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APPLICATION OF UNSTEADY AEROELASTIC ANALYSIS TECHNIQUES ON THE NATIONAL AEROSPACE PLANE

A. S. Pototzky, C. V. Spain, D. L. Soistmann, and T. E. Noll

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Langley Research Center
Hampton, Virginia 23665-5225

APPLICATION OF UNSTEADY AEROELASTIC ANALYSIS TECHNIQUES ON THE NATIONAL AEROSPACE PLANE

Anthony S. Pototzky, Charles V. Spain and David L. Soistmann
Planning Research Corporation
Hampton, Virginia

and

Thomas E. Noll
NASA Langley Research Center
Hampton, Virginia

SUMMARY

This report documents a presentation provided at the 4th National Aero-Space Plane Technology Symposium held in Monterey, California during February, 1988. The objective of the presentation was to provide a status report and current results of ongoing investigations at LaRC to develop a methodology for predicting the aerothermoelastic characteristics of NASP-type (hypersonic) flight vehicles. The presentation was provided in three parts concentrating on the unsteady aerodynamic, the structural modeling and the wind tunnel model issues associated with vehicle aeroelastic stability in a hot environment.

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INTRODUCTION

This report provides charts and facing page text that describe the current status of an investigation to develop a methodology for predicting the aerothermoelastic characteristics of a hypersonic flight vehicle. The first few charts discuss the background associated with aerothermoelasticity. The body of the report discusses the issues related to unsteady aerodynamics, structural modeling and wind tunnel testing. Initially several existing subsonic and supersonic unsteady aerodynamic codes applicable to the hypersonic class of flight configurations that are generally available to the aerospace industry are described. These codes were evaluated by comparing calculated results with available measured wind tunnel aeroelastic data. Comparisons with test data were shown to be quite good in the subsonic speed range, but were somewhat mixed (good to poor depending upon Mach number and configuration) in the supersonic range. A future endeavor to extend the aeroelastic analysis capability to hypersonic speeds using CFD steady aerodynamics with a low reduced frequency expansion is also outlined. Next, an investigation using simplified finite element models to identify the critical parameters affecting the aeroelastic characteristics of a hypersonic vehicle, and to define and understand the various flutter mechanisms and trends for these parameters is summarized. The value of performing inexpensive and timely aeroelastic calculations using simplified structural and aerodynamic models during preliminary design and evaluation phases is illustrated. Finally, ongoing analytical investigations being conducted to assist in the design of simple, and later, complex aeroelastic models representative of the NASP configurations for wind tunnel testing is discussed. Some high speed aeroelastic wind tunnel tests involving simple models are now being conducted and complex model tests are being planned to obtain measured data for validating and calibrating new or modified codes that are required for application to hypersonic vehicle design.

AEROTHERMOELASTICITY
(HYPERSONIC AEROELASTICITY)

High fuel mass fractions are required to adequately design a vehicle for transatmospheric/hypersonic flight. A high fuel mass fraction means that the ratio of the structural weight to the gross weight will be very low resulting in a configuration with structural vibration modes near the rigid-body short-period frequency. Classically, flexible structural designs are prone to aeroelastic instabilities; since the elastic modes are expected to be near the rigid-body modes significant elastic/rigid-body mode interaction may also be encountered. In addition, because of the extremely high speeds involved, aerothermoelastic interactions are possible. The diagram shows a generic flight trajectory for the National Aerospace Plane. The aeroelastic boundary is often most critical in the transonic speed regime for flight vehicles capable of achieving these conditions. For hypersonic vehicles this may not necessarily be the case. Currently, it is not possible to evaluate the effect of aerothermoelasticity; therefore, the severity of the degradation of the boundary cannot be determined. The objective of this task is to develop a methodology for including thermal effects in the aeroelastic design and analysis of hypersonic flight vehicles.

