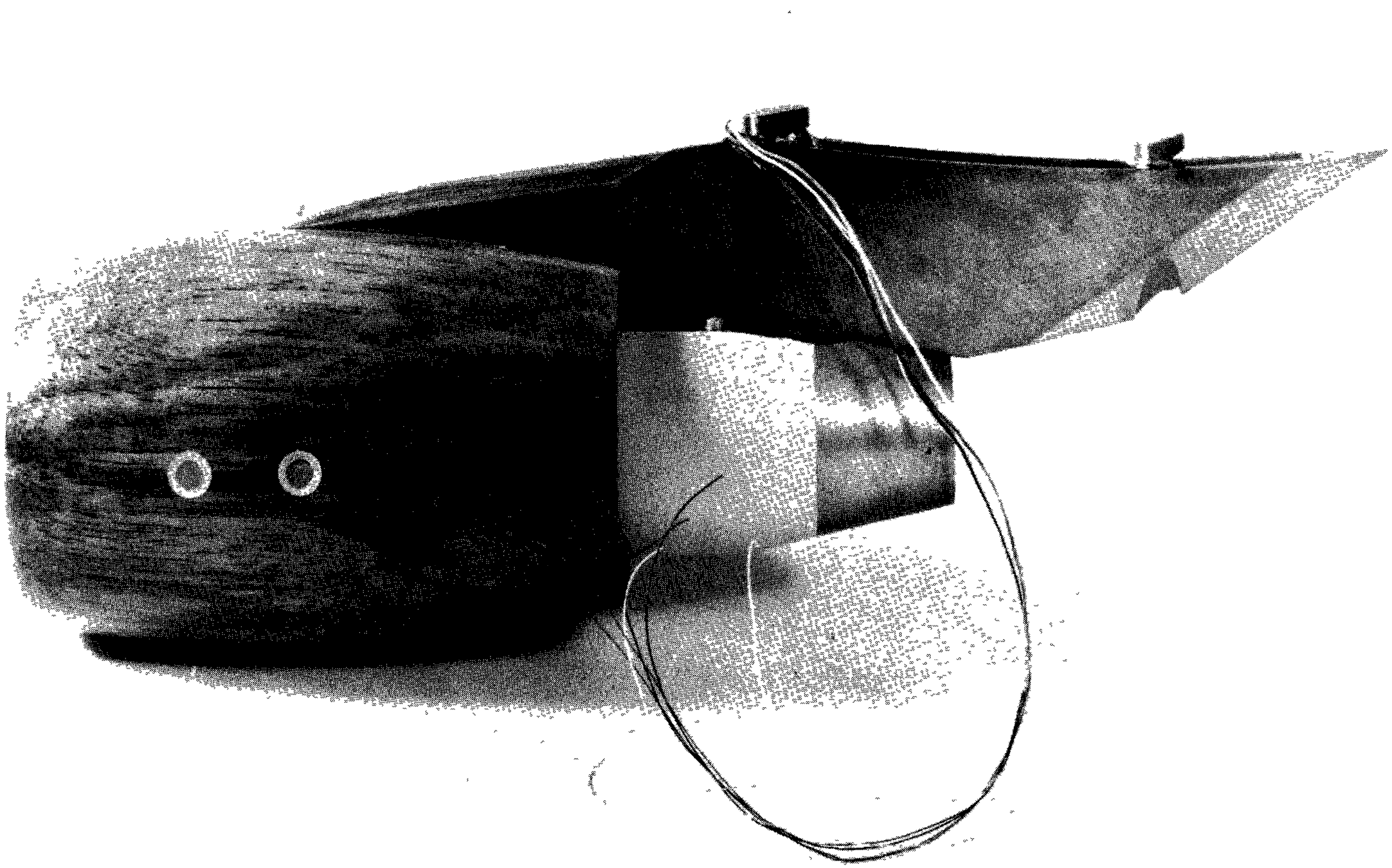


Fig.3 Fan engine nacelle and pylon

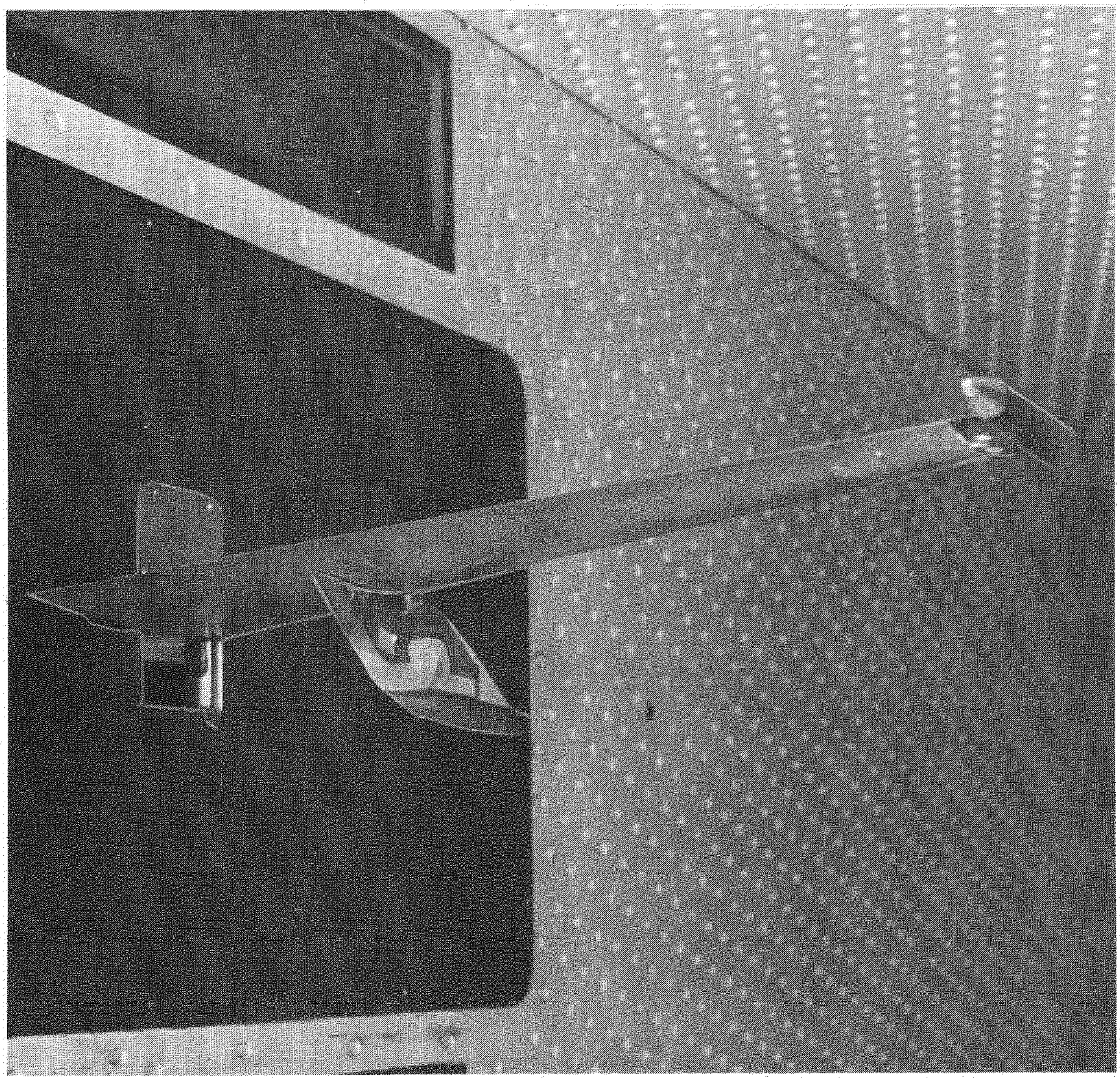


Fig.4 Wing with pylon and pencil

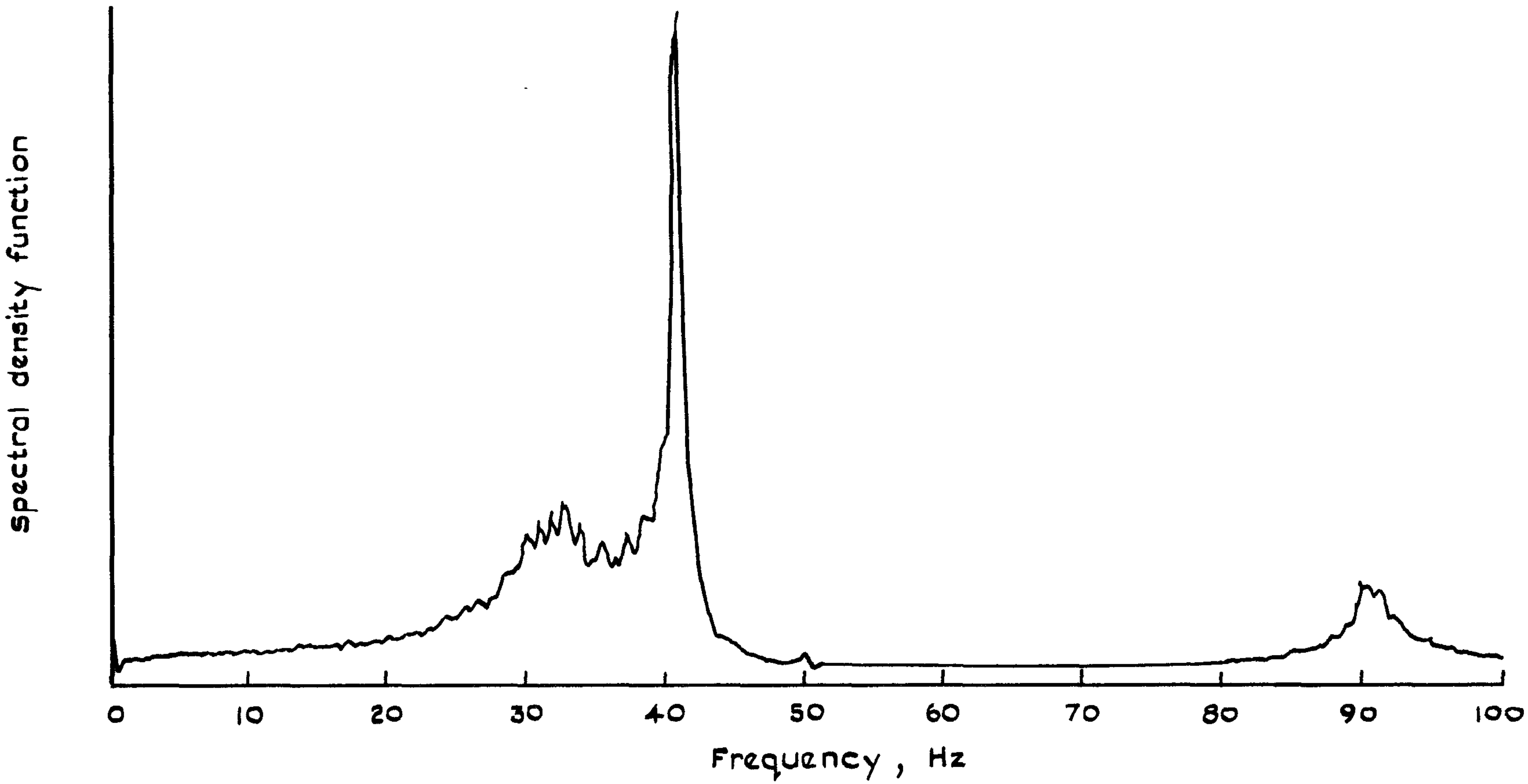


