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THE APPLICATION OF ACTIVE CONTROLS TECHNOLOGY TO A GENERIC HYPERSONIC AIRCRAFT CONFIGURATION

M. G. Gilbert, J. Heeg, A. S. Pototzky, C. V. Spain,
D. L. Soistmann, and H. J. Dunn

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Langley Research Center
Hampton, Virginia 23665-5225

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M.G. Gilbert, J. Heeg
NASA Langley Research Center
Hampton, VA 23655

A. S. Pototzky, C. V. Spain, D. L. Soistmann
Lockheed Engineering and Sciences Company
Hampton, VA 23666

H. J. Dunn
NASA Langley Research Center
Hampton, VA 23655

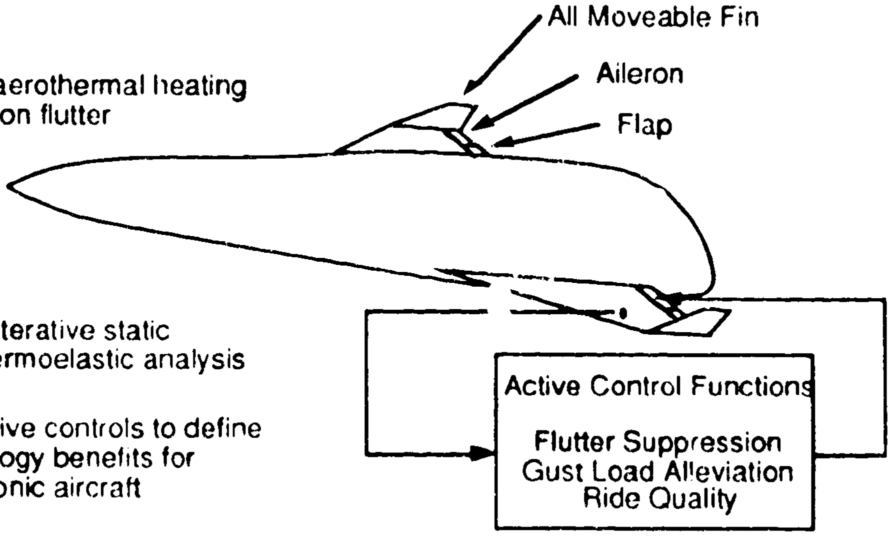
SUMMARY

This report documents a presentation provided at the 7th National Aero-Space Plane Technology Symposium held in Cleveland, Ohio, during October 1989. The objective of the presentation was to provide a status report and current results of ongoing investigation at the Langley Research Center to develop a methodology for predicting the aeroservothermoelastic characteristics of NASP-type (hypersonic) flight vehicles. The presentation was provided in three parts concentrating on the structural modeling and unsteady aerodynamics, the aeroelastic flutter results, and the use of active controls to improve structural response.

GENERIC HYPERSONIC AEROSERVOTHERMOELASTICITY

This paper 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 are shown below. They include 1) the application of thermal loads due to aerodynamic heating to the finite element model of the aircraft structure and the determination of the thermal effects on flutter, 2) the development of an iterative static aeroelastic trim analysis procedure including thermal effects, and 3) the assessment of active controls technology for flutter suppression, ride quality improvement, and gust load alleviation to overcome any potential adverse aeroelastic stability or response problems due to aerodynamic heating. 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.