AEROTHERMOELASTICITY
(HYPERSONIC AEROELASTICITY)

o Design for High Speed, High Fuel Mass Fraction

o Vehicle Design Requires Minimum Weight Leading to Flexible Structure

o Flexible Structures Prone to Aeroelastic and Aerothermoelastic Instabilities
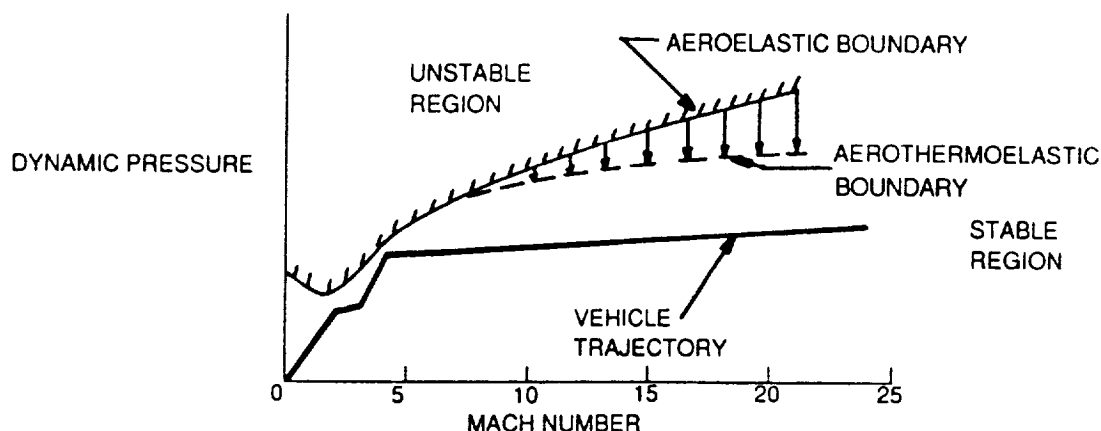
AEROTHERMOELASTICITY
AEROELASTIC PROFILE

The National Aerospace Plane will be expected to transverse the Mach range from low subsonic to hypersonic speeds over a large range of dynamic pressures and thermal environments. Therefore, aeroelastic evaluations are required that not only consider the effects of automatic flight-control systems but also the hot structure. The applicability of state-of-the-art unsteady aerodynamic codes to generic hypersonic flight vehicles needs to be evaluated at all speed regimes in which the vehicle is expected to pass through (subsonic, transonic, supersonic and hypersonic). Once the available unsteady aerodynamic codes have been evaluated, sufficient information will be available to define which codes are suitable, which codes need to be improved, and what new codes are required to be developed. For subsonic aeroelastic calculations both a doublet lattice method and a kernel function method have been evaluated; at transonic speeds, CAP-TSD is being considered; at supersonic speeds, a kernel function method, a panel method, and piston theory have been applied; and at hypersonic speeds, a quasi-steady approach is being investigated.

AEROTHERMOELASTICITY
AEROELASTIC PROFILE

MACH NO.	STRUCTURE	AERODYNAMICS	AEROELASTIC ISSUES
0.0 - 0.8	Cool	Subsonic	**Trim, Gust, Maneuver, Flutter, ASE and Heating**
0.8 - 1.1	Cool	Transonic	
1.1 - 3.5	Cool	Supersonic	
3.5 - 10.0	Heated	Hypersonic (low)	
10.0 - 25.0	Hot	Hypersonic (high)	

AEROTHERMOELASTICITY
OBJECTIVES AND APPROACH

The goal of the aerothermoelasticity activity is to develop a methodology of including the effects of temperature distributions and gradients in the aeroelastic design and analysis of hypersonic flight vehicles. The approach consists of four tasks ranging from analyses to aeroelastic wind-tunnel tests. Initially, the unsteady aerodynamic codes generally available to the aerospace industry will be evaluated as to applicability to the hypersonic class of flight vehicles. This will be accomplished by correlating calculated data with measured aeroelastic data. If limitations are defined, or if it is determined that the aerodynamic theory is lacking in certain areas, then the most promising codes will be improved as necessary. Additional aeroelastic wind-tunnel tests will be performed using simple to complex models representative of the National Aerospace Plane configurations and root boundary conditions to expand the experimental data base for code validation. In addition, thermoelastic laboratory tests are planned to obtain model deformations, elastic frequencies, and mode shapes as the temperature of the environment is increased. The next task will involve the development of a methodology for including thermal effects on stiffness and material properties and its subsequent impact on the aeroelastic characteristics of the vehicle. The final task involves complete vehicle analyses to determine the static, dynamic, and aeroservoelastic characteristics of the vehicle over all the flight regimes. It is expected that shell-type modes and the use of exotic composite and ceramic materials with internally circulated cooling fluid will greatly affect and complicate the modelling and analysis of these investigations.

