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STRUCTURAL DYNAMIC AND AEROELASTIC CONSIDERATIONS FOR HYPERSONIC VEHICLES

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Abstract

The special geometric, structural, and operational environment characteristics of hypersonic vehicles are discussed with particular reference to aero-space plane type configurations. A discussion of the structural dynamic and aeroelastic phenomena that must be addressed for this class of vehicles is presented. These phenomena are in the aeroservothermoelasticity technical area. Some illustrative examples of recent experimental and analytical work are given. Some examples of current research are pointed out.

Introduction

There are many structural dynamic and aeroelastic concerns that must be addressed in all aircraft designs, ranging from relatively simple general aviation configurations to complex, high performance military concepts. Of course, the degree of concern for a particular dynamic issue depends on the airplane design in question. In this paper, structural dynamic and aeroelastic considerations applicable to hypersonic vehicles will be discussed. Although much of the discussion is generic in the sense that it applies generally to hypersonic airplanes that operate within the atmosphere, the presentation does focus on aero-space plane configurations such as that illustrated by the artist's conception shown in figure 1. The authors offer no apology for this focus, but rather admit they have chosen the route of least resistance because much of their own recent work experience has been in support of the National Aero-Space Plane (NASP) Program. Furthermore, in selecting illustrative results for inclusion herein they have also chosen work with which they are personally familiar.

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Aero(servo)thermoelasticity Defined

The structural dynamic concerns for hypersonic airplanes are usually considered to be in the aerothermoelasticity technical area which is, as the name implies, the combining of thermal considerations with aeroelastic considerations. Because aerothermoelasticity is a very specialized field and perhaps not too familiar to many scientists and engineers, it will be useful to discuss the term. It has become more or less standard practice to use geometric shapes in a pictorial fashion to depict aeroelasticity related phenomena. Garrick and Cunningham[1] suggested that the tetrahedron shown in figure 2 be used to depict aerothermoelasticity. The apexes A, I, E, and H of the tetrahedron represent aerodynamic force, inertia force, elastic force, and heat (thermal forces), respectively. The various subelements of aerothermoelasticity are indicated by the edges and faces of the tetrahedron. For example, the line 1 that connects apex E with apex I represents natural vibrations which are governed by the inertia and elastic (stiffness) characteristics of a structure. The triangular plane 7 connecting the apexes A, I, and E represents dynamic aeroelasticity which is a coupling of aerodynamic, inertia, and elastic forces. Flutter is an example of such a phenomena. The triangle 7 is the Collar Triangle, named after the British scientist who was the first to use this figure to represent aeroelastic phenomena.[2] To arrive at their tetrahedron representation Garrick and Cunningham simply added a fourth apex H which expanded the Collar Triangle to a tetrahedron. The entire tetrahedron represents aerothermoelasticity.

Because aeroservoelastic (active control) methods have significant potential for improving aeroelastic performance/characteristics of a design[3], for example, increasing flutter speeds and improving ride quality, aerothermoelasticity expands to aero*servo*thermoelasticity. Because controls can be used to affect all the forces, either individually or collectively, Doggett[4] has suggested that a sphere representing controls be circumscribed about the tetrahedron, the sphere touching the tetrahedron at each apex. This pictorial representation is shown in figure 3. The sphere represents the various controls interconnections between the apexes of the tetrahedron. For example, active flutter suppression is represented by the spherical triangle that connects apexes A, E, and I.

The structural dynamic considerations of hypersonic airplanes actually fall into the aeroservothermoelastic technical discipline, which includes all of the various technical areas within the sphere. Note that the sphere rests on the plane of materials.

Operational (Flight) Environment

The flight environment of a hypersonic airplane will encompass a large portion of the Earth's atmosphere, from sea level to perhaps orbital altitude. A sketch of this arena in terms of altitude and Mach number is shown in figure 4. The larger shaded area applies to hypersonic airplanes in general. The smaller, darker shaded area is the envelope for an aero-space plane configuration. A listing of the environmental factors for a hypersonic airplane is given in figure 5. Obviously the craft operates in all speed regimes - subsonic, transonic, supersonic, and hypersonic. Because it operates at extremely high speeds within the atmosphere, aerodynamic heating will be significant. Structural temperatures will range from ambient at take off to very hot during flight. Not only will the structure be heated, but there will be significant temperature gradients present. Gradients will exist because of accelerated flight, temporal gradients, and because in unchanging flight conditions all portions of the structure will not be heated to the same temperature, spacial gradients. The elevated temperatures which degrade material moduli and the internal prestresses resulting from thermal gradients will affect structural stiffness.

The broad range of altitudes and speeds coupled with aerodynamic heating ensure that there are many structural dynamic and aeroelastic issues that must be addressed in the design of a hypersonic airplane. Some of these issues will be discussed subsequently. However, before doing that it will be useful to discuss some of the aerodynamic and structural characteristics that will make a hypersonic airplane different from a "conventional" airplane. This is done in the following section.

Aerodynamic and Structural Characteristics

Some characteristics of a hypersonic airplane that make it different from "conventional" designs are listed in figure 6. The geometry will undoubtedly be a highly blended wing-body-fin configuration. Indeed, the airframe and the engine most likely will be blended together. The structure will not only be composed of new materials but will also employ novel structural arrangements and concepts, such as actively cooled structures. Some designs may incorporate large, all-moveable wings, and trailing-edge control surfaces considerably larger than those used heretofore.

In particular, aero-space plane configurations must meet the structural and aerodynamic requirements of horizontal takeoff and landing and single-stage-to-orbit operations as well as perform efficiently at hypersonic cruise and satisfactorily during ferry operations. Such airplanes will experience very high dynamic pressures during portions of their operating envelope. Furthermore, they will likely have a very low structural weight fraction which suggests that they will be very flexible.

