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RESEARCH MEMORANDUM

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SUMMARY

Methods and techniques developed for the study of buffeting by use of wind-tunnel models are described. Requirements on model damping and frequency characteristics, the model support system, and the effects of wind-tunnel turbulence on buffet tests are outlined. The results are shown of a recent comparison of buffet loads measured on a research airplane with thin unswept wings and on two different models of the airplane in two different wind tunnels.

INTRODUCTION

One objective of buffet research has been to learn how to predict flight buffet loads from wind-tunnel measurements. A method for meeting this objective is described in reference 1. Bending-moment measurements were made with electrical strain gages mounted near the wing root. By combining knowledge from two different fields, those of structural beam theory and statistical analysis, an equation was derived for predicting flight bending moments from the buffet measurements on the model. Results were presented for two specific cases, and they were encouraging.

Additional experience has been gained, since the publication of reference 1, with regard to test techniques and model requirements. The primary purpose of the present paper is to discuss these factors.

SYMBOLS

c_{AV}	average chord
$C_{L_{\alpha},1}$	first-mode generalized lift-curve slope for damping component of aerodynamic force due to wing vibration
M	Mach number
V	velocity

α	angle of attack
ρ	air density
σ_M	root-mean-square value of bending moment due to buffet
$\Phi_{C_{N,1}}$	aerodynamic input parameter; power spectral density, at first-mode resonant frequency, of generalized normal-force coefficient for first-mode vibration
ω	circular frequency

Subscript:

MAX	maximum

DISCUSSION

Model Damping Requirement

One requirement for a buffet model concerns the damping of the buffet vibration. The question that arises is whether the damping is aerodynamic, structural, or some combination of the two. This question can be answered, in a given case, by studying the variation of buffet bending moment with air density as is done in figure 1. In order to facilitate comparison between different tests, the density values for a particular test have been normalized in figure 1 by dividing by the maximum density for that test. Similarly, the bending moments for a particular test have been normalized by dividing by the bending moment at the maximum density. The bending moment is herein defined as the root-mean-square value of the vibratory part of the wing-root bending moment; the static bending moment has been removed from the data.

If the damping is structural, the damping coefficient will be constant and the bending moment will be directly proportional to the exciting force and thus to the air density. This variation is shown by the dashed line in figure 1.

If the damping is aerodynamic, on the other hand, the damping coefficient and the exciting force will both be directly proportional to the density. By the methods of power spectral analysis, the root-mean-square bending moment is found to be proportional to the square root of the density. (See ref. 2.) This variation is shown by the solid line in figure 1.

Flight-test data indicate that the damping of the buffet vibration is primarily aerodynamic. (See refs. 1 and 3.) In order to illustrate this point, some flight results are plotted with circular symbols in figure 1. Such results led to the assumption of aerodynamic damping in developing the equation of reference 1 for scaling buffet bending moments from wind-tunnel models to full-scale airplanes. The equation is applicable, therefore, only when the damping is primarily aerodynamic for the model as well as for the airplane.

In order to determine whether the damping of models actually is aerodynamic, bending-moment data for three ordinary force-test models are plotted in figure 1. Model 1 is suitable for buffet loads tests because the damping is primarily aerodynamic. For models 2 and 3, on the other hand, the damping is largely structural; thus, the scaling equations of reference 1 do not apply to these models. The model data shown in figure 1 represent two extremes, and anything between these extremes is possible.

If the model is tested in a variable-density wind tunnel, a plot like figure 1 provides a means for learning, after the test is finished, whether the model was suitable for buffet loads tests. It would be better, of course, to know this before making the test. As a guide for that purpose, the following procedure is suggested. With tabulated flutter coefficients, make a rough estimate of the aerodynamic damping. In order to approximate the structural damping, measure the damping of the wing in a still-air vibration test. If the measured structural damping is as low as 1/10 of the estimated aerodynamic damping, the model will probably be satisfactory. Experience in transonic tunnels operating at atmospheric stagnation pressure has shown that solid metal wings are generally satisfactory if the wing-fuselage joints are tightly clamped. Difficulty has been experienced when insufficient joint fixity resulted in high structural damping and when tests were run at such low dynamic pressures that the aerodynamic damping was too low.

