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The Development of Rapid-Testing Techniques for Flutter Experiments

by

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SUMMARY

Developments in digital-analysis make it possible to reduce, by a large factor, the amount of testing time required for flutter experiments. A research programme is being undertaken to develop test techniques which combine short-duration tests with an acceptable standard of accuracy. The programme covers the investigation of three systems (i) an electrical analogue of a flutter model, (ii) a low speed flutter model and (iii) a high speed flutter model. For each system, appropriate methods of excitation and response analysis are applied in order to determine the subcritical response behaviour. This Report covers the work done with the electrical analogue.

The results show that where the level of background noise excitation is low, the impulse response of the system enables modal characteristics to be determined with accuracies comparable to those obtained from conventional steady-state tests. With higher levels of background noise, a sweep-frequency input gives optimum results.

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CONTENTS

1 INTRODUCTION

It is standard practice, in wind-tunnel and flight-flutter testing, to obtain a quantitative measure of the dynamic behaviour of the model or aircraft at aerodynamic conditions below the critical flutter condition. These sub-critical tests provide data from which the variation of damping and frequency in each mode of interest can be obtained. The results may be used to predict the critical speed by extrapolation, or to compare with calculations, or more generally, for both these purposes. In low speed wind-tunnel tests, the critical speeds may also be established by allowing the model to flutter, but this is not usually so in high speed tests, where control of model behaviour is more difficult, and a flutter condition can rapidly become a failure condition. For flight and high speed wind-tunnel tests, therefore, an accurate measure of subcritical behaviour is essential, and it is the emphasis on accuracy, particularly in the measurement of modal damping, that has led to the development of the widely-used 'vector plot' technique.

The vector plot, which is a representation on the complex plane of the variation of response vector magnitude and phase with frequency, can be obtained by exciting the structure sinusoidally with a force of constant amplitude at a series of discrete frequencies, and measuring at each frequency the amplitude of the response, and its phase angle relative to the exciting force. The resulting plots, which are closely circular in the region of a resonance, may be analysed to yield the resonance frequency and damping of each mode. The important characteristic of a vector plot is that it enables modal frequency and damping to be determined to a significantly higher accuracy than any other form of modal response presentation. For this reason, it has continued to be and is likely to continue to be, the output data format of a flutter test, whatever form of excitation or response processing adopted.

In 1961, in an unpublished RAE paper[1], Winn advocated the use of random process analysis in flight-flutter tests where atmospheric turbulence could be used as the excitation input to the aircraft structures. In 1966 in another RAE paper[2] Skingle considered various methods of dealing with the situation where turbulence causes a structural response, but one that is insufficient, for one reason or another, for an adequate flutter analysis. Again, the methods advocated made use of random process analysis. The use of supplementary forms of excitation were also considered such as sweeping a sinusoidal force input through a frequency band at a sweep rate well in excess of what would be required for effectively steady-state response.

Unfortunately, the theories of Refs.1 and 2 were somewhat in advance of the facilities then available for practical implementation, and it was not until the advent of the fast Fourier transform algorithm in digital analysis that the way was opened for worthwhile improvements to be made in flutter testing. In 1969, Turner and Elkins[3] investigated the application of digital analysis to flight-flutter testing, aiming their investigation at minimising the effect of noise in the analysis of response records, and at reducing the amount of flight test time. The need to reduce the time spent in making wind-tunnel flutter tests has also become more pressing recently; the need arises not only from the general desirability of reducing cost and avoiding delays to other work which result from excessive tunnel occupation, but also from the longer-term trends in wind-tunnel design which may well result in short-running-time tunnels replacing continuous flow tunnels. It is obviously highly desirable that techniques of flutter testing should be developed that can be applied in such tunnels, in order to take advantage of the improved flow conditions that they will offer.

The first stage in the development of useful techniques is to apply the methods of excitation and analysis that appear most promising to representative structural systems with known flutter characteristics, and thereby assess the viability of the techniques. Inevitably technique development will go hand in hand with such investigations, until the aim of finding satisfactory techniques has been fully satisfied. A research programme on these lines has been started, and this Report gives the results of the first part of the programme, in which the structural system is represented by an electrical analogue of a high speed flutter model. Subsequent parts of the programme will cover tests on models in both low and high speed flow.

The analogue investigation has shown that meaningful flutter data can be obtained from much shorter tests than are necessary when conventional steady-state techniques are used. The required form of excitation and analysis depends on the level of background noise (representing atmospheric turbulence in flight tests and flow unsteadiness in wind-tunnel tests). Where the level is low, the model may be excited by an impulsive input; at higher levels of unsteadiness different forms of excitation are necessary. In the former case, extremely short test runs are possible, whereas in the latter, rather longer test durations are necessary. In all cases, however, the test duration is significantly less than that of current techniques. The accuracy of the results obtained from such tests depends on the level of background noise; nevertheless, it is probable that accuracies which are no worse than those of current techniques in similar conditions, could already be obtained with existing new techniques, and it is reasonable to expect that further development will lead to improvement in this respect.

2 TEST EQUIPMENT AND ANALYSIS FACILITIES

2.1 Flutter analogue

The electrical analogue represented the equations of antisymmetric motion of a high speed, T-tail, flutter model which had previously been tested in the RAE 3ft × 3ft tunnel[4]. Two degrees of freedom were represented, (a) the fin-fundamental bending mode and (b) the fin torsion mode, and the aerodynamic forces were appropriate to a Mach number of 0.9. The equations of motion are given in the Appendix for variable air density, so that they represent tunnel conditions in which density is varied, whilst Mach number and forward speed are maintained constant.

The equations of motion were programmed into a Solartron HS7 analogue computer. The input/output arrangements were such that an excitation signal could be fed to both degrees of freedom in any chosen proportion, and the responses of each degree of freedom could be similarly summed. It is important to ensure that the excitation and response arrangements are such that the contribution of each mode in the measured response signal is sufficient to enable modal frequency and damping to be determined, at all test conditions, to an acceptable degree of accuracy. This is particularly important where analysis techniques are to be compared and where there should be no doubt about the suitabaility of the signal to be analysed. The input forcing ratio and output response ratio were therefore set to values that resulted in acceptable levels of modal response over the range of air density of interest. In practical terms, this procedure represents choosing excitation and response measurement points on the model so as to ensure adequate response signals from each mode.

Digital computer solution of the equations of motion differs from the analogue solution obtained from steady state response tests (which are discussed in section 4.1 and shown in Fig.1). The discrepancy arises from small errors due to phase shifts in the analogue computer amplifiers at the frequency of operation. These phase shifts manifest themselves, in part, as small errors in the nominal damping coefficients. Correction, at least in the direct terms, of these errors was made by reducing the relevant coefficient potentiometers until instability occurred in each degree of freedom singly, thereby giving the effective zero offset for each coefficient. If necessary the coefficient potentiometers were reset. The direct stiffness coefficients (including aerodynamic stiffnesses) were checked by frequency measurements. In the remainder of the paper the 'true' solution is taken to be that given by the analogue in response to steady state sinusoidal inputs.

2.2 Analyser

The response records were analysed using a Hewlett-Packard Digital Fourier Analyser. This machine is based on the Hewlett-Packard 2100A digital computer with 16k storage capability. The analyser can accept two simultaneous analogue signals, convert these to digital form, store this data, and then perform a range of operations on the data. These operations include forward and inverse Fourier transforms, convolution, correlation, complex multiplication etc. The programming facilities enable sequences of operations to be performed as automatic routines. Data output can be in the form of punched paper tape, or as a graphical display on an xy plotter. A visual display on a storage oscilloscope allows data to be viewed at any stage of a process.

2.3 Excitation

Three forms of excitation were used in the programme (a) a step input, (b) a frequency sweep and (c) pseudo-random noise. A step input was preferred to an impulse of finite duration for two reasons. The first is that a step is a form of excitation that can be applied to most wind-tunnel models by releasing the model from an off-datum position; the second is that if the velocity response to a step is measured the initial response is equivalent to the displacement response following an inpulse. Throughout the paper therefore the term 'impulse response' will refer to velocity response following a step input.

The frequency sweep was linear with time and the frequency limits were determined by the frequencies of the modes to be excited. The frequency sweep extended from 20 to 65 Hz which, for all test conditions, spanned the range of modal frequencies (see Fig.1).

The pseudo-random noise was provided by a generator using conventional feedback shift register techniques[5], feeding into a low pass filter the output of which had a flat power spectrum from zero to 100 Hz over a complete sequence (approximately 500 seconds).

3 TEST PROGRAMME

3.1 General

The broad pattern of the test programme has been to investigate the subcritical behaviour of the model analogue for variations in (a) duration of available test time (representing tunnel running times), (b) form of excitation input and (c) level of background noise (representing unsteadiness of tunnel flow). From the steady-state solutions in Fig.1 it may be seen that the critical flutter condition occurs when the relative air density, σ, is 1.295. Test durations of 5 and 10 seconds were chosen to represent typical test times that might be available in a high Reynolds number tunnel having limited running time. The levels of background noise introduced into the excitation were based on the level of maximum response of the analogue before overload occurred. The overload condition may be regarded as analogous to the maximum allowable response level of the model, so that the maximum noise level is that at which the peak response coincides with the overload condition. Taking this noise level as 100%, tests were made with intermediate noise levels of 10, 20, 40 and 80%. In each case, the excitation level (where the excitation was other than noise itself) was such that the maximum response of the analogue just reached the overload point.

3.2 Impulse tests

The response of a damped multi-degree-of-freedom linear system to a unit impulse is the sum of a series of exponentially-decaying sinusoids, each of which exhibits the natural frequency and damping characteristics of an appropriate mode of the system. If the excitation is, in practice, an impulse of finite level and duration, the initial response, during the application of the input, will differ from the response to unit impulse, but thereafter the response will again be the sum of a series of decaying sinusoids. The only difference will, in fact, be that the 'finite' impulse imposes different 'starting' conditions at the beginning of the free decay, and this will affect the magnitudes and initial phase relationships of the modal components. Where a finite duration impulse is applied, it will be necessary to remove from the response record the portion during which the impulse is applied and to analyse only the free-decay record. In the present investigation, a step force input was applied and the velocity response was measured. It has already been noted that this is equivalent to applying a unit impulse and measuring the displacement response.

The Fourier transform of the impulse response will give the frequency response of the system, which may be presented on the complex plane as the well-known vector plot. In deriving the vector plot in this way, it may be necessary to modify the response record before taking the Fourier transform. It is essential to ensure that the response has decayed to a very low level by the end of the record in order to avoid spurious lobes and distortion of the vector plot. White has suggested[6] that the dynamic range of the response record should not be less than 55 dB. In using the analyser experience has shown that significant levels of response at the end of a decay record may not be detected by visual inspection of the data until the Fourier transform is examined - when their presence becomes only too obvious.

