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**NASA
SPACE VEHICLE
DESIGN CRITERIA
(STRUCTURES)**

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PANEL FLUTTER

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FOREWORD

NASA experience has indicated a need for uniform criteria for the design of space vehicles. Accordingly, criteria are being developed in the following areas of technology:

Environment
Structures
Guidance and Control
Chemical Propulsion

Individual components of this work will be issued as separate monographs as soon as they are completed. A list of all published monographs in this series can be found at the end of this document.

These monographs are to be regarded as *guides* to the formulation of design requirements and specifications by NASA Centers and project offices.

This monograph was prepared under the cognizance of the Langley Research Center. The Task Manager was G. W. Jones, Jr. The author was E. H. Dowell of Princeton University. A number of other individuals assisted in developing the material and reviewing the drafts. In particular, the significant contributions made by the following are hereby acknowledged: C. P. Berry, D. L. Keeton, and D. A. Stewart of McDonnell Douglas Corporation; J. Dugundji of Massachusetts Institute of Technology; L. D. Guy of NASA Langley Research Center; M. H. Lock of The Aerospace Corporation; M. H. Shirk of U.S. Air Force Flight Dynamics Laboratory; and H. M. Voss of Boeing.

NASA plans to update this monograph periodically as appropriate. Comments and recommended changes in the technical content are invited and should be forwarded to the attention of the Structural Systems Office, Langley Research Center, Hampton, Virginia 23365.

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GUIDE TO THE USE OF THIS MONOGRAPH

The purpose of this monograph is to provide a uniform basis for design of flightworthy structure. It summarizes for use in space vehicle development the significant experience and knowledge accumulated in research, development, and operational programs to date. It can be used to improve consistency in design, efficiency of the design effort, and confidence in the structure. All monographs in this series employ the same basic format – three major sections preceded by a brief INTRODUCTION, Section 1, and complemented by a list of REFERENCES.

The STATE OF THE ART, Section 2, reviews and assesses current design practices and identifies important aspects of the present state of technology. Selected references are cited to supply supporting information. This section serves as a survey of the subject that provides background material and prepares a proper technological base for the CRITERIA and RECOMMENDED PRACTICES.

The CRITERIA, Section 3, state *what* rules, guides, or limitations must be imposed to ensure flightworthiness. The criteria can serve as a checklist for guiding a design or assessing its adequacy.

The RECOMMENDED PRACTICES, Section 4, state *how* to satisfy the criteria. Whenever possible, the best procedure is described; when this cannot be done, appropriate references are suggested. These practices, in conjunction with the criteria, provide guidance to the formulation of requirements for vehicle design and evaluation.

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PANEL FLUTTER

1. INTRODUCTION

Panel flutter is a self-excited, dynamic-aeroelastic instability of thin plate or shell-like components of a vehicle. It occurs most frequently, though not exclusively, in a supersonic flow. At subsonic speeds, the instability more often takes the form of a static divergence or aeroelastic buckling. Flutter is caused and maintained by an interaction among the aerodynamic, inertial, and elastic forces of the system. Initially, the amplitude of the motion of an unstable panel increases exponentially with time, although frequently the amplitude is limited because of nonlinearities, usually structural.

Panels are normally designed to avoid flutter. If it should occur during flight, however, then limited-amplitude and limited-duration flutter may be tolerated for some vehicles as long as the amplitude and duration do not cause: (1) structural failure of the panel or supporting structure due to fatigue, (2) functional failure of equipment attached to the structure, or (3) excessive noise levels in space vehicle compartments near the fluttering panel.

Panel flutter has occurred on a number of flight vehicles. Early experience, largely aircraft, is surveyed in reference 1. More recently, panel flutter has occurred on the X-15 during flight operation (ref. 2), during wind tunnel tests in the development program of the X-20 (refs. 3 to 5), on Titan II and III (ref. 6), and on the S-IVB (ref. 7).

The structural damage resulting from panel flutter was judged destructive on the X-15, the X-20, and the aircraft. The structure of these vehicles was stiffened to prevent panel flutter throughout the flight envelope. For the Titans and S-IVB, the flutter was judged nondestructive because it was determined that the severity and duration of the flutter would not be great enough to degrade unacceptably the structural integrity of the panel. Hence, no stiffening was added (and no weight penalty incurred) to prevent flutter of these panels.

This monograph is concerned with the prediction of panel flutter, determination of its occurrence, design for its prevention, and evaluation of its severity. Theoretical analyses recommended for the prediction of flutter stability boundaries, vibration amplitudes, and frequencies for several types of panels are described. Vibration tests and wind tunnel tests are recommended for certain panels and environmental flow conditions to provide information for design or verification of analysis. Appropriate

design margins on flutter stability boundaries are given and general criteria are presented for evaluating the severity of possible short-duration, limited-amplitude panel flutter on non-reusable vehicles.

The occurrence of flutter in a particular panel configuration depends upon the mass, damping, and stiffness of the panel; local Mach number, dynamic pressure, density; in-plane flow angularity; and, for some conditions, boundary layer profile and thickness. The parameters affecting panel stiffness which are reflected in panel natural frequencies include the panel length, thickness, material modulus, length-to-width ratio, edge conditions, curvature, orthotropy (variation in stiffness with direction), in-plane loads, transverse pressure differential across the panel, and acoustic cavity (closed-in space) beneath the panel. For some configurations geometric imperfections in the panel may be important as well.

Related NASA design criteria monographs include those on natural vibration modal analysis (ref. 8); structural vibration prediction (ref. 9); and flutter, buzz, and divergence of lifting surfaces (ref. 10).

2. STATE OF THE ART

One of the difficulties in assessing the state of the art with respect to panel flutter is the large number of parameters which may be important for any particular application. References 11 and 12 present some of the historical background of the problem. More recent surveys are those of references 13 and 14, which give bibliographies complete to the time of publication. Much of this state-of-the-art section is based on reference 15, dealing with theoretical aspects of panel flutter, and reference 16, which is concerned primarily with the experimental aspects and theoretical-experimental correlation of the problem. Two additional general references that are of great use are reference 17, which is a survey of the literature on free vibrations of plates, and reference 18, which gives simplified criteria in graphical form for most, though not all, of those parameters which may be important for panel flutter design. Little previous knowledge of the subject is assumed on the part of the reader of reference 18, and the premise is that no panel shall be permitted to experience flutter; however, reference 18 provides no method for the inclusion of boundary layer effects, for handling orthotropy and damping, or for handling pressurized or buckled panels accurately.

Some background knowledge of the physical nature of the panel-flutter problem is useful for assessing the state of the art. The flutter boundary is commonly defined as the variation with Mach number of the dynamic pressure at which the onset of panel flutter begins (refs. 19 to 22). Below the flutter boundary, random oscillations of the panel occur which have predominant frequency components near the panel's lower natural frequencies. These oscillations are the panel response to pressure fluctuations in the turbulent boundary layer (i.e., "noise"). The amplitudes of the oscillations are normally some small fraction of the panel thickness. As the flutter boundary is exceeded at some critical dynamic pressure, called the flutter dynamic pressure, q_f , the oscillation becomes nearly sinusoidal with an amplitude that tends to increase with the dynamic pressure and approaches or exceeds the plate thickness. One major limitation of the present state of the art is the lack of data covering an extensive range of dynamic pressure, q , greater than q_f particularly at supersonic speeds. However, limited data of this type have been obtained for S-IVB type panels (ref. 23).

Flutter onset is more a matter of definition than it is some point which can be determined with great precision. Using the best available techniques, the onset can be estimated within about 10 percent of the dynamic pressure (ref. 21). There has been some effort to obtain a more precise experimental determination of the flutter boundary by using admittance techniques and the concept of a linear plate impedance (ref. 24).