Model Frequency Requirements

Another requirement for the buffet model is that the vibratory mode shape and reduced resonant frequency be the same as those for the airplane. Of these two quantities, simulation of the resonant frequency probably is the more important. The power spectral density of the wing-root bending moment is plotted as a function of the reduced frequency in figure 2 for an airplane and for a 0.075-scale model of the airplane at the same Mach number. The vibration of the airplane wing is concentrated in the first symmetrical bending mode. This is also the case for the model; furthermore, the reduced resonant frequency for the model is about the same as that for the airplane. This comparison is interesting because the model has a standard solid-metal force-test wing. In the design of this model, there was no consideration whatever given to the resonant frequencies of the wing and yet frequency simulation of the first symmetrical bending mode was obtained. This seems to be a normal characteristic of solid-metal models of fighter-type airplanes (at least in the absence of external stores); thus, the simulation of wing resonant frequency for such airplanes presents no serious model design problems.

In the case of the tail, however, the situation is very different. The power spectral density of the bending moment at the root of a horizontal stabilizer is plotted as a function of the reduced frequency in figure 3 for an airplane and for a 0.25-scale model of the airplane. Again there was no attempt in the model design to simulate the frequency characteristics of the airplane. For the airplane, the most prominent mode is associated with fuselage torsion but this mode is hardly visible on the model, presumably because the model fuselage is more rigid than that of the airplane. Note also that, for the model, the frequencies of the various vibration modes are very different from those for the airplane. Buffet bending moments measured on this model stabilizer would probably bear little relation to those measured on the airplane. It appears then that, although force-test models are usually satisfactory for the study of wing buffet loads, the scaling of tail buffet loads will require models specially designed for that purpose.

Support System

The vibration modes of the model may be influenced by the support system. Figure 4 shows power spectrums obtained with two different types of model supports. The spectrum at the left is for a floor-mounted semispan model that was tested in the Ames 12-foot pressure tunnel. The predominant mode is first symmetrical bending as it was in the case of the airplane wing in figure 2. The spectrum on the right is for a sting-mounted full-span model. Two new modes are evident in this spectrum. The antisymmetrical bending mode is actually a wing mode but the other new mode is essentially a rigid-body rolling vibration due to the torsional flexibility of the sting support. This mode has no counterpart in flight and therefore should be eliminated before an attempt is made to calculate flight bending moments.

At present, there are three methods of eliminating the mode due to the sting support. The first method is to determine the power spectrum and then subtract the response in this mode. The second method, which is the same in principle but less costly in practice, is to remove the sting mode with an electrical filter either at the time the data are taken or later. For some combinations of model and sting supports, the natural frequency of the sting mode is so close to that of the symmetrical bending mode that these two methods are not applicable. When these methods cannot be used, the third method can be used. The sting torsion response can be canceled by placing bending-moment gages on both wings and summing the outputs electrically. The dashed line in the plot at the right of figure 4 shows a spectrum that was obtained by this method.

Note, however, that not only the sting torsion mode but also the antisymmetrical wing mode is eliminated. The elimination of this antisymmetrical mode would be undesirable in a case where this mode contributed a large part of the total wing-root bending moment. Fortunately, however, the contribution of modes higher than the first-symmetrical bending mode is small for the fighter airplanes for which flight spectra are available.

Wind-Tunnel Turbulence

Experience has shown that wind-tunnel turbulence sometimes complicates the results of buffet tests. An example is illustrated in figure 5. The ordinate for the curves in this figure is a parameter that is proportional to the root-mean-square value of the wing-root bending moment. The numerator is associated with the input force that causes the wing to buffet and the denominator with the damping force that limits the amplitude of the buffet vibration. This parameter is plotted as a function of the angle of attack for three different Mach numbers. At a Mach number of 0.4, the flat portion of the curve at low angles of attack is the response due to wind-tunnel turbulence. The point where the curve rises steeply is considered to be the buffet boundary. At Mach numbers of 0.7 and 0.85, the response to turbulence is much higher. This increase has two effects. First, the turbulence tends to obscure the buffet boundary, as is the case at a Mach number of 0.7. In addition, the bending moments are higher because of the contribution of the wind-tunnel turbulence. The manner in which the turbulence and buffet inputs add to give the total is not yet completely understood. Any correction of the measured total for the effects of turbulence depends upon the frequency distribution of this input and on the degree of correlation between the two inputs, factors that have not yet been determined. A subtraction process is indicated schematically on the curve for a Mach number of 0.85 where the buffet response is considered to be only the part labeled "buffeting." Note that the results in figure 5 that were chosen for purposes of illustration are for a particularly bad case. The effects of turbulence are not always so severe as shown here. On the other hand, it is important to realize that because the wing is a resonant system with very little damping, a small exciting force due to turbulence may cause a sizable response.