When the excitation to the system includes noise, the impulse response will be contaminated, and a direct Fourier transform of the response results in a vector plot with considerable scatter. If the contamination is severe, graphical analysis of the plot may be impossible.

Similar problems of inadequate dynamic range, and noise contamination, of the impulse response, occur in the analysis of the response to frequency-sweep excitation.

3.3 Frequency-sweep tests

The use of a frequency-sweep input, and the analysis of the resultant response, has been studied by many workers in recent years[6,7]. If the input is a rapid frequency sweep ('rapid' in this context meaning that the response cannot be analysed as a quasi-steady-state response) then the excitation can be regarded as transient in that there is a finite energy input to the system. The steady-state vector plot may be obtained by dividing the Fourier transform of the response by the Fourier transform of the excitation. This procedure is unsatisfactory in the presence of extraneous noise excitation, and the method of analysis followed in the present investigation is based on the autocorrelation of the response. The energy spectrum of a linearly-swept-frequency sinusoidal input is approximately flat between the frequency limits of the sweep, although there are characteristic 'oscillations' in the spectrum near the limits which arise from the initial and terminal conditions. If the bandwidth of the frequency sweep is sufficiently wide to ensure that the spectrum is flat over the bandwidth of the structural modes of interest, then the autocorrelation of the response is the sum of exponentially decaying sinusoids which have the frequencies and dampings of the structural modes. Skingle showed[2] that the presence of extraneous noise (provided it has an approximately flat spectrum over the frequency range concerned) serves to increase the ordinates of the correlogram. It follows, therefore, that any response signal which is compounded of responses to a rapid frequency sweep and to noise may be analysed *via* the autocorrelogram of the response provided the inputs satisfy the spectral requirements mentioned above. The autocorrelogram is, of course, an even function, and only one side is required for the subsequent analysis.

In practice, the autocorrelogram obtained from the response record exhibits peaks (often of very small amplitude) at large values of lag. These peaks are due to correlation between the transient responses that occur at the start and finish of a frequency sweep, and the forced response to the sweep itself as it passes through the system resonance frequencies. The peaks may be reduced in magnitude if the frequency sweep starts and finishes at a zero force crossing point, but they will not be entirely eliminated because a discontinuity in excitation will still be present. When the Fourier transform of the positive lag side of the autocorrelogram is formed, the small peaks at large lags cause scatter of the points in the resulting vector plot. Methods of dealing with this problem are given in section 3.5.

3.4 Pseudo-random noise tests

As is implied in section 3.3, noise may be used as a form of system excitation provided the spectrum of the input is flat over the frequency range of interest. The resulting response may be analysed in the same way as the response to a frequency-sweep excitation. The pseudo-random noise tests represented a 100% background noise excitation (defined in section 3.1).

When the autocorrelogram of the response is formed, it is found to exhibit relatively small but significant magnitudes at large values of lag. Subsequent Fourier transformation of one half of the autocorrelogram leads to a vector plot having a high degree of scatter. The power spectrum of a random force input is subject to statistical uncertainty if the record length is relatively short.

The record lengths considered in this Report are very much shorter than the sequence length of the noise generator and therefore large variations in the power spectrum of a single record of force input are inevitable. The irregularities of the power spectrum, produce in the autocorrelogram of the response, the significant magnitudes at large lags.

3.5 Vector plot modification

As mentioned in sections 3.2, 3.3 and 3.4 the direct Fourier transform of either the impulse response of the system with noise or the autocorrelogram of the noise and sweep responses produces a vector plot with large scatter amongst the points. Such vector plots can often be analysed on the digital computer although they may defy graphical analysis, but it was felt that the representation of the data as a recognisable vector plot was necessary. The process adopted was to inspect the impulse response or autocorrelogram on the display screen of the analyser and to clear the data after the initial decay such that the remaining data appeared as a truncated decaying sinusoid. Depending on the severity of the truncation, the Fourier transform of the modified data produced vector plots with spurious lobes. If, before taking the Fourier transform the modified response record was multiplied by an exponential decay (having a decay rate approximately equal to that of the response envelope) then acceptable vector plots were obtained when the modified data was transformed. This procedure increases the apparent damping in each mode and if the values of damping represented by the exponential decay at the system natural frequencies are subtracted from the estimated dampings from the vector plots the true dampings of the system are obtained.

The results of the process described above are illustrated in section 4.

3.6 Vector plot analysis

The vector plots obtained by the processes described in sections 3.2 to 3.5 were analysed using the numerical method described in Ref.8.

Briefly, the vector plot data, in the form of point coordinates and frequency, form the input to a computer program which evaluates the frequency and damping of each component mode and, in addition, the relative amplitudes of the modal responses, the phases of the modal components relative to a datum, and the force inputs to each mode. The program is essentially interactive, requiring the operator to provide initial estimates of modal characteristics from inspection of the vector plot. The advantages of using such a program are (1) that it allows maximum use to be made of all the relevant vector plot data (2) it enables all the plots to be analysed in a consistent manner (3) it saves a great deal of manpower and time and (4) it removes the need to modify the vector plots in order to facilitate graphical analysis. Experience with the program shows that it gives good results when the response data contains random errors, and in these circumstances, of course, it is much superior to graphical analysis.

4 RESULTS

4.1 Steady-state tests

A conventional subcritical response investigation, with sinusoidal force input at a series of discrete frequencies, was made for σ = 1.0, 1.1, 1.2, 1.24 and 1.28. The frequency and damping curves are shown in Fig.1, from which it will be seen that as air density is increased up to the flutter condition, the frequencies of the two modes approach each other, mode 1 frequency increasing and mode 2 decreasing. Near the flutter condition, the damping in mode 1 increases rapidly whilst that of mode 2 falls to zero at σ = 1.295 which thus represents the critical condition. Figs.2 and 3 show the vector plots for σ = 1.0, 1.2, 1.24 and 1.28; the vector plot for σ = 1.1 has been omitted since it was essentially the same as that for σ = 1.0. As σ is increased, and the damping in mode 1 increases, the contribution of mode 1 to the response vector becomes smaller; conversely, the contribution of mode 2 increases as the damping value falls.

4.2 Impulse tests

The impulse response of the model was investigated for σ = 1.0, 1.1, 1.2, 1.24 and 1.28, with background noise levels of 0, 10 and 20 per cent. Higher levels of background noise were not investigated because the scatter in the damping results for 20 per cent noise level clearly ruled out the use of an impulsive test method in these conditions.

Fig.4 shows a typical response record to an impulse in the presence of background noise. The record has a duration of five seconds, and it can be seen that the response to the impulse has merged into the general background of noise response in less than the first half-second of the record. For the remaining four and a half seconds, the response envelope maintains a constant rms level. If the whole record of Fig.4 is transformed, the resulting vector plot shown in Fig.5a is so distorted that it is virtually impossible to analyse it graphically, and results from computer analysis could hardly be regarded with confidence. Fig.4 must, therefore, be modified, and the first step is to truncate the record. This was done at t = 0.35 second, the response levels for t > 0.35 second being reduced to zero. The Fourier transform of the truncated response is shown in Fig.5b from which it may be seen that spurious lobes are evident. These occur because truncating the record has left a step in the response at 0.35 second; the truncated record may be smoothed by applying an exponential weighting function, giving the transform shown in Fig.6. The value of damping represented by the exponential weighting function must be subtracted from the damping yielded by the vector plot in order to obtain the true modal damping. Examination of Fig.6 shows that the lobes that were evident in Fig.5b are much reduced in size.

It is of interest to compare with the steady-state results the values of modal frequency and fraction of critical damping, C/C_c, obtained by computer analysis of Figs.5a, 5b and 6. After allowing for exponential weighting in Fig.6, the values are

	f_1 (Hz)	f_2 (Hz)	$(C/C_c)_1$	$(C/C)_{c\ 2}$
Fig.5a	39.94	45.46	0.077	0.027
Fig.5b	39.35	45.65	0.080	0.027
Fig.6	38.64	45.49	0.091	0.018
Steady-state	37.68	45.79	0.076	0.017

It is surprising that the computer analysis yielded answers for Fig.5a, and even more surprising that the values obtained were not far different from those obtained for Fig.5b. Apart from this, it should be noted that the variations in the modal frequencies from the steady-state values are much less than for the modal dampings, particularly in mode 2 where the damping is low. Although the vector plot of Fig.6 gives excellent agreement with the steady-state value of damping in mode 2 this must be considered somewhat fortuitous since the same plot gives worse agreement on mode 1 damping than the plots of Figs.5a and 5b.

The results for all the impulse tests are summarised in Fig.7. It will be seen that for the three noise levels that were investigated (0, 10 and 20 per cent), the modal frequencies were obtained with acceptable accuracy. The scatter on the damping values, however, increased with increasing noise. With zero noise, the damping in mode 1 was higher, and that of mode 2 lower, than the steady-state values. If these results are used for flutter prediction by extrapolating the mode 2 damping curve to zero, they give a critical condition at $\sigma = 1.29$ which is very close to the steady-state value of $\sigma = 1.295$. With increasing noise it becomes more difficult to predict the flutter condition with confidence; with 10 per cent noise the mode 2 damping values still lie on a fairly smooth curve (though the mode 1 values do not) but with 20 per cent noise, quite large scatter is evident and an operator would have little confidence in the test results.

In order to investigate the degree of scatter that could be expected from an analysis of several records, four impulse response records were taken at $\sigma = 1.24$ with 10 per cent noise, and gave the results shown in Fig.7. It will be seen that mode 2 dampings between 0.010 and 0.023 are obtained; the mean of these is close to the steady-state value of 0.017, and this suggests that, in practice, several measurements should be made for each test condition. Even in a wind tunnel of limited duration this should present no difficulty, bearing in mind that only a short response record is required. In the present case, for example, a repeated impulse every half second would enable ten sets of results to be obtained in a test of 5 seconds duration.

It must be concluded, therefore, that provided background noise is at a low level, subcritical response measurements may be made to an acceptable degree of accuracy for flutter purposes by using an impulsive input force. The duration of a test of this sort is very short, and will be of the order of one or two seconds depending on the test conditions.

4.3 Noise excitation tests

With the analogue excited by noise, an analysis was made of 5-second and 10-second records of the response over the range of σ covered in the previous test.

Some of the resulting vector plots are shown in Figs.8 and 9, and the overall frequency and damping values in Fig.10. It will be seen that the vector plots are of good quality with little scatter of the measured points; they would present no difficulties in graphical analysis. Fig.10 indicates, however, that there is an unacceptable scatter of the damping values, and some scatter of the frequency values. The results from the two different record lengths are not significantly different in their scatter about the true values.

With no knowledge of the true values, it would be difficult to judge, on the basis of the damping values in mode 2, whether, at values of σ close to the critical it was safe to make an incremental increase in σ. On the other hand, most aeroelastic engineers have, at some time, been faced with making this sort of judgement on test data having similar scatter - even though it has come from steady-state tests. One cannot, therefore, entirely reject the technique of extracting modal properties from noise excitation. What is certainly true is that a better technique should be used whenever possible.

