SOME EXPERIENCE USING SUBCRITICAL RESPONSE METHODS IN WIND-TUNNEL FLUTTER MODEL STUDIES

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SUMMARY

Experiences obtained with four methods to predict flutter of wind-tunnel models from subcritical response data are described. The four methods are: co/quad, randomdec, power spectral density, and the peak-hold spectrum. Model excitation techniques included both forced (sinusoidal sweep) and random (tunnel turbulence). These methods were successfully used to measure the frequency and damping (or an inverse response amplitude proportional to the damping) in the predominant flutter modes. Implementation and application of each method are discussed. Some results and comparisons between methods are presented.

INTRODUCTION

Transonic flutter model testing has become an integral part of the development of high-speed aircraft such as the Grumman F-14, Rockwell B-1, Boeing 747, and Lockheed C-5A. Wind-tunnel studies to establish transonic flutter clearances and to provide data for correlation with analysis and with flight tests are made using dynamically scaled aeroelastic models. Some examples of correlation between flight and wind-tunnel model tests in the Langley transonic dynamics tunnel (TDT) are given in reference 1. These models simulate the complete aircraft under near free-flying conditions and are quite sophisticated and expensive. Since flutter can be an explosive-type, destructive instability, there is a substantial risk of damaging the model when flutter is encountered. Consequently, there is a need to develop methods to predict the flutter condition without having to actually experience flutter. The requirements are similar to those in flight flutter testing, namely, to identify the vibration modes critical to flutter and to measure and track the frequency and damping in these modes as the test conditions are varied, and the flutter boundary is approached.

The state of the art of subcritical flight flutter testing was surveyed in late 1972 (ref. 2). At the time of this survey, United States industry relied almost exclusively on sinusoidal excitation provided by auxiliary aerodynamic vanes, inertia shakers, or the power control system. Random excitation techniques had not been used for flight flutter testing. For a number of years the staff of the TDT has used various subcritical response methods in wind-tunnel flutter model studies. In some cases external excitation of the model has been used, similar to full-scale flight flutter testing. However, the methods of excitation of models are usually more restricted. For instance, the model control system is normally provided for trim and is not capable of high-frequency inputs. Space and weight are also usually too limited to allow internal shaker equipment. Consequently, most of the model subcritical damping work at Langley has been associated with methods that use natural wind-tunnel turbulence as the excitation force.

The purpose of this paper is to describe some experiences in the application of four subcritical response methods to predict model flutter characteristics in the Langley TDT. The four methods examined are co/quad, which requires sinusoidal forced excitation, randomdec and power spectral density (PSD), which require only random excitation, and the peak-hold spectrum method, which is applied to both a forced and random excitation system. The implementation of each method is described, and results from the application of all four methods to a cantilever, delta-wing model in the TDT are presented. Since this model was designed and built for active flutter suppression studies and was equipped with fast acting oscillating controls, it provided a unique opportunity for determining subcritical response data where sinusoidal forced excitation is required for comparison with damping data obtained using random excitation produced by turbulence. Also, co/quad and randomdec results obtained by using a complete, cable-mounted B-52 model are discussed.

FOUR PREDICTION METHODS

The four methods used to measure the subcritical (below the actual flutter speed) response characteristics are referred to herein as co/quad, randomdec, PSD, and peak-hold spectrum methods. These methods were used to measure the frequency and damping (or an inverse response amplitude proportional to the damping in the peak-hold spectrum case) in the predominant or critical vibration modes. By suitably plotting and extrapolating the subcritical damping in the vibration mode or modes of interest, the flutter point can usually be established. With each method, it was assumed that the response can be approximated by that of a single-degree-of-freedom system. The response data consisted of an accelerometer on the model under either a forced excitation or the random excitation from the tunnel turbulence. All of these methods can be used on-line, that is, used to translate the response time history samples into quantitative information for the test engineer while the test is in progress.