Structural Dynamic and Aeroelastic Areas of Concern

Presented in figure 7 is a listing of some of the dynamic and aeroelastic phenomena that must be addressed for a hypersonic airplane. For convenience this listing has been divided into two parts. On the left is a list of dynamic loads/response items; on the right is a list of aeroelasticity items. Admittedly this division is somewhat arbitrary because an item such as gust response could appear in either of the two categories. This list is not much different from the list that which would apply to just about any class of airplane. For a hypersonic airplane all of the items are likely to be significant whereas for other classes of airplanes some of the items on the list may not be very important, or, if important, there may be proven methods of solution to potential problems. For example, propellant dynamics/fuel slosh is typically not a serious problem for most airplanes, and there are accepted panel flutter criteria that can be used to ensure that panels of conventional design are free from flutter.

Some comments relative to each of the items shown in figure 7 are given in the following sections.

Dynamic Loads/Response

Vibration characteristics: The key to the understanding of the structural dynamics/aeroelastic characteristics of an airplane is the ability to accurately predict its natural vibration characteristics. Such modal data are needed because many dynamic analyses are accomplished by using modal methods of solution. This is a difficult task at best for any advanced airplane configuration, but it is made more difficult for hypersonic configurations because the effects of aerodynamic heating on structural stiffness must be taken into account. Furthermore, a hypersonic airplane may have a relatively high ratio of gross weight to empty weight because of a high fuel fraction. This may mean that the vibration characteristics may change considerably as fuel is burned. These changes in vibration characteristics during flight will significantly complicate the design of the flight control system and make the assessment of aeroelastic characteristics very difficult as compared to conventional airplanes.

Landing/taxi: Of course, landing gear loads and dynamics must be properly accounted for in all airplane designs. There are some characteristics of a hypersonic vehicle that have special significance for the landing gear system. One is that the airplane may have relatively high takeoff and landing speeds which will require special considerations to tire dynamics. Indeed, advances in the state of the art in tire design may be required to provide tires that will withstand the internal dynamic stresses that will be generated during landing and takeoff. Another is the potential for a relatively large ratio of takeoff weight to landing weight. The stiffness of a landing gear system that provides satisfactory performance for takeoff may not be acceptable for landing where a lower stiffness gear system would be required. An active control landing gear system might be an attractive solution to this problem. Such systems, however, are not fully developed and are yet to be proven in flight operations. Third, configuration geometry and attitude requirements at takeoff may require an usually long nose gear strut. Perhaps a seemingly mundane consideration, but such a long strut would require careful attention to avoid nose wheel shimmy.

Propellant dynamics/fuel slosh: Undoubtedly a hypersonic airplane will have large tankage to accommodate the volume of fuel required for the high speeds and long range. These tanks may be either integral, load carrying components of the structure, or may be bladders that are contained within the structure. For most airplanes the fuel can be considered as simply a concentrated mass. For a hypersonic airplane the "stiffness" of the fuel will have to be accounted for as well. That is, at the very least, the fuel will have to be modeled as a simple mass oscillator that is coupled to the structure. Baffles will undoubtedly be required and the dynamic loads imparted to them by the sloshing fuel will have to be accounted for in design.

Coupled dynamics - structure, control system, fuel: The frequencies of the lower structural modes, the frequencies of the flight control system, and the frequencies of the fuel sloshing in the tanks may be very close together for a hypersonic configuration. What this means is, that, during flight, the natural vibration characteristics of the airplane are significantly affected by the interactions of the structure, control system, and fuel. Vibration characteristics as used here includes both rigid body modes and elastic modes. Because the attitude of a hypersonic airplane will have to be quite closely controlled, careful attention must be paid to these dynamic couplings in the design of the flight control system.

Acoustic/noise: A hypersonic airplane would be expected to have extraordinarily large sound pressure level over portions of the configuration. High intensity noise may be generated by either the engine or the high speed aerodynamic flows. Sources of engine noise are combustion noise and exhaust noise. Aerodynamic sources are turbulent boundary layer, shock/boundary layer interactions, and turbulent flows. Engine exhaust sound intensities of 190dB appear to be possible. Although it is likely that the highest noise will come from the engine exhaust, the noise produced by shock-wave/boundary layer interactions may be only slightly less, perhaps of the order of 185dB.

Aeroelasticity

Lifting surface flutter: To a great degree there is a general lacking of flutter data for highly blended wing-body configurations that are candidates for use for hypersonic airplanes. Unsteady aerodynamics methods applicable to such configurations, although under development, are not yet ready for routine use. There are, however, some experimental data throughout the speed range for simple highly swept delta wings. From a flutter point of view, hypersonic airplanes may offer further complications because of unconventionality in the design. The all-moveable wing mentioned previously is a example of this.

Panel flutter: Although panel flutter is a concern for all airplanes that operate at supersonic Mach number, fortunately panel design criteria have been developed that, if followed, during design will ensure that panels are flutter free. Hypersonic airplanes, however, offer new challenges because panels may be at high temperatures and have significant thermal gradients. There is an insufficient data base to use to develop a reliable design criteria for such panels. Furthermore, the structural design of some panels for hypersonic vehicles may be quite different from traditional designs, nonisotropic arrangements being the rule rather than the exception. Concern is raised, therefore, as to the applicability of design criteria based on previous, traditional structures.

Control surface buzz: Control surface buzz could be a concern for a hypersonic airplane because such a configuration may employ very large aerodynamic control surfaces. Such surfaces may include full-span elevons mounted to the wing, large rudder(s) mounted to vertical fin(s), or flaps mounted to the aft end of the body. Buzz is a transonic phenomena which is associated with oscillating shocks. It occurs over a very narrow range of Mach numbers and at low angles of incidence. For a very large trailing edge control surface, careful attention must be paid in the design to ensure that sufficient rotational stiffness of the control surface about its hinge line is provided to ensure a rotational frequency high enough to preclude buzz from occurring. The stiffness of the backup structure on the main airframe will be an important contribution to the total stiffness, and its effects must be accounted for properly.

Buffeting: One can argue that the local response of the structure that would be produced by turbulent boundary layer flow is local buffeting. Because sound pressure levels of the order of 150dB may results from such flows, considerable response could result . As the present authors define the term such a response is, indeed, local buffeting. Of course, the magnitude of local buffeting loads and response are important, but structural fatigue considerations may be equally important.