GENERIC HYPERSONIC AEROSERVO-THERMOELASTICITY

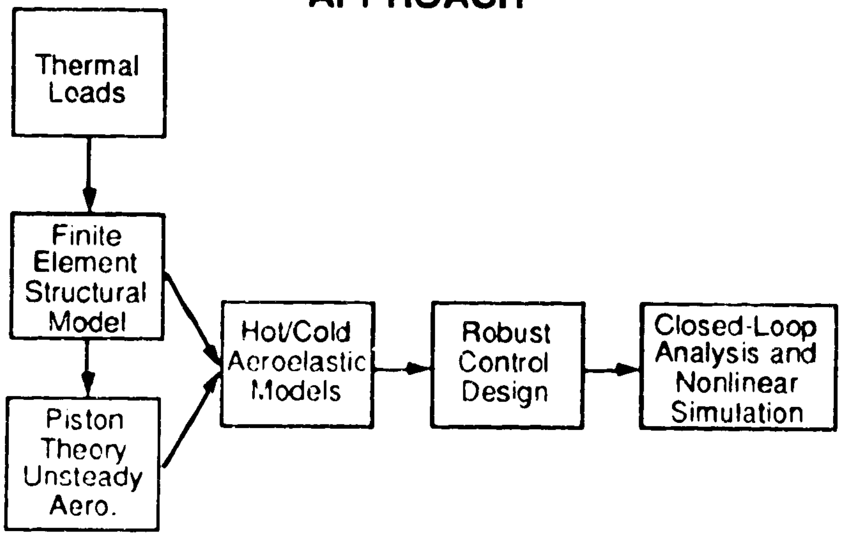


Objectives

- Analyze aerothermal heating effects on flutter
- Develop iterative static aerothermoelastic analysis method
- Apply active controls to define technology benefits for hypersonic aircraft

HYPERSONIC ASTE 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. To date, this analysis and design capability does not include iterative looping to determine the static aerothermoelastic trim condition of the vehicle. The schematic also serves as an outline for the remainder of the paper, as each item is discussed in turn.



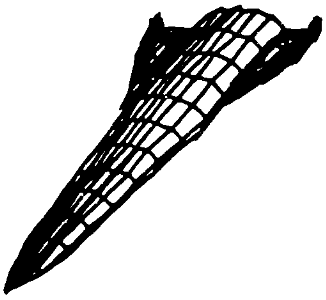
HYPERSONIC ASTE ANALYSIS AND DESIGN APPROACH

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 deflections), 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 later 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.

1. Sova,G. and Divan, P., " Aerodynamic Preliminary Analysis System II, Part II User's Manual," North American Aircraft Operations, Rockwell International.

APAS AEROTHERMODYNAMIC MODEL



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

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

Results used to

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

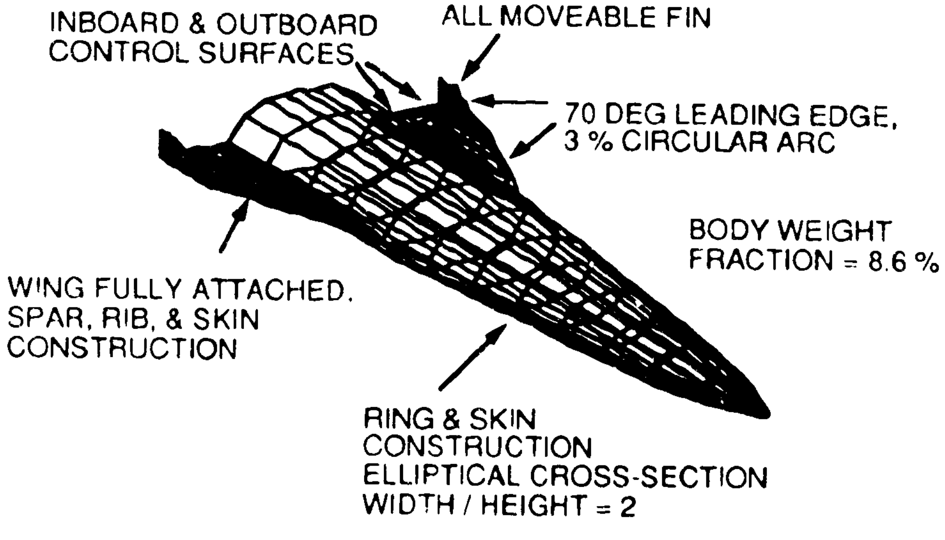
EAL FINITE ELEMENT STRUCTURAL MODEL

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.