The behavior of panels after flutter onset is largely dominated by system nonlinearities, the most prominent of which is the nonlinear structural coupling between bending and

stretching of the plate. The plate stretches as it bends, thereby inducing a tension in the plate. Limited-amplitude, post-flutter onset oscillation results from a balance between the (unstable) linear-plate and fluid forces and this tension force, which increases the effective plate stiffness. Qualitative estimates of the flutter amplitude that account for this balance can be made by order-of-magnitude considerations (ref. 25).

Not a great deal of study has been directed toward flutter failure mechanisms; however, at least two are readily identifiable and have occurred in practice. If the flutter-induced stress level exceeds the yield stress of the plate material, then catastrophic or rapid failure occurs; on the other hand, even a relatively low stress level stemming from a sustained period of flutter can induce fatigue or long-term failure. Fatigue life can be estimated if the stress level and frequency of the oscillation are known. Current analytical methods are inadequate for predicting failure mechanisms; hence, wind tunnel or flight flutter tests must be conducted for this purpose.

Current practice is to design a panel to avoid any flutter. However, should flutter occur during developmental testing or flight operation, the designer has, on occasion, exercised the option of demonstrating that flutter is nondestructive rather than redesigning the panel. This approach is normally only attempted for short-lived, nonreusable operational vehicles.

2.1 Consideration of Flutter in Panel Design

Conventional practice in the initial structural design of panels has been to design each panel to withstand the steady and dynamic load environments it is expected to encounter with little or no consideration given to a possible panel-flutter instability. However, certain rules-of-thumb have been developed which lead to increased resistance to panel flutter without the necessity of detailed analysis or testing.

2.1.1 Flutter-Resistant Design

Minimum-gage panels are particularly flutter-prone. Conversely, panels designed to withstand large static (e.g., compressive, lateral) or dynamic (e.g., acoustic, bending) loads are apt to be so thick that flutter is not likely to occur. Because of the many possible panel configurations, general guidelines to flutter-resistant panel design have not been well documented in the literature. Nevertheless, the following guidelines for flutter-resistant design have emerged:

- Align short edges of rectangular panels parallel to the airflow, and stiffeners in stiffened panels also parallel to the flow, and where feasible, provide extra stiffening of edge supports perpendicular to the panel stiffeners.

- Avoid designs having closely spaced natural frequencies, or natural frequencies which are abnormally sensitive to any parameter.
- Where panel configurations cause flutter behavior that is sensitive to structural damping or geometrical imperfections, make design changes to eliminate this sensitivity. (Normally, such changes involve the separation of closely spaced natural frequencies.)
- Panel curvature perpendicular to the direction of airflow is beneficial, but curvature in the same direction as the flow is to be avoided.
- In order to avoid destabilizing loads, design panels for compressive loads to have the loading in the spanwise rather than streamwise direction.

2.1.2 Flutter Margins and Conservative Assumptions

Generally speaking, the ability to predict panel flutter by experimental and theoretical means has improved greatly in the past ten years. However, there are still panel configurations, loadings, and flow conditions for which the understanding of and ability to predict panel flutter are lacking. Hence, the current practice is to use conservative assumptions for panel or flow parameters to ensure an adequate panel design. In addition, a margin on flutter dynamic pressure is often specified to allow for the uncertainty in some instances as to what constitutes a conservative assumption (i.e., an assumption which leads to the prediction of a lower flutter dynamic pressure than that encountered in practice). By tradition, and also on the basis of the differences observed between the results of theory and experiment, a margin of 50 percent on flutter dynamic pressure is frequently used.

An overly conservative assumption or several moderately conservative assumptions which have a cumulative effect, may result in an excessively thick (hence, heavy) structure. The designer has several alternatives to avoid an excessive weight penalty. First, he may make basic changes in the panel design that will result in flutter resistance with no weight penalty. This is usually impossible because conventional practice is to design the basic structural configuration initially on the basis of other load conditions.

Secondly, the designer may use more accurate (but usually more complicated) methods to estimate the flutter dynamic pressure and hence reduce the uncertainty and conservatism in the determination of flutter dynamic pressure, due to overly conservative assumptions. This is frequently done and leads to a hierarchy of methods ranging from theoretical analyses to wind-tunnel model testing to flight testing of the full-scale structure.

Lastly, if it has become clear from flight test data that flutter does occur, but that it may not be damaging, the designer, rather than redesign the vehicle, may attempt to demonstrate that such flutter does not compromise the integrity of the vehicle or its mission. This demonstration requires the determination of the flutter dynamic pressure and the panel amplitude and frequency in the flutter regime (i.e., beyond the flutter boundary), so that a fatigue or failure analysis can be made to assess the damage potential of the flutter. Such a demonstration has occasionally been made on short-lived, nonreusable vehicles. The potential damage may take the form of excessive noise or excessive vibration, as well as structural fatigue. No generally agreed upon margins for these types of damage have been developed.

2.1.3 Panel Flutter Prediction in Preliminary Design

Many designers predict panel flutter boundaries in preliminary design through the use of design charts based upon theoretical and experimental data for certain panel configurations and flow conditions. In addition to reference 18, which contains such design charts, special mention should be made of references 26 to 28.

Reference 26 contains empirical and theoretical results for flat, rectangular panels under compressive loads in terms of flutter dynamic pressure (at high Mach number) versus panel length/width ratio. Equivalent length/width ratios for orthotropic panels (panels with different but constant stiffness in two directions) are given in terms of isotropic panels (panels with same stiffness in all directions). Although the limitations of these results with respect to Mach number and unknown variations in test conditions are now well appreciated, this document continues to be widely used.

Reference 27 provides additional data of the type presented in reference 26 and also presents a discussion of the accuracy and usefulness of such data.

Design charts are developed in reference 28 for rectangular, isotropic panels (again at high Mach numbers) on the verge of buckling (a critical design condition) using theoretical methods. Correlations with a limited quantity of experimental data are offered to support the theoretical results. A limitation of the theoretical methods is the necessity of specifying the structural damping of the panel. Also, caution is required in applying the results of references 18 and 26 to 28 at low supersonic-transonic Mach numbers and for pressurized or buckled panels where the simplified nondimensional correlating parameters used in these references are inadequate.

Nevertheless, results such as those given in references 18 and 26 to 28 are useful for preliminary evaluation of panel flutter if one keeps in mind the limitations of the data and approaches. These sources are frequently used to make an initial assessment of all panels in an effort to identify those which require more detailed study. If a

flutter-dynamic-pressure margin of 2 or more is indicated for some panels, these panels are often considered to pose no serious flutter problem. The number of different possible panel configurations subject to varying flow conditions usually make a comprehensive study of each configuration impossible. Hence some simple screening method such as that just described must be used to identify those panels most likely to encounter flutter so that the design effort can be most effectively expended.

2.2 Panel Flutter Analysis

It is essential to examine the structural and aerodynamic parameters systematically and assess their relative importance to, and our present ability to predict their effect on, panel flutter. Parameters in the former category characterize the mass, stiffness, and damping of the panel or, alternatively, the modal mass, natural frequencies, and damping of the structure; parameters in the latter category describe the nature of the flow (e.g., subsonic or supersonic Mach number, mass density, and dynamic pressure).

2.2.1 Structural Parameters

The importance of the structural parameters for any specific panel flutter analysis can be assessed by noting their effect on the panel's natural frequencies. The ability to determine accurately the effect of these parameters on flutter can be measured by the accuracy with which the natural frequencies of the panel can be predicted. The effect of the structural parameters on the panel's natural modes and frequencies can be determined either theoretically or experimentally. Normally, the most efficient procedure is to use theoretical methods to as great extent as possible with occasional experimental checks to verify the accuracy of the theoretical model. Typical methods of analysis used are Rayleigh-Ritz, Galerkin, finite-difference, and finite-element methods as well as exact solutions to the structural equilibrium equations (refs. 8 to 10, 17, and 29 to 32).