The other part of buffeting is the response of some large structural component to random forces that produce low frequency, random vibrations of the component. It does not appear that component buffeting will be a major concern for a hypersonic airplane, certainly not to the extent that it is for a high performance fighter airplane, but there could be designs that are buffet prone. Buffeting could occur for a design for which the turbulent wake produced by an upstream component, say the forward fuselage, is transported downstream and impinges on a downstream component, say a vertical fin.

Gust response/ride quality: Careful attention must be paid to the gust response characteristics of hypersonic vehicles. A hypersonic airplane will be a relatively low-g airplane and is likely to be relatively flexible. The gust response characteristics may be made more complicated than it is for conventional, lower-speed designs because of the close proximity of structural, control, and fuel frequencies mentioned previously. What this means is that the gust response will contain significant elastic motion of the structure as well as rigid body motion of the airplane. For an aero-space plane configuration the gust design loads may be dictated by ferry considerations, rather than normal operation considerations. Whatever the case, the maximum gust response will most likely occur in the lower altitude range. This is fortunate because there is a lack of measurements of atmospheric gusts for long wavelengths at very high altitudes. To ensure pilot/passenger comfort a ride quality control system may be required.

Static aeroelasticity: Static aeroelastic phenomena have to be considered as well as the dynamic phenomena discussed in the preceding paragraphs. Elastic deformations of the structure produced by aerodynamic loading will affect the loading and thus change the aerodynamic stability derivatives of the airplane. These effects must be properly accounted for in the design of the airplane flight control system to ensure stable flight. These considerations are complicated by the effects of temperature and thermal gradients on the structural stiffness. In addition, static divergence of any all-moveable lifting surfaces used will have to be addressed as will potential divergence of any forwarding projecting structure such as an engine inlet lip.

Examples of Recent Results

During the NASP Technology Maturation Program some research was conducted under the Aerothermoelasticity element of the program. The name of this element more appropriately should have been aeroservothermoelasticity. A summary of the work in this area is given in ref. 5.

All-Moveable Delta-Wing Aeroelastic Studies

As mentioned previously all-moveable delta-wing configurations are candidates for use in aerospace plane applications. In concept an all-moveable wing is not any different from all-moveable horizontal tails which have been used on aircraft for many years. What is different, however, is the relative size. The all-moveable surface that might be used on a hypersonic airplane could be very large, and thus require outsized actuators and heavy backup structure to provide the needed torsional stiffness to prevent aeroelastic instabilities.

To provide insight some wind-tunnel studies were conducted using a 72°-swept delta-wing model that was mounted to a flexure which allowed variable pitch and plunge stiffness as well as variations in mass and mass unbalance.[6] The variable stiffness provision allowed simulation of actuator and fuselage attachment flexibilities. A photograph of the model is shown at the upper left in figure 8. A sketch of the model and the flexible support system is shown at the upper right. The experimental flutter boundary for the pivot point at 37.5 percent of the mean aerodynamic chord (MAC) is indicated by circle symbols at the lower left in the figure as the variation of flutter dynamic pressure with Mach number. Also shown in the figure are analytical flutter results, square symbols, that were obtained by using kernel function unsteady aerodynamics. The experimental and analytical flutter boundaries are in good agreement. One static divergence condition was obtained for the pivot at 60 percent of the MAC. The divergence results are shown at the lower right in the figure where both experimental and analytical results are presented. Again, the theoretical result is in good agreement with the experimental value.

Engine Inlet Lip Aeroelastic Analysis

Because concern had been expressed about possible aeroelastic instabilities of a scramjet engine inlet lip, an aeroelastic analysis was conducted of a generic design that is representative of those being considered for aero-space plane applications.[6] A sketch of the engine lip arrangement is shown in the sketch at the lower left in figure 9. An equivalent-plate finite-element model was used to represent the built-up structure of the full-scale design. Added mass was included to represent active cooling requirements. Aeroelastic analyses were performed using kernel function unsteady aerodynamic theory over the Mach number range from 0.6 to 2.0. Analyses were conducted using piston theory over the Mach number range from 1.2 to 2.5. Two piston theory analyses were made, one without thickness effects included and one with thickness effects included. Results of the analyses, shown in the lower right in the figure as the variation of dynamic pressure with Mach number, indicated that static divergence of the lip was the critical aeroelastic instability.

Thermal Effects on Vibration Frequencies

Conley and Spain have recently conducted some experimental and analytical studies of the effects of heating on a aluminum wing-box model that was built up with spars, ribs and curved skin panels. (Some highlights of their work are given in ref. 7.) A photograph of the test specimen that was instrumented with accelerometers to measure dynamic response and thermocouples to measure temperature distribution is shown in the photograph at the upper left in figure 10. Natural frequencies were measured while the article was heated up and while it was allowed to cool down to ambient temperature. Shown on the lower left in the figure are contours of constant temperature obtained for the hottest condition. These data were obtained by interpolating the temperature readings obtained from the array of thermocouples mounted on the structure. As these contours indicate there were significant temperature gradients.

Shown on the right in the figure is the variation of the natural frequencies for the first four natural modes as the specimen was heated up and then allowed to cool down. The experimental frequencies are indicated by the open symbols. Analytical results obtained by using an existing finite-element code that was modified to include the effects of both elevated temperature and thermal gradients on structural stiffness[8] compare reasonably well with the experimental results. These data clearly indicate that the effects of temperature gradients on the natural frequencies of a built-up structure may be quite complicated and can result in either stiffness decreases or stiffness increases.

Aerodynamic Heating Effects on Flutter

The finite-element analysis method used in the previous example was applied to a generic aerospace plane design to assess the effects of heating on flutter.[9] A sketch of the configuration studied is shown at the top in figure 11. Two structural configurations were studied. For one, the structure was assumed to be made of titanium-aluminide; for the other, the structure was assumed to be made of carbon-carbon. The temperature distributions were based on calculated radiation equilibrium temperatures.