2. Spain, C. V., Soistmann, D. L., and Linville, T. W., "Integration of Thermal Effects Into Finite Element Aerothermoelastic Analysis With Illustrative Results", NASP CR 1059, August 1989.

3. Whetstone,W., "EISI-EAL Engineering Analysis Language Reference Manual," Engineering Information Systems, Inc, San Jose, CA, 1983.

EAL FINITE ELEMENT STRUCTURAL MODEL

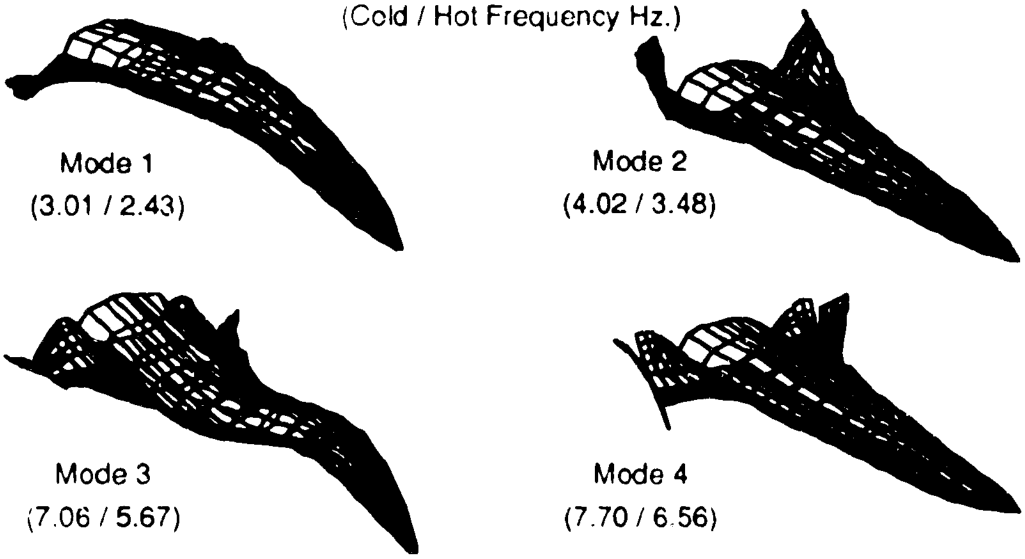


VEHICLE VIBRATION MODE SHAPES

The first four symmetric flexible mode shapes of the cold structure are shown in the figure. The visual appearance and overall character of these modes did not change with variations in temperature, although significant changes did occur in frequencies. Frequencies ranged from about 3.0 to 7.7 Hertz cold, and 2.4 to 6.7 Hertz hot. Note that the first and third elastic modes include significant fuselage motion.

VEHICLE VIBRATION MODE SHAPES

(Cold / Hot Frequency Hz.)



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 pressure for small (subsonic) variations in Mach number. For the supersonic case, the MSC/NASTRAN Mach Box and Piston Theory methods [6] 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 [7] 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. The FORTRAN version aerodynamic force results were ultimately used for flutter analyses because of consistency with the earlier APAS steady-state results.

4. Geising, J. P., Kalman, T. P., and Rodden, W. P., "Subsonic Unsteady Aerodynamics for General Configurations, Part 1, Vol. 1 - Direct Application of the Nonplanar Doublet-Lattice Method", AFFDL TR-71-5, Part 1, Vol. 1, 1971.

5. Cunningham, A. M. Jr., "A Steady and Oscillatory Kernal Function Method for Interfering Surfaces in Subsonic, Transonic, and Supersonic Flow", NASA CR-144895, 1976.

6. Rodden, W. P., editor, "MSC/NASTRAN Handbook for Aeroelastic Analysis, Volume 1", Nov. 1987.

7. Morgan, H. G., Huckel, V., and Runyan, H. L., "Procedure for Calculating Flutter at High Supersonic Speed Including Camber Deflections, and Comparison With Experimental Results", NACA TN 4335, Sep. 1958.