The following structural parameters are adequately handled by classical linear plate or shell theory: plate thickness, modulus of elasticity, length, length-to-width ratio (refs. 19, 20, 29, and 30), acoustic cavity effect (ref. 19), orthotropy (refs. 26 and 33 to 40), and, for many cases, flexural boundary conditions (refs. 17, 38, 39, and 41) and spanwise curvature (refs. 42 to 45).

For simple isotropic panels, plate thickness, modulus of elasticity, and length are usually combined with flutter dynamic pressure into a single nondimensional parameter.

$$\lambda^*_f = 24 (1 - \nu^2) q_f a^3 / Eh^3 \quad (1)$$

where ν is the Poisson's ratio of the panel material, a is the panel span, E is the material modulus of elasticity, and h is panel thickness. For such panels, flutter is characterized by λ^*_{f} exceeding some critical number determined by aerodynamic parameters. For more complex panels, λ^*_{f} is also a function of the remaining structural parameters (refs. 15 and 16).

The simplest procedure for mathematically modeling panels with elastic supports will normally be to judge the flexibility of these supports by measuring the natural frequencies (perhaps only the fundamental panel mode) and selecting the theoretical support flexibility which will best match the measured natural frequencies. Linear structural theory is also used to determine the effects of in-plane mechanical or thermal loads if they do not cause buckling. The degree of in-plane as well as out-of-plane support conditions is determined experimentally for such loads through a vibration test, the simplest procedure, although a buckling test can also be used.

Nonlinear structural theory is required to predict the natural frequencies of panels with loads which cause buckling, panels with curvature in the direction of flow (which will consequently have aerodynamic preloading due to their inherent geometry), or panels under pressurization (refs. 15, 26, and 46 to 48). This requirement is necessary because there are substantial changes with changes in stress in the natural frequencies of panels subjected to a significant pre-flutter static stress. Structures sensitive to geometric imperfections also require a nonlinear treatment (refs. 45 and 49). Nonlinear theory is always required to predict the limit-cycle amplitude and stresses of any panel that has penetrated into the flutter regime.

Because no reliable theory is available for predicting structural damping, it can only be determined from experiment, either by the decay or frequency-bandwidth method (ref. 9).

With regard to structural theory for orthotropic panels (an important consideration for many practical designs), the situation is somewhat complex. If a panel is truly orthotropic, then a well developed linear structural theory is available for determining the panel's natural modes and frequencies (refs. 26 and 32 to 40). The corresponding nonlinear theory, although basically understood (ref. 17), has not been applied to the panel flutter problem, and hence no capability exists for handling buckling, pressurization, or streamwise curvature of orthotropic plates. An orthotropic model of a panel is usually acceptable if the wavelength of the flutter mode (or distance between nodal lines) is large compared to the distance between stiffeners or other discontinuities.

If an orthotropic model is inappropriate, the only recourse is to use a more complicated model which treats the structure in terms of its individual components.

Finite-element, finite-difference, or component mode methods may be used for analyzing these more complicated models (refs. 8, 9, and 17). The principal criterion of success is the ability to compute the natural panel modes and frequencies accurately. For some stiffened panels the eccentricity of the stiffeners may be important to its flutter behavior. Although this parameter has been widely studied for its effect on buckling, reference 50 is one of the few which discuss its effect on flutter.

It is usually desirable to verify the theoretical predictions of frequencies and modes by measurement. If the theoretical model proves to be inaccurate, these measurements may sometimes replace the theoretically predicted natural frequencies and modes in the flutter analysis. (See Section 2.4.) For some panels, the number of natural modes required for an accurate flutter analysis may be too large to measure in practice. Orthotropic panels or those with large length-to-width ratio are typical.

Finally, various types of panels can be ranked approximately in order of the precision with which theory and/or tests can predict the onset and severity of their panel flutter oscillations. This is roughly the same order in which one can accurately determine the panels' natural modes and frequencies. The main difficulty lies in predicting panel stiffness, and perhaps the most difficult parameters to evaluate are (1) variable stiffness (e.g., orthotropy or determination of equivalent orthotropy of built-up panels); (2) the effective stiffness of buckled plates; (3) curvature; and (4) panel boundary support conditions particularly for variable-stiffness, loaded plates whose stiffness may be sensitive to support conditions.

An approximate ranking of various panel types in order of their increasing difficulty of prediction of panel flutter onset and severity is given in the following listing. In constructing this list we distinguish between geometric factors and types of panel loadings.

- Geometric Factors
 - (a) Flat, isotropic panels
 - (b) Flat, orthotropic panels
 - (c) Flat, stringer-stiffened panels
 - (d) Isotropic panels with spanwise curvature
 - (e) Isotropic panels with streamwise curvature

- Loadings
 - (a) In-plane loads below buckling
 - (b) Pressurization
 - (c) In-plane loads beyond buckling

Nonlinear flutter theory is required to determine the panel flutter boundary for isotropic panels with streamwise curvature or panels under pressurization or under compressive loads beyond the buckling load, and to determine such panels' natural modes and frequencies. Nonlinear flutter theory is also required for any panel geometry or loading to calculate flutter stress levels and frequencies. Nonrectangular planform shapes will offer analytical difficulty with some theoretical methods (e.g., Rayleigh-Ritz or Galerkin); however, the accuracy of the basic theory normally is not affected significantly.

2.2.2 Aerodynamic Parameters

There has been almost exclusive reliance on theoretical methods to evaluate the aerodynamic parameters and assess their effect on panel flutter. Attempts have been made to evaluate aerodynamic theory by measuring aerodynamic pressures over rigid, sinusoidally deformed surfaces and also over oscillating panels, for comparison with theory (e.g., ref. 51). These measurements, and the construction of accurate models, have proven to be quite difficult. The experiments nevertheless appear to have yielded limited verification of the aerodynamic theory or, at least, they have not invalidated it. Confidence in the theory is based largely upon airfoil experience and the indirect evidence of flutter results; the aerodynamic theory appears basically sound.

There are essentially three levels of aerodynamic theory available: (1) a quasi-steady, two-dimensional or "piston" theory appropriate to high supersonic Mach number (refs. 29 and 30); (2) an unsteady (linearized, inviscid) theory (refs. 48, 52, and 53) appropriate from zero up to high supersonic Mach number; and (3) an unsteady, shear-flow theory which accounts for the variable, mean-velocity profile due to boundary-layer effects (ref. 54). The last theory is generally most needed at transonic to low supersonic Mach numbers or when there are thick boundary layers. The first theory is the simplest but also has the smallest range of applicability and hence is the least accurate. The second and third theories offer systematic improvements and include the first or first and second as special cases.

For very high Mach numbers or relatively blunt vehicle configurations, one must use the aerodynamic variables (e.g., Mach number, etc.) appropriate to the local flow field

over the panel, which may be substantially different from the free-stream values. The important aerodynamic parameters are generally the local values of Mach number, dynamic pressure, and density, the in-plane flow angularity, and for some flow conditions the boundary-layer velocity profile and thickness.

The aerodynamic theory in any of its several forms is most reliable at high supersonic Mach number and when the boundary layer is so thin that it may be neglected. For such flow conditions, the quasi-steady, two-dimensional aerodynamic theory is quite accurate. As the Mach number decreases to 2 or less, the quasi-steady or piston-theory analysis no longer accurately predicts the aerodynamic forces on an oscillating plate for the following reasons: (1) the three-dimensionality of the flow field becomes important when $(M^2-1)^{1/2}$ times the panel aspect ratio is less than 1, and (2) the unsteadiness of the flow field gives rise to significant phase shifts between aerodynamic force and panel deformation, which can be accurately described only by a fully unsteady theory. Such phase shifts may give rise to negative aerodynamic damping in a given panel mode, which in turn leads to an instability in that mode. This so-called single-degree-of-freedom instability, which usually only occurs for $M < \sqrt{2}$, is more sensitive to various parameters than the flutter which occurs at a higher Mach number.