Some effects of aerodynamic heating on structural stiffness can be assessed by examining the calculated frequencies for the titanium-aluminide and carbon-carbon models shown on the left in the figure. These data are for M=6. Three sets of frequencies are presented: the first for the cold, unheated condition; the second where only the temperature effects on material properties are considered; and the third where both the effects of property change and internal thermal stresses are included. It is interesting to note that for this case the frequencies were reduced by changes in material properties (decrease in stiffness), but were increased by thermal stress effects, (increase in stiffness). Although the natural frequencies were changed by heating effects, the mode shapes essentially remained unchanged.

Some calculated flutter results in the form of the variation of flutter dynamic pressure with Mach number are shown at the lower right in the figure. The solid circle symbols are the boundary for the cold titanium-aluminide configuration. The flutter mechanism is primarily a coupling of the second and third natural vibration modes, the fundamental wing-bending mode and a highly coupled wing-bending/second fuselage-bending mode, respectively. Generally speaking the flutter dynamic pressure was decreased by including aerodynamic heating effects on structural stiffness, the greater reduction being for the hot titanium-aluminide configuration. At M=4 the flutter dynamic pressure for the hot carbon-carbon configuration is the same as for the cold titanium-aluminide configuration. At the higher Mach numbers the flutter dynamic pressure is lower. This "dog-leg" trend that appears in the flutter boundary is probably due to a change in the flutter mechanism from the previously mentioned modal coupling to a coupling of the third and fourth natural vibration modes. The primary component of the fourth mode is wing torsion. It is not uncommon for changes in modal coupling to cause sharp changes in flutter boundaries as observed here.

Active Control of Aeroelastic Response

As indicated in the preceding discussion the flutter dynamic pressure of a generic aero-space plane configuration can be significantly reduced by aerodynamic heating effects. Because active control concepts have been shown to be effective in increasing flutter speeds and improving other types of aeroelastic response as well, some advanced aeroservoelastic analysis methods were applied to a generic configuration.[10] Two concepts were studied, flutter suppression and ride quality control (gust load alleviation). A sketch of the configuration studied is shown at the top of figure 12. At the bottom right in the figure are some flutter results in terms of the ratio of the flutter dynamic pressure q_f for a hot vehicle to the flutter dynamic pressure of the vehicle cold ($q_{f_{cold}}$) for M=2 and 4. Aerodynamic heating reduces the flutter dynamic pressure at both Mach numbers as evidenced by the tops of the cross-hatched bars being at values of the ratio less than one. For the M=2 hot vehicle predictions, a deacceleration from M=4 was assumed such that the heat loads at M=4 were used for the M=2 calculations. The tops of the shaded bars indicate the increased flutter dynamic pressures that are achieved using active controls. The top of the shaded bar for M=2 represents a sea level condition. Presented at the lower left in the figure are some ride quality results as measured by normal acceleration at the pilot's station. These results are for a cold configuration at M=4. Results for the hot configurations were similar. The sharp peaks associated with response in elastic modes of the vehicle are sharply attenuated by the use of the active ride control system.

Current Studies

Phase 2 design of the NASP vehicle is currently in progress by the three airframe and two engine contractors. The objectives of this phase of the development are to insure that all of the needed technology is in hand and to identify the design that will be developed for construction and flight tests. As a part of this phase, the government is conducting additional studies to further mature the technology and to identify and solve potential problems. A listing of areas of work pertinent to the present paper is presented in figure 13. Each of these areas has specific goals and milestones which directly support the design studies being done by the contractors. This work is being conducted by researchers at the NASA Langley Research Center (LaRC) and at the USAF Wright Laboratories (WL). The organization listed first following each entry on the figure is the one primarily responsible for the effort. It is noteworthy that most of the dynamic and aeroelasticity concerns listed in figure 7 are covered by the areas of work listed in figure 13.

The first three items listed in the figure, namely, Airframe Flutter Evaluation, Engine Flutter Evaluation, and Panel/Shell Flutter, are primarily experimental efforts that will identify fundamental mechanisms of dynamic and aeroelastic response and develop a data base of information for use in evaluating and validating computational methods. Models of the airframe, the engines and external structural panels will be designed and tested in wind tunnels to assess aeroelastic characteristics in the transonic, supersonic and hypersonic flight regimes. The next two items, Unsteady Aerodynamics and Aeroservothermoelasticity, are efforts to develop and assess the computational capabilities that are needed for aeroservothermoelastic analysis. This includes the development of CFD (computational fluid dynamics) unsteady aerodynamics codes for NASP representative geometries and for analysis at hypersonic speeds. Furthermore, an assessment of codes for predicting the thermal effects on aeroelasticity and for integrating active controls in the design will be made. The objectives of the final item in the list, Acoustics and Sonic Fatigue, are to validate means for predicting the response of external structure to high intensity, randomly varying pressure loads, and to validate means for predicting internal loads resulting for acoustic transmission.

Work in the areas indicated in figure 13 is just getting under way. It is expected to be completed by mid 1993. Although, as stated, NASP is the focus of these studies, much of the work has application to hypersonic airplanes in general. For example, unsteady aerodynamics methods developed during these studies will have application to virtually all types of configurations.

Concluding Remarks

The special geometric, structural, and operational environment characteristics of hypersonic vehicles have been discussed with particular reference to aero-space plane type configurations. These phenomena are in the aeroservothermoelasticity technical area. Some of the structural dynamic and aeroelastic phenomena that must be addressed for this class of vehicles were pointed out. It was indicated that a list of structural dynamics areas of concern for a hypersonic airplane is not much different from the corresponding list for more conventional designs. It is pointed out, however, that the high speeds, elevated temperatures, and unconventional geometries and structural designs that are characteristic of hypersonic airplanes make many of there potential problem areas considerably more complex Some illustrative examples of recent experimental and analytical work were presented. These examples ranged from wind-tunnel flutter model studies of the aeroelastic characteristics of all-moveable wings to analytical studies of the use of advanced active control methods to attenuate unwanted aeroelastic response resulting from aerodynamic heating of the structures. Some elements of current research were pointed out. Work just getting under way in the areas of airframe/engine aeroelasticity, panel flutter, unsteady aerodynamics, aeroservothermoelasticity, and acoustics/sonic fatigue was cited.