UNSTEADY AERODYNAMICS - LESSONS LEARNED

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

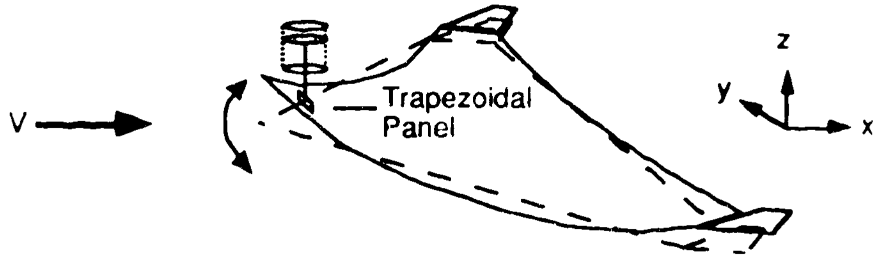
Supersonic solution: Write a new piston theory code

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

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 entire wing surface was represented by trapezoidal panels similar to the one indicated in the figure. The circular arc thickness characteristics of the wing incorporated into the pressure equation, however, the thickness effect of the fuselage were not included in the present aerodynamic modelling. The normal velocities over the wing surface were computed using surface spline interpolation with the normal velocities located at the center 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 points forces, weighted by the interpolated mode shapes, over the whole wing surface.

PISTON THEORY AERODYNAMIC IMPLEMENTATION



Linearized, second-order equations including thickness effects

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

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

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

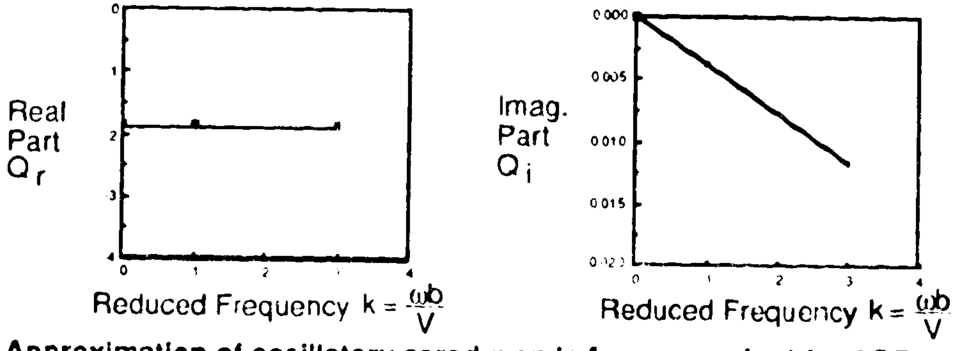
Generalized aerodynamic force for each mode computed by numerical integration of the pressure over the surface

QUASI-STEADY AERODYNAMIC APPROXIMATIONS

Aeroservoelastic equations of motion are formulated in the frequency domain. Unsteady aerodynamics code results consist of values of generalized aerodynamic forces (GAF's) for discrete values of reduced frequency. For inclusion in the equations of motion, the aerodynamics must be represented in the Laplace domain. To this end, an approximation is generally made, employing a curve fit to the tabular data. In the case of piston theory aerodynamics, the real parts of the generalized aerodynamic forces are constant, and the imaginary parts are linear with reduced frequency. This characteristic allows the aerodynamics to be represented exactly by a first order equation. Incorporating the aerodynamics into the state-space models for control law design requires no additional states to represent the aerodynamic loads.