Fig. 5 Typical graphical output from spectrum analyser system

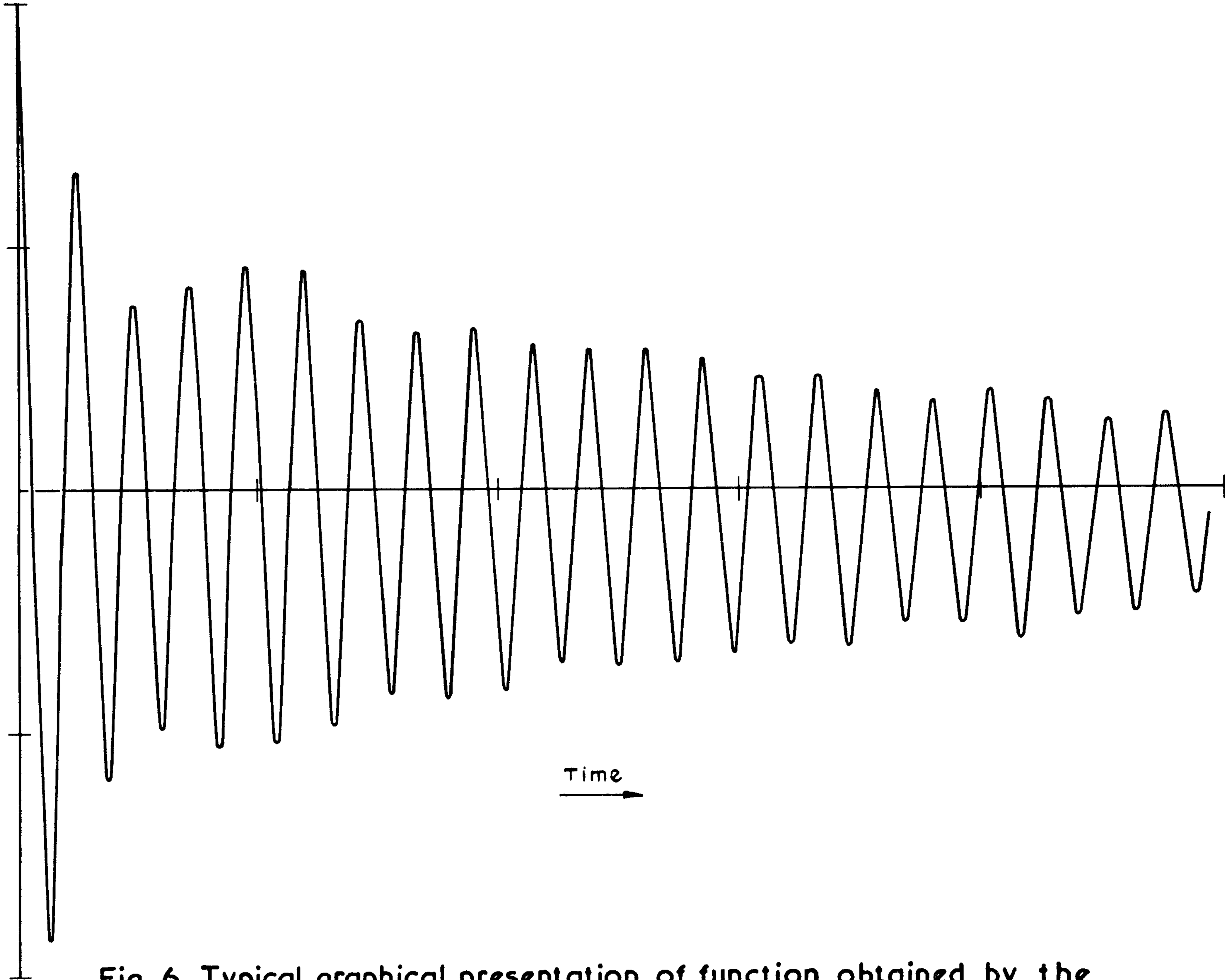


Fig. 6 Typical graphical presentation of function obtained by the Random Decrement method

