N91-10320

STATIC & DYNAMIC AEROELASTIC CHARACTERIZATION OF AN AERODYNAMICALLY HEATED GENERIC HYPERSONIC AIRCRAFT CONFIGURATION

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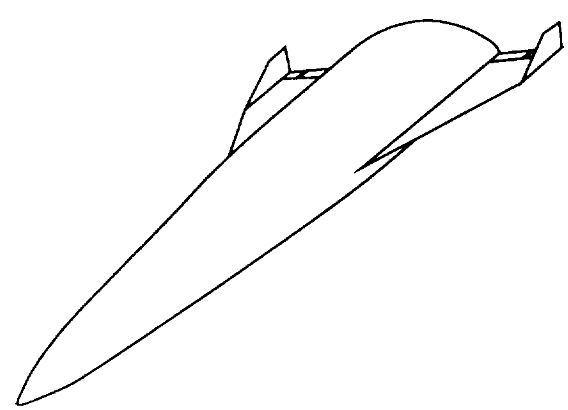
OBJECTIVES

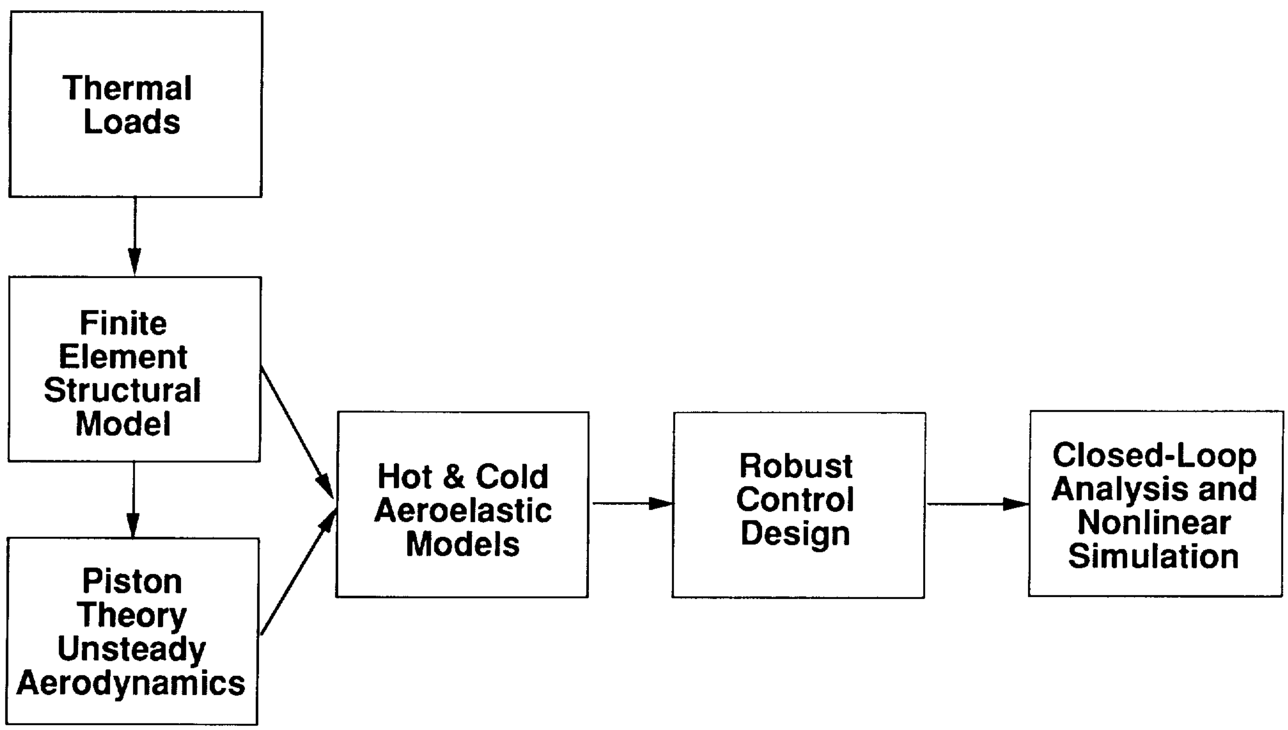
This work-in-progress presentation describes an ongoing research activity at the NASA Langley Research Center to develop analytical methods for the prediction of aerothermoelastic stability of hypersonic aircraft including active control systems. The objectives of this research include application of aerothermal loads to the structural finite element model, determination of the thermal effects on flutter, and assessment of active controls technology applied to overcome any potential adverse aeroelastic stability or response problems due to aerodynamic heating- namely flutter suppression and ride quality improvement. For this study, a generic hypersonic aircraft configuration was selected which incorporates wing flaps, ailerons and all-moveable fins to be used for active control purposes. The active control systems would use onboard sensors in a feedback loop through the aircraft flight control computers to move the surfaces for improved structural dynamic response as the aircraft encounters atmospheric turbulence.