4.4 Frequency-sweep tests

Two durations of frequency-swept force input were used, nominally 5 and 10 seconds, and in both cases the frequency band was from 20 Hz to 65 Hz with a constant rate of change of frequency with time. The actual duration of the frequency sweep was slightly less than the total response record duration in order to allow time for the response to the input to die away.

Typical responses to the frequency-sweep input are shown in Figs.11 (for zero noise) and 12 (20 per cent noise); both responses are for $\sigma = 1.1$, and are 10 second records. The peaks corresponding to the two modes can be easily seen in both records. After correlation, truncating, exponential weighting and transforming the vector plots are as shown in Fig.13 (zero noise) and Fig.14 (20 per cent noise); these plots present no analysis difficulties.

The overall results for modal frequency and damping are shown in Figs.15 and 16 for 5 and 10 second sweeps respectively. It will be seen in Fig.15 that frequencies are accurately determined except for conditions close to flutter when there is a large noise background (20 and 40 per cent); for these cases there is some scatter in the frequencies of mode 1 (i.e. the mode with highest damping). The damping values for the modes also show an increase in scatter as the critical flutter condition is approached or the level of noise is increased. Even with only 10 per cent noise, the mode 1 dampings show poor agreement with the steady-state values although similar scatter of the mode 2 damping does not occur until the noise is increased to 40 per cent. Because, in practice, the parameter of interest is the mode 2 damping, it can be concluded from Fig.15 that with a 5 second frequency sweep, adequate results for flutter prediction are obtained with noise levels up to 20 per cent, although the scatter increases with increasing noise level. As an indication of scatter in damping values obtained from records taken under identical conditions, several sweeps were made at $\sigma = 1.24$ with 20 per cent noise giving the results shown in Fig.15. These yielded damping values for mode 2 between 0.014 and 0.026 compared with the steady-state value of 0.017. Rather more scatter occurred in the damping values for mode 1. These results suggest that, as with impulse inputs in the presence of noise, it is advisable to make repeated tests in order to establish a mean of the scatter band. Unfortunately, it is not possible to obtain several tests in as short a time as can be achieved with impulsive inputs, and the advantages of increasing the sweep rate in order to repeat the frequency sweep within a given test duration need to be explored.

5 DISCUSSION

5.1 General

The investigation that has been described in the foregoing sections, and the results obtained, give a guide to the techniques that will have to be used if appreciable reductions in the duration of flutter tests are to be achieved. It is clear that all these techniques can result in a degradation in accuracy compared to steady-state tests and that this degradation increases as the amount of background noise increases. However, a general conclusion that the techniques are inferior to the steady-state technique should not be reached too hastily. There are two factors that must first be considered, one concerning the validity of the analogue in the present investigation, the other more general.

In respect of the analogue, there is evidence that its behaviour was not wholly consistent throughout the tests. It was pointed out in section 2.1 that the steady-state response tests did not give the same solutions to the equations of motion as a digitial computer solution, and this was ascribed to certain characteristics of the analogue. However, as the tests proceeded, it was evident that analogue behaviour could vary slightly from day to day, and, perhaps more importantly, from one type of input to another. Clues to this behaviour are not easy to identify, but if, for example, the values of the frequency in mode 1 at $\sigma = 1.1$ are examined in Figs.1, 7, 10, 15 and 16 it is found that those obtained from impulse, noise and frequency-sweep tests are always slightly greater than those obtained from steady-state measurements. Such discrepancies, minor though they are, do tend to throw some doubt on the validity of a comparison of absolute values from different techniques, particularly close to the flutter condition where small errors in damping are very significant.

A more general factor to be considered is that the results from the tests of the techniques in the presence of noise are being compared with steady-state results obtained under ideal conditions of zero noise. It is not difficult to find wind-tunnel and flight-flutter test results, using steady-state techniques, in which, because of the presence of noise, the vector plots were extremely difficult to analyse, and the resulting damping curves showed a high degree of scatter. In the present investigation, therefore, the datum for comparison represents a high standard of accuracy which could almost certainly not be achieved by steady-state methods in the noisy environment to which the other techniques have been subjected.

The general conclusion, therefore, must be that techniques for reducing the duration of flutter test measurement appear to yield results that suffer increasing degradation in accuracy with increase of background noise, but that this degradation is unlikely to be significantly worse than that of steady-state tests in the same environment.

5.2 Analysis

In all the analyses, whether of response to impulse, pure noise or frequency sweep, a weighting function has been applied to the record at some stage of the processing. Although the application of a weighting function serves a number of purposes (such as ensuring an adequate dynamic range in a record or smoothing a record) before taking the Fourier transform, the main aim is to ensure that the resultant vector plot is capable of analysis by whatever method is available. Throughout this investigation, it has been assumed that graphical analysis will generally be employed, even though computer analysis has in fact been used here. It is clear, however, that computer analysis has much greater potential for successful analysis of 'poor' vector plots than have graphical methods. A glance at Fig.5a, which was computer-analysed with meaningful results shows that the computer can handle a vector plot which looks little better than a jumble of points to the graphical analyst. It is logical, then, to ask what advantages can be taken of the computer's potential in this respect. One answer would seem to be that some of the steps now taken in the initial treatment of raw records, to render them suitable for graphical analysis in their final form, might be omitted. It is possible that the processes, such as truncation and weighting, would be found to be unnecessary in some circumstances, and research into this possibility is needed. Several avenues merit exploration, including the effects of restricting the data ranges before computer analysis, in order to remove from the data unwanted material from the ends of the vector plot.

5.3 Further work

The work that has been described here is the first part of an investigation into ways of reducing the test time in flutter experiments. The remaining parts will be concerned with actual tests on wind-tunnel flutter models, both low and high speed. Although the crucial test of any technique is in its application under real conditions, the tests to be made in the wind tunnel will necessarily be more restricted than those described here, because the background noise (in the form of tunnel unsteadiness) cannot be varied. Thus it is unlikely that tests, for example, in the RAE 3ft wind tunnel (which, at some conditions, exhibits considerable flow unsteadiness), will yield a great deal of useful information on the suitability for flutter tests of a limited duration smooth flow tunnel such as the proposed ECT[9]. What will be demonstrated by such tests, however, is whether the techniques considered here can be applied in conditions where tunnel unsteadiness may not have the idealised characteristics of randomness and where the model may not conform to all the assumptions inherent in a linear analogue.

It should be mentioned at this point that in either flight tests, or wind-tunnel tests where turbulence is used as a method of excitation, and where a much longer test time is available than is considered in the Report, an improvement can be made in the method of analysis. This is achieved by forming the autocorrelogram of the response from the Fourier transform of the average power spectrum of the response over a number of records; the aim being to produce a power spectrum of the force input with less variability than that produced by analysis of a single record.

6 CONCLUSIONS

(1) Digital analysis of the response of an electrical analogue of a flutter model to various forms of input has indicated that flutter test techniques which are now available can offer a significant reduction in test duration. Under conditions of high background noise, there may be some penalty in the form of reduced accuracy, but it is probable that the loss of accuracy for the parameters of importance will be no greater than occur with current techniques of steady-state excitation in similar conditions.

(2) Where noise levels are low, tests may be made using an impulsive input force, and such tests will be of very short duration - of the order of a second. With a higher level of background noise, an impulse test may still be made, and it will be advantageous to use response records from several impulses to establish a mean of the results. With increasing noise levels, the impulse test is increasingly inaccurate, and difficulties will undoubtedly occur with high noise backgrounds.

(3) The use of noise alone as the means of excitation for short tests does not appear very promising, and in these conditions a swept-frequency force input should be used. The longer the duration of the sweep, the more accurate will be the results, but a sweep of 5 seconds duration in a high noise environment should give results that are comparable to those from steady-state techniques in the same environment.

(4) It is accepted that current techniques of steady-state excitation are sometimes unsatisfactory in practice because of unwanted responses due to noise; it is probable that an appropriate 'fast' technique will be no more unsatisfactory, and in this respect it is concluded that the fast techniques should be used whenever possible both to save testing time, and hence cost, and also to acquire experience which will, in time, lead to improvements in accuracy as the techniques are improved.

Appendix

EQUATIONS OF MOTION FOR FLUTTER MODEL ANALOGUE

For a fixed Mach number, the equations of motion may be written:-

$$[A][\ddot{q}] + \{\sigma[B] + [D]\}[\dot{q}] + \{\sigma[C] + [E]\}[q] = 0$$

where A is a diagonal inertia matrix

B is a square matrix of aerodynamic damping coefficients

C is a square matrix of aerodynamic stiffness coefficients

D is a diagonal matrix of structural damping

E is a diagonal matrix of structural stiffness

q is a column matrix of generalised coordinates appropriate to still-air normal modes

σ is the ratio of air density to that at sea level.