Briefly, the co/quad method measures the in-phase and out-of-phase components of the forced response generated by the sinusoidal frequency sweep technique. The randomdec method, a relatively new method described in reference 3, makes use of ensemble averaging of transient response to random excitation. The PSD method is a well-known procedure for the analysis of random response data. It is obtained directly from an ensemble average of the square of the magnitude of the Fourier transform of a number of segments of the time history. In the peak-hold spectrum method, Fourier components of a number of time history segments are determined and the envelope of the peak values of these components is obtained as a function of frequency.

DESCRIPTION AND IMPLEMENTATION

Co/quad Method

The co/quad method involved measuring the forced response of a model to an input force such as that generated by a trailing-edge control surface as illustrated schematically in figure 1. If a transfer function relating the response to the input force is determined as a function of frequency, then the damping in each mode can be obtained. For the model applications presented herein, the excitation force was provided by oscillating an aerodynamic control surface, and the model dynamic response $\ddot{h}$ was measured with an accelerometer. Since the measured actuator phase lag and amplitude variation over the frequency range of interest was small and the aerodynamic phase lags of the control surface were assumed to be small, the control surface actuator command signal δ_c was used as a measure of the excitation force. Cross spectrum between the control surface command signal and the model dynamic response was determined with a Spectral Dynamics SD109B co/quad analyzer. This analyzer presents two outputs in terms of in-phase (called co for coincident) and out-of-phase (called quad for quadrature) components between signals. Several means of calculating the damping are available directly from a co and quad type of presentation. As indicated in figure 1, the damping of a mode was estimated from the out-of-phase component by the frequencies labeled f_A and f_B. These are the frequencies at the half-power points and the structural damping g can be expressed in terms of these frequencies (fig. 1).

Randomdec Method

To obtain a randomdec signature, one simply collects a number of segments of the random response signal, each segment having the same initial amplitude, and ensemble averages them. If the system is linear and the excitation random, the ensemble average converges to the transient response of the system due to the selected set of initial conditions.

The implementation of randomdec as used in this paper is shown schematically in figure 2. The response time history shown in figure 2 contains many modes and is normally recorded on analog tape. For the on-line randomdec process, a band-pass analog filter was used for mode isolation and noise reduction. The starting point of each ensemble member was selected with the gating circuit (a standard laboratory oscilloscope triggering circuit was used). A Technical Measurement Corporation 400C computer of average transients was used for ensemble averaging. As the signature develops, it is monitored on an oscilloscope. An electronic counter records the number of segments averaged and a X-Y plotter provides a hard copy of the final signature. Structural damping ratio may be determined directly as indicated on figure 2.

With the implementation as described (fig. 2), the different time segments were averaged sequentially. That is, the computer processed all the results for one time segment before beginning to collect and average data for the next segment. Also, in the implementation as described, the averaging process for each time segment was obtained by taking only segments which cross the selected trigger level with a positive slope. Thus, the randomdec signature represents the system transient response due to an initial amplitude and velocity.

PSD and Peak-Hold Spectrum Methods

The PSD and the peak-hold spectrum methods were implemented as shown in figure 3. Both methods were implemented using a Spectral Dynamics SD330A Spectrascope. This analyzer employs time compression techniques to achieve minimum analysis time for the frequency-tuned band-pass filter to convert the input signal from the time domain to the frequency domain. Following compression, the input signal is frequency analyzed using 250 synthesized filter locations that are tuned by a built-in sweep generator. With operator-selected modes of operation, this analyzer is highly flexible. When the averaging mode of operation is selected, the average spectrum characteristics of the random signal $\ddot{h}$ are obtained. The averager examines successive ensembles of spectrum functions and computes the averaged sum over a predetermined length of time. Shown on the left of figure 3 is a typical PSD obtained from the model dynamic response $\ddot{h}$. The resulting signature has a peak for each structural mode and, for well-separated peaks, the damping ratio may be obtained. As indicated in figure 3, the structural damping is equal to the frequency bandwidth, taken at the half-power point, and divided by the mode frequency.