- **Construct a Generic Hypersonic Vehicle to Use in Performing Analytical Studies**
- **Develop and Analyze Aeroelastic Models Incorporating the Effects of Aerodynamic Heating**
- **Apply Active Controls to Compensate for Degraded Dynamic Responses**
  - **Flutter Suppression System**
  - **Ride Qualities Augmentation System**



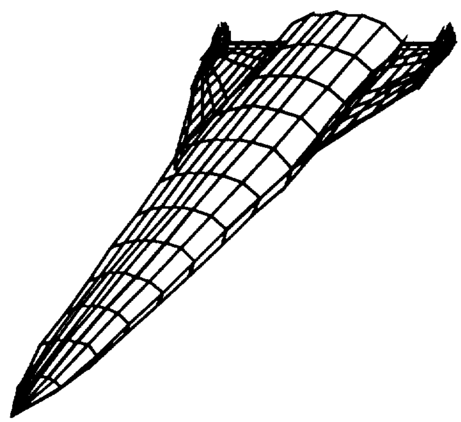
HYPERSONIC ANALYSIS AND DESIGN APPROACH

The current aeroservothermoelastic (ASTE) analysis and design capability is outlined schematically below. The method consists of three primary steps; 1) the determination of thermal loads acting on the structure due to aerodynamic heating, 2) the development of hot and cold aeroelastic mathematical models for flutter analysis including the computation of unsteady aerodynamic forces acting on the structure, and 3) the design, analysis, and simulation of active control laws.



APAS AEROTHERMODYNAMIC MODEL

The Hypersonic Arbitrary Body Program (HABP) of the Aerodynamic Preliminary Analysis System [1] (APAS) was used to model the generic hypersonic aircraft configuration and obtain steady-state aerodynamic forces and heat loads. For a given flight condition (angle-of-attack and control surface deflection), the HABP module was used to compute aerodynamic lift and moment coefficients and aerodynamic center location, as well as the radiation equilibrium wall temperatures on the vehicle. The aerodynamic results were used to calibrate the unsteady aerodynamic force calculations by comparison of pitching moment coefficient and aerodynamic center location. The unsteady aerodynamic force models were then modified to yield compatible results. The radiation equilibrium wall temperatures were used directly as heat loads in the finite element structural model to determine structural stiffness changes caused by thermal stresses and material property changes.



Aerodynamic Preliminary Analysis System (APAS) Hypersonic Arbitrary Body Program (HABP) module used for steady-state aerodynamic calculations