For buffet tests, the important quantity is not the overall turbulence level in the wind tunnel but rather the power spectral density of the turbulence at the resonant frequency of the wing. There is little information available on the turbulence spectra of various wind tunnels in the frequency range of interest here. Wind-tunnel turbulence has been investigated rather extensively in connection with studies of boundary-layer transition. The frequencies of interest for boundary-layer transition, however, are much higher than the buffet frequencies.

At the present time, therefore, the best way to learn whether a given tunnel is suitable for buffet tests probably is to make such a test.

The effect of turbulence on buffet measurements is not a problem for the wind tunnels only. On occasion, turbulence has interfered with buffet tests of both rocket-propelled free-flight models and airplanes. In these cases, the solution to the problem is to avoid atmospheric turbulence when making buffet tests.

Instrumentation

With regard to instrumentation, tape recordings of the wing strain-gage output have been particularly useful. Power spectrums are obtained by recording the strain-gage output on magnetic tape and later analyzing the tape records (ref. 4). Root-mean-square bending-moment values can be obtained from the tape record or they can be obtained at the time of the test by means of a thermocouple meter, which is sensitive to the mean-square value of a random electrical current. The Ames Aeronautical Laboratory has developed an instrument that measures the peak buffet loads in successive 10-second intervals over a period of several minutes. The instrument is basically a condenser charged through a diode that conducts current only during a peak that is higher than any previous peak. Thus, the charge on the condenser is a measure of the highest peak. Either peak or root-mean-square measurements can be used to study buffeting. The measured peak values in the tests at the Ames laboratory were two to four times higher than the root-mean-square values and thus were about what would be expected for a Gaussian random process.

Additional Results Bearing on Validity of Theory

The experimental technique that is discussed in this paper is based on the assumption that buffeting is essentially a Gaussian random process and that the response of the wing can be treated as the linear response of a lightly damped single-degree-of-freedom elastic system. A recent analysis of flight-test data (ref. 5) has shown that wing buffet loads do indeed exhibit the characteristics of a Gaussian random process. For a representative stall maneuver, the loads are normally distributed, and the probability that a load peak will exceed a given level is in agreement with the theoretical results obtained in reference 6. For a representative pull-up into buffeting in the shock regime, the buffet intensity appears to vary linearly with penetration beyond the buffet boundary. The loads under maneuvering conditions are therefore not stationary and are thus non-Gaussian. By means of a simple linear transformation, however, the buffet loads in maneuvering flight can be treated as a Gaussian process.

Another result of theoretical interest has been established by an analysis (unpublished) of power spectrums of wing bending moments obtained in a wind tunnel. It was found that the relationship of the maximum value of the spectrum, the band width of the spectrum at the 1/2-power points, and the integrated mean-square bending moment is the same for the wing during buffeting as for a lightly damped linear single-degree-of-freedom system. This result is important not only as verification of a basic assumption but also because it implies that the magnitude of the wing damping forces can be evaluated, at least in principle, from the power spectrum.

Comparison of Flight and Wind-Tunnel Results

Wing-root bending moments during buffet have been measured in flight on a thin, unswept wing, research airplane (X-1E). They have also been measured on two models of different sizes in two different wind tunnels. The wind-tunnel results have been scaled up to flight conditions by using the equation presented in reference 1. The values obtained are compared with the flight bending moments in figure 6. When the fact that buffeting is inherently a random process is considered, the agreement between flight and wind-tunnel results shown in this figure is regarded as satisfactory. Apparently, flight buffet loads can be estimated from wind-tunnel results, at least for simple wings. It follows from this result that wind tunnels can also be used to study the effect of airplane modifications on the buffet loads.

CONCLUDING REMARKS

A description has been given of recent developments in the application of a method for predicting flight buffet loads from wind-tunnel model measurements. Model requirements have been outlined for proper scaling of the damping characteristics and vibration frequencies. These requirements appear to be easily met for wing loads, but special care will be needed in the construction of models for the study of tail loads.