In particular, structural damping or boundary layer effects tend to provide positive damping to offset or diminish the negative aerodynamic damping and may result in substantial increases in the dynamic pressure at which flutter occurs. For high-Mach-number, coalescent flutter (typically a coupling of two panel modes by the in-phase aerodynamic forces leading to a merging or coalescing of two panel modal frequencies), these parameters are much less important. Some authors (refs. 55 and 56) have suggested that quasi-steady, two-dimensional theory may be used for $M \geq 1.6$ for all length-to-width-ratios, a/b , and for $M \geq 1.3$ if $a/b \geq 2$. These conclusions were based on analytical and experimental results for panels with all edges restrained.

As for boundary layer effects, recent theoretical advances (ref. 54) show considerable promise and give results in reasonable agreement with the best available experimental data (refs. 21 and 22). Because of the newness of this complex theory, it has not been used extensively.

When "piston theory" or quasi-steady, two-dimensional theory is applicable, the Mach number may be incorporated into a non-dimensional flutter parameter, $\lambda \equiv \lambda_f^*/M$ or $\lambda \equiv \lambda_f^*/(M^2-1)^{1/2}$ (see refs. 15 and 16 and Section 2.2.2.1).

2.2.3 Assessment of Panel Flutter Theory

In summary, linear flutter theory is useful and may be employed with confidence for determining the flutter stability boundary for unbuckled, unpressurized panels which

undergo rapidly destructive flutter and which have no streamwise curvature or significant boundary layer effects. This assessment applies if the structural theory that is used adequately describes the natural modes and frequencies of the panel. Linear theory for these conditions has been verified by comparison with experiment (see Section 2.4).

Nonlinear flutter theory has been developed to the extent that it is now practical to use to account for the parameters of buckling, pressurization, and streamwise curvature. This also has been verified by comparison with experiment although such comparisons are less extensive than those available for the verification of linear theory. The nonlinear theory may also be used to determine flutter amplitudes, stresses, and frequencies from which the severity of the flutter oscillation may be evaluated (e.g., prediction of fatigue life). Unfortunately, no systematic experimental data are available to assess the quantitative validity of the theory in this regard. Available experimental data are only adequate for qualitative comparisons of results and to that limited extent show agreement with theory.

There are a number of different mathematical techniques available for use in flutter analysis. Among these are modal analyses (Galerkin or Rayleigh-Ritz), finite-difference, finite-element, and Laplace transform methods and also so-called "exact solutions" which utilize the method of separation of variables and the classical exponential-factor method for solving ordinary differential equations with constant coefficients. All of these methods have been employed successfully for linear flutter analysis using "piston-theory" aerodynamics. Modal and Laplace transform methods have been used with the full linearized potential-flow aerodynamic theory and, in principle, the finite-difference and finite-element methods could be used as well, though to date they have not. Only the modal method has been used with the boundary-layer aerodynamic theory. Also, only the modal method has been used with a nonlinear structural theory, although, again, the finite-difference and finite-element methods could also be used.

The linear panel-flutter problem is usually treated by determining the complex eigenvalues (i.e., complex frequencies whose negative imaginary parts indicate flutter) as a function of dynamic pressure. For nonlinear flutter analyses, time histories of the limited amplitude motion are normally calculated. Reference 15 discusses the advantages and disadvantages of these mathematical methods in greater detail.

Aerodynamic theory is generally accurate, with the possible exception of accounting for boundary layer effects. Recent advances in the aerodynamic theory to account for boundary layer effects suggest that this may soon be in hand; however, verification of the theory by additional comparisons with experimental data is still needed. At present, the use of experimental flutter data is the most accurate means of predicting

or assessing boundary layer effects. In terms of increasing complexity, high-Mach-number flows are the simplest, low supersonic-transonic flows are more difficult, and flows with significant boundary layer effects (usually in the transonic regime) are the most difficult of all to handle theoretically.

Few mathematical methods for determining the aerodynamic pressures on a fluttering panel are available. An analytical expression for pressure is known as "piston theory" or quasi-steady, two-dimensional theory. The "Mach Box" method and also Laplace and Fourier transform methods have been used for the linearized inviscid aerodynamic theory. Only the Fourier transform combined with a finite-difference approach has been used for boundary layer effects (see refs. 15 and 54 for details).

2.3 Panel Flutter Tests

Vibration testing of panels to determine modes and frequencies is valuable for assessing the adequacy or accuracy of the structural theory used in flutter analyses, and it is essential on new panel configurations for which no previous experience exists. Such testing frequently provides useful information for evaluating the theoretical model; that is, the test results (modes and frequencies) can be used to determine how well the stiffness of the theoretical model simulates the stiffness of the real panel.

Wind-tunnel and flight-panel flutter testing are very valuable, but unfortunately, very expensive. It may be impossible to scale all of the significant parameters in a given wind tunnel facility if a panel design is substantially affected by a large number of parameters. Hence, partially scaled tests may be necessary, with theory used to assess the effect of the unscaled parameters.

2.3.1 Wind-Tunnel Panel-Flutter Testing

Wind-tunnel flutter testing is essential to evaluate boundary layer effects and to determine amplitudes, stresses, and frequency of the flutter oscillation. High-Mach-number flows are the most difficult to simulate properly because of the high temperatures and low dynamic pressures that accompany such flows in most wind tunnels. Early flutter experiments (pre-1963) lacked adequate control or failed to measure all important parameters to be simulated. Even today great care must be exercised in order to perform meaningful tests. Because full-scale panels can frequently be mounted in a wind tunnel and because panel flutter frequently does not result in major structural failure, there has been a tendency to make greater use of wind tunnel tests of flight hardware panels as proof tests rather than to use flight tests for this purpose.

The success of a wind-tunnel flutter test is largely determined before the test specimen

is placed in the tunnel. The first step, and often the most difficult, is the construction of the panel models and their boundary support without inducing significant prestresses. Experience has shown that bench vibration tests to determine panel natural frequencies and modes are excellent indicators of the quality of panel construction and support simulation. Conventional practice is to use acoustic excitation for vibration tests and to measure structural responses with strain gages and capacitance or inductance-deflection transducers.

Normally, the next step is to determine the sensitivity of the model to environmental factors, particularly static pressure loadings and thermal stresses due to a temperature differential between the model and its support. Changes in material modulus of elasticity at very high temperatures may also be significant. These effects may require considerable effort to control and measure in the wind tunnel. Hence, the sensitivity of the panel to these factors is usually determined early in the experimental program by bench vibration tests prior to wind tunnel test.

Another concern may be the dynamics of the air in an enclosed cavity beneath the plate (acoustic cavity). However, available theory may be used to establish a cavity size which will ensure a valid test simulation (refs. 19 and 57).

Next, an appropriate wind tunnel is chosen. In practice, the choice is often rather limited. A wind tunnel with the appropriate Mach number range (usually supersonic), of size sufficient to avoid aerodynamic wall interference on the panel, with adequate dynamic pressure range and with good control over tunnel temperature is desired.

Two techniques have been used for mounting the panel in the wind tunnel: (1) wall mount; and (2) splitter plate. Generally, the former is more desirable because of easier access to the model, though its use may be impractical in some tunnels.

Instrumentation is chosen so that the temperature of the panel model and support, pressure differential across the model, and plate deflection, strain, and frequency can be measured (e.g., thermocouples, pressure transducers, strain gages, and capacitance or inductance-deflection transducers). Lightweight, if possible noncontacting, instrumentation is used which will not alter the dynamic characteristics of the plate nor disturb the aerodynamic flow.

Once the model is installed in the tunnel, the test is then normally carried out by increasing dynamic pressure while holding a fixed Mach number. Other experimental techniques have been employed, however. Some experimenters (ref. 58) have varied the Mach number while holding the stagnation pressure constant. Others (ref. 59) have penetrated the flutter regime at constant stagnation pressure by heating the panel to induce compressive thermal stresses which decrease the plate stiffness. In the latter

investigations, blowdown wind tunnels were employed. Changing stagnation pressure in precise steps in these tunnels is impractical. Although the use of a blowdown tunnel is feasible, it is difficult to determine and control the plate environment, particularly with regard to thermal stresses and static pressure loading.