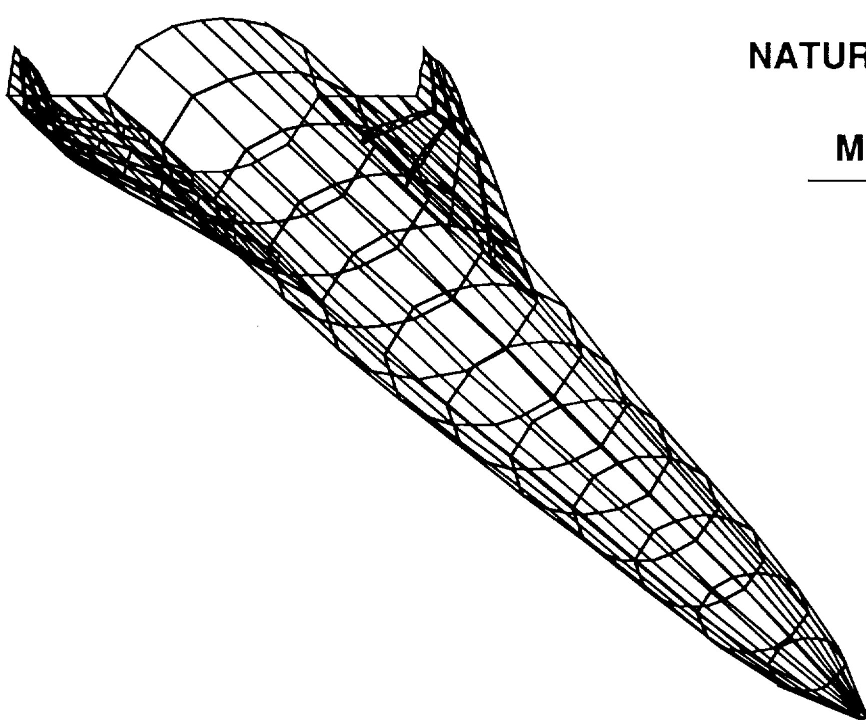
- Radiation equilibrium wall temperatures
- Lift and moment coefficients, aerodynamic center locations

Results used to

- Provide heat loads for thermal structural analysis
- Calibrate unsteady aerodynamic codes

FINITE ELEMENT MODEL

A conventional structural concept was used for the generic aircraft configuration of this study [2]. The fuselage was modeled as an elliptical cross section (width/height ratio 2) consisting of stiffened ring and skin construction. The low-aspect wings were modeled as fully attached to the fuselage consisting of spars, ribs, and skins. The wing leading edge sweep is 70 deg. and the wing section is a 3% circular arc airfoil. A body weight fraction, defined as the weight of the structural material contributing to stiffness divided by gross takeoff weight, of 8.6% was used to determine the required structural mass. Material properties consistent with titanium aluminide were assumed for all structural elements. The wing flaps, ailerons, and all movable fin were modeled separately and attached to the fuselage/wing model by spring stiffness elements modeling actuator stiffness characteristics. The Engineering Analysis Language [3] (EAL) structural analysis code was used to compute hot and cold vibration mode frequencies and mode shapes. The visual appearance and overall character of the mode shapes did not change with variations in temperature, although significant changes did occur in frequencies. Heating effects decreased the frequencies by thirteen to twenty percent.



NATURAL FREQUENCIES (Hz)

MODE	COLD	HOT
1	3.01	2.43
2	4.02	3.48
3	7.06	5.67
4	7.70	6.56
5	9.47	7.63
6	10.96	8.84

UNSTEADY AERODYNAMICS - LESSONS LEARNED

Significant problems were encountered in computing valid unsteady aerodynamic forces for use in aeroelastic stability analyses in both subsonic and supersonic flight regimes. For the subsonic case, two versions of the Doublet Lattice Method [4] (DLM) aerodynamic panel code were used, as was a Kernal Function Method [5] (KFM) code. In the case of the DLM, the two versions were inconsistent in force results (both magnitude and phase). This was attributed to nonconvergence of the DLM due to insufficient numbers of aerodynamic boxes. The minimum number of required boxes was later estimated to be on the order of 675, far exceeding reasonable computational cost. Subsonic flutter boundary predictions using the KFM code were erratic, showing wide oscillations in flutter dynamic pressurefor small subsonic variations in Mach number. For the supersonic case, the MSC/NASTRAN [6] Mach Box [7] and Piston Theory [8] methods were tried. It was found that the Mach Box result would not compare with analytical solutions for simple check cases. The Piston Theory method was found to be restricted to rigid chords, typically valid for high aspect ratio wings which are very stiff chordwise, and did not include airfoil thickness effects. Two new second-order Piston Theory codes including thickness, camber and chordwise bending effects were written, one in EAL and one in FORTRAN, both taking advantage of an existing aero/structure interface [9]. The FORTRAN version aerodynamic force results were ultimately used for flutter analyses because of consistency with the earlier APAS steady-state results.