An additional mode of operation of the Spectrascope allows for detection and storage of the peak values for each of 250 frequency windows. In this mode of operation, an ensemble spectrum composed of 250 frequency windows is obtained. Upon receipt of each subsequent spectrum, peak filter response at each location is updated in a positive direction. That is, only an increase in value causes an update to the new higher value. On the right of figure 3, a typical peak-hold spectrum is shown. With this method the damping parameter is not obtained. However, the reciprocal of the peak spectrum amplitude $1/P$ is proportional to the damping ratio and is used as a measure of system stability. The peak-hold method was applied using two forms of excitation, model response to tunnel turbulence and model response to sinusoidal force.

APPLICATIONS TO WIND-TUNNEL MODEL TESTING

The four subcritical response methods were applied to flutter test data of a delta-wing research model. Further application of the co/quad and randomdec methods were made using a B-52 flutter suppression model. Some results and comparisons are presented in figures 4 to 7.

Delta-Wing Flutter Model

A photograph of the delta-wing model is shown in figure 4. The trailing-edge control surface was used to provide the forced excitation. A detailed description of this wing is given in reference 4. The flutter motion of this model involves primarily the second natural vibration mode coupled with some primary bending.

The subcritical flutter characteristics of this model in the TDT at a Mach number of 0.90 is presented in figure 5. Two sets of the model data are shown. Figure 5(a) presents the variation of structural damping coefficient of the flutter mode with dynamic pressure. The damping results obtained with the co/quad, randomdec, and PSD methods are indicated with the open symbols. The model fluttered at a dynamic pressure of 5.89 kPa (123 lbf/ft^2) as indicated with the closed symbol. The solid line in the figure is faired through the randomdec data which, of the three methods shown, appears to give the most consistent forecast of the flutter point.

As a word of caution, it should be noted that frequency sweep methods, when used close to a flutter condition, may lead to dangerously large amplitude response as the forcing frequency sweeps through the flutter mode frequency.

A plot of the inverse amplitude of the peak spectrum (used as the stability criteria) is presented in figure 5(b) as a function of dynamic pressure. Shown are results from forced excitation (same excitation system as used in co/quad method) and results from random excitation (model response to tunnel turbulence). The best results were obtained with the forced excitation (faired data) while the response-only data showed some scatter. Although experience is limited in the use of this method, it is included since it appears promising as a flutter indicator.

Further illustration of the type of data generated with the use of the four subcritical methods is presented in figure 6. Shown are the data plots from which the damping levels presented in figure 5 were obtained. The wind-tunnel conditions were the same for each method (Mach number $M = 0.90$; dynamic pressure $q = 5.42$ kPa (113 lbf/ft^2)). In the implementation of the co/quad method, a 3.33-minute logarithmic sweep from 5 to 25 Hz was used. A damping level of 0.037 at a frequency of 10.8 Hz is indicated. Approximately 40 seconds of data were taken for the randomdec method giving a damping level of 0.048 for a frequency of 10.6 Hz. Forty seconds of data were used for the PSD and peak-hold spectrum methods (3.33 minutes for the peak-hold forced excitation procedure). A frequency of 10.7 Hz and a damping level of 0.037 is indicated for the PSD method. The flutter mode frequency for the peak-hold spectrum is 10.6 Hz.

B-52 Model

Further experience with the co/quad forced response method and the randomdec method were obtained using a 1/30-scale, dynamic model of a B-52. The model was equipped with fast acting control surfaces for flutter suppression studies which are described in reference 5. For this model, shown on the right of figure 7, the ailerons were used to generate the forcing function. Thus, for the co/quad method, the damping was estimated by determining the ratio of the outboard-accelerometer response to the aileron command for a frequency range of 4 to 24 Hz. The subcritical flutter characteristics of this model in the TDT are presented in figure 7. The damping results obtained with the co/quad and the randomdec methods are indicated with the open symbols. Both of these methods satisfactorily predict the measured flutter point at a dynamic pressure of 2.65 kPa (55.4 lbf/ft^2) as indicated by the closed symbol.