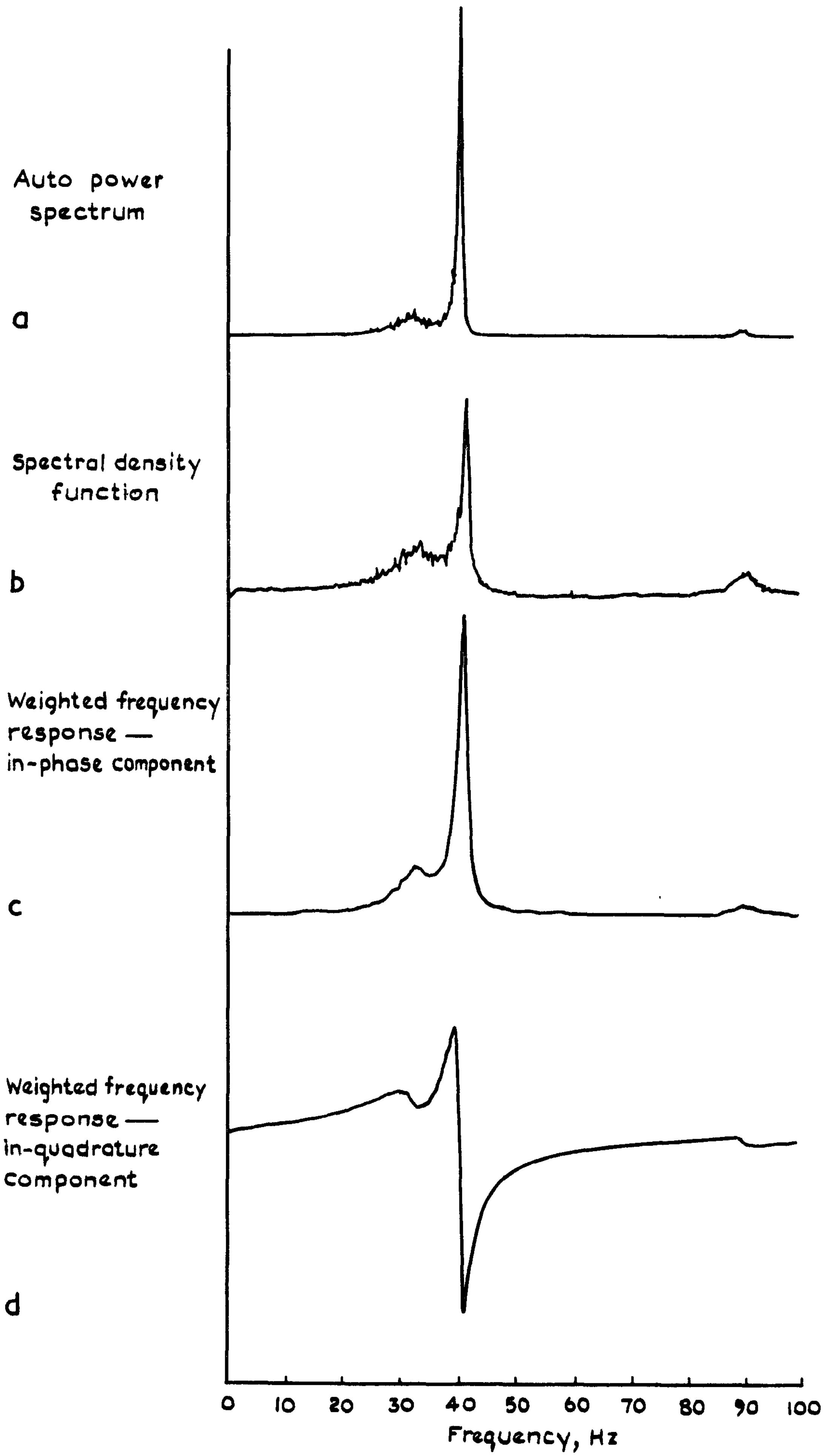


Fig. 7 a–d Typical displays on Fourier analyser viewing screen

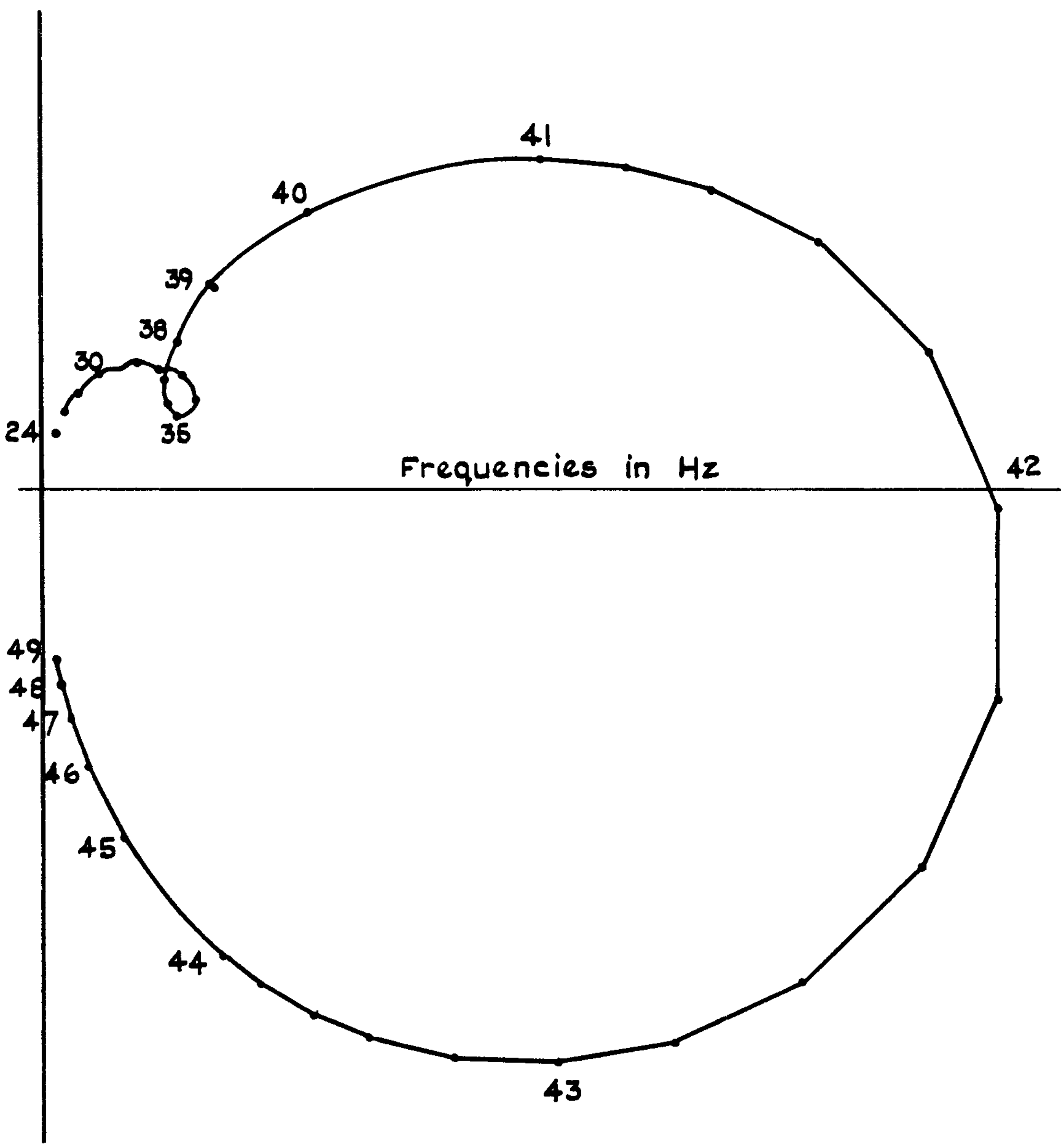


Fig. 8 Typical graphical output from Fourier analyer.
Turbulence excitation vector plot; exponential weighting
0·015 c/cc at 40 Hz