SUBSONIC:

Doublet Lattice

- Inconsistent between code versions (ISAC and NASTRAN)
- Estimated 675 aerodynamic boxes required for convergence
- Exceeds inhouse code capability, very expensive in NASTRAN

Kernel Function

- Erratic flutter boundary predictions

SUPERSONIC:

Mach Box

- NASTRAN results do not agree with analytical solutions for simple cases

Piston Theory

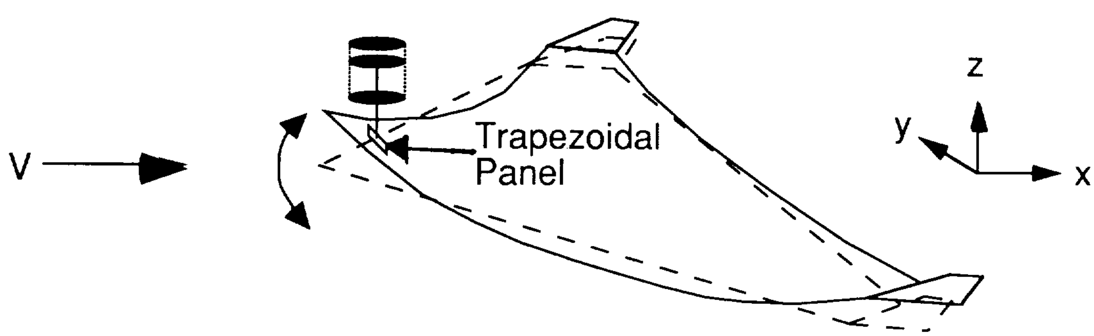
- NASTRAN model limited to (a few) rigid chord panels

SUPERSONIC SOLUTION: Write a new piston theory code

- Linked to ISAC aero/structure interface to model nonrigid chords and thickness

PISTON THEORY AERODYNAMIC IMPLEMENTATION

At sufficiently high Mach numbers "local" wave theory is a good approximation to the unsteady aerodynamics. The local pressure is related to the normal free stream velocity in a similar manner as the pressure in a one-dimensional piston chamber is related to the velocity of the piston. A local, linearized pressure equation is represented by the equation shown in the figure. The various aircraft surfaces were represented by trapezoidal panels similar to the one indicated in the figure. The normal velocities over the surfaces were computed using surface spline interpolation with the normal velocities located at the center of each trapezoidal panel. The point forces subsequently created by the piston theory pressures were also concentrated at the center of each panel. The generalized aerodynamic force for each mode was generated by summing these point forces, weighted by the interpolated mode shapes, over the aircraft surfaces. The additional symbols used in the figure are defined as follows: Δp, pressure difference between upper and lower surfaces; ρ, density; a, the local speed of sound; γ, ratio of specific heats; Z, the relation describing the contour, or the thickness of the vehicle component; z, the displacement of the discrete point; and V, the freestream velocity.



(U) Linearized, second-order equations including thickness effects

$$\Delta p(x,y,t) = -2\rho a\left[1 + G\frac{\partial}{\partial x} Z(x,y)\right]\left[\left(V\frac{\partial}{\partial x} + \frac{\partial}{\partial t}\right)z(x,y,t)\right]$$

$$G = \frac{M^4(\gamma + 1) - 4\beta^2}{2\beta^3} \; ; \; \beta = \sqrt{M^2 - 1}$$

(U) z(x,y,t) calculated at discrete points using surface spline interpolation of mode shape data

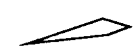
(U) Generalized aerodynamic force for each mode computed by numerical integration of the pressure over the surface

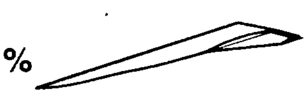
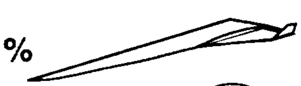
AERODYNAMIC MODELING INFLUENCE ON FLUTTER DYNAMIC PRESSURE