OBSERVATIONS

Although all four methods assumed that the response can be characterized by a single-degree-of-freedom system, they successfully provided a measure of the subcritical damping level. Each method can be implemented with commercially available instrumentation. The randomdec and PSD methods which depend on random unknown excitation, i.e., turbulence and buffeting, complement the forced sweep co/quad method. Both types of excitation inputs have their advantages. What is "noise" for co/quad is "input" for randomdec. Randomdec works best when there is large response to turbulence or buffet excitation — the region where co/quad data are least reliable. One limitation of the random excitation methods is when the flutter condition involves high frequency modes that may not be excited by random excitation such as turbulence and buffeting. In this instance the forced sweep method should be used.

Difficulties that may be encountered with the use of subcritical response methods include unwanted noise and closely spaced resonant frequencies. Methods (currently used in flight flutter testing) for eliminating or masking noise effects have been evaluated and several new techniques suggested in reference 6. Several system identification schemes were also developed in reference 6 to handle the situation where two or more frequencies of the system are close together.

As a result of experience gained during this early implementation of the randomdec method, further development of this method was undertaken. A current implementation (utilizing the new TDT data system) of the randomdec procedure is presented in reference 7. The feasibility of using the randomdec method in conjunction with a signature analysis procedure to determine the damping and frequency values of a two-mode aeroelastic system was established in reference 8. The signature analysis procedure was based on a least-squares curve fitting of the randomdec signature. The randomdec method was applied during the YF-16 flight flutter tests and for this application provided a satisfactory alternate to more costly conventional subcritical methods (ref. 9).

The reader is cautioned that for a case where a few knots increase in speed spells the difference between a well-damped response and violent flutter, subcritical damping techniques may not be applicable to predict the flutter condition. However, in this case, subcritical techniques will still be of value in correlation with subcritical analytical data and for use in parameter identification techniques to define the system mathematical model.

CONCLUDING REMARKS

Four subcritical response methods were applied to flutter test data for the same model, a cantilever delta wing. Excitation methods included forced excitation (co/quad and peak-hold spectrum) and random excitation (randomdec, PSD, and peak-hold spectrum). Further experience with the co/quad and the randomdec methods was obtained with flutter test data of a complete cable-mounted B-52 flutter model. With both flutter models, the subcritical methods tested in the paper satisfactorily predicted the measured flutter points.

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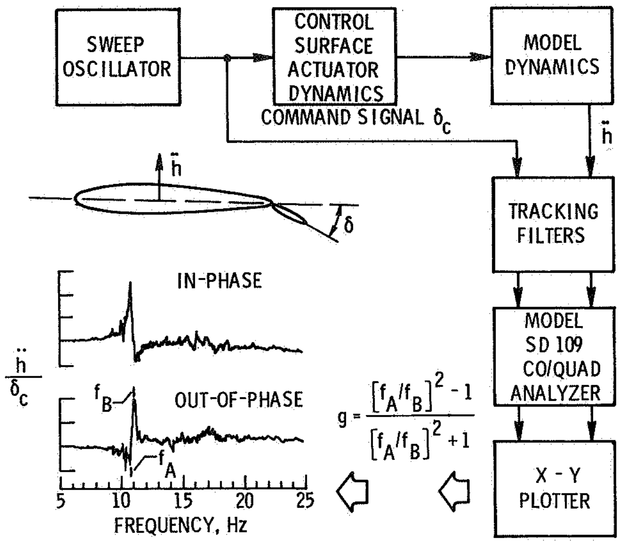


Figure 1.- Implementation of co/quad method.