When extrapolating from existing data to predict flutter on new panel designs, or when planning an experimental program, it is important to consider the appropriate scaling laws. Because it is frequently possible to test a geometrically full-scale panel in a wind tunnel, there is sometimes an unfortunate and unfounded belief that complete full-scale simulation has been achieved. This is rarely the case. Usually thermal stresses, pressurization loads, flow density, boundary layer, and/or other parameters can not all be correctly scaled. Hence, one must rely upon theory to assess the effects of some of these variables or sacrifice the full-scale geometry to help scale other variables correctly. A valuable general discussion of these problems which is applicable to panel flutter is given in reference 60. If the effect of some parameter is thought to be well understood and accurately predictable by theory, it has proven to be wise to sacrifice proper scaling of that parameter in a test, if necessary, to obtain a more nearly true scaling for some other parameter which is not as well understood. References 16 and 19 to 22 should be consulted for detailed discussions of testing techniques.

2.3.2 Flight Flutter Testing

Relatively few flight tests have been made solely for panel flutter. Generally, panels have been instrumented with strain gages or accelerometers to check for panel vibration response whether due to flutter or other causes. The difficulties of flight test beyond those of wind-tunnel test are largely those of data retrieval from a remote source and the associated telemetry problems (ref. 9). No adequate documentation of flight-test technique is available in the open literature; however, discussion of flight test results are available in references 61 to 63 for the X-15, S-IVB, and Atlas Centaur panels. The pre-flight test preparation is substantially the same as that for pre-wind tunnel test. It should be pointed out that flight flutter tests can only determine whether flutter occurs within the flight envelope but cannot demonstrate that the desired flutter margin has been achieved.

2.4 Correlation of Analytical and Test Results

Comparisons of results obtained from theoretical analyses with results from flutter tests for various panels help to demonstrate the capabilities and limitations of both theory and tests and give insight into the confidence with which present state-of-the-art techniques can determine panel-flutter boundaries and the nature of panel flutter. Reference 16 presents extensive correlation between theory and experiment for certain typical classes of panel geometries and loading conditions. These are listed and the

results summarized in the following paragraphs. Also summarized are additional comparisons for buckled plates (refs. 64 and 65), for cylindrical shells (ref. 66), conical shells (ref. 67), orthotropic panels (ref. 39), and boundary layer effects (ref. 54).

Flat Plates. In general, linear structural theory coupled with an aerodynamic theory chosen to fit the Mach number range and including cavity effects, where applicable, agrees well with experiment in the determination of the flutter boundary (refs. 19, 21, 22, and 56). A possible exception is the effect of a fluid boundary layer, although limited experimental-theoretical correlations are encouraging (ref. 54).

Flat Plates Under Static Pressure Loads. A flat plate exposed to a transverse pressure load undergoes a static deformation in its middle surface, causing membrane stresses and associated stretching which induce middle surface curvature and a change in natural frequencies. These changes can be determined by nonlinear structural theory. Reasonable agreement between theory and experiment, both for natural frequencies and prediction of the flutter boundary, has been obtained by assuming zero in-plane edge restraint, which is probably typical for flat panels of practical construction (ref. 41).

Flat Plates Under Compressive In-Plane Loads. In general, reasonable agreement between theory and experiment for the flutter boundary has been obtained by at least two methods. In the first, nonlinear structural theory (nonlinear stiffness) is used with quasi-steady aerodynamic theory appropriate for the high Mach number of the tests and the assumption of values of in-plane edge restraint inferred from the measured static Euler buckling load (ref. 41). In the second method, a linear-plate structural theory is combined with quasi-steady aerodynamic theory and an appropriate model of structural damping (ref. 20, 64, and 65). See references 20 and 68 for a discussion of pressurized, buckled plates. It should be mentioned that the available comparisons between theory and experiment apply to a limited range of panel geometries and types.

Orthotropic Panels. The comparisons of theory and experiment shown in reference 39 are typical of much recent work on orthotropic panels. In general, satisfactory agreement between theory and experiment appears feasible, provided careful attention is paid to items such as panel boundary conditions and determination of natural modes and frequencies. The boundary conditions are important because many practical orthotropic panels have significant support flexibility along edges perpendicular to the direction of largest stiffness. Accurate mode shapes and frequencies for complicated built-up panels typical of orthotropic panels must often be determined by careful experimental measurements (ref. 5) to obtain sufficient accuracy for panel flutter analysis that correlates well with flutter test results. In more recent work on stressed orthotropic plates (ref. 33), it has been found that flutter theory and experiment are not in satisfactory agreement, and it has been suggested that structural damping should

be included in the analysis to resolve the discrepancy. It has been determined that, generally, the direction of maximum stiffness should be aligned with the direction of airflow to obtain the largest flutter dynamic pressure.

Curved Plates. For the limited data available for which comparisons have been made (curvature in the flow direction) there are several quantitative discrepancies between theory and experiment (refs. 25 and 69); however, the qualitative (trend) shapes of the flutter boundaries from theory and experiment are in reasonable agreement. It is felt that the chief sources of the discrepancies were that the very thin plates tested ($h = 0.008$ in.) were sensitive to manufacturing imperfections and possibly thermal stresses and that the in-plane edge supports had unaccounted-for flexibility that affected the curved panel.

Cylindrical and Conical Shells. The correlation between theory and experiment regarding cylindrical and conical shells presents a rather confused picture. A number of comparisons have been made using various types of aerodynamic and structural theories and, in general, the agreement of theory with experiment at low supersonic Mach number has been poor, with some theoretical values for dynamic pressure substantially higher than those obtained experimentally for the flutter boundary, while other theory yields lower values (ref. 70). At high Mach number ($M \approx 3$), theory and limited test data agree fairly well for unpressurized shells (refs. 71 to 73). It has been shown theoretically that cylindrical panels are sensitive to small imperfections on the order of the shell thickness which change the flutter characteristics of these panels in a manner which may account for some of the differences between theory and experiment for pressurized shells (ref. 45). For one recent study (ref. 66), the results indicate that linear shell theory used with quasi-steady, two-dimensional aerodynamics is satisfactory for predicting flutter onset, but nonlinear theory is required to predict accurately the flutter mode and frequency (see also ref. 74). Only quasi-steady aerodynamic theory has been used in flutter analyses to date for comparison with experiment, although a more accurate aerodynamic theory is available (refs. 75 to 77). Limited experimental flutter data have been obtained for a pressurized conical shell at high Mach number, and comparison with theory gives results similar to those for a cylindrical shell (ref. 67). Very recent experiments have suggested the importance of the fluid boundary layer in determining whether the flutter is catastrophically destructive or of a limited-amplitude, nondestructive type (ref. 78).

Systematic, unclassified experimental flutter data which may be correlated with theory do not exist for edge conditions, planform geometry, cavity effect, structural damping, geometric imperfections, angle-of-flow, multibay panels, or post-flutter stress amplitudes. Edge conditions and planform geometry effects should be adequately described theoretically if their effect on panel natural modes and frequencies can be predicted. The cavity effect is thought to be adequately handled by theory on the basis of

theoretical prediction of measured panel/cavity natural frequencies (ref. 19). If measured values of structural damping and/or geometric imperfections are used, then flutter theory is probably reliable at least for qualitative trend studies. On physical grounds, the angle-of-flow effect should be adequately handled by flutter theory (ref. 36) if an appropriate aerodynamic analysis is employed. Multibay effects are not likely to be important but the flutter theory for multibay effects (refs. 79 to 81) should be fundamentally neither more nor less reliable than for a single isolated panel. The quantitative accuracy of nonlinear flutter theory for predicting post-flutter stress amplitudes remains an open question in the absence of adequate experimental data.