The numerical values of the matrices are:-

$$A = 10^{-6}\begin{bmatrix} 22.1019 & 0 \\ 0 & 33.2216 \end{bmatrix}$$

$$B = 10^{-3}\begin{bmatrix} 2.9999 & -0.0512 \\ 0.3031 & 0.5266 \end{bmatrix}$$

$$C = \begin{bmatrix} 0.2414 & -0.5782 \\ 0.4072 & -0.9314 \end{bmatrix}$$

$$D = 10^{-3}\begin{bmatrix} 0.0639 & 0 \\ 0 & 0.4142 \end{bmatrix}$$

$$E = \begin{bmatrix} 0.6841 & 0 \\ 0 & 4.3662 \end{bmatrix}$$

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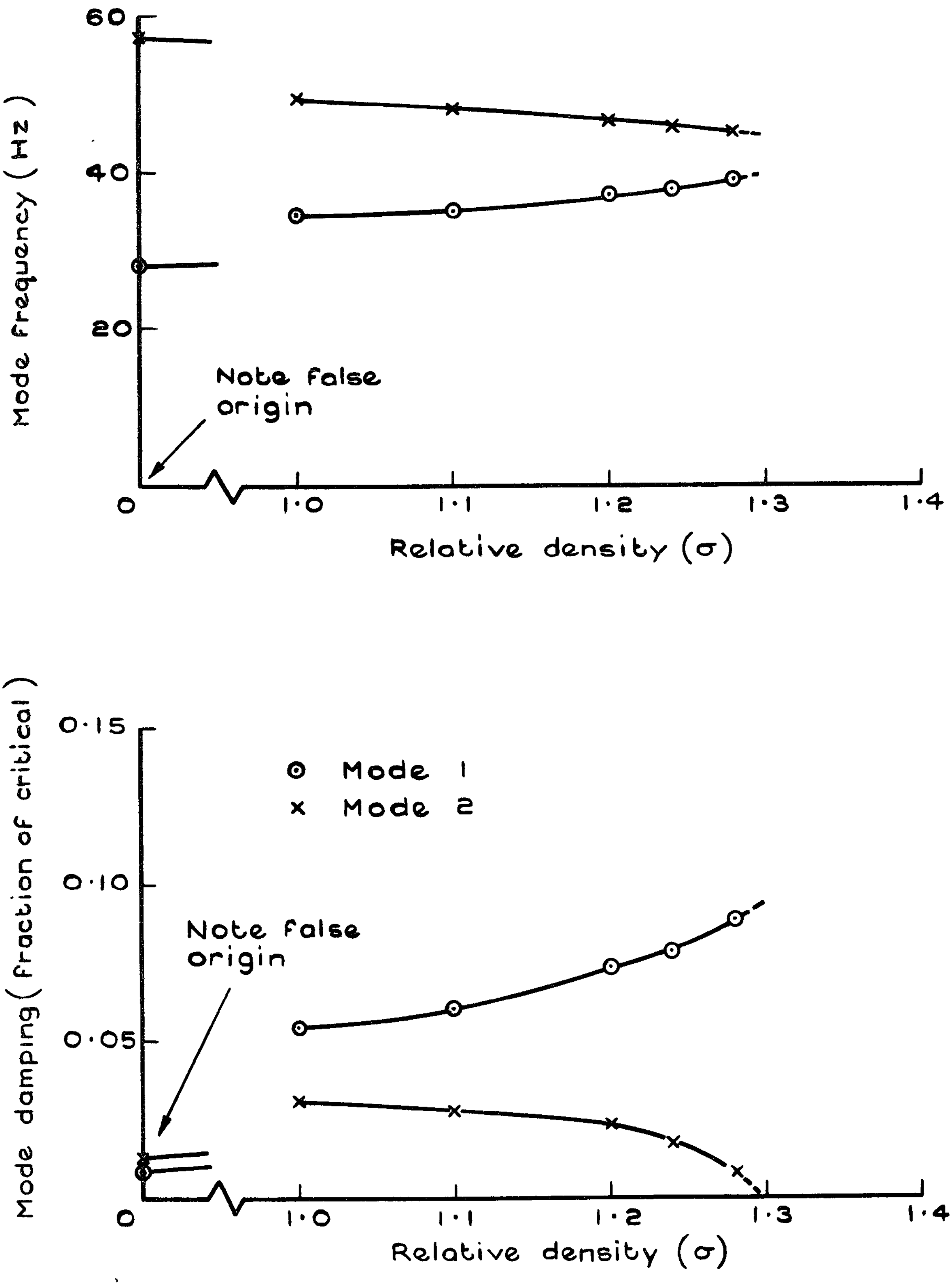