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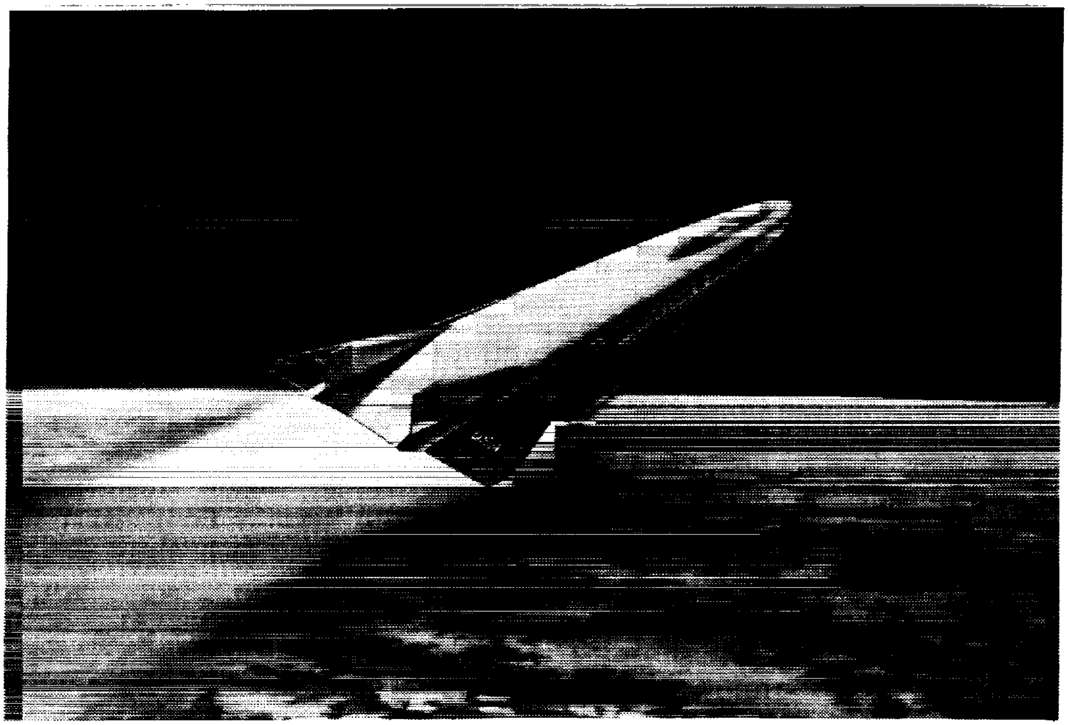
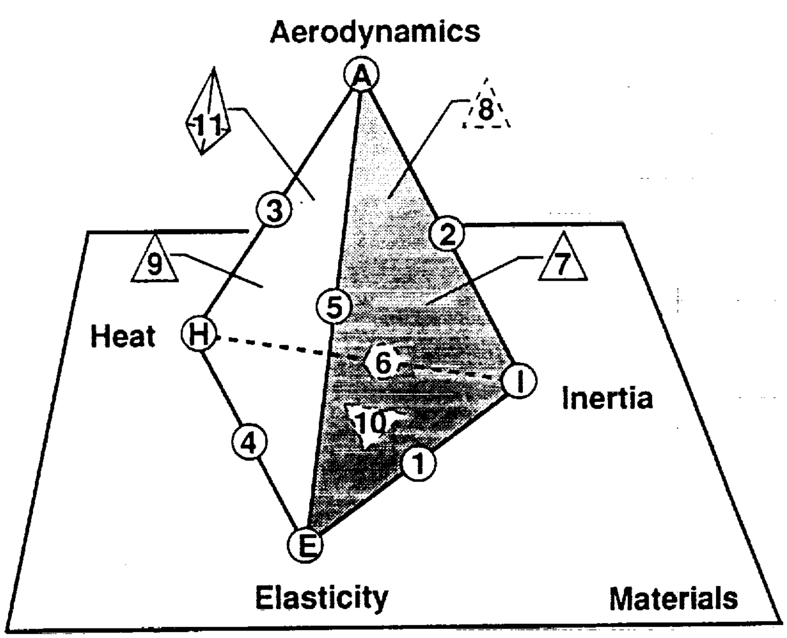
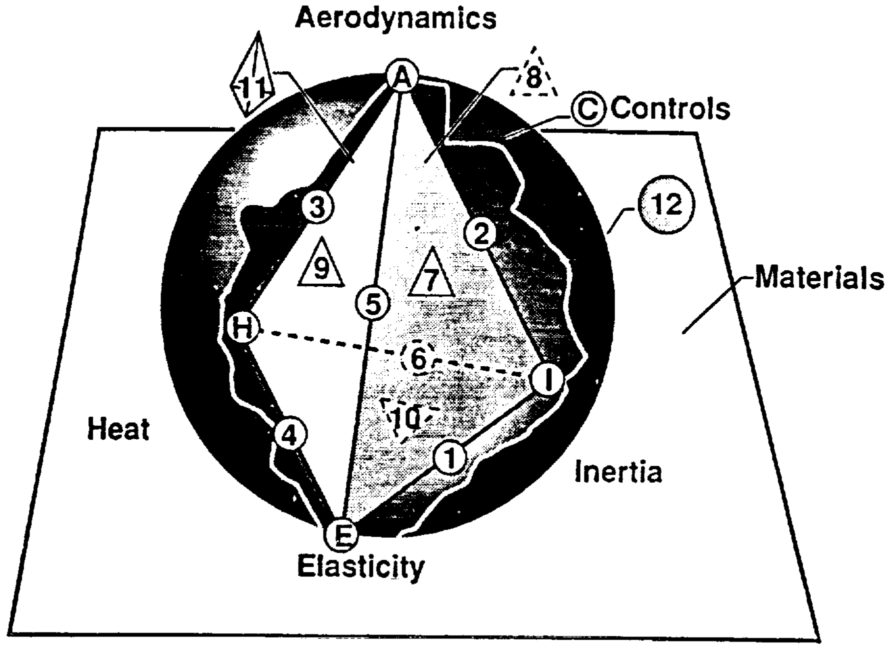


Figure 1. - Artist's conception of aero-space plane configuration.