The influence of the model support system and of the turbulence level in the wind tunnel on test results has been discussed, and the instrumentation for wind-tunnel studies has been described. A comparison has been made of the wing buffet loads on a research airplane with thin unswept wings and the loads that were measured on two models of the airplane built to different scales and tested in different wind tunnels. The comparison indicates that flight wing loads can be estimated from wind-tunnel results; thus, wind tunnels could also be used to study the effects of airplane modifications on buffet loads.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., March 7, 1957.

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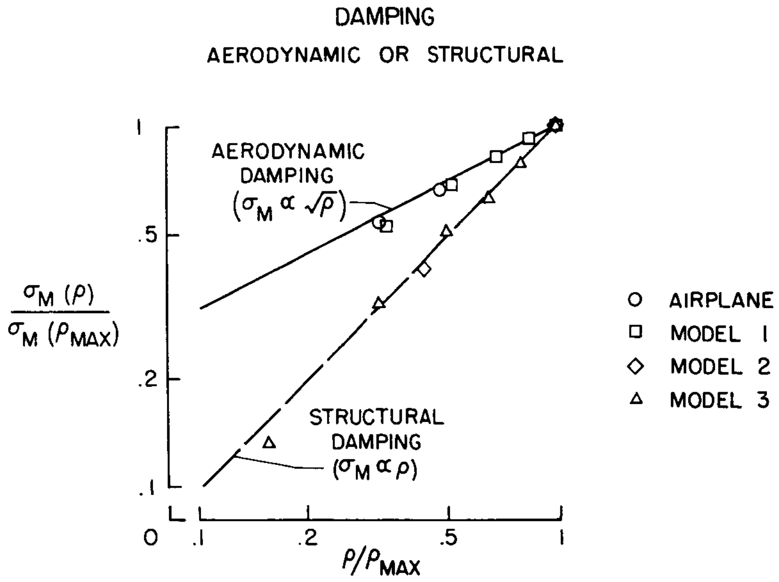