3. CRITERIA

The panels of space vehicles which are exposed to a flow shall be designed to be free of flutter at all dynamic pressures up to 1.5 times the local dynamic pressure expected to be encountered at any Mach number within the normal operating flight envelope and during aborts from normal operating conditions. Flutter of limited amplitude and short duration, occurring during flight on panels of a nonreusable space vehicle, shall not necessitate redesign if it can be demonstrated that no fatigue failure of any structural panels, no functional failure of equipment, and no excessive noise levels in compartments near a fluttering panel will occur during the vehicle mission lifetime. Adequacy of the space vehicle panels with respect to these criteria shall be demonstrated by a suitable combination of analysis and tests.

3.1 Analyses and Model Tests

Analysis shall be considered adequate for predicting the onset of panel flutter as defined by dynamic-pressure flutter boundaries if: (1) the structural portion of the analysis adequately predicts the panel's natural modes and frequencies under anticipated critical environmental conditions, and (2) an aerodynamic theory appropriate to the relevant Mach number range and panel geometry is employed. Conservative assumptions shall be employed for any structural or aerodynamic parameter where precise knowledge concerning its magnitude or effect is unavailable. When flutter boundaries are determined solely or partially by wind tunnel test, as far as possible, all significant flight parameters shall be conservatively simulated by the model and the wind tunnel. If no previous experience exists for a given panel type, natural modes and frequencies under anticipated critical environmental conditions, including thermal, mechanical, and pressure loads, shall be determined by vibration tests before flutter analyses or flutter tests are undertaken.

Analyses and/or model tests shall account for the effects of at least the following factors:

- Mass, damping, and stiffness of the panel
- Local Mach number
- Local dynamic pressure
- Local density
- In-plane flow angularity
- Boundary layer profile and thickness (where applicable)

Simulation of panel stiffness shall include the effects of at least the following factors:

- Panel thickness, length, and material modulus
- Length-to-width ratio
- Edge conditions (in-plane and out-of-plane, as required)
- Curvature
- Orthotropy
- Thermally induced and mechanically applied in-plane loads
- Static pressure differential across the panel
- Acoustic cavity beneath the panel

Where previous analytical or test data exist for panels of similar structural configuration and edge support conditions in a similar environment, such data shall be acceptable in lieu of further tests.

3.2 Flight Tests

During developmental flight tests, instrumentation for detecting panel flutter shall be installed on flutter-critical panels of one or more vehicles. For panels for which a verification of ability to withstand nondestructive, limited-amplitude flutter is desired, the instrumentation shall be sufficient to determine clearance with other equipment, maximum stress amplitudes, and frequencies of vibration.

3.3 Nondestructive, Limited-Amplitude Flutter

When on a nonreusable space vehicle, flutter of limited amplitude and short duration is thought to have occurred and verification of ability to withstand the flutter is desired in lieu of redesign, the following procedure shall be utilized. Amplitudes and frequencies of suspected nondestructive, limited-amplitude flutter shall be determined by wind tunnel or flight flutter test unless it can be shown that theory can be used to adequately interpolate or extrapolate existing test data. The data thus obtained shall be utilized to establish that the limited-amplitude flutter is nondestructive in that, for each case, chosen margins exist on fatigue life, noise levels, and vibration amplitudes and frequencies of the fluttering panel.

4. RECOMMENDED PRACTICES

The design goal with respect to panel flutter should be to prevent flutter from occurring while using the lightest possible structure that will withstand the expected load and other environments. The general recommended procedure is to utilize, in initial design, good design practices for flutter-resistant panels. Because of the many possible panel configurations, however, it is difficult to provide general guidelines for flutter-resistant design. Nevertheless, some good practices have emerged. Examples are as follows:

- Short edges of rectangular panels should be aligned parallel to the airflow.
- Stiffeners should be aligned parallel to the airflow and extra stiffening of edge supports perpendicular to the panel stiffeners should be provided, if possible.
- Panel designs with closely spaced natural frequencies or whose natural frequencies are abnormally sensitive to any parameter, should be avoided.
- Serious consideration should be given to changing panel designs to eliminate flutter behavior that is sensitive to structural damping or geometric imperfections. This normally implies design changes that will separate closely spaced natural frequencies.
- Panel curvature perpendicular to the direction of the airflow, as opposed to the same direction as the flow, should be incorporated in the design.
- Spanwise rather than streamwise loading should be directed for panels under compressive loading, since loads in the streamwise direction are destabilizing.

The panel design should be checked for panel-flutter susceptibility by use of design charts, where applicable, such as those contained in references 18, 27, and 28. For these panels whose flutter margins fall below a factor of 2 on dynamic pressure, this check should be supplemented by a systematic flutter investigation (Section 4.1), utilizing an efficient combination of analysis and model tests to determine the flutter margin.

Under conditions of known sensitivity or high uncertainty relative to the state of the art, good judgment may require a systematic flutter investigation for panels having margins of 2 or larger as determined by design charts. Note that there is no assurance that use of the data of references 18, 27, and 28 will provide a conservative estimate of the possible occurrence of flutter. Hence, considerable judgment is required in assessing

the results obtained from such sources for a given panel design. If flutter is still predicted after the systematic flutter investigation, the design should be modified and the analysis and model tests of the modified design iterated until the panel-flutter behavior meets the criteria of Section 3.

4.1 Analyses and Model Tests

The first step in a systematic flutter evaluation should be to determine by analysis or test the natural modes and frequencies of the panel, including the significant effects of likely design variations of thickness, material modulus, length, length-to-width ratio, edge conditions, thermally induced and mechanically applied in-plane loads, static pressure differential, curvature, orthotropy, and acoustic cavity beneath the plate. Secondly, the panel's flutter dynamic pressure should be determined from theory using an appropriate aerodynamic model and local aerodynamic flow parameters.

If the theoretical result, using an initial choice of conservative estimates of the structural stiffness parameters (or equivalently, the panel's natural modes and frequencies) and aerodynamic parameters, indicates that flutter will exist for dynamic pressures less than 1.5 times the maximum expected dynamic pressure at any Mach number within the flight envelope, then a systematic effort should be made to improve the accuracy of the analysis by removing some of the conservative assumptions in order to establish the required flutter margin. A conservative assumption is defined as one that results in the prediction of a lower dynamic pressure for destructive flutter or a higher stress level (for a given dynamic pressure) for limited-amplitude, nondestructive flutter. Unconservative assumptions should be avoided.

If the analysis still fails to establish the required margin, then such a margin should be established by wind tunnel test, or the panel should be redesigned.

For panels with flutter margins not adequately established by design charts, the simplest type of analysis or test that will verify that the panel satisfies the design criteria should be used. Specific conservative (and simplifying) assumptions derived from references 1 to 88 are summarized in table I (Appendix) for structural parameters and in table II (Appendix) for aerodynamic parameters.

The parameters presented in tables I and II are accompanied by pertinent comments concerning their relative importance and means of evaluating their effect on flutter, recommendations for conservative, simplifying assumptions, and citations of the most valuable references containing information with respect to each parameter.

Theoretical flutter analyses should be made employing conservative assumptions for all parameters as recommended in tables I and II. References 15, 16, 29, 30, and 52

should be consulted for their general recommendations on theoretical methods and references 16 and 19 to 22 for their recommendations on experimental methods. Good judgment is required in balancing the gain in simplicity of analysis or test for a given conservative assumption versus the loss in predicted flutter margin.

Prior to model flutter tests, principal normal modes and frequencies of the panel should be determined by vibration tests. The flutter tests should be planned to simulate accurately but conservatively all structural parameters determined to be significant for panel natural modes and frequencies as well as the aerodynamic parameters, dynamic pressure, flow Mach number, and flow density (where the latter is determined to be important). Furthermore, if boundary layer effects are used to obtain the flutter margin, boundary layer profile and thickness also should be accurately but conservatively simulated.