The relative importance of the aerodynamic influence of various vehicle components to flutter was evaluated. The importance of the inclusion of a modeling effect was measured by the percent change in flutter dynamic pressure. Four of the effects examined were found to be significant. The baseline analysis contained a restrained flat plate representation of the wing and used the first six flexible modes. Introducing the rigid body plunge and pitch modes into the analysis increased the flutter dynamic pressure by ten percent. Because the structural frequencies are very low, the structural modes are influenced by the short period mode. For this configuration, the rigid body motion helps to dissipate the system's energy into the airstream, thus inhibiting flutter. The addition of a flat plate representation of the fuselage decreases the flutter dynamic pressure by ten percent. Fuselage motion dominates the first and third flexible modes; including this motion in the analysis increases the aerodynamic force input and encourages flutter. Addition of an aerodynamic representation of the vertical fin further decreases the flutter q by ten percent for the same basic reason. The fifth flexible mode has significant vertical fin contributions, making it important to the analysis. The remaining changes to the aerodynamic model are inclusion of the thickness effects of the wing and the fuselage, both of which cause an increase in the flutter dynamic pressure. The wing contour effects changed the flutter value by ten percent, while the fuselage contour effects changed it by only two percent. The final model used for analysis and design incorporated all of the above effects except for fuselage thickness.

Basic Model:

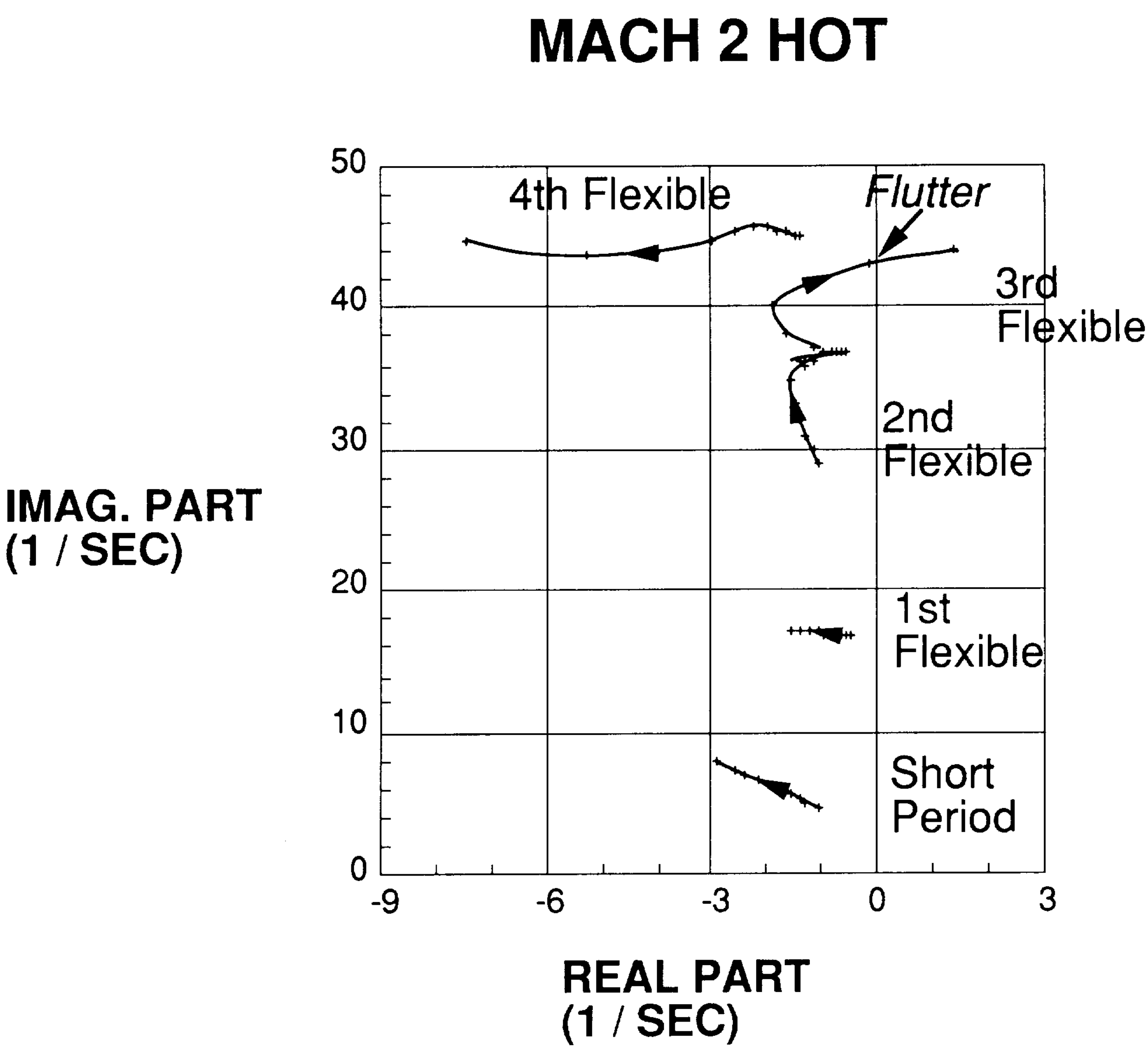
Flat Plate Clipped Delta Wing with 70 Degree Leading Edge Sweep
First 6 Flexible Modes