QUASI-STEADY AERODYNAMIC APPROXIMATIONS

Unsteady lift due to oscillatory pitch motion



Approximation of oscillatory aerodynamic forces required for ASE

- Quasi-steady approximation used

$$Q(k) \approx Q_r + Q_i \frac{bs}{V} ; s = j\omega$$

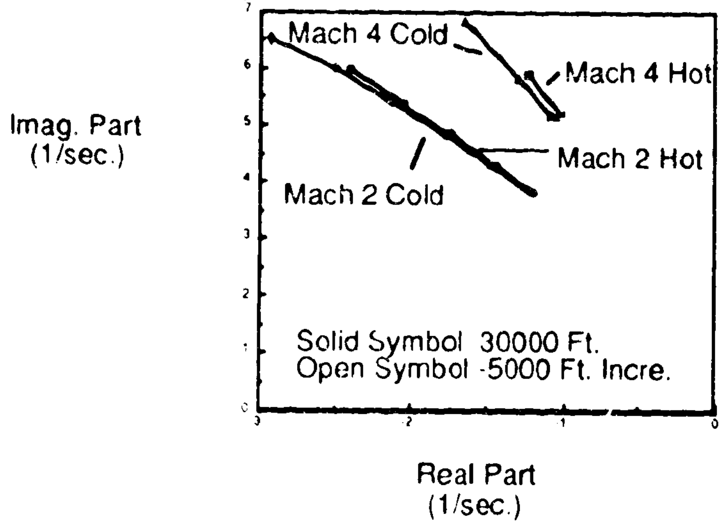
- No additional aerodynamic modeling states required in state space models for control law design

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 models with the same heating conditions use the same structural model (i.e. identical model shapes, natural frequencies, generalized mass and stiffnesses). Differences in short period behavior due to variations in the structural models reflecting aerodynamic heating can be observed by comparing either the Mach 2 data (hot versus cold) or the Mach 4 data (hot versus cold). For either set of data, the destabilizing effect of the heating is seen as the roots for the hot data fall further to the right in the s-plane. To determine the effects of the aerodynamics, the curves for the hot data and 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 has a destabilizing effect on the short period dynamics. Comparing the curves in these ways shows clearly that the Mach number has a much larger influence than the heating.

EFFECTS OF MACH NUMBER AND HEAT ON SHORT PERIOD MODE DYNAMICS

Short period root locations at various altitudes

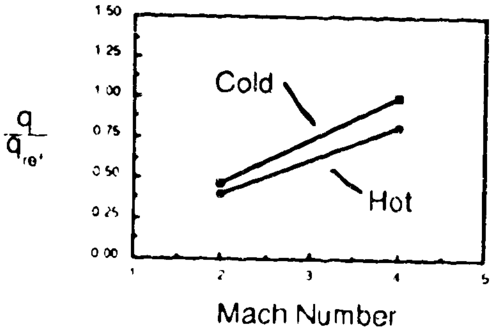


HOT / COLD FLUTTER RESULTS

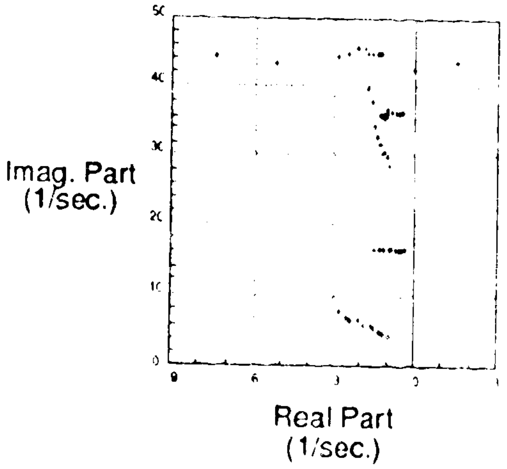
The flutter characteristics are presented in two ways: as a set of curves showing the regions of instability and as a root locus showing the location of the eigenvalues as a function of the flight condition. The flutter boundaries illustrate the destabilizing effects of both heating and Mach number. The region below either curve represents the region for flutter-free flight. As the Mach number is increased, the models require higher dynamic pressures be applied before they become unstable. Heating the model lowers the flutter boundary over the entire range of Mach numbers, indicating that there will be an instability at lower dynamic pressures. The figure on the right is a root locus plot with altitude variation, calculated for the Mach 2 hot model. The eigenvalues associated with the vibrational modes are plotted as the altitude is lowered; both the density and the velocity are changed. The flutter condition is given by the altitude corresponding to the root lying on the imaginary axis.