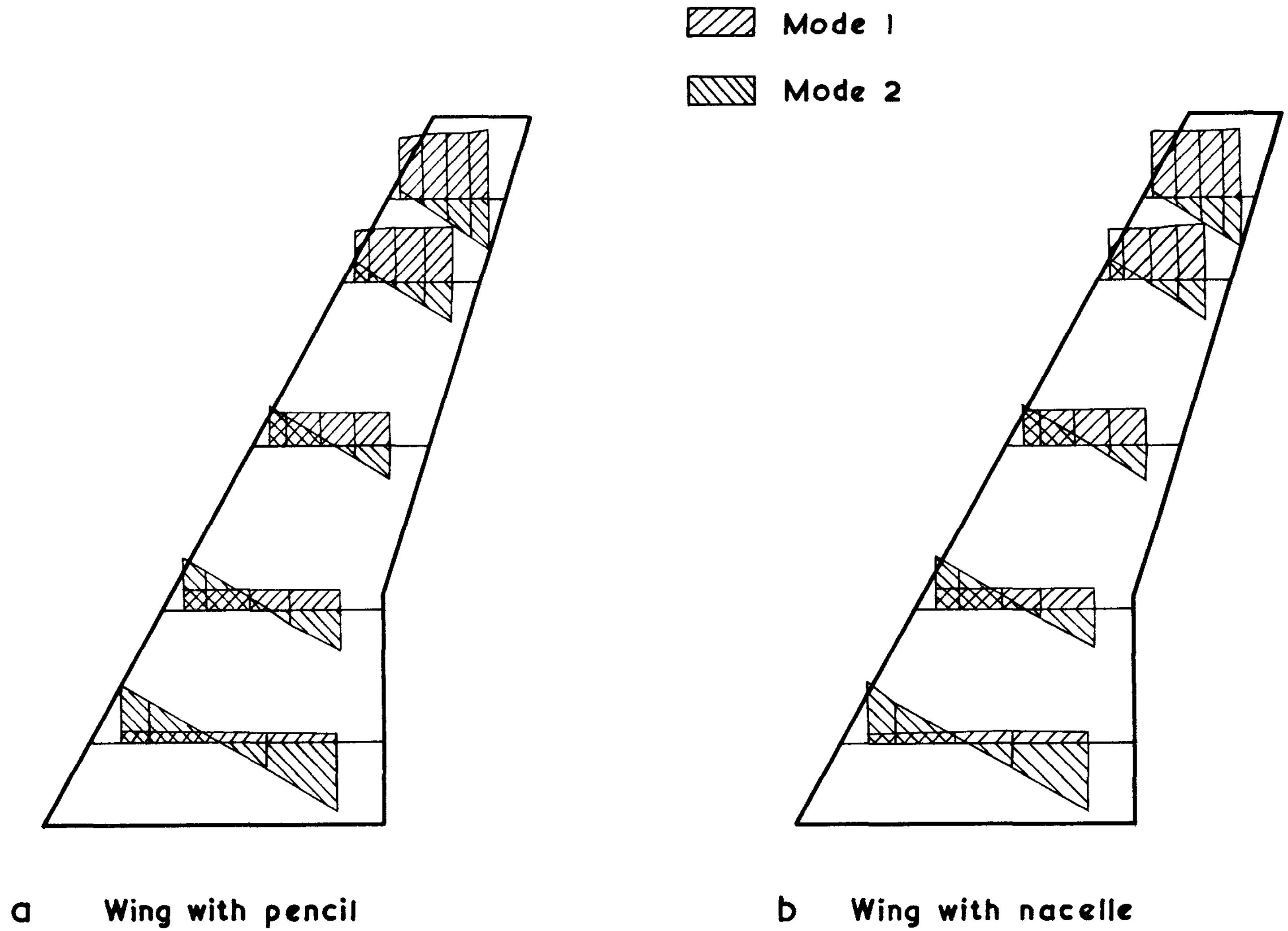


Fig 9 a & b Modal displacements in still air

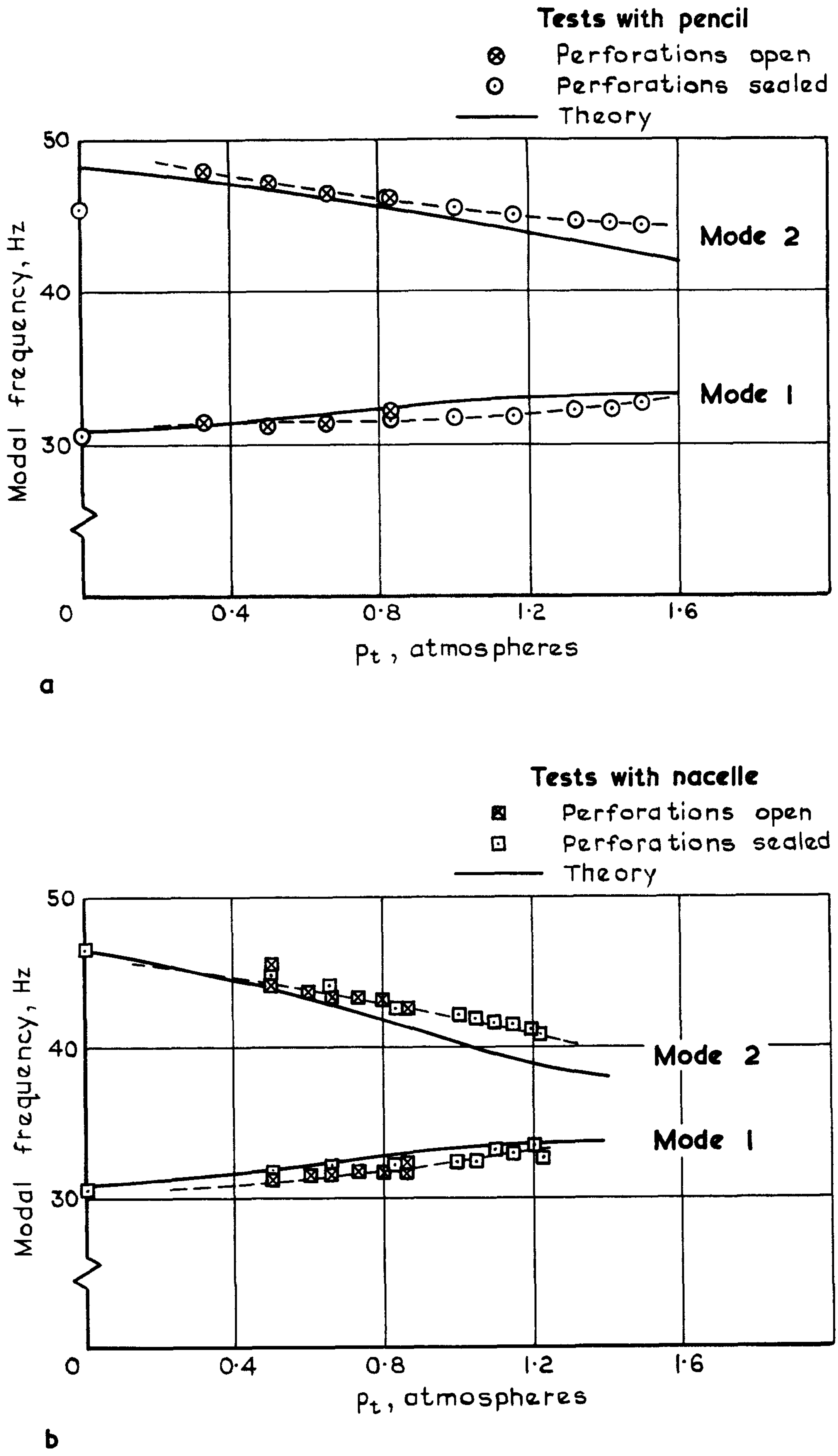


Fig. 10 a&b Modal frequencies, M = 0·6.
Results from Fourier analyser