1 Vibration
2 Stability
3 Aerothermodynamics
4 Thermoelasticity
5 Aeroelasticity, static
6 Thermal molecular processes
7 Aeroelasticity, dynamic
8 Stability and heat
9 Aerothermoelasticity, static
10 Vibration and heat
11 Aerothermoelasticity, dynamic

Figure 2.- Aerothermoelastic tetrahedron.



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10 Vibration and heat
11 Aerothermoelasticity, dynamic
12 Aeroservothermoelasticity

Figure 3. - Aeroservothermoelastic spheroid.

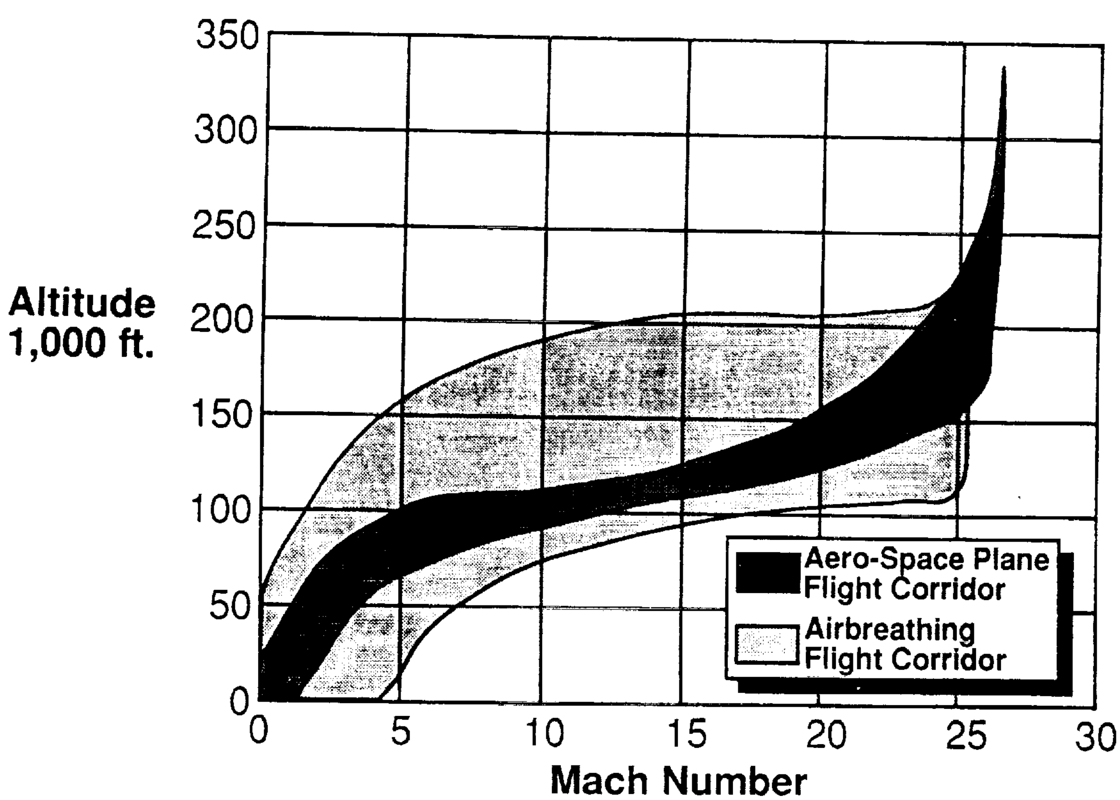

Figure 4.- Typical flight corridors.

Speed Regime
- -Subsonic
- -Transonic
- -Supersonic
- -Hypersonic

Thermal
- -Cold
- -Transient
  - -Time gradient
  - -Spacial gradient
- -Hot

Altitude
- -Sea Level
- -100,000K ft+
- -Orbit

Figure 5. - Operational environment.

Novel Geometry
- -Blended wing-body-fin
- -Integrated (blended) engine
- -All-moveable wing
- -Large control surfaces

Novel Structural Arrangements
- -New materials
- -Non-isotropic panels
- -Actively cooled structure

Aerodynamics
- -Hypersonic cruise
- -Ferry
- -Single-stage-to-orbit

Figure 6. - Aerodynamic and structural characteristics.

Dynamic Loads/Response

- -Vibration characteristics
- -Landing/taxi
- -Propellant dynamics/ fuel slosh
- -Coupled
  - -Structure
  - -Control System
  - -Fuel
- -Acoustic/noise

Aeroelasticity

- -Lifting surface flutter
- -Panel flutter
- -Control surface buzz
- -Buffeting
- -Gusts
- -Static

Figure 7. - Dynamic and aeroelastic phenomena.