Fig.1 Subcritical response characteristics from steady state tests

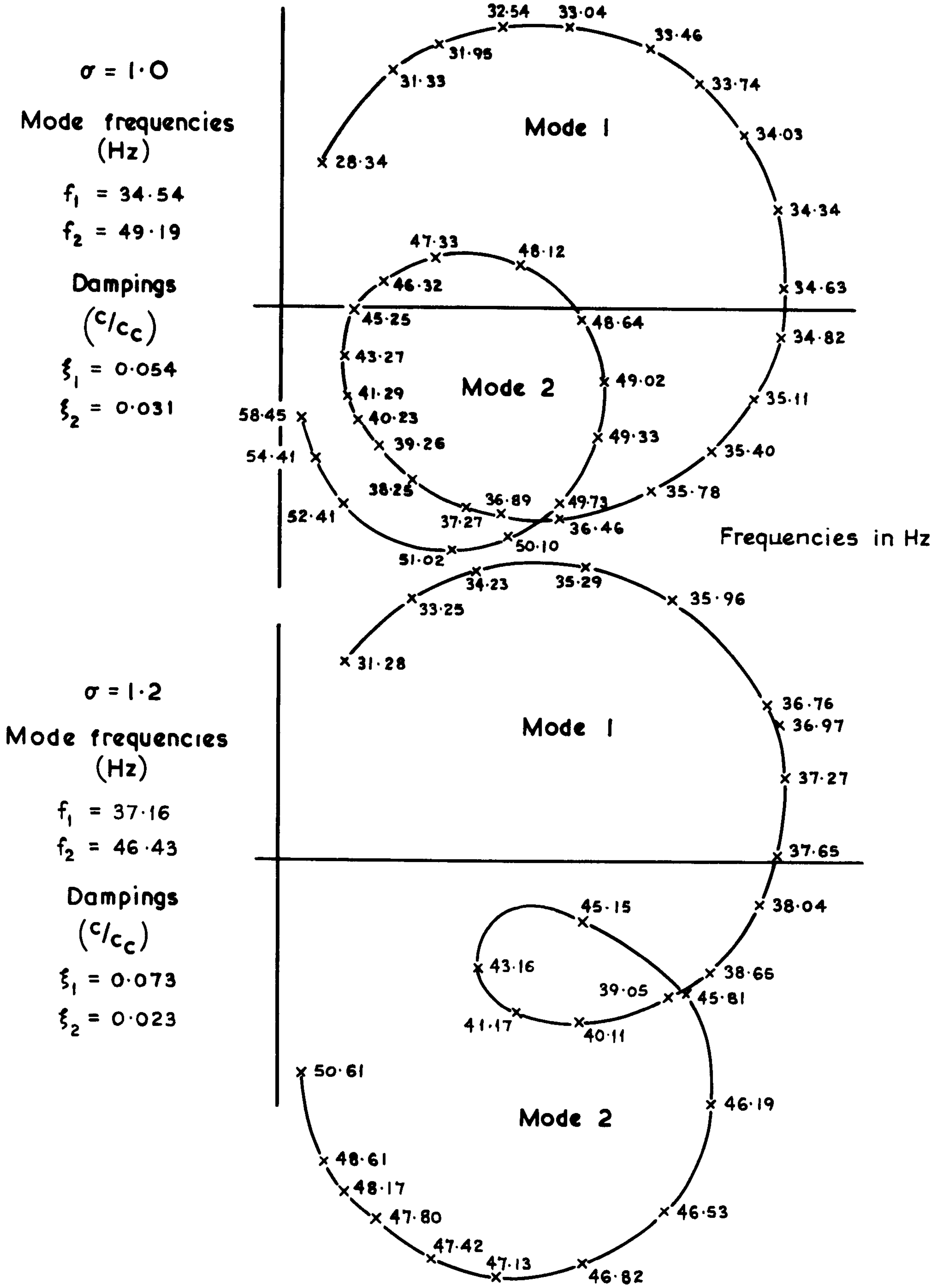


Fig.2 Steady state vector plots for σ = 1·0, 1·2

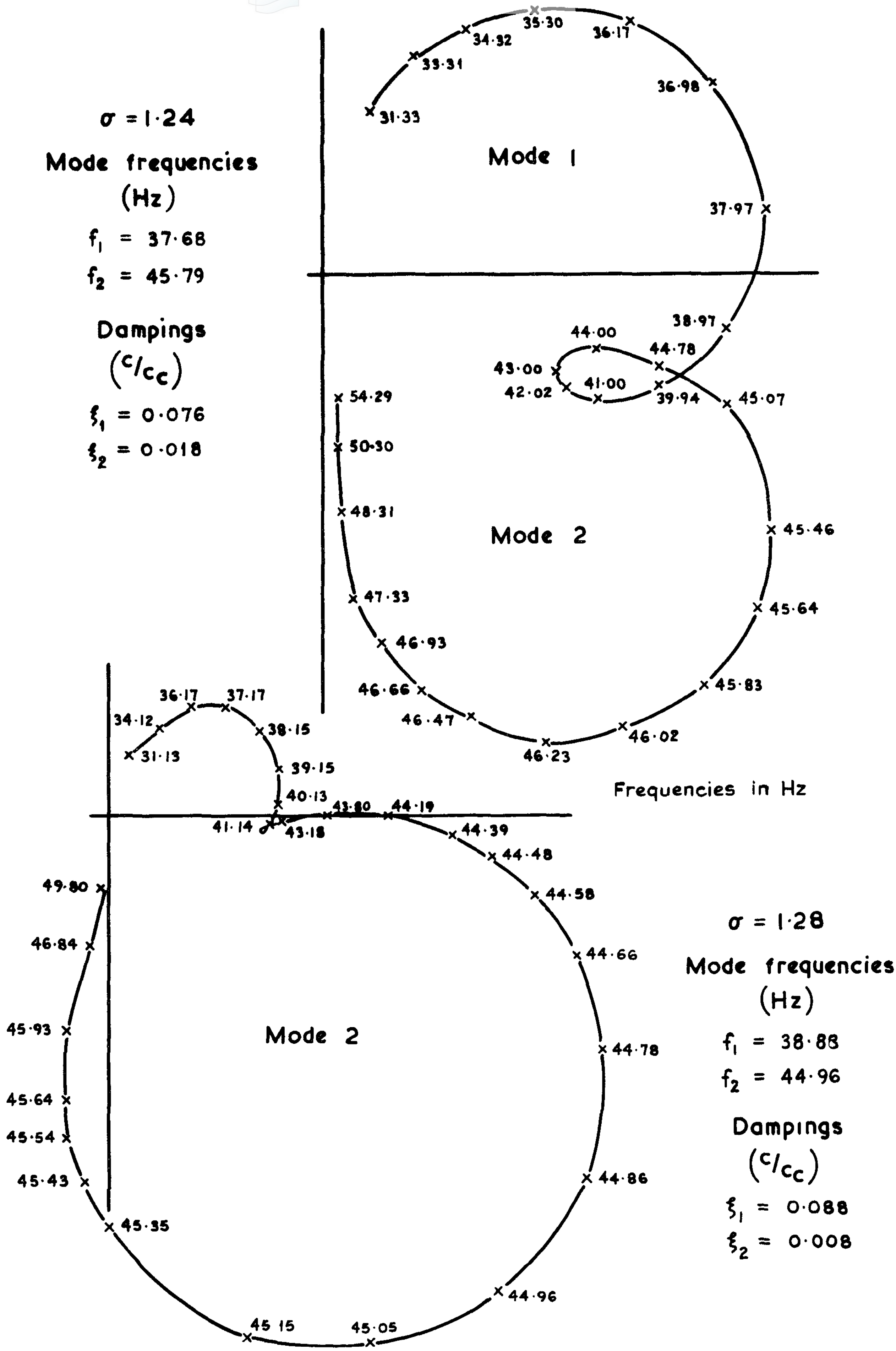


Fig.3 Steady state vector plots for $\sigma = 1{\cdot}24, 1{\cdot}28$

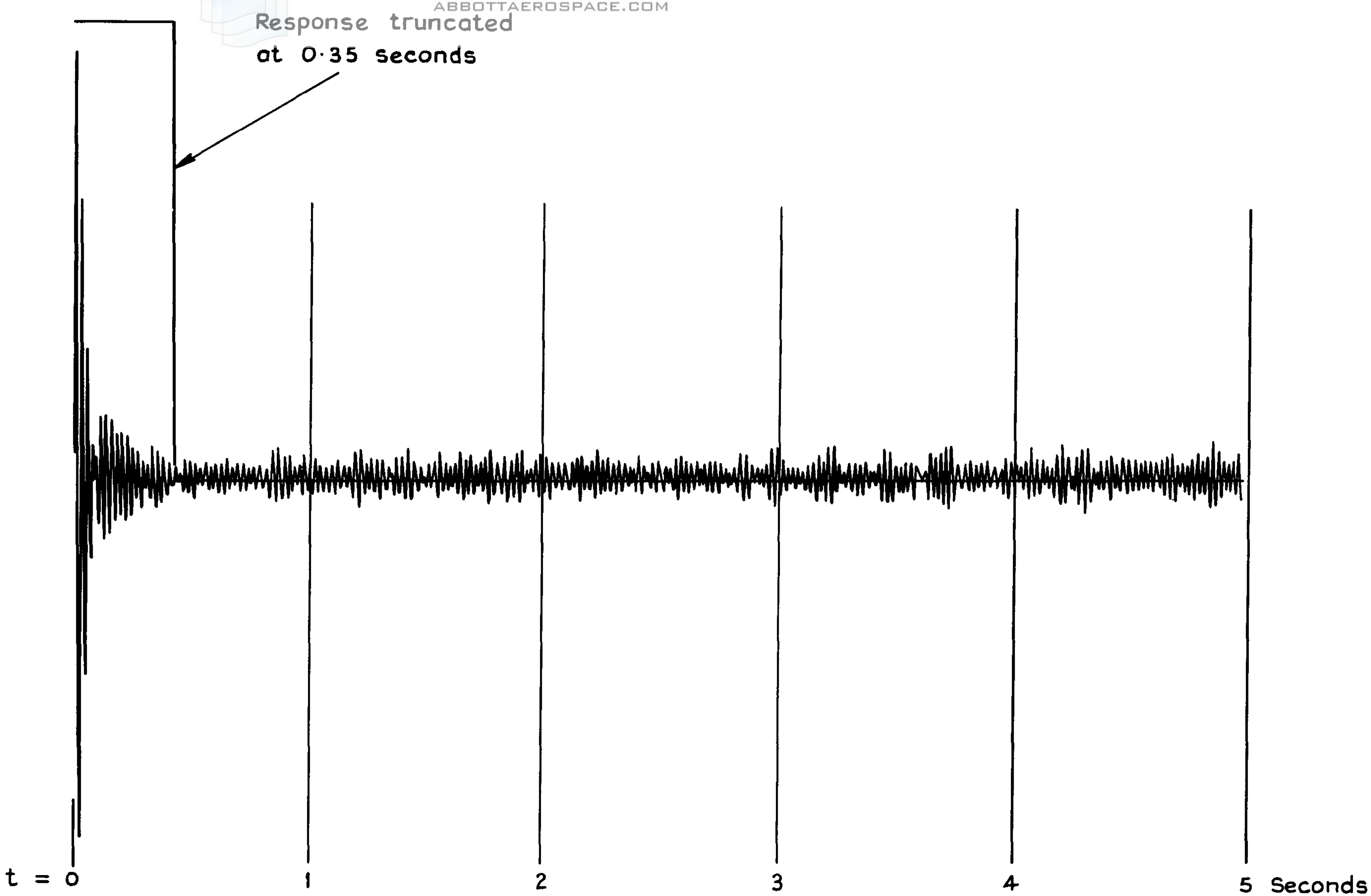
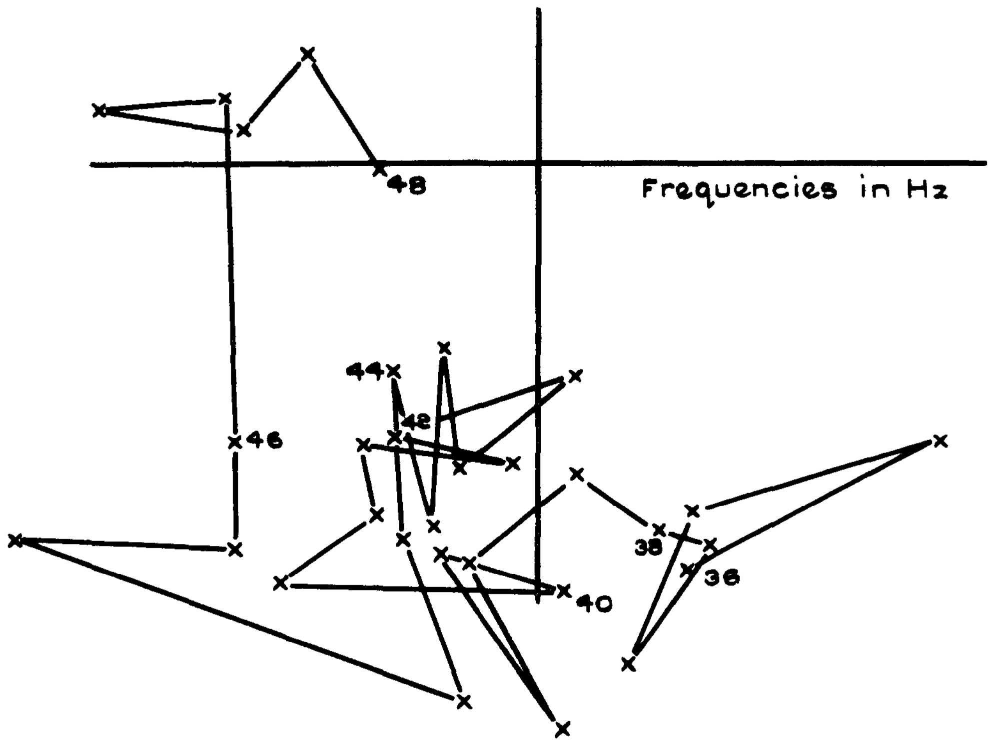
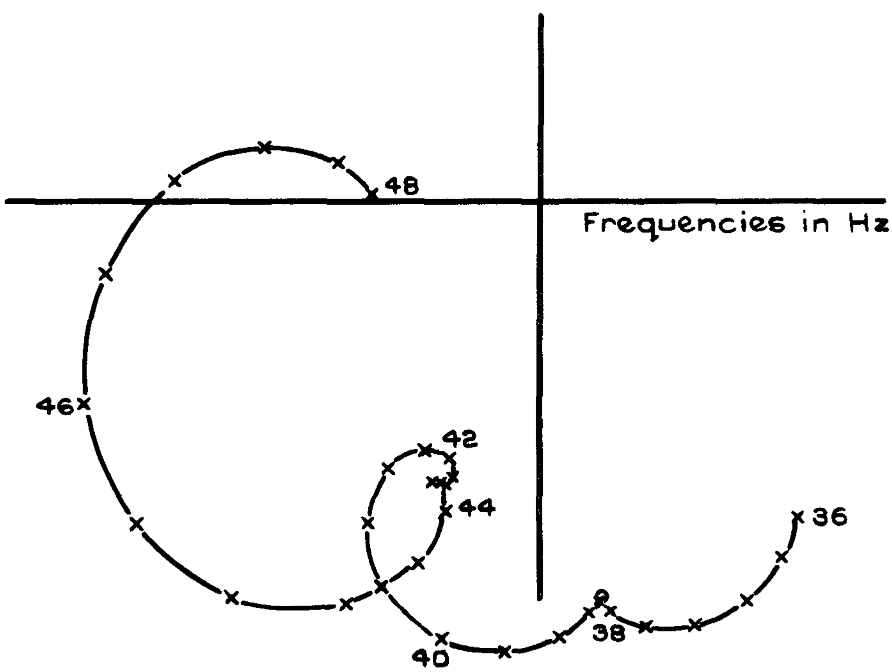