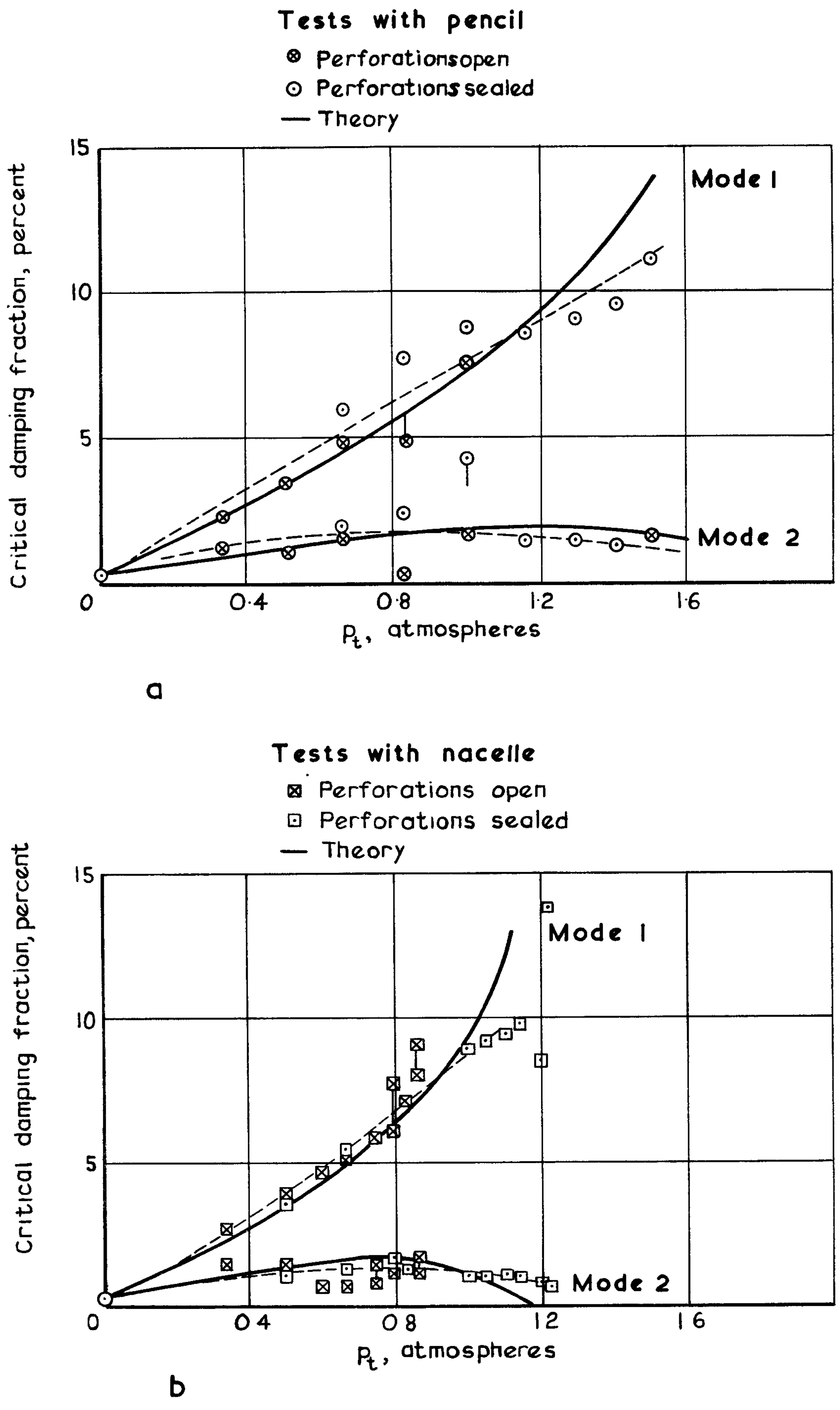


Fig. 11 a&b Modal damping ratios, M=0·6. Results from Fourier analyser

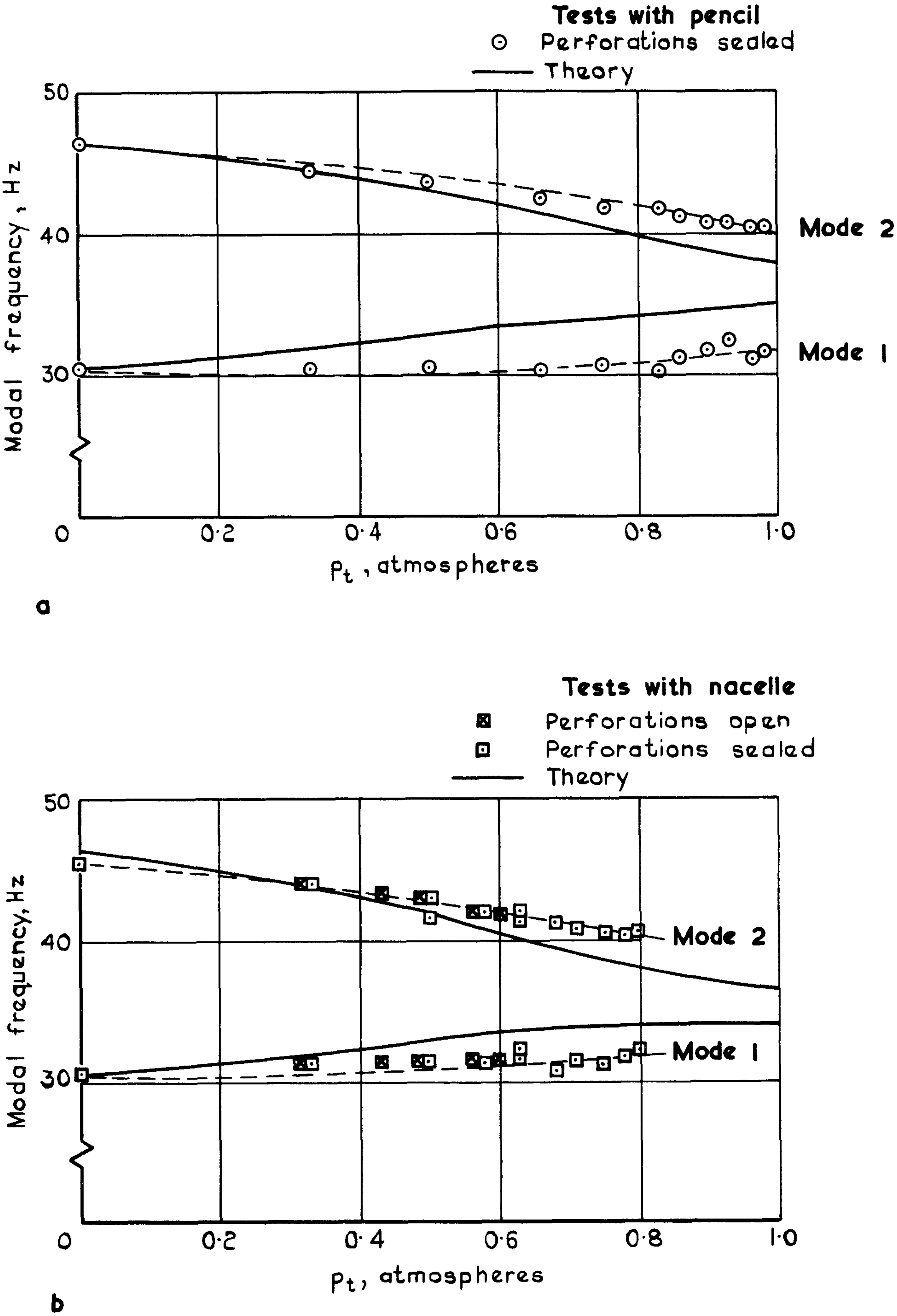
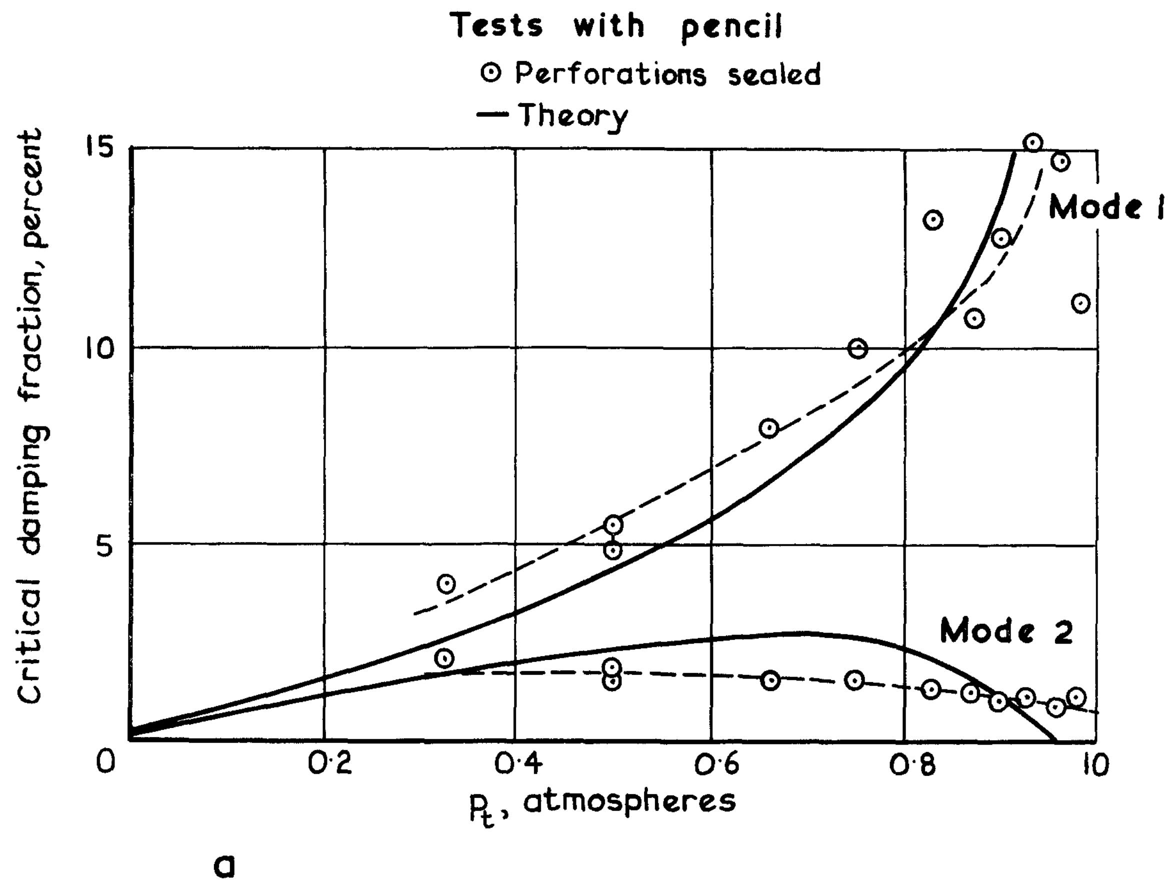