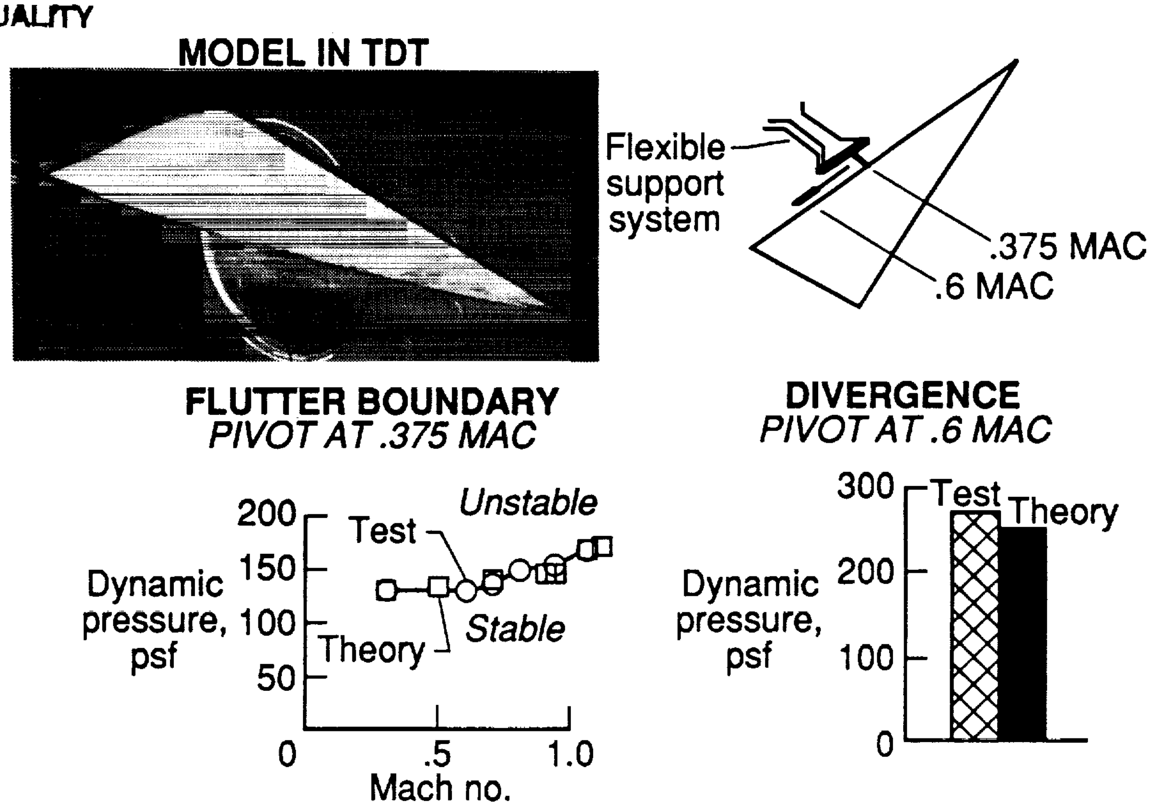

Figure 8. - Flutter and divergence characteristics of all-moveable wing model.

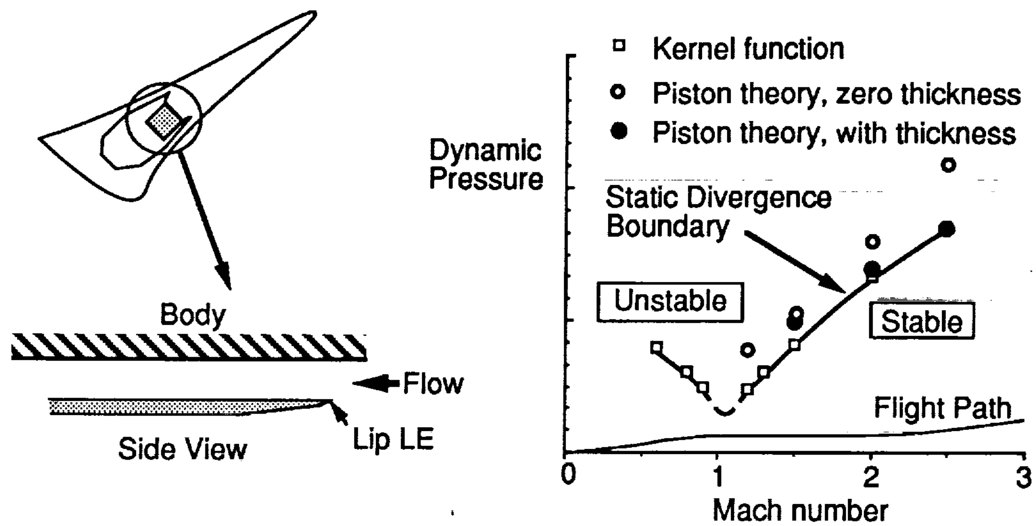

Figure 9. - Aeroelastic characteristics of engine inlet lip.

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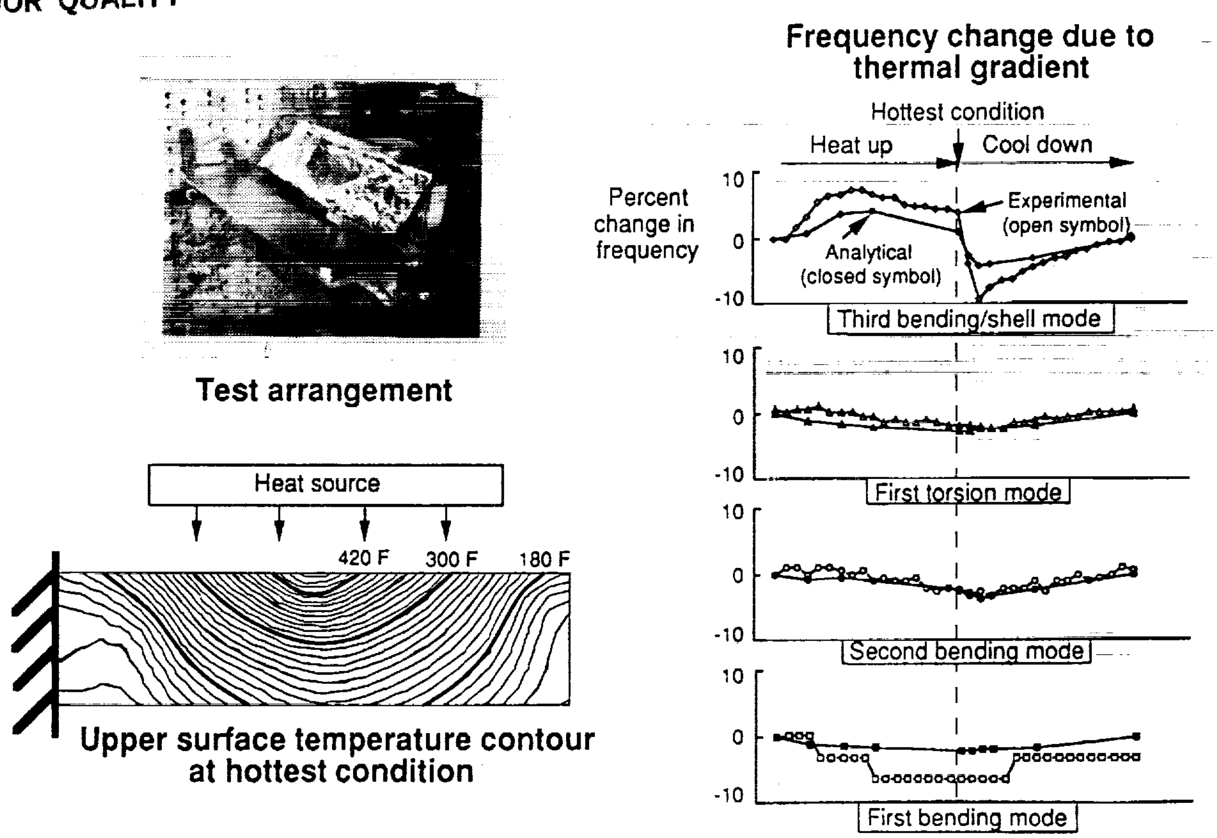

Figure 10. - Thermal effects on vibration characteristics of built-up panel.