AEROTHERMOELASTICITY
OBJECTIVES AND APPROACH

OBJECTIVES

* Validate Aerodynamic Methods Using Experimental Data, and Improve Codes as Required

* Obtain an Experimental Data Base of Thermoelastic and Aeroelastic Trends

* Develop Computational Methods for Predicting Thermoelastic Characteristics

* Conduct Analytical Studies to Identify and Solve Potential Aero/Servo/Thermo/Elastic Problems

APPROACH

* Correlate Existing Experimental Data Base with Analyses to Verify Accuracy of Aerodynamic Codes

* Design, Fabricate, and Test Thermoelastic Models and Aeroelastic Wind-Tunnel Models

* Develop Aeroelastic Methodology that Includes Thermal Effects on Stiffness

* Conduct Vehicle Studies to Determine Static/Dynamic Characteristics over Flight Envelope

UNSTEADY AERODYNAMIC METHODS DEVELOPMENT
FOR NASP CONFIGURATIONS

This part of the presentation is about some of the unsteady aerodynamic methods we are incorporating for analyzing NASP configurations. The NASP ascent mission is viewed in terms of our aerodynamic capabilities. ACUNN and ZONA are supersonic codes which are discussed. Piston Theory, as implemented in a finite element code, is proposed for use in the low hypersonic regime. A quasi-steady approach is also discussed, which may allow the use of existing steady hypersonic codes for unsteady predictions.
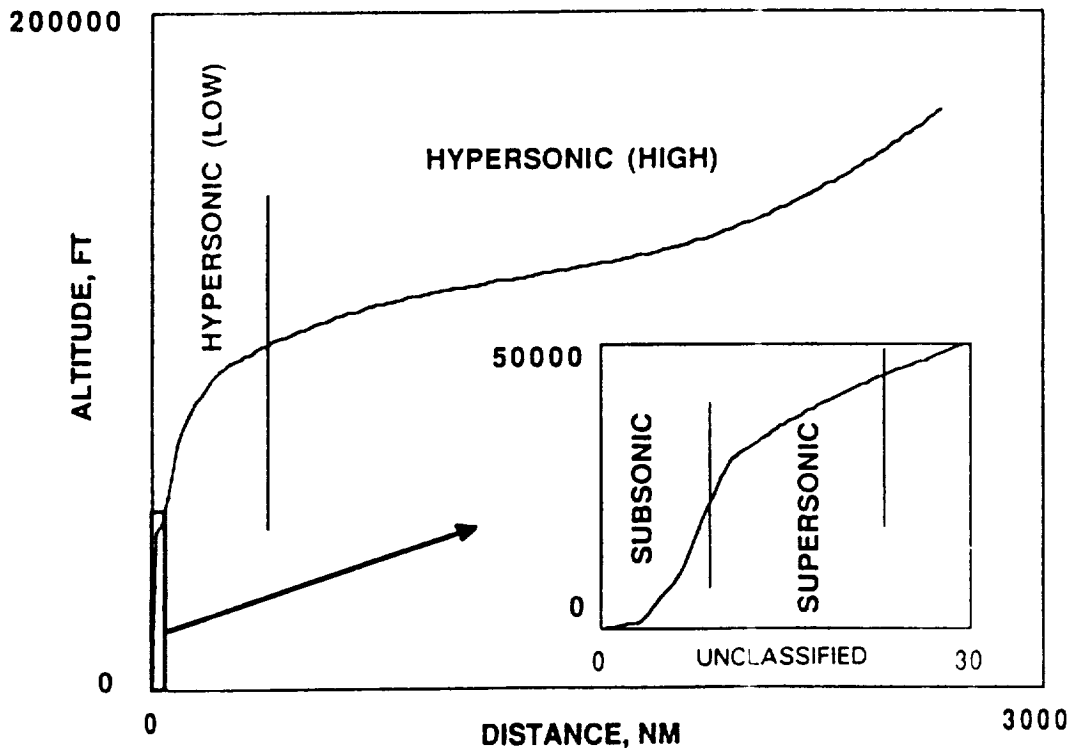
Unsteady Aerodynamic Methods
Development for NASP Configurations