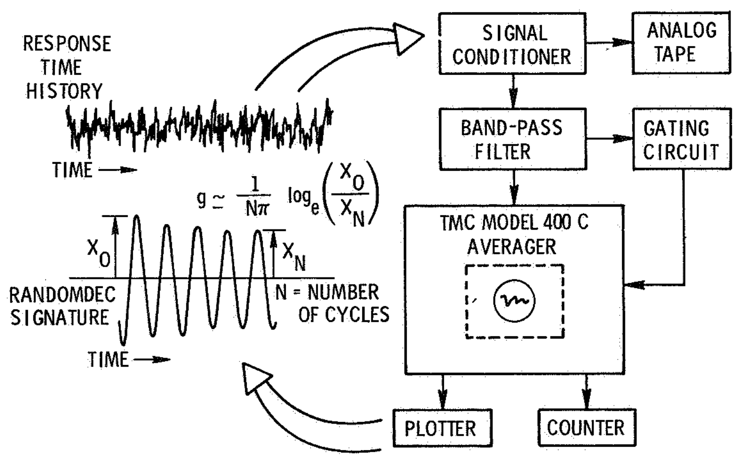


Figure 2.- Implementation of randomdec method.

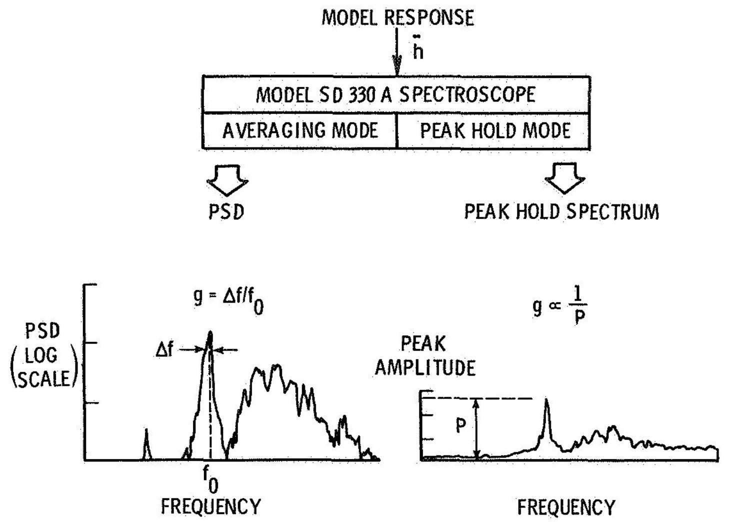


Figure 3.- Implementation of spectrum methods.

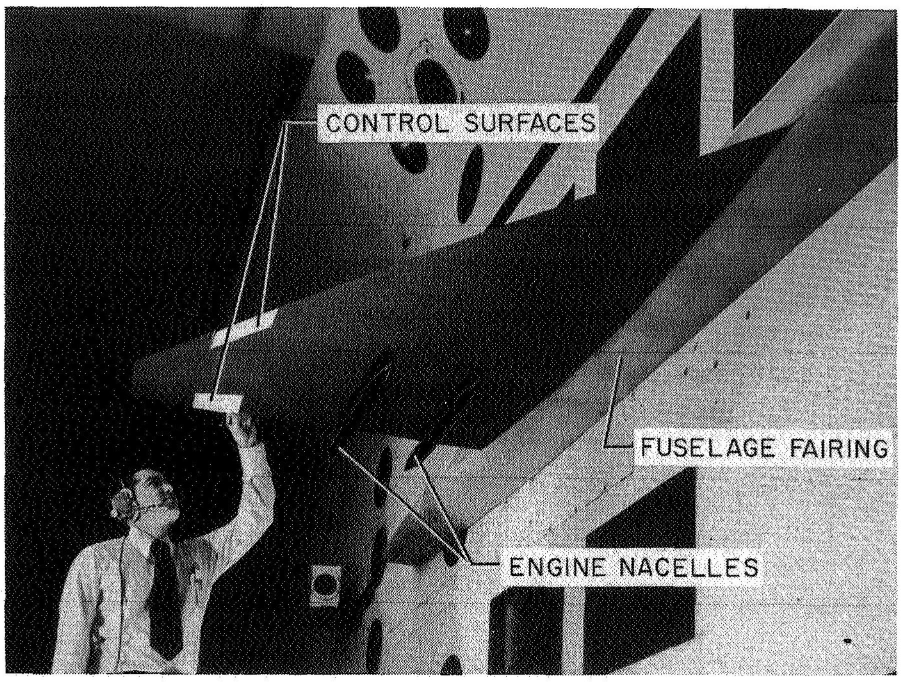
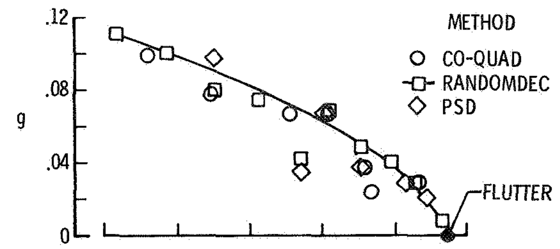
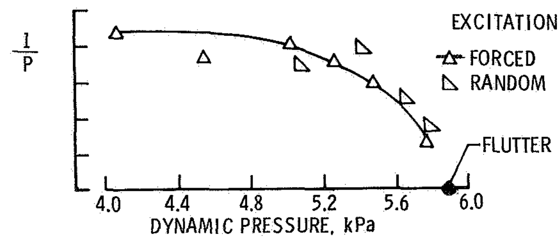