CHANGE TO MODEL	EFFECT ON $\bar{q}_f$	
▪ Inclusion of Rigid Body Pitch & Plunge Modes	↑ 10 %	
▪ Addition of Flat Plate Fuselage	↓ 10 %	
▪ Addition of Wing Thickness Effects	↑ 10 %	
▪ Inclusion of Flat Plate Vertical Fin	↓ 10 %	
▪ Addition of Fuselage Thickness Effects	↑ 2 %	

ALTITUDE ROOT LOCUS

This figure shows the variation of the eigenvalues associated with the rigid body and first four flexible modes, as altitude is varied. The model used for this typical root locus was the heated structure at Mach 2.0. The arrows indicate decreasing altitude. This analysis was performed at a matched point, so both the density and velocity changed with altitude. Flutter is determined as the cross-over of the imaginary axis. From the figure it is seen that the eigenvalue associated with the third flexible mode moves into the right half plane at a frequency of 43.5 radians per second.



EFFECTS OF MACH NUMBER AND HEAT ON SHORT PERIOD MODE DYNAMICS

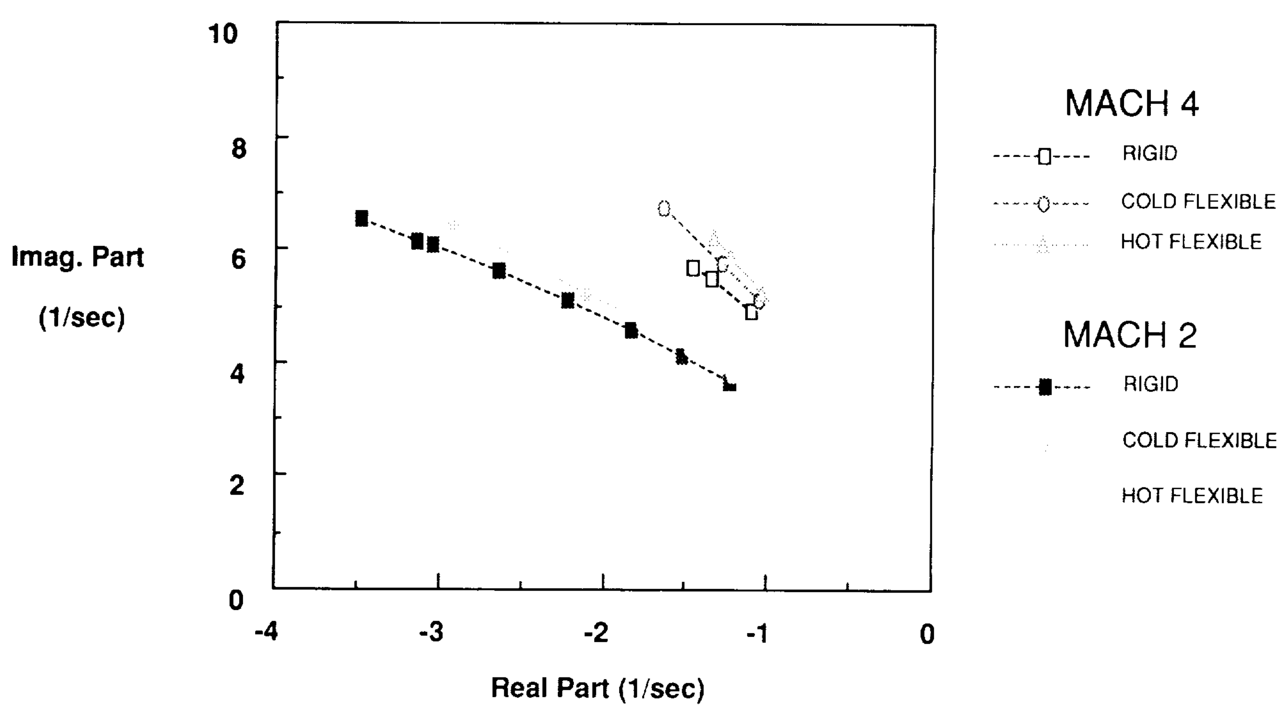
The short period mode dynamics are influenced by both the structural properties and by the aerodynamics. The figure shows the changes in short period behavior incurred due to the effects of structural flexibility, heating and Mach number. The six curves represent the trace of the short period eigenvalue in the complex plane as the altitude is varied (altitude decreases from right to left along each curve).