- NASP mission vs. our capabilities

- Capabilities - implemented, existing, and planned

- ACUNN and ZONA supersonic codes

- Finite element Piston Theory

- Quasi-steady approach for future modelling at hypersonic speeds
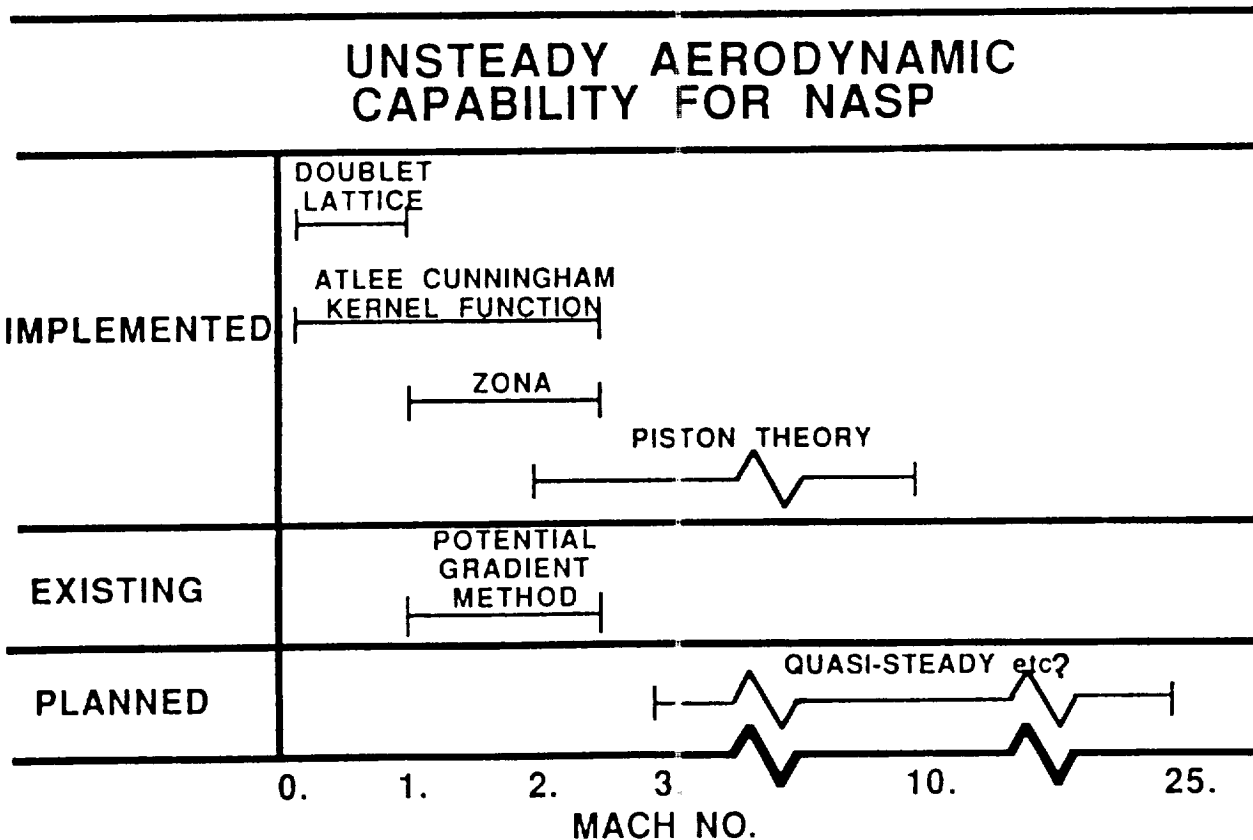
NASP ASCENT TRAJECTORY