Figure 4.- Delta-wing model.

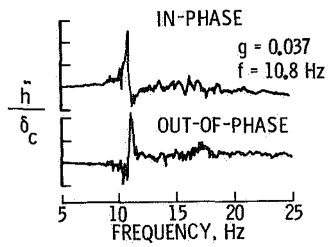


(a) Co/quad, randomdec, PSD results.

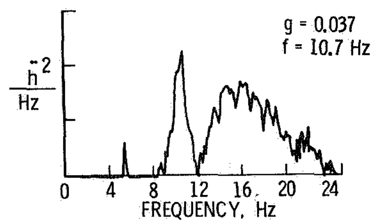


(b) Peak-hold spectrum results.

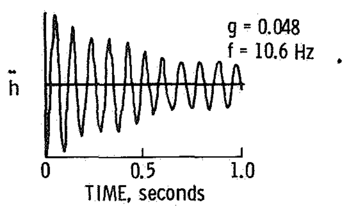
Figure 5.- Comparison of subcritical methods, delta-wing model (M = 0.90).



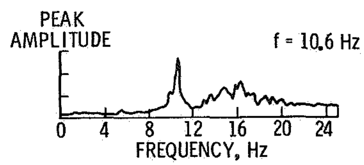
(a) Co/quad.



(c) PSD.



(b) Randomdec.



(d) Peak-hold spectrum.

Figure 6.- Illustration of subcritical methods. M = 0.90; q = 5.42 kPa (113 lbf/ft^2).

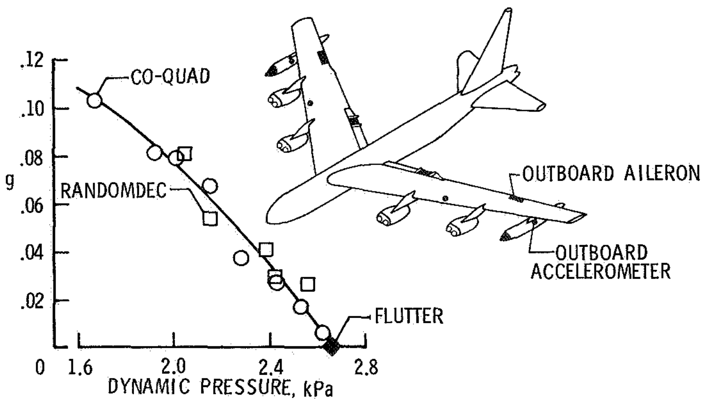


Figure 7.- Subcritical response of B-52 model.