If simulating all important parameters proves impossible, careful attention should be given to identifying and simulating those parameters for which theory is known to be inaccurate for a particular panel configuration. The simulated conditions should be at least as severe as the anticipated operating conditions. Whenever possible, a continuous-flow rather than a blowdown wind tunnel should be used to obtain better control over environmental factors such as temperature, static pressure differential, etc. For the remaining unsimulated parameters, theory should be used to interpolate or extrapolate the flutter test results.

If it is determined by wind tunnel test that flutter occurs at dynamic pressures below the required flutter margin, then the design should be altered to prevent flutter (e.g., panel thickness should be increased). The previous design process should be repeated until an adequate flutter margin is established by analyses or tests, including a substantial effort to resolve any discrepancy between test and analysis.

4.1.1 Structural Parameters

Where prior experience or the use of table I and the references cited therein do not provide a basis for judging a particular structural parameter's importance to panel flutter, the importance of the parameter should be assessed by evaluating its effect on panel natural modes and frequencies. If a parameter has a small effect on the natural modes and frequencies, then it can normally be neglected as far as flutter is concerned.

Where feasible, the accuracy of theoretical structural models used in the flutter analysis should be verified by vibration tests. Any of the standard methods of vibration and flutter analysis (refs. 8 to 10) are recommended, provided they accurately predict panel natural modes and frequencies for a given panel configuration. Recommended methods include Galerkin, Rayleigh-Ritz, finite-element, and finite-difference. When

significant differences exist between measured and theoretical panel natural frequencies, measured values should be employed in the flutter analysis to the extent possible. If structural damping is thought to be important, it should be measured for the principal natural panel modes and incorporated into the flutter analysis or the value of damping used in the analysis should be demonstrated to be smaller than in the actual structure (ref. 9).

Normally, it will be necessary to use an analysis that models panel nonlinear stiffness (refs. 15, 47, and 48), when accounting for the effects of streamwise curvature, panel buckling, pressurization, or when predicting flutter stress amplitudes to verify the nondestructiveness of flutter (Section 4.3). In-plane panel boundary supports (and hence, nonlinear stiffnesses) should be adequately simulated in flutter tests conducted to derive this information. Before wind tunnel testing, however, the degree of in-plane panel-boundary support should be verified by vibration tests of buckled panels or panels under static pressure differential.

4.1.2 Aerodynamic Parameters

An aerodynamic theory appropriate to the Mach number and panel geometry should be used in the flutter analysis. Generally, for $M > 2$, the "piston theory" or quasi-steady, two-dimensional aerodynamic theory should be used if the effective aerodynamic aspect ratio is greater than 1 (refs. 29 and 30). A conservative estimate of the effective aspect ratio is the geometric aspect ratio multiplied by $(M^2-1)^{1/2}$, e.g., for a rectangular flat plate it is $(M^2-1)^{1/2} b/a$.

For simple panels with all edges restrained, the quasi-steady, two-dimensional theory (ignoring aerodynamic damping) may be used for $M \geq 1.6$ for all length-to-width ratios (a/b), and for $M \geq 1.3$ for $a/b \geq 2$ (refs. 55 and 56). For lower Mach numbers, the full three-dimensional, unsteady, potential flow theory (refs. 47 and 49 to 53) should be used. Even this theory may be quantitatively inaccurate if boundary layer effects are significant. Initially, it should be assumed there is no flutter stabilization due to boundary layer effects; if found necessary to demonstrate an adequate flutter margin, the boundary layer effect must be verified by flutter test. Table II lists recommended conservative assumptions for the aerodynamic parameters, and references for further study.

As far as possible, local flow conditions over the panel throughout its operating flight envelope should be adequately represented in both theoretical and experimental studies. The accuracy of representation required should be determined by reviewing table II and its listed references.

It will generally be impossible to simulate simultaneously, in a given wind tunnel, Mach number, dynamic pressure, and flow density, even if the test specimen is a full-scale panel under appropriate thermal loads, pressurization, etc. (in itself a rather unlikely circumstance). Normally, the requirement on flow density may be relaxed; however, if the mismatch between wind tunnel and flight-trajectory flow density is a factor of 3 or more, theoretical calculations should be made to assess the possible importance of the mismatch (refs. 48 and 52).

4.2 Flight Tests

The selection of panels to be instrumented in the flight test should be based on the extent to which the predicted flutter margins exceed the design criteria margins. Critical panels are those whose flutter margins have been previously established to be less than 2. Under conditions of known sensitivity or high uncertainty relative to the state of the art, the instrumentation of panels with higher margins should be considered.

Critical panels should be instrumented sufficiently to measure all significant structural and aerodynamic parameters including, where necessary, panel and support temperatures, static pressure pressure differential, in-plane loading, Mach numbers, dynamic pressure, air density, and boundary layer thickness. The flight-test data obtained will permit correlation with ground data and the formulation of appropriate corrective action for flutter suppression or alleviation as required. The recommended flight test measurements are in addition to those required to detect the presence or absence of flutter. Flight tests using techniques such as those discussed in references 61 to 63 are recommended.

4.3 Nondestructive, Limited-Amplitude Flutter

If flutter is detected during the flight test of a short-lived, nonreusable space vehicle, the designer may choose to demonstrate that the flutter is nondestructive rather than redesign the panel. For the former alternative, nonlinear theory, if available, may be applied over a range of dynamic pressures (from the flutter dynamic pressure to 1.5 times the anticipated maximum dynamic pressure over the flight envelope) to estimate panel flutter amplitudes, stresses, and frequencies of oscillation. The theoretical model should include, where feasible, in-plane edge support conditions (or more generally, nonlinear structural stiffnesses) which have been verified experimentally by vibration tests, buckling tests, or static pressure loading. These flutter calculations should be verified experimentally by wind tunnel or flight tests conducted to obtain panel flutter amplitudes and resulting panel stresses of a sufficient number of points over the flight envelope to establish the validity of the theoretical results. If the theoretical model is inadequate or unavailable, the preceding information should be

determined experimentally either by wind tunnel or flight test at a sufficient number of additional points to permit the designer to ascertain that the structural integrity of the panel under limited-amplitude flutter is assured. These analyses and tests will normally be in addition to those previously conducted before the discovery of flutter during flight test.

Once the panel flutter stresses and frequencies of oscillation have been determined, fatigue life, vibration levels of nearby sensitive components, and noise levels should be determined by standard methods (refs. 9 and 82 to 84). At least one panel should be tested sufficiently to ensure that no failure due to any of the above means is possible under actual operating conditions.

Instrumentation should be sufficient to measure all significant structural and aerodynamic parameters including, where necessary, panel and support temperatures, static pressure differential, in-plane loading, Mach number, dynamic pressure, air density, and boundary layer thickness. The recommended flight test measurements are in addition to those required to determine clearance with other equipment, maximum-stress amplitudes, and vibration frequencies.