Fig. 12 a & b Modal frequencies, M = 0·8. Results from Fourier analyser



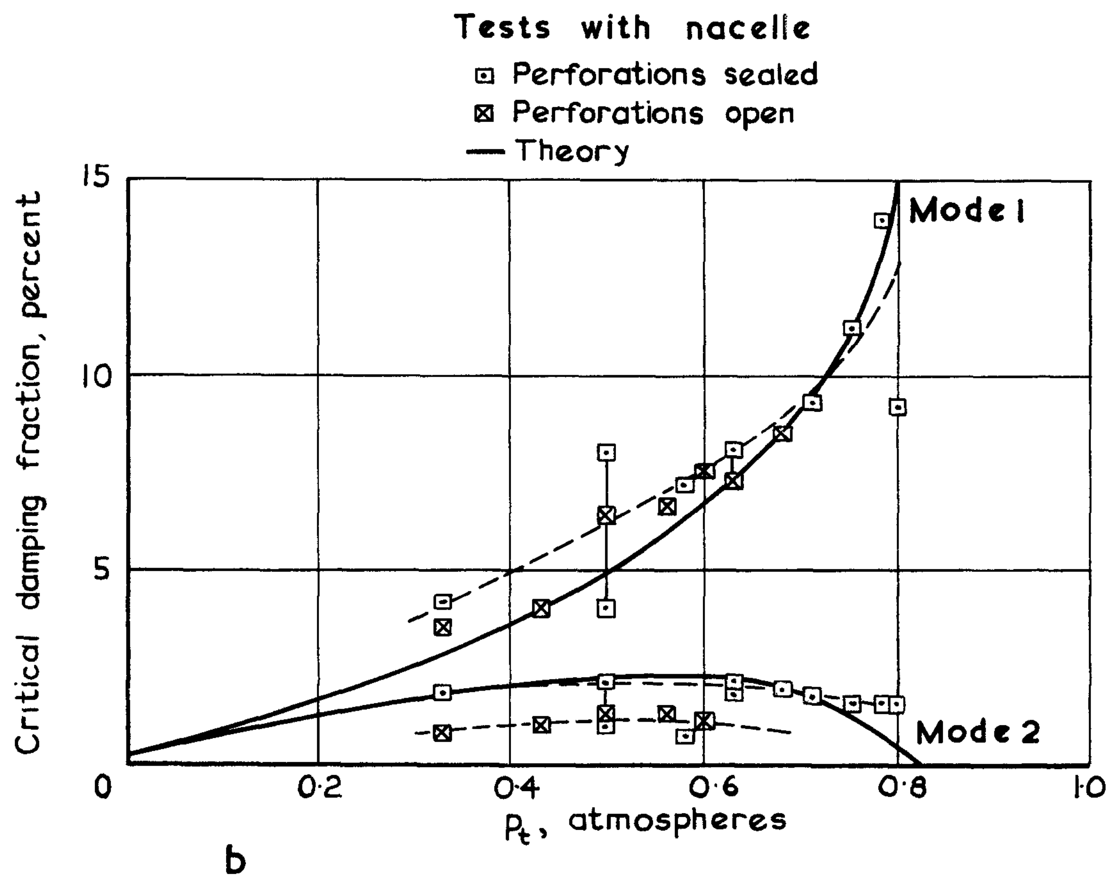


Fig.13 a&b Modal damping ratios, M=0·8, Results from Fourier analyser

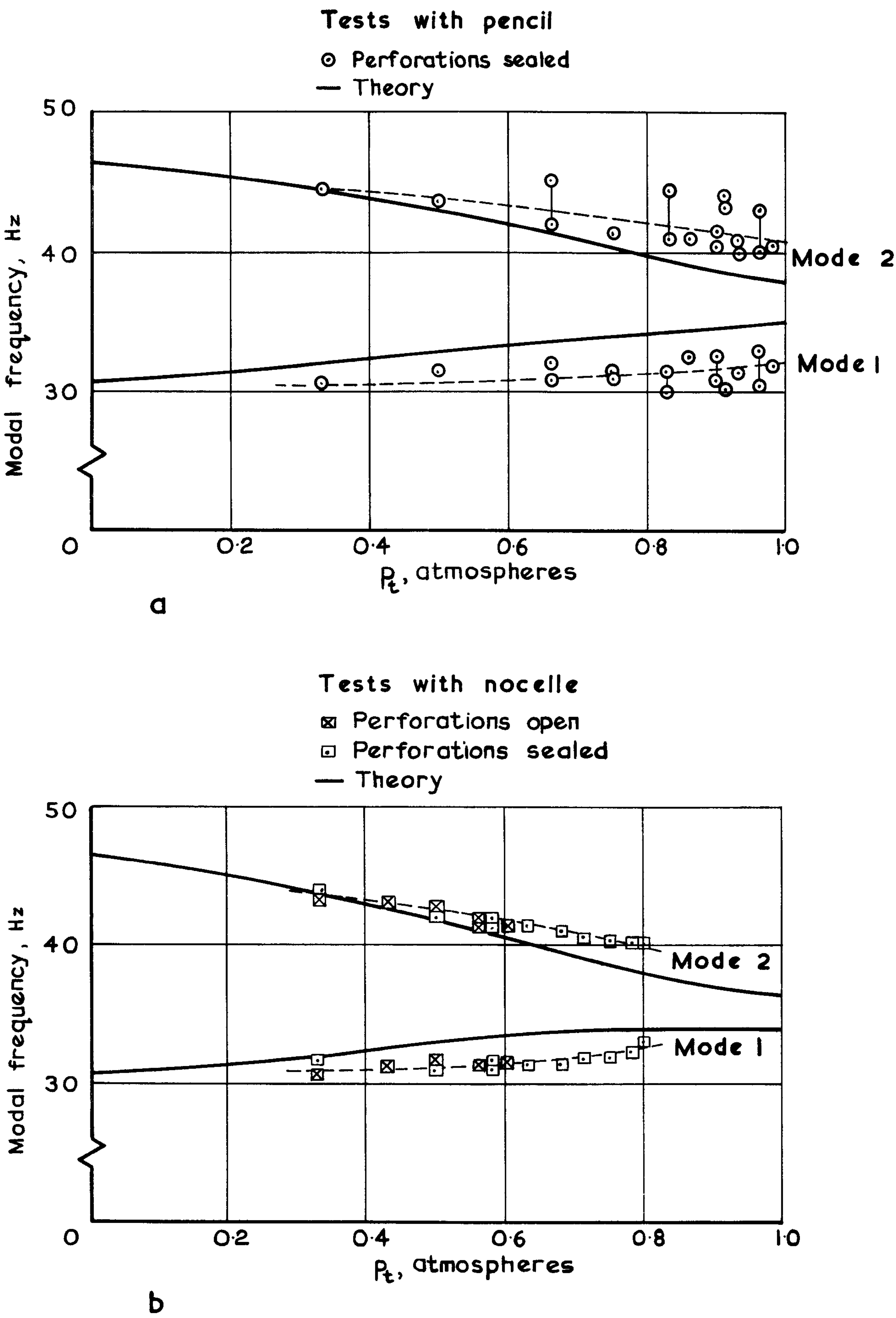
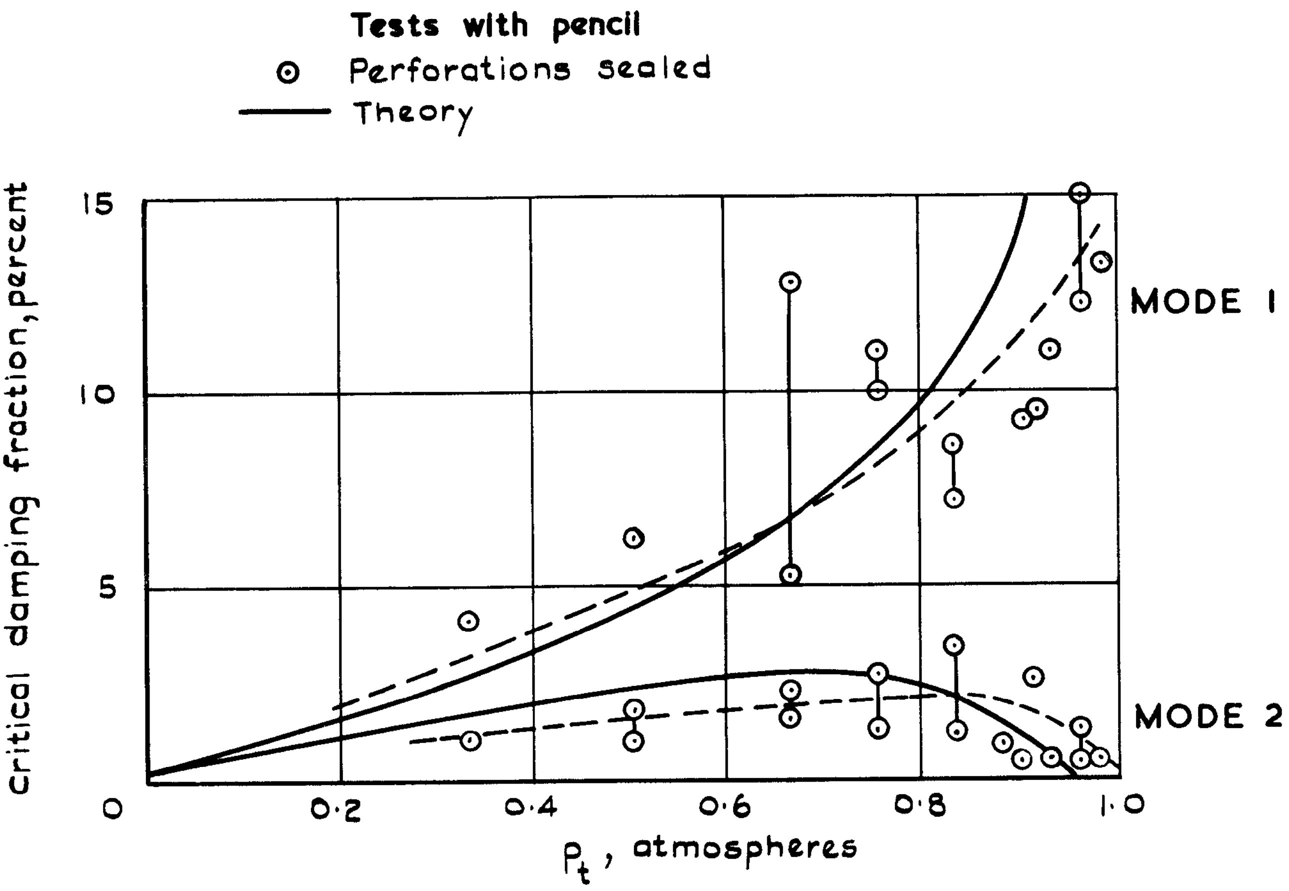
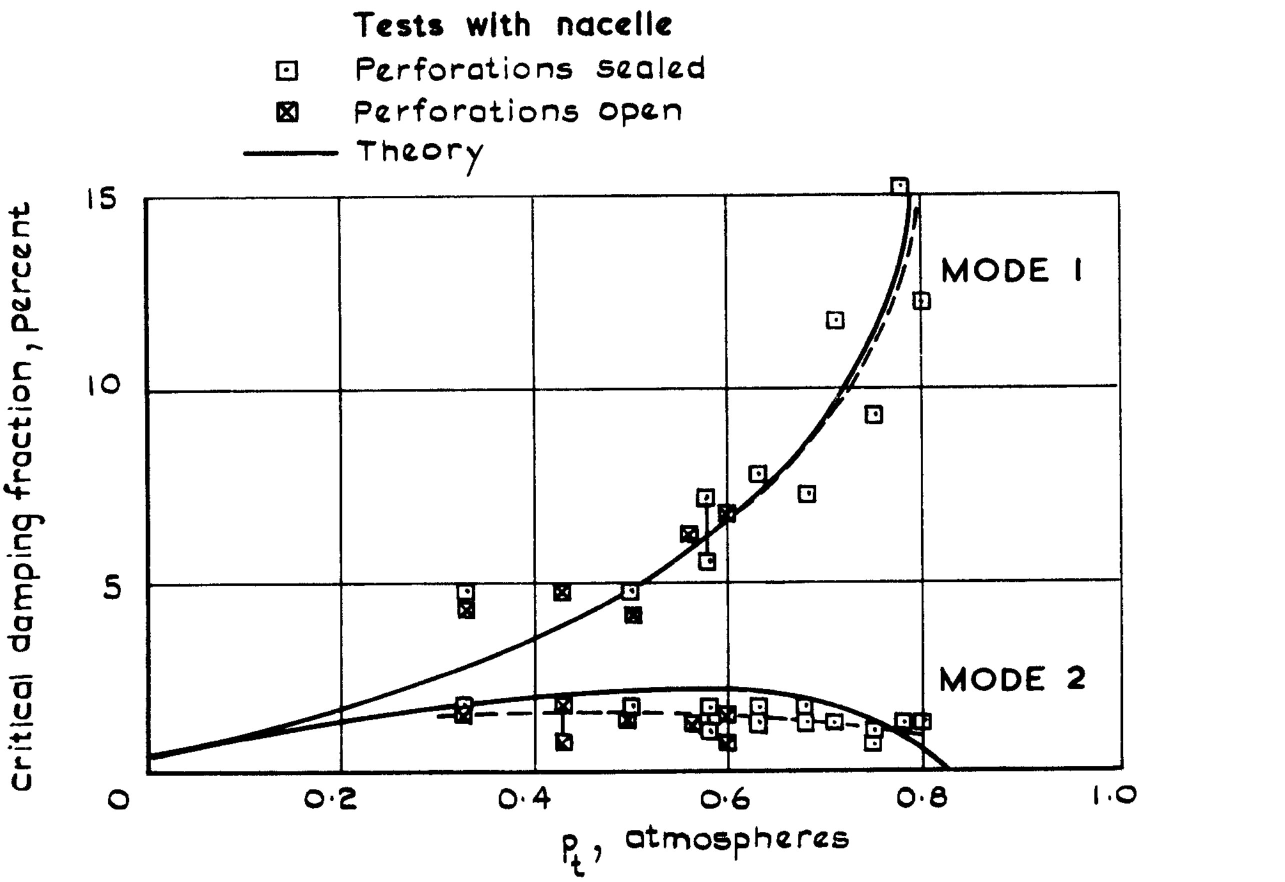