In an aeroelastic system, the roots of any one mode are influenced by the other modes near it. Because the structural frequencies for these configurations are low, in the neighborhood of the rigid body frequency, it is anticipated that they would exhibit a large degree of influence over the short period mode. This influence can be seen by examining the roots of the rigid vehicle versus the eigenvalues after the effects of flexibility have been included. The figure indicates that including flexibility tends to have a destabilizing effect . The effects due to the aerodynamic heating can be seen by comparing the hot and cold data for the same Mach number. At either Mach number, the destabilizing effect of the heating is seen as the roots for the hot data fall further to the right in the s-plane than those corresponding to the cold data.

To determine the effects of the aerodynamics, the curves for the rigid data, the hot data and the cold data must be examined separately. It is seen that as the Mach number is increased, the short period frequency is increased and the damping is decreased. Thus, increasing Mach number also has a destabilizing effect on the short period dynamics.

Comparing the curves in these three ways shows clearly that the Mach number has a much larger influence than either the flexibility or the heating.

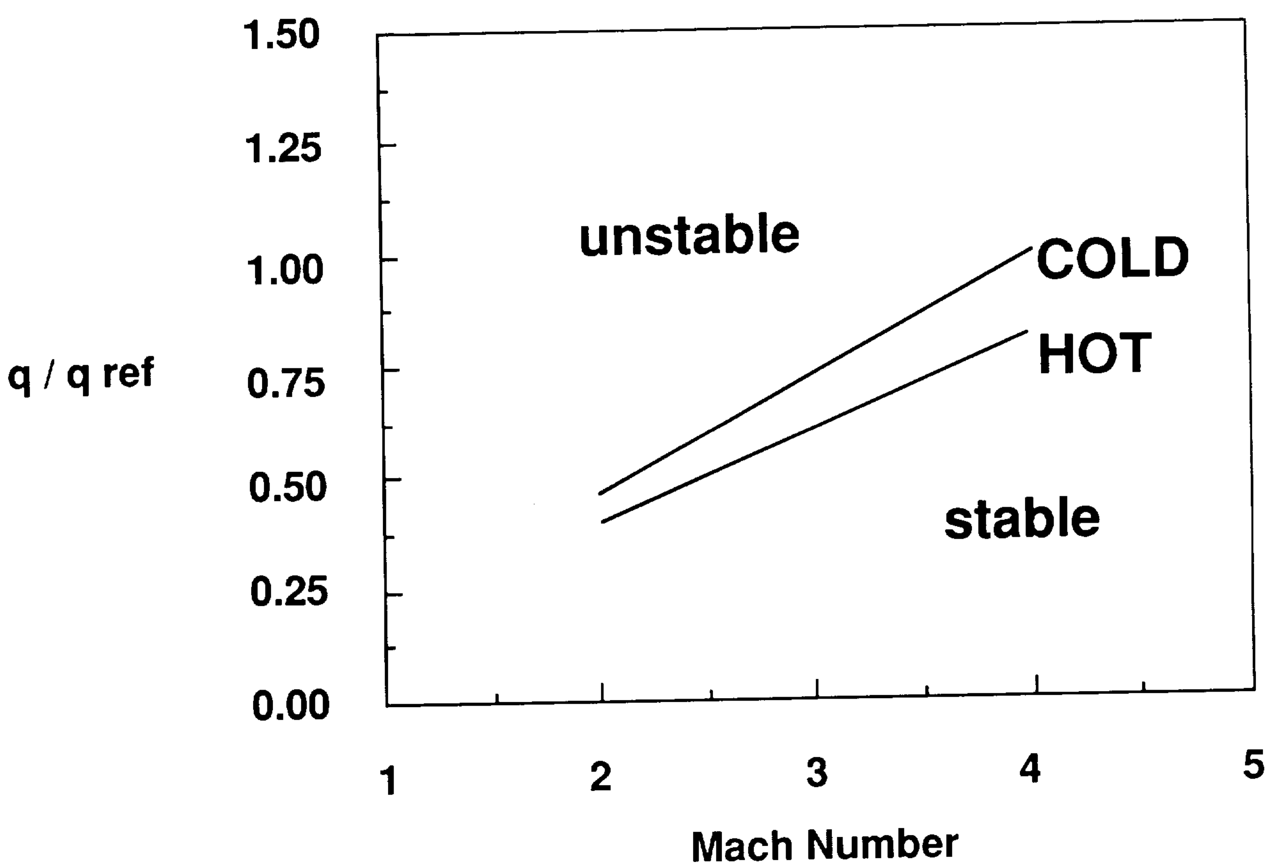
Short period root locations at various altitudes



HOT / COLD FLUTTER RESULTS

The flutter characteristics are presented as a set of curves showing regions of instability. The flutter boundaries illustrate the destabilizing effects of both heating and Mach number. The region below either curve represents the region for flutter-free flight. As the Mach number is increased, the flutter dynamic pressure is increased. Heating lowers the flutter boundary over the entire range of Mach numbers, indicating that there will be an instability at lower dynamic pressures.