APPENDIX

IMPORTANT STRUCTURAL AND AERODYNAMIC PARAMETERS

TABLE I. -- STRUCTURAL PARAMETERS

Parameter	Comments	Recommended Conservative Assumptions	References
Panel thickness	Specified for a given panel configuration; however, it is frequently the design parameter to be determined if the dynamic pressure below which flutter shall not occur is specified. For simple isotropic panels at high Mach number, flutter dynamic pressure is approximately proportional to thickness cubed.	Use smaller thickness	All, but particularly refs. 18, 27, 28
Modulus of elasticity	For simple isotropic panels, flutter dynamic pressure will be approximately proportional to modulus	Use smaller modulus	All, but particularly refs. 18, 27, 28
Panel length	For simple isotropic panels at high Mach number, the flutter dynamic pressure will be approximately proportional to the inverse cube of length for fixed length-to-width ratio	Use larger length	All, but particularly refs. 18, 27, 28

APPENDIX

TABLE I. – STRUCTURAL PARAMETERS – Continued

Parameter	Comments	Recommended Conservative Assumptions	References
Panel length-to-width ratio	Easy to simulate experimentally and theory generally reliable. For $a/b < 0.1$, plate is effectively two-dimensional, $a/b \equiv 0$; for large a/b , $a/b > 10$, normalize dynamic pressure with b and extrapolate to higher a/b , assuming no significant changes with a	Use smaller a/b for given a or larger a/b for given b	18 to 20, 27 to 30, 52, and 56
Edge conditions	Should be assessed by natural vibration tests whenever feasible; may be particularly sensitive to some combinations of other variables (e.g., loaded or stiffened plates). In-plane as well as out-of-plane boundary conditions should be considered	Use out-of-plane boundary conditions of lesser restraint. For in-plane boundary conditions situation is somewhat more delicate; rely on theory as guide to conservative assumptions. Usually use lesser in-plane restraint	17, 38, 39, and 41
Orthotropic or stiffened plates	A basic question is whether a given plate may be considered effectively orthotropic and how stiffness constants may be determined. Orthotropicity may make estimation of support	If large angle-of-flow variations anticipated, assume direction of greater stiffness will align perpendicular to flow	3 to 5, 26, 33 to 40, 50, and 85

APPENDIX

TABLE I. -- STRUCTURAL PARAMETERS -- Continued

Parameter	Comments	Recommended Conservative Assumptions	References
Orthotropic or stiffened plates (Cont.)	conditions for panel edges perpendicular to greater stiffness extremely important. Plate also becomes more sensitive to angle of flow. For a plate with greater stiffness in flow direction, panel will usually behave like a panel with small a/b and for greater stiffness perpendicular to flow, like an equivalent isotropic plate with large a/b. Theory reliable if equivalent stiffnesses and edge conditions are known or, alternatively, if natural modes and frequencies are known. Particularly careful attention to edge support modeling required for experiments. Panels which are eccentrically stiffened frequently cannot be treated as equivalent orthotropic plates		
Pressurization	In-plane support conditions are important; measurement of natural frequencies and/or static deflection under pressure load is convenient means for assessing in-plane	For flat plate assume zero pressure; for curved plates, assume pressure acts in opposition to curvature. Quantitative	41, 47, and 68

APPENDIX

TABLE I. – STRUCTURAL PARAMETERS – Continued

Parameter	Comments	Recommended Conservative Assumptions	References
Pressurization (Cont.)	edge support. Theory (nonlinear) reliable and the loading is moderately easy to simulate experimentally. May be difficult to determine the pressure load actually present	effect will be small if static deflection under load is much less than plate thickness for flat plate or rise height for curved plate	
In-plane loads	Loads may be of thermal or mechanical origin. Whenever feasible measure natural frequencies under such loads to determine effective-in-plane edge conditions (for alternative, see Pressurization); theory used for flutter determination should accurately predict natural frequencies and buckling conditions. For some panel configurations, linear theory will predict the flutter dynamic pressure to be zero. Design changes should be made to these configurations if possible. May be difficult to determine in-plane loads actually present	Ignore spanwise in-plane loads. If streamwise loads are tensile, ignore them. If compressive, assume buckling will occur. For loads substantially below buckling load, quantitative effect will be small	15, 20, 28, 41, 47, 59, and 68. Ref. 28 contains useful preliminary design charts for varying a/b, in-plane loads, edge conditions, and structural damping at high Mach number

APPENDIX

TABLE I. – STRUCTURAL PARAMETERS – Continued

Parameter	Comments	Recommended Conservative Assumptions	References
Spanwise curvature	<p>In-plane support conditions along the streamwise edge are extremely important; for small restraint, flutter dynamic pressure increases while for nearly rigid restraint it decreases. Limiting case of complete cylindrical shell has proven sensitive to several parameters (e.g., pressurization and geometric imperfections). Theory is qualitatively reliable; experiments will usually be required. Panels may be flutter-free to small disturbances, but not if subjected to large ones</p>	<p>Quantitative effect is small if rise height is only a few panel thicknesses or less. Usually conservative to ignore curvature for typical (flexible) in-plane support conditions</p>	<p>42 to 45 and 70 to 78</p>
Streamwise curvature	<p>In-plane support conditions are important as well as static aerodynamic pre-loading prior to flutter. Theory (nonlinear) is qualitatively reliable; experiments will usually be required</p>	<p>Quantitative effect of curvature is small if rise height is only a few panel thicknesses or less. Conservative to assume larger rise height than actual, though this may not be practical</p>	<p>25, 46, and 69</p>

APPENDIX

TABLE I. – STRUCTURAL PARAMETERS – Continued

Parameter	Comments	Recommended Conservative Assumptions	References
Structural damping	Trouble is indicated if this parameter is important; configurations determined to be theoretically sensitive to structural damping will generally be sensitive to other parameters as well (e.g., boundary layer effects, pressurization, and geometrical imperfections). Damping must be determined by experiment	Assume no structural damping	9, 20, 28, 30, and 60
Odd planform geometries	Too many possibilities for specific recommendations. Consult references for some guidance	(See Comments)	9, 17 (general), 13, 14 (circular, elliptic), 86 (parallelogramic), and 87 (triangular)
Acoustic cavity	Theory very reliable in predicting effect on panel natural frequencies; hence, thought to be adequately handled by theory for flutter purposes. Simple to incorporate into modal flutter analysis	Quantitative effect small for cavity depths greater than panel length and width. Conservative to ignore cavity effect for single-degree-of-freedom flutter. Otherwise assume smaller cavity depth and use one-term acoustic model. See References	19 and 57

APPENDIX

TABLE I. – STRUCTURAL PARAMETERS – Concluded

Parameter	Comments	Recommended Conservative Assumptions	References
Multi-bay panels	Unimportant unless a large number of nearly identical panel bays; most significant in low supersonic, transonic regime	For spanwise arrays, treat as a single bay panel	79, 80 and 81
Geometric imperfections	Only important in exceptional circumstances (e.g., cylindrical shell under loads and buckled plates). If less than one plate thickness, effect of imperfections is usually small. Will be difficult to determine imperfections actually present	For a flat plate, ignore them	45 and 49
Fatigue life	Analysis must use nonlinear theory. Experiments must penetrate into flutter regime. No systematic experimental data presently available to evaluate theory, which is in rapid state of development	Underestimate nonlinear stiffness, (e.g., assume zero in-plane edge restraint for flat plates)	41, 47, 48, 82, and 84

APPENDIX

TABLE II. – AERODYNAMIC PARAMETERS

Parameter	Comments	Recommended Conservative Assumptions	References
Dynamic pressure	Essential ingredient in any theory or test; at high M, q and M may be combined into single parameter, q/M or $q/(M^2 - 1)^{1/2}$	Use larger values, though this is not usually practical	All, but particularly refs. 18, 27, and 28
Mach number	Theory reliable if boundary layer effects are negligible; must always be simulated in tests. However, for large M, q_f proportional to M	None possible	19, 21, 22, 48 and 52
Flow density	Normally not a very sensitive parameter; sometimes becomes important at transonic, low supersonic speeds or for structures with closely spaced natural frequencies. Theory reliable; difficult to simulate experimentally	Use smaller values for a given dynamic pressure	19, 21, 22, 48, and 52
Angle of flow	Important if nominal direction of flow is aligned with direction of highest panel stiffness. Theory probably reliable though little systematic experimental data for comparison and validation. May be difficult to determine angle of flow actually present	Assume nominal direction of flow is aligned with direction of lowest panel stiffness	36 and 85

APPENDIX

TABLE II. – AERODYNAMIC PARAMETERS – Concluded

Parameter	Comments	Recommended Conservative Assumptions	References
Boundary layer	Important for single-degree-of-freedom flutter at low supersonic-transonic speeds and, more generally, whenever damping forces are significant. Experiment requires careful simulation of boundary layer profile and thickness; theory under rapid development but not yet reliable for routine use. May be difficult to determine boundary layer characteristics actually present	Ignore or use thinner boundary layer	21, 22, 54, and 88

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