HOT / COLD FLUTTER RESULTS

Flutter Boundaries



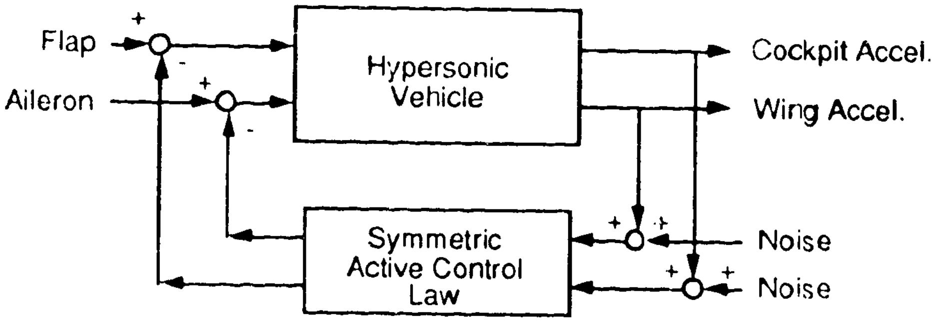
Mach 2 hot altitude root locus



ACTIVE CONTROL LAW CONCEPTS

Two active control concepts were considered for the generic hypersonic aircraft configuration. The first was an active flutter suppression system (FSS) to recover the flutter dynamic pressure lost due due to aerodynamic heating, and the second was an active Ride Quality (RQ) system to improve structural response at the pilot station. In both cases, only symmetrical motion in the longitudinal direction was considered for active control. For the FSS, a full-order state estimator was used for compensation in the feedback loop. The controller was designed using Linear Quadratic Gaussian (LQG) control law design methods with Loop Transfer Recovery (LTR) to improve stability robustness in the face of changes in flight dynamic pressure. Normal acceleration at the pilot station and at a location very near the wing aileron were used as measurements for feedback to the compensator. Both measurements were assumed to be noisy. The FSS control law was designed to minimize total system energy by weighting of the sum of the structural strain and kinetic energy, and the commanded control surface deflections (a measure of control energy). The ride quality system was designed to reduce cockpit acceleration levels due to structural motion induced by encounters with turbulence. It was designed using a pole-placement technique to locate closed-loop system eigenvalues to achieve desired dynamic response. Full state feedback was assumed, and normal acceleration at the pilot station was used as the figure of merit.

ACTIVE CONTROL LAW CONCEPTS



Symmetric rigid and flexible body motions

Flutter suppression system design

- Full-order LQG control law design with loop transfer recovery
- Pilot station and wing acceleration measurements used for feedback

Ride quality improvement system

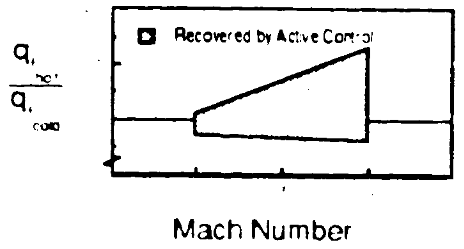
- Pole placement design using full state feedback
- Design to reduce cockpit accelerations due to turbulence