Fig.14 a&b Modal frequencies, M=0·8. Results from spectrum analyser



a



b

Fig. 15 a & b Modal damping ratios, M=0·8. Results from spectrum analyser

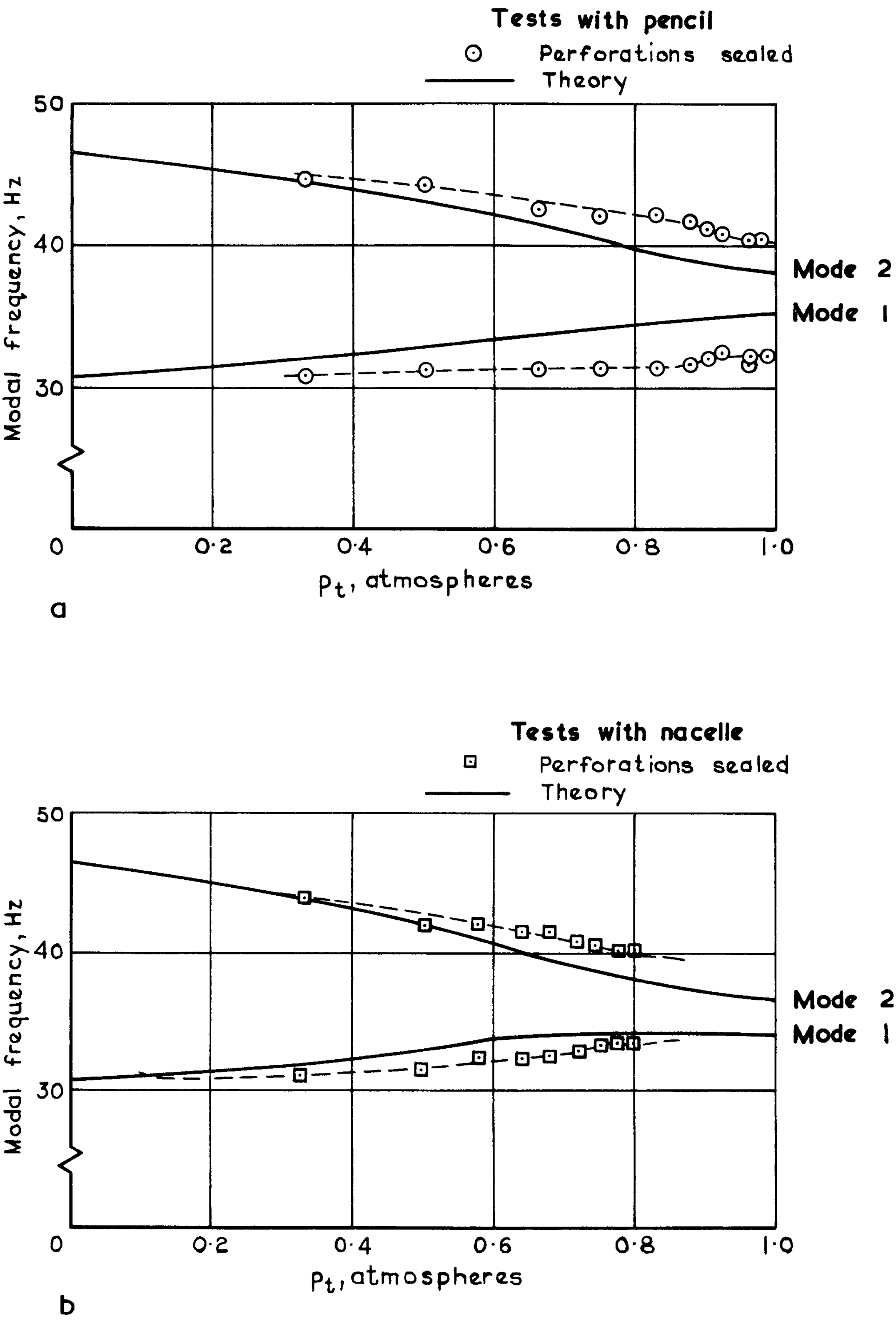
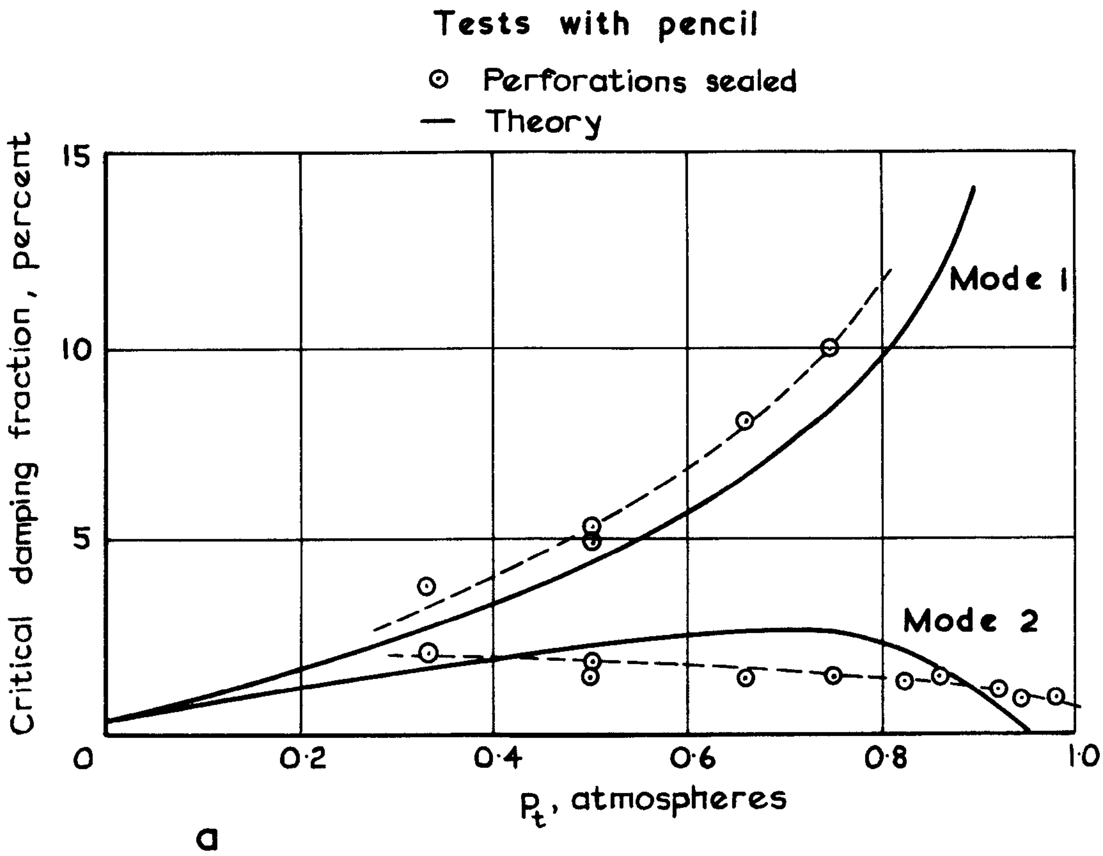