FLUTTER BOUNDARIES FOR HEATED AND UNHEATED VEHICLES



CONCLUSIONS / FUTURE PLANS

An aerothermoelastic analysis method has been developed. The thermal loads due to aerodynamic heating are incorporated into the finite element analysis. Application of the aerothermal effects reduced structural frequencies and lowered the flutter boundary. The flutter was found to be influenced by all components of the vehicle; analyses of hypersonic configurations must consider aircraft flutter versus wing flutter.

Future work in this area will concentrate on control law design and closed loop analysis. Plans include design of a flutter suppression system which will raise the flutter boundary of the heated vehicle up to that of the cold vehicle. Ride qualities improvement will also be a focus in the control law design phase of the project. Additionally, the linear unsteady aerodynamic codes will continue to be evaluated and improved. Flutter boundaries for the heated and unheated vehicles will be defined from the subsonic flight conditions to hypersonic speeds.

CONCLUSIONS

- Aerothermoelastic Analysis Method Developed
- Aerothermal Loads Incorporated into Finite Element Analysis
    - Reduced Structural Frequencies
    - Lowered Flutter Boundary
- Flutter influenced by all vehicle components
    - Must Consider Aircraft Flutter Instead of Wing Flutter

PLANS

- Further Evaluate and improve Linear Unsteady Aerodynamics Codes
- Define Flutter Boundaries for Hot and Cold Vehicles from Subsonic to Hypersonic Speeds
- Apply Active Controls to Define Technology Benefits for Hypersonic Aircraft

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