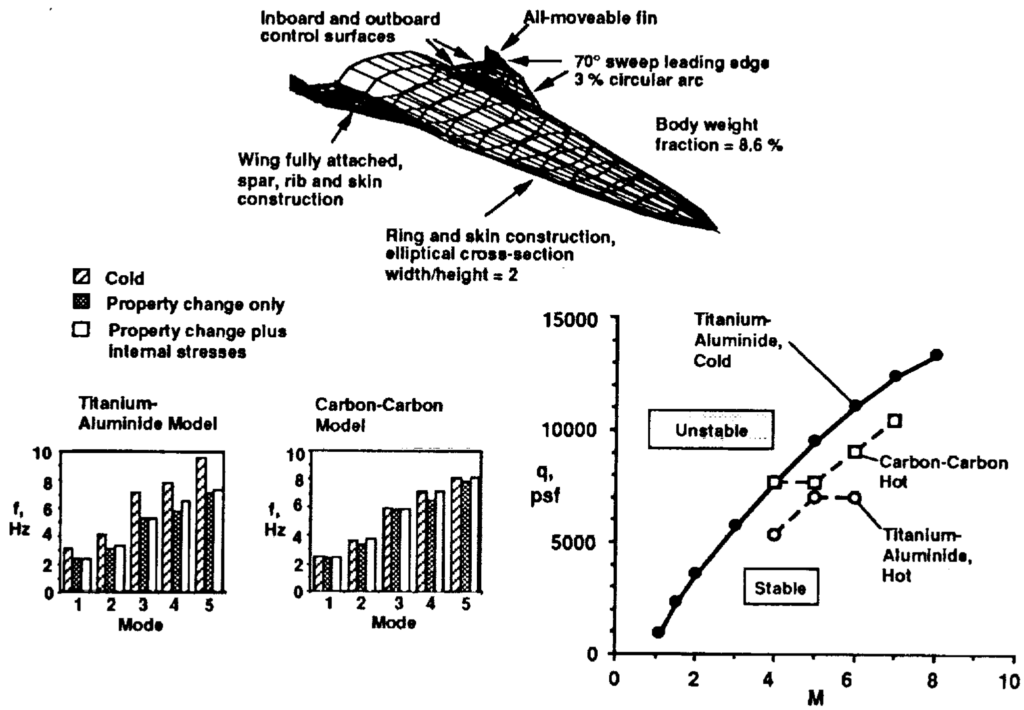

Figure 11. - Effects of aerodynamic heating on flutter characteristics of a generic aero-space plane design.

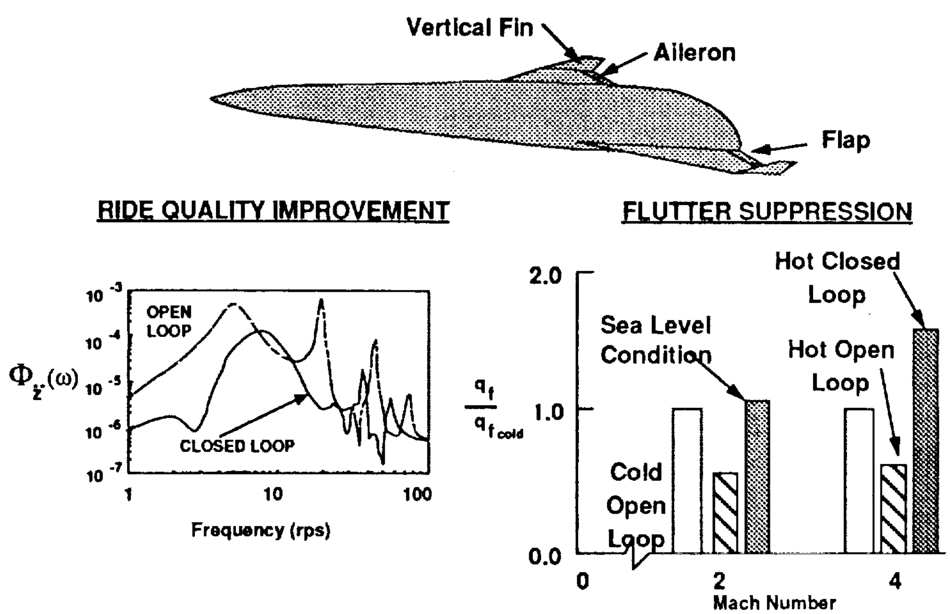

Figure 12. - Active flutter suppression and ride quality control for a generic aero-space plane design.

-Airframe Flutter Evaluation (LaRC, WL)
-Engine Flutter Evaluation (LaRC)
-Panel/Shell Flutter (WL, LaRC)
-Unsteady Aerodynamics (LaRC, WL)
-Aeroservothermoelasticity (LaRC)
-Acoustics and Sonic Fatigue (WL, LaRC)

Figure 13. - Current studies.

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16. Abstract

The special geometric, structural, and operational environment characteristics of hypersonic vehicles are discussed with particular reference to aero-space plane type configurations. A discussion of the structural dynamic and aeroelastic phenomena that must be addressed for this class of vehicles is presented. These phenomena are in the aeroservothermoelasticity technical area. Some illustrative examples of recent experimental and analytical work are given. Some examples of current research are pointed out.

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