Fig.4 Response to an impulse for $\sigma = 1{\cdot}24$ with 10% noise



a Transform of 5 seconds of response



b Transform of 0·35 seconds of response

Fig.5 a&b Fourier transforms of Fig.4

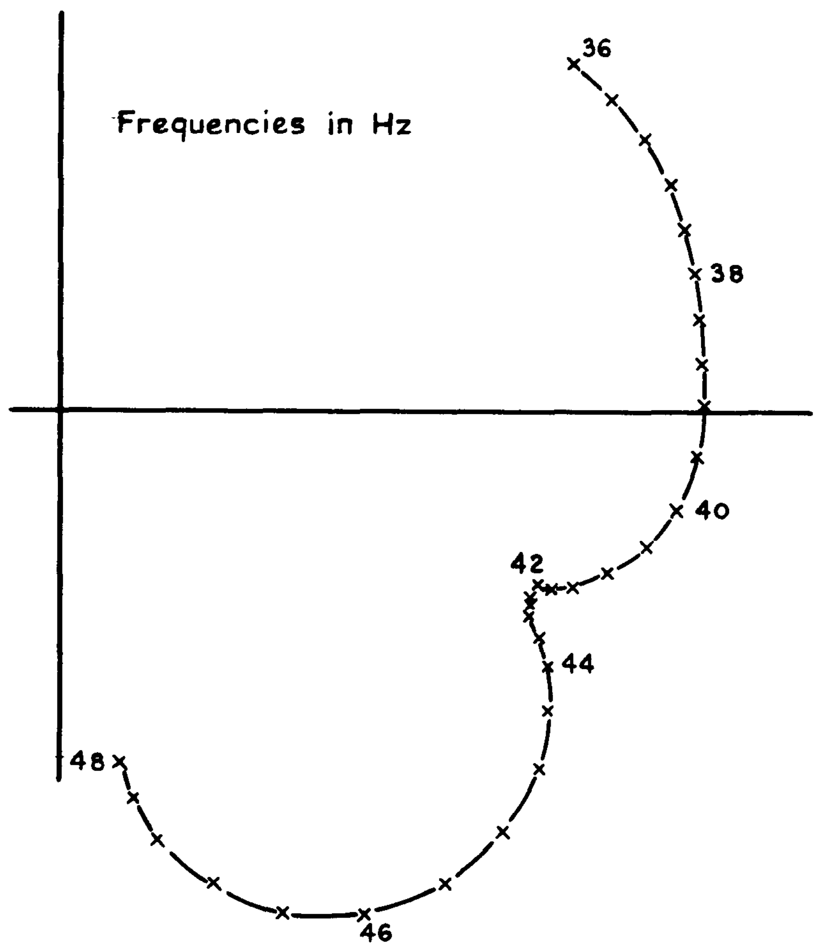


Fig.6 Fourier transform of Fig.4 after truncation and weighting

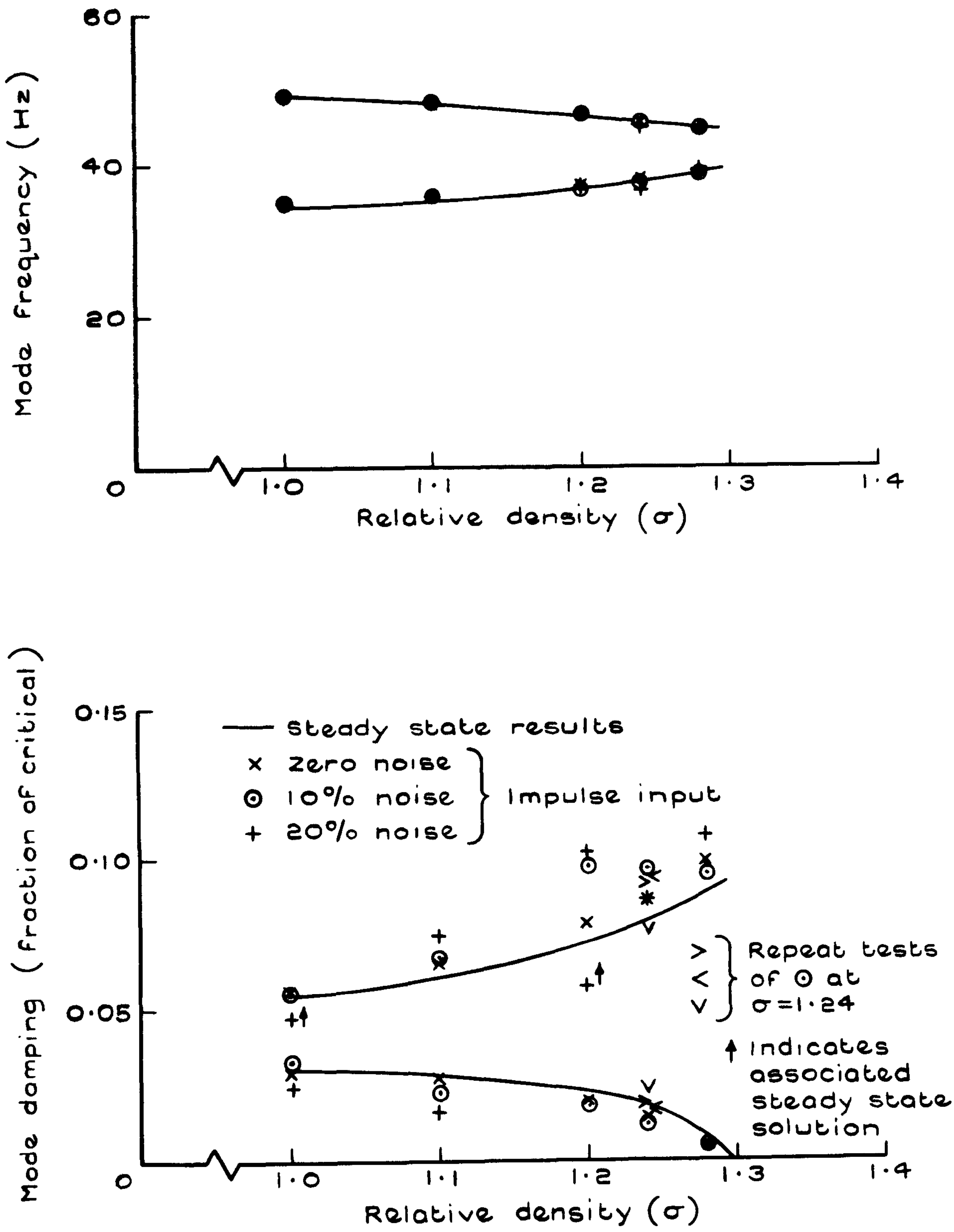
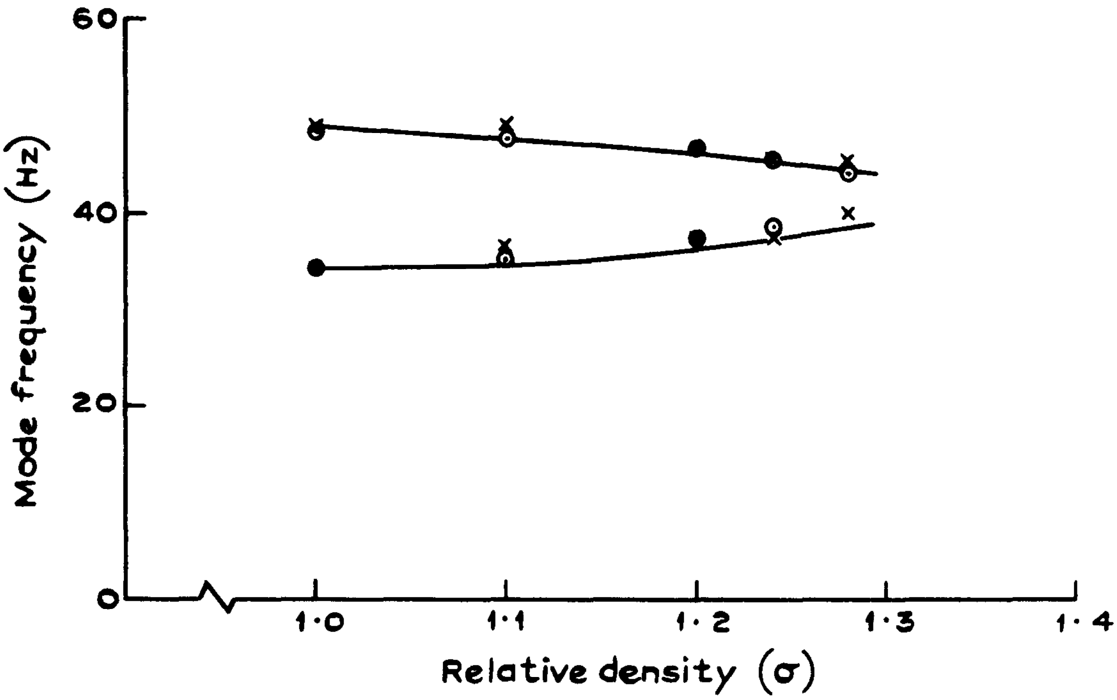
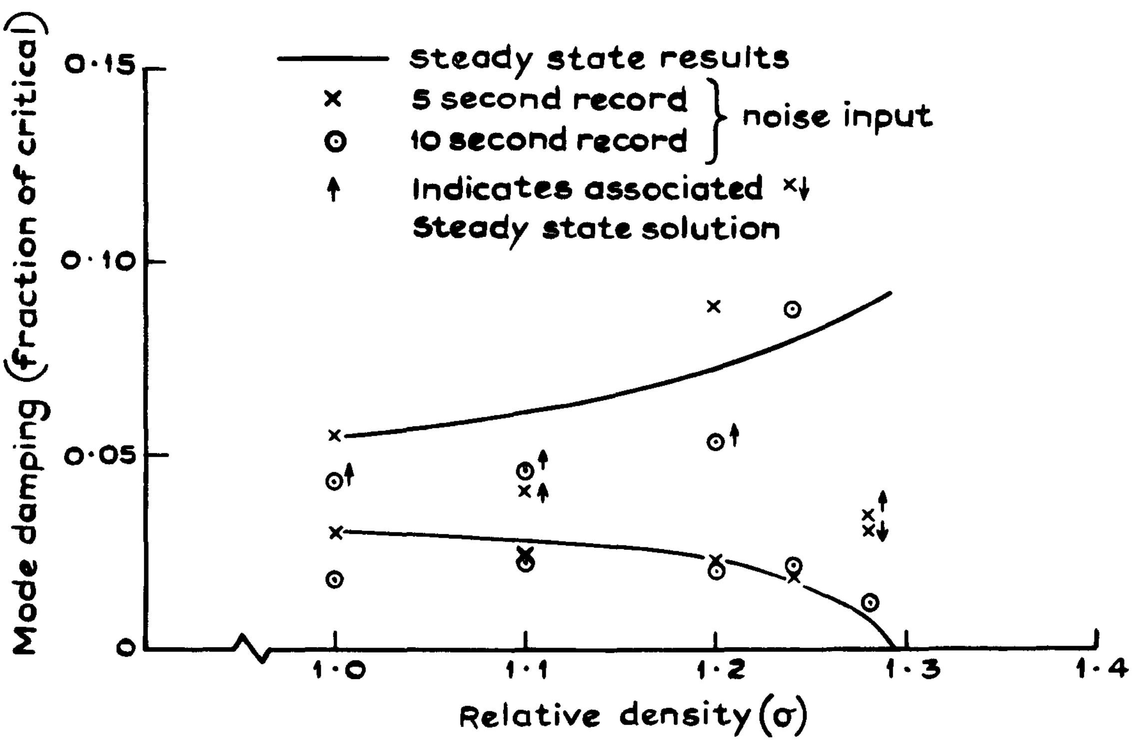


Fig.7 Subcritical response characteristics from impulse tests





Note: The 10 second response record at $\sigma = 1{\cdot}28$ did not contain a sufficient contribution from mode 1 to enable an estimate of the modal frequency and damping to be made