Fig.16a&b Modal frequencies, M = 0·8. Results using Random Decrement method



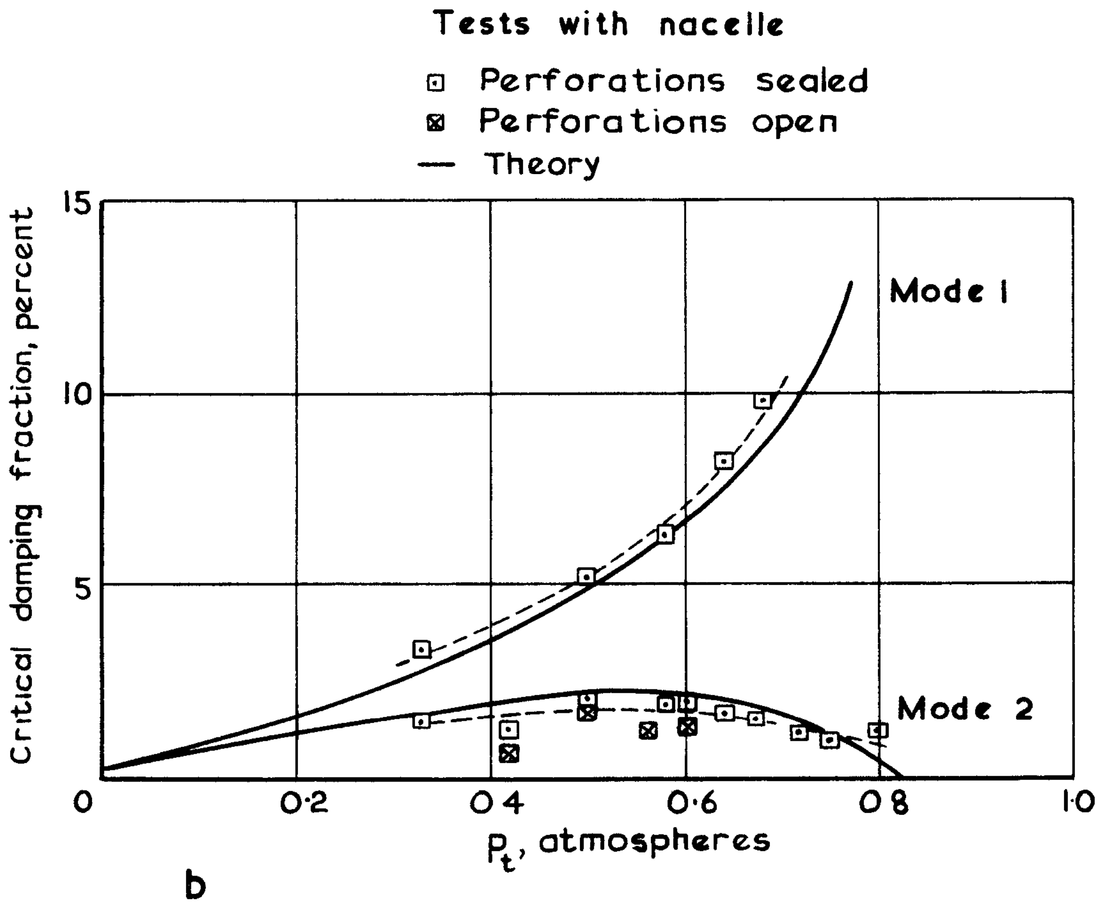


Fig.17 a&b Modal damping ratios, M=0·8. Results using random decrements method

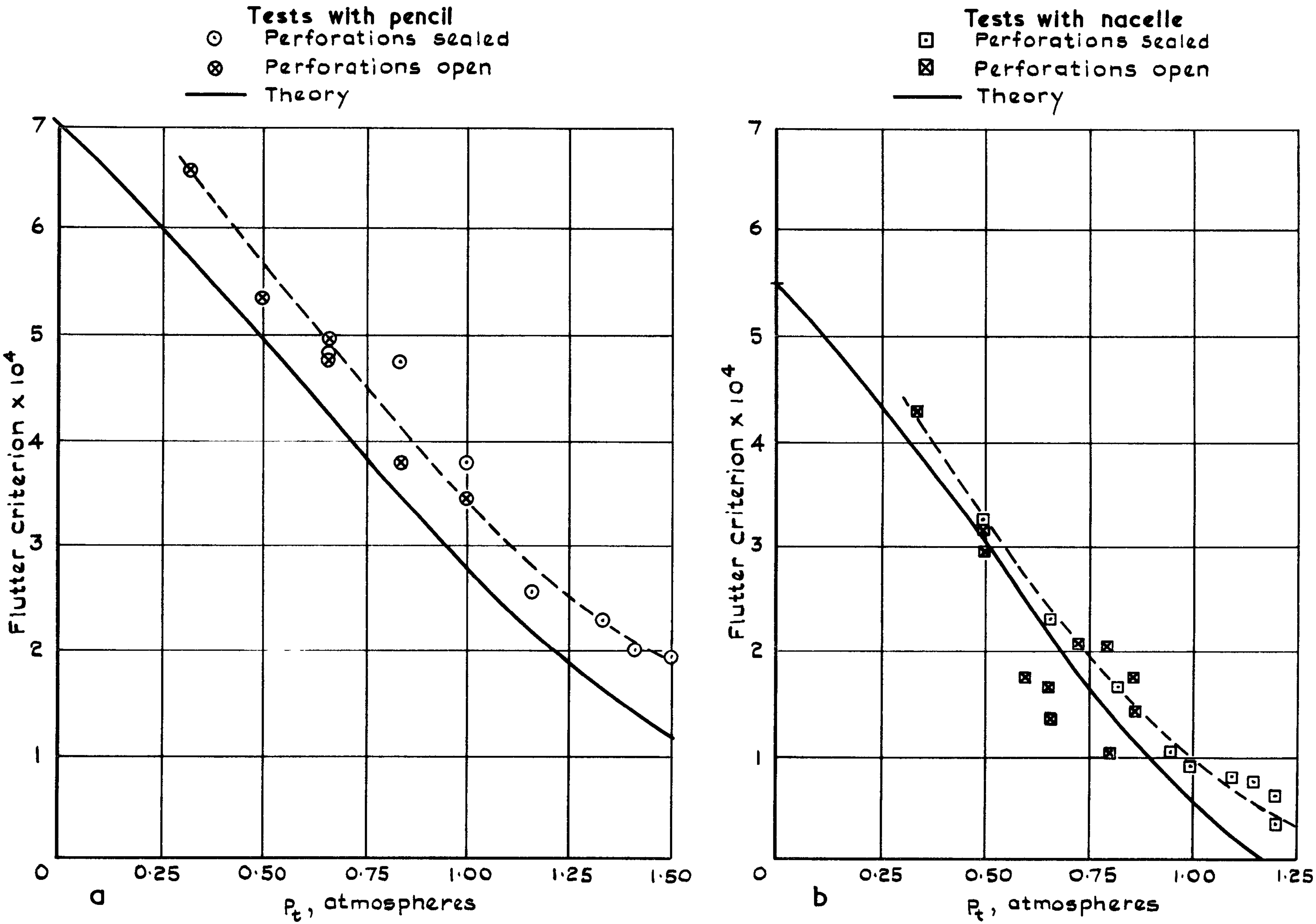


Fig.18 a&b Flutter criterion versus p_t M=0·6

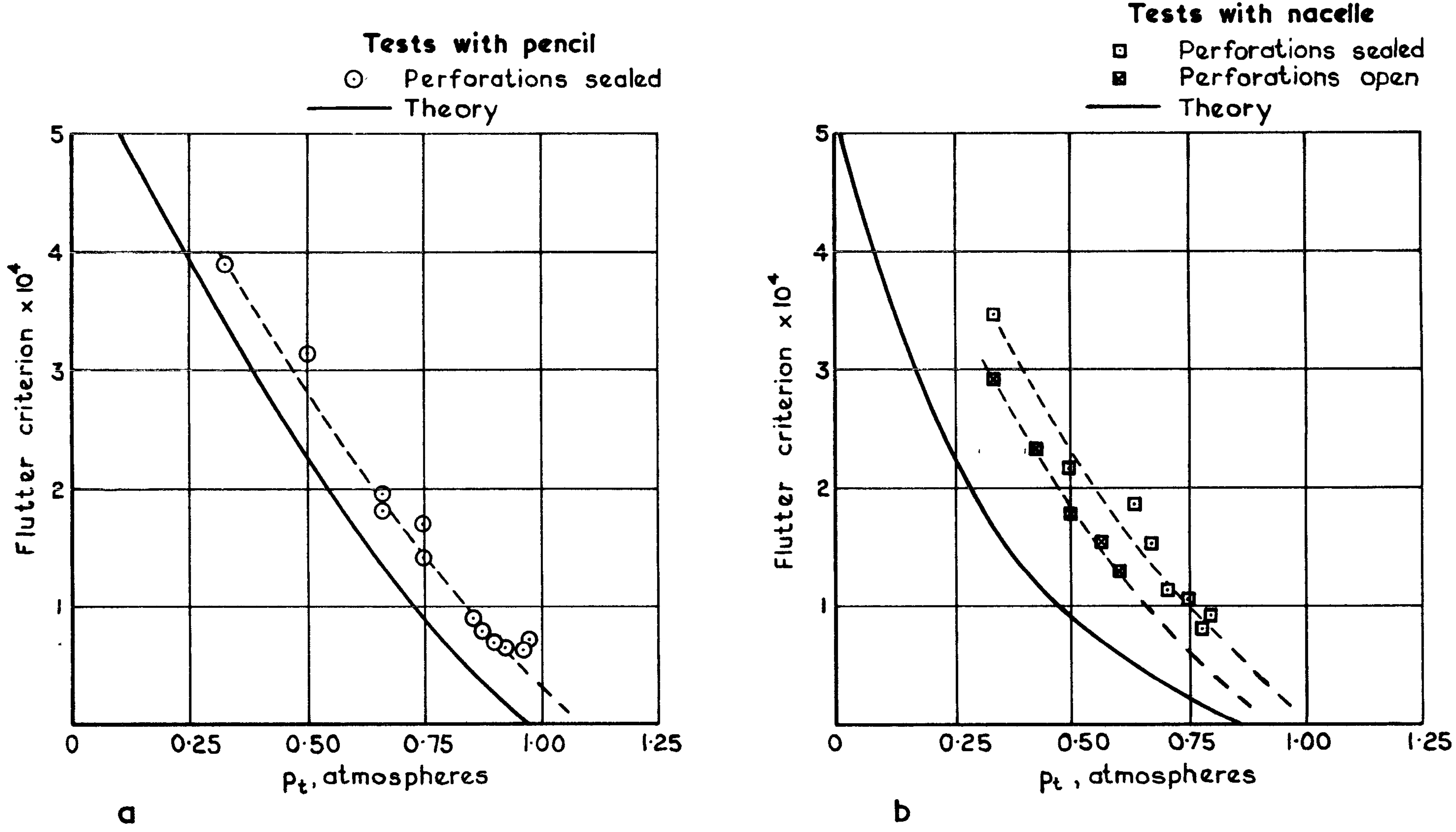


Fig.19 a&b Flutter criterion versus p_t M=0·8

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Hutton, G. B.

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