Figure 1

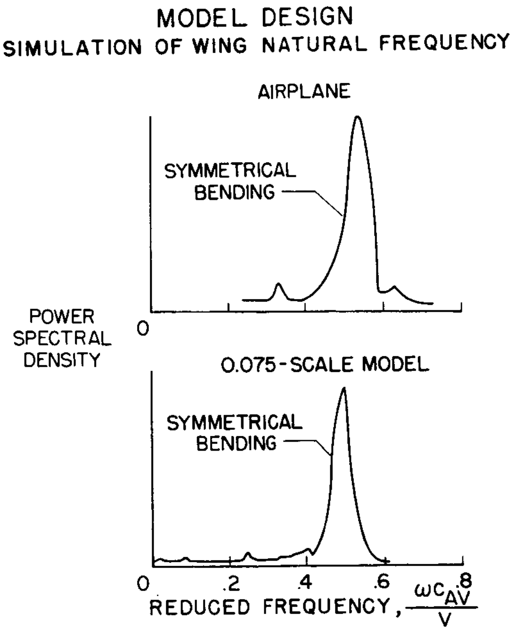

Figure 2

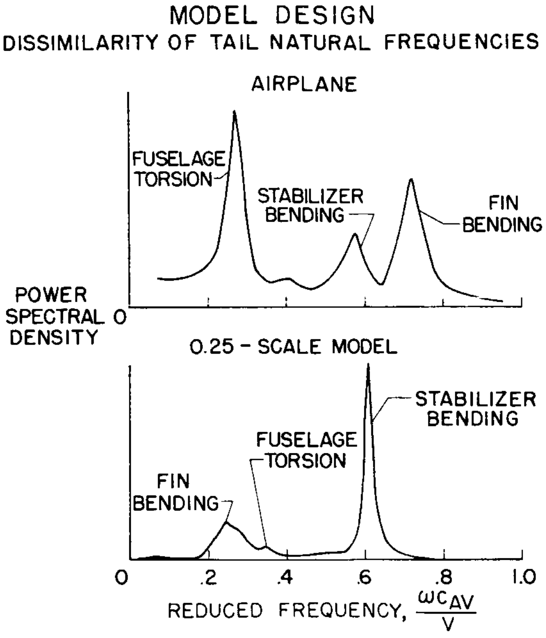

Figure 3

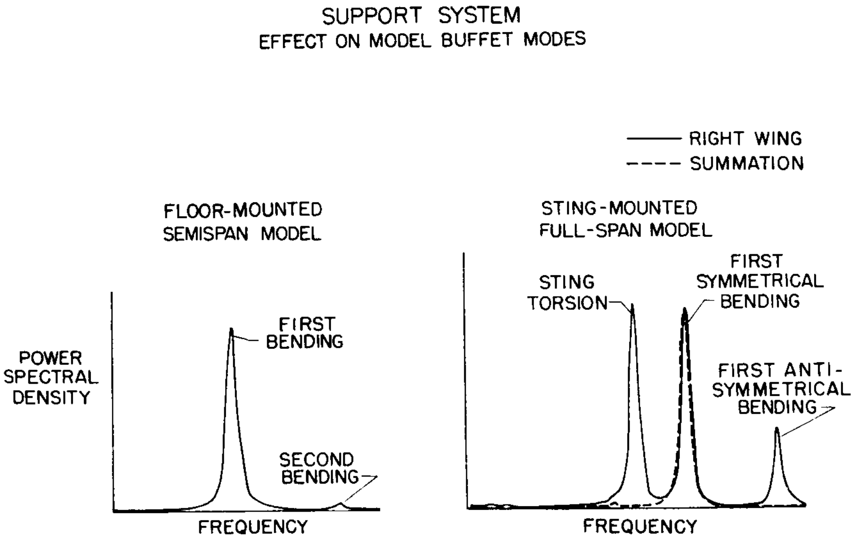

Figure 4

TURBULENCE COMPLICATES BUFFET TESTS

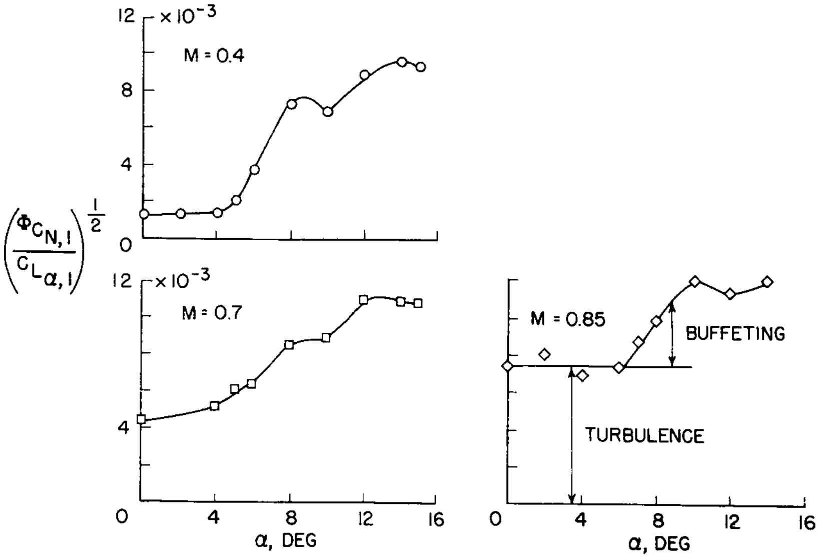

Figure 5

BUFFET LOAD
FLIGHT AND WIND-TUNNEL COMPARISON FOR X-1E

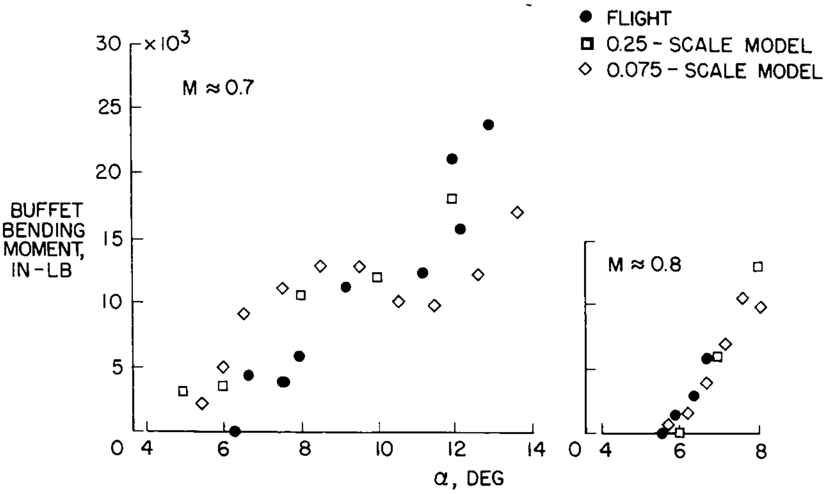

Figure 6

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