Fig.10 Subcritical response characteristics from noise tests

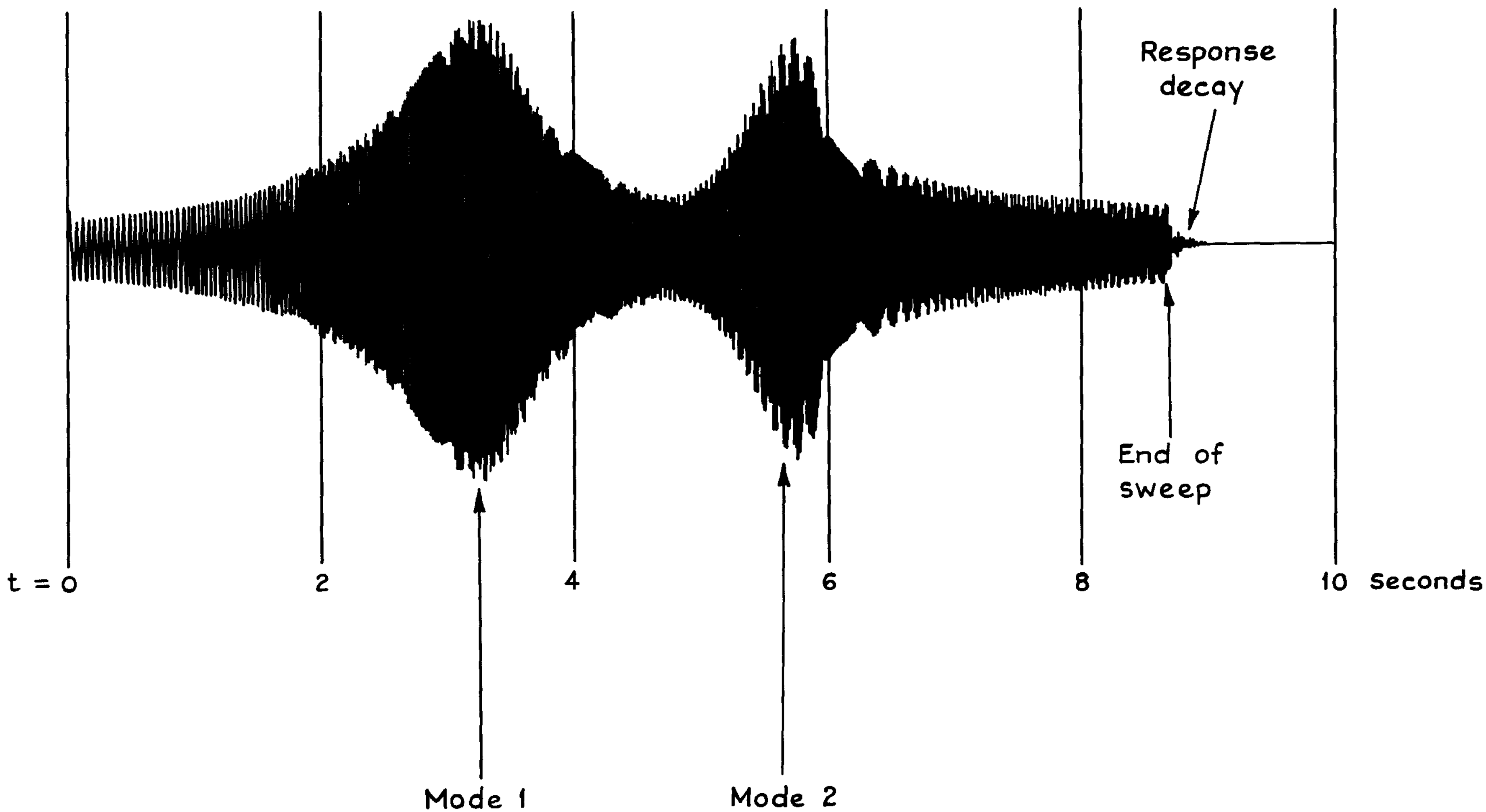


Fig.11 Response to a frequency sweep for $\sigma = 1{\cdot}1$ with zero noise
(10 second record)

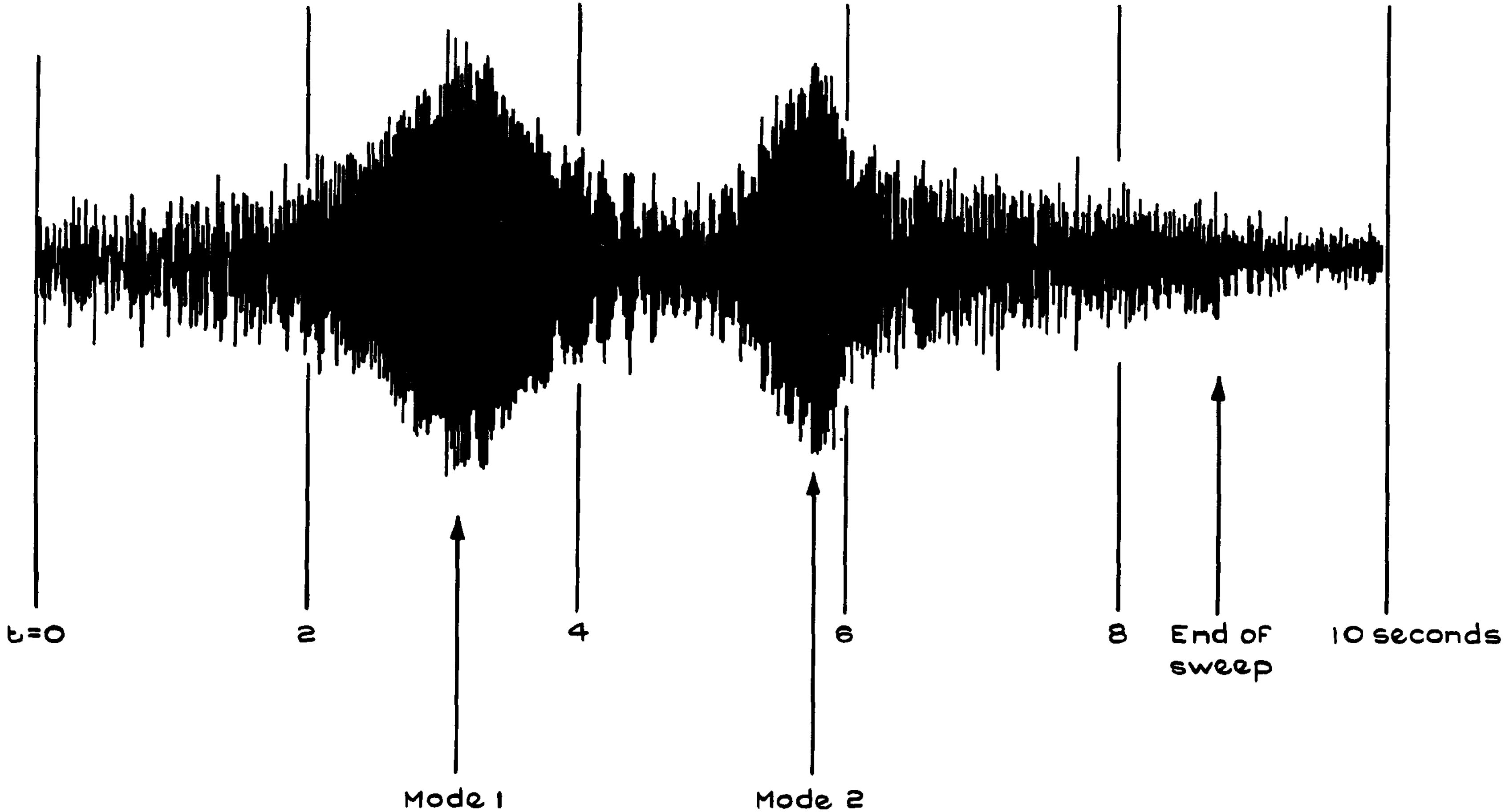


Fig. 12 Response to a frequency sweep for $\sigma = 1{\cdot}1$ with 20% noise (10 second record)

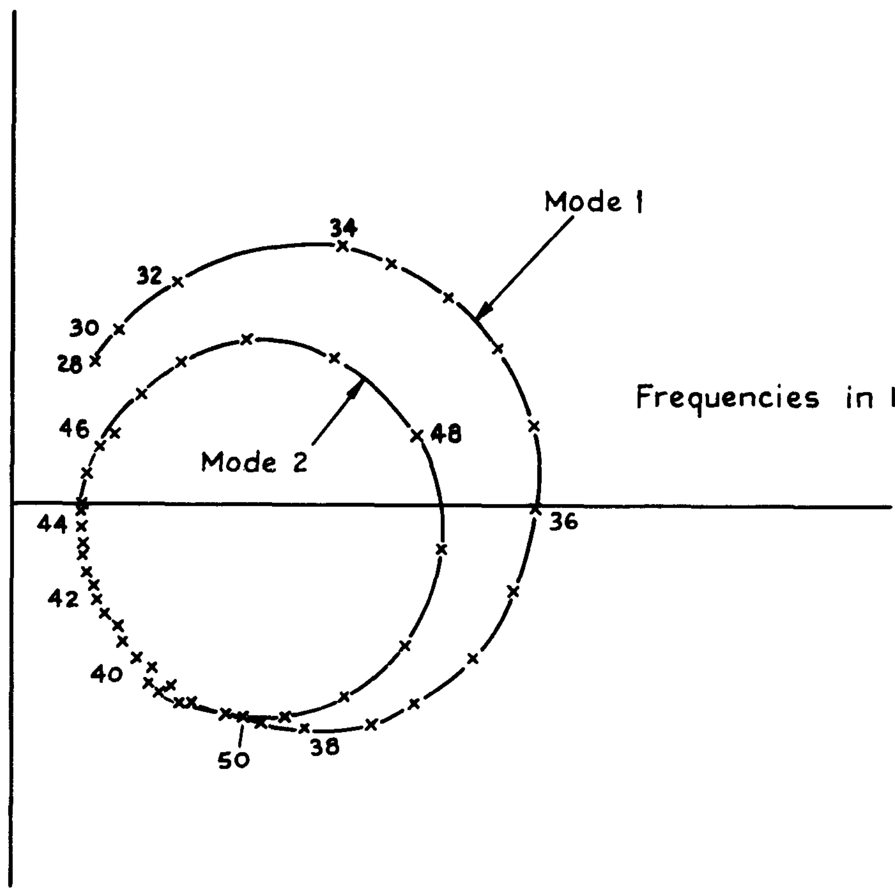
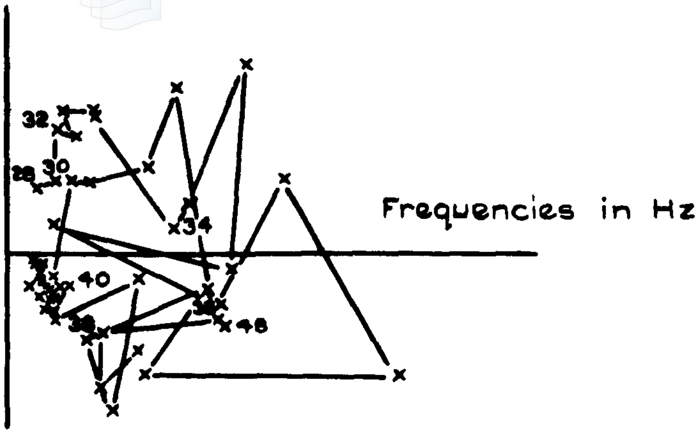
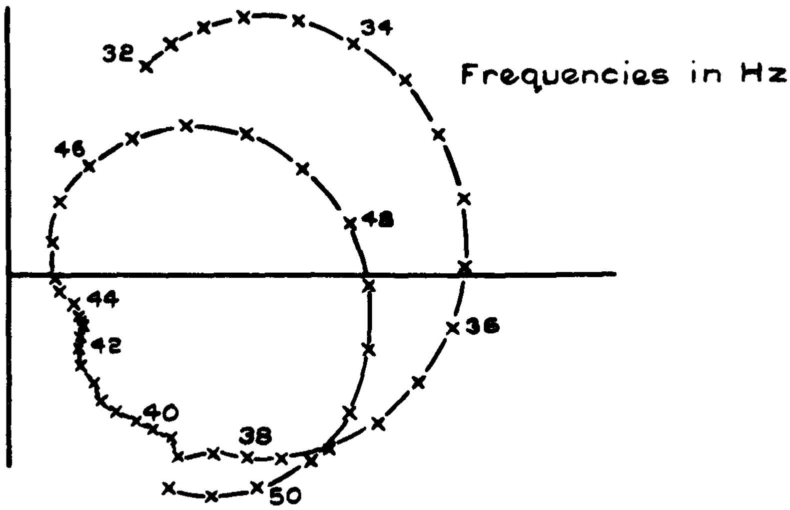