ACTIVE CONTROL FUNCTION RESULTS

Typical results for the implementation of the active FSS and RQ control functions are shown below. On the left the hot to cold flutter dynamic pressure ratio is shown as a function of Mach number. The uncontrolled (open-loop) flutter dynamic pressure ratio for the heated structure is less than 1.0, indicating a negative effect of thermal loading on the aeroelastic stability of the structure. Closed-loop flutter analysis using a single FSS control law shows dynamic pressure ratio (hot to cold) greater than 1.0 over the Mach 2.0 to 4.0 range. The FSS control function has not only recovered the lost flutter dynamic pressure of the hot structure, it has increased the flutter dynamic pressure beyond that of the cold structure as well. This was accomplished without gain scheduling while maintaining finite gain and phase margins and acceptable control surface deflections and rates in random wind gust environments. The RQ control function showed significant reductions in the peak acceleration responses being measured at the pilot station for Mach 4.0, cold structure at 30000 ft. altitude. It also achieved an overall 30% reduction in RMS normal acceleration response while maintaining acceptable control surface deflections and rates during random wind gust encounters.

ACTIVE CONTROL FUNCTION RESULTS

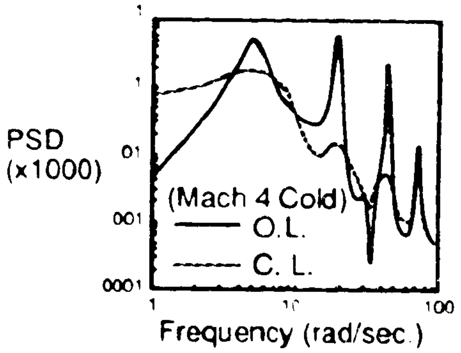
Hot / cold flutter dynamic pressure ratio



Flutter Suppression System

- Finite gain and phase margins at all dynamic pressures
- Fed back normal acceleration at pilot station and aileron location
- Acceptable flap and aileron deflections and rates in gust

Normal Acc. at Pilot Station due to 1 ft./sec. gust



Ride Quality System

- Reduced structural mode response at pilot station
- 30% reduction in overall RMS response with reasonable control deflections and rates

CONCLUDING REMARKS

This paper has described an aeroservothermoelastic analysis and design methodology for the implementation of active control law functions to hypersonic aircraft. With this methodology, the aerodynamic heat loads for hypersonic flight are determined and applied to finite element models of the aircraft structure to determine stiffness changes due to thermal stresses and material property changes. Using the hot structure vibration modes, an aeroelastic analysis is performed with Piston Theory unsteady aerodynamic forces to determine the thermal effects on flutter dynamic pressure. Once the flutter characteristics of the hot structure are known, active control functions such as flutter suppression, gust load alleviation, and ride quality improvement systems can be designed. These systems can overcome the adverse dynamic response characteristics brought on by the thermoelastic destiffening of the aircraft structure.

CONCLUDING REMARKS

Aerothermoelastic analysis capability available

- APAS HABP used for stability derivatives, aerodynamic center locations, and aerodynamic heat loads
- Heat loads applied to finite element structural model for hot/cold vibration modes
- Nonrigid chord Piston Theory unsteady aerodynamics coupled with quasi-steady aerodynamic approximation method

Active controls can compensate for thermoelastic effects

- Thermoelastic effects result in lower flutter boundaries
- Twenty-third order LQG FSS control law more than recovered cold structure flutter boundary using normal acceleration feedbacks
- Pilot station ride quality in turbulence improved using full-state feedback gain to place closed-loop eigenvalues
- Effects of control system nonlinearities yet to be determined by simulation

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15. Supplementary Notes

M. G. Gilbert, J. Heeg, and H. J. Dunn: NASA Langley Research Center, Hampton, Virginia.
A. S. Pototzky, C. V. Spain, and D. L. Soistmann: Lockheed Engineering and Sciences Company, Hampton, Virginia.

16. Abstract

This paper 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 are 1) the application of thermal loads due to aerodynamic heating to the finite element model of the aircraft structure and the determination of the thermal effects on flutter, 2) the development of an iterative static aeroelastic trim analysis procedure including thermal effects, and 3) the assessment of active controls technology for flutter suppression, ride quality improvement, and gust load alleviation to overcome any potential adverse aeroelastic stability or response problems due to aerodynamic heating. 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.

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