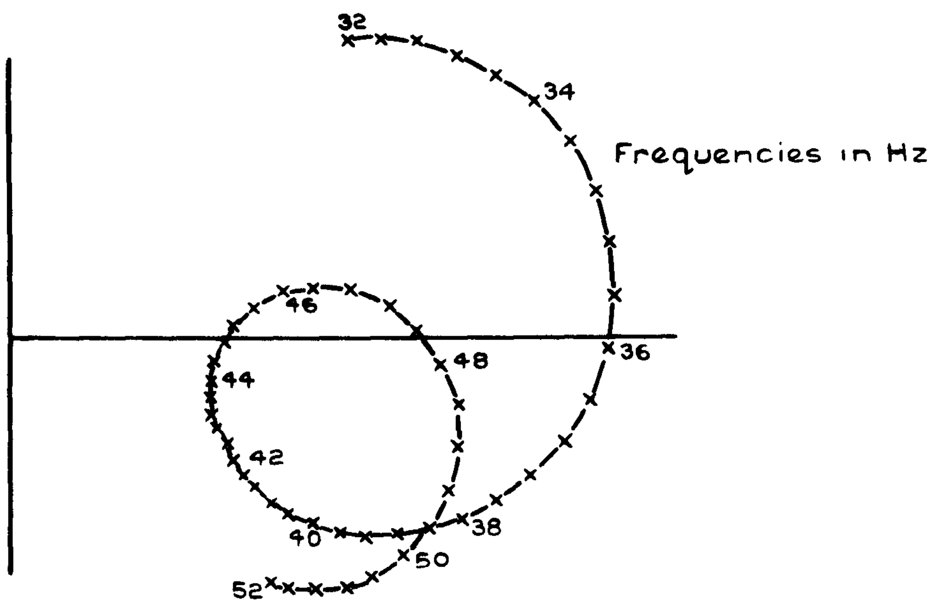
Fig. 13 Frequency sweep vector plot for $\sigma = 1{\cdot}1$ with zero noise (10 second sweep)



a Transform of 10 seconds of autocorrelation function

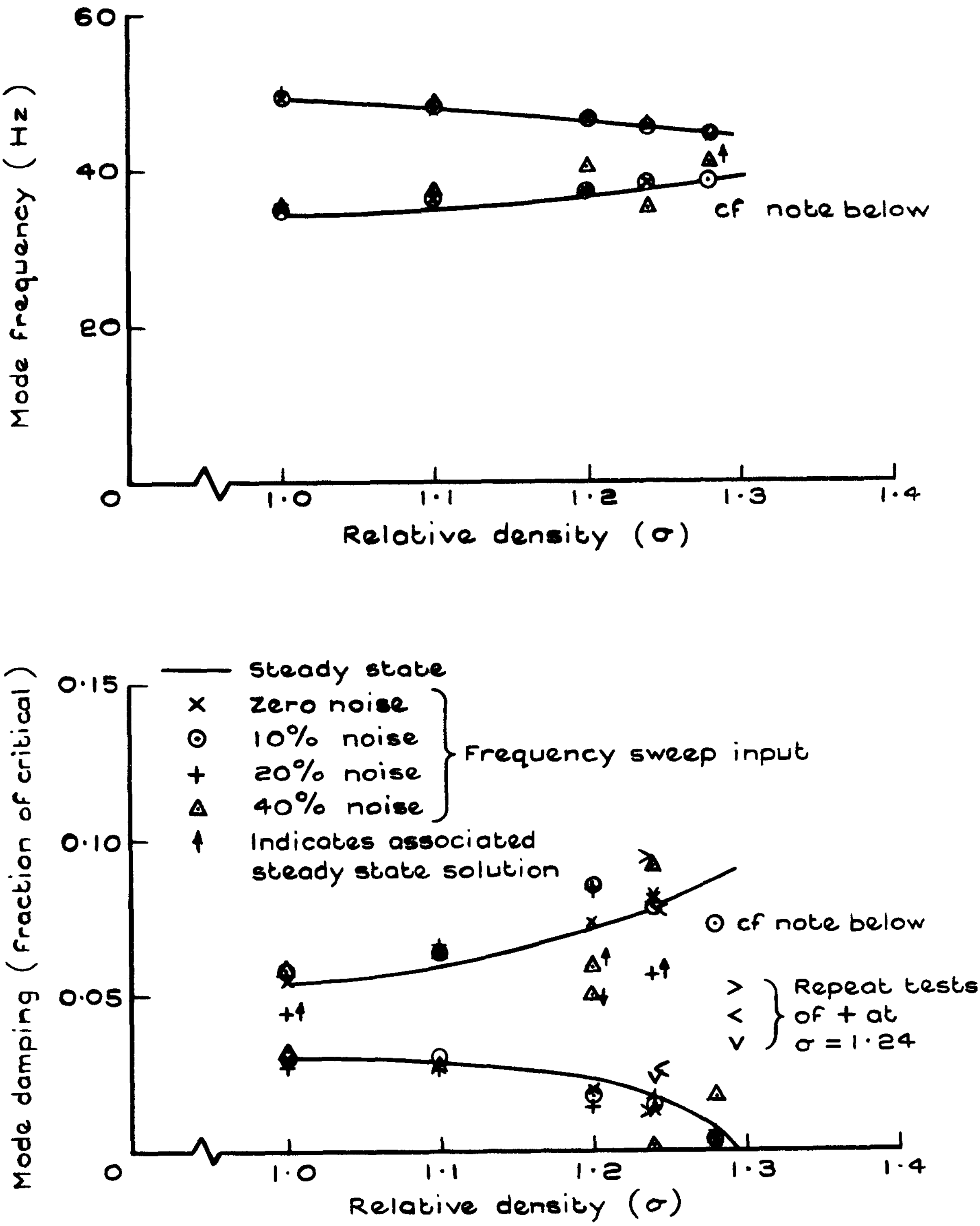


b Transform of first 0·41 seconds of autocorrelation function



c Transform of first 0·41 seconds of autocorrelation function after exponential weighting

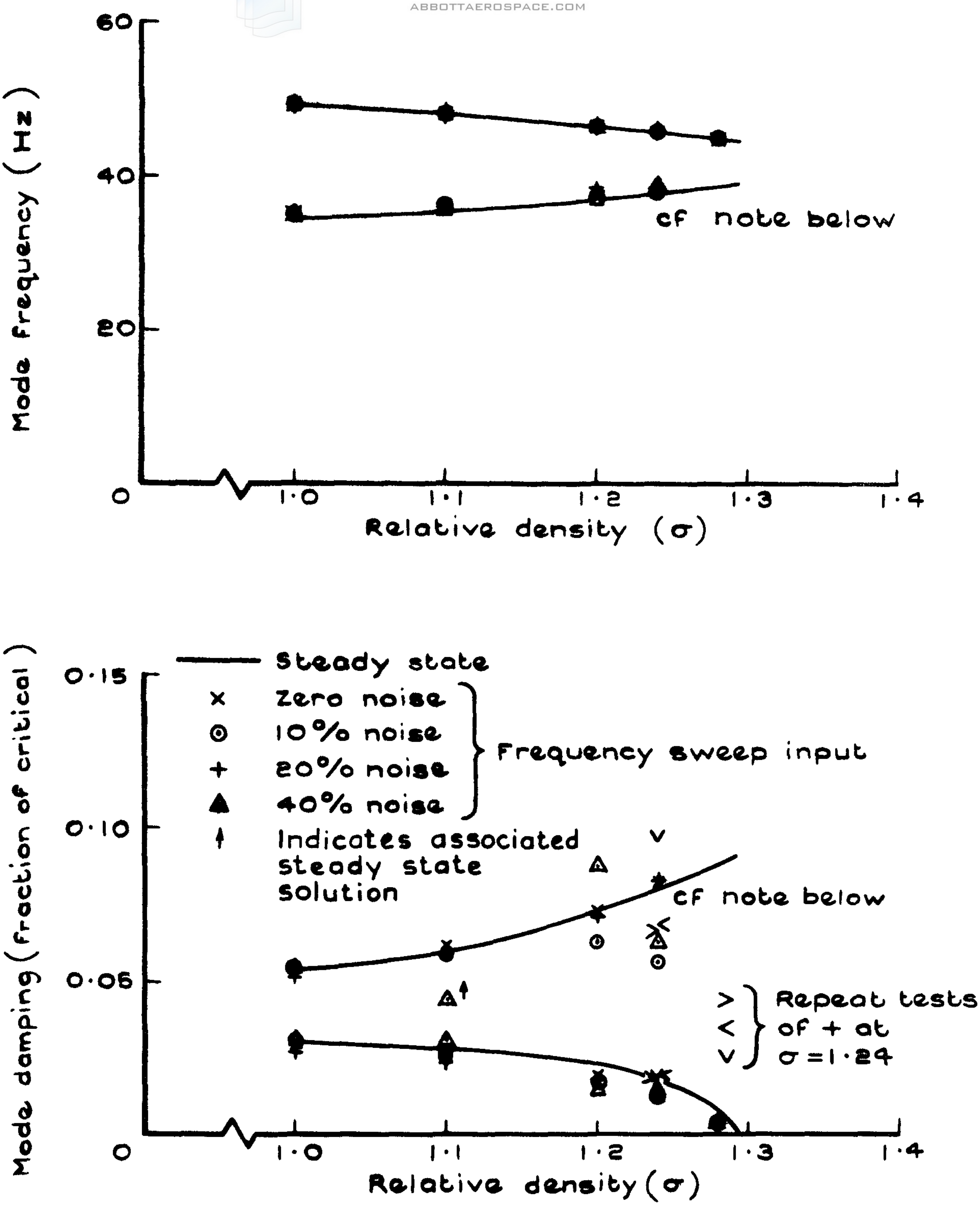
Fig.14 a-c Frequency sweep vector plots for $\sigma = 1 \cdot 1$ with 20% noise (10 second sweep)



Note:

A number of the response records at σ=1·28 did not contain a sufficient contribution from mode 1 to enable an estimate of the modal frequency and damping to be made

Fig.15 Subcritical response characteristics from frequency sweep tests (5 second sweep)



Note

A number of the response records at $\sigma = 1{\cdot}28$ did not contain a sufficient contribution from mode 1 to enable an estimate of the modal frequency and damping to be made

Fig.16 Subcritical response characteristics from frequency sweep tests (10 second sweep)

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Skingle, C. W.
Gaukroger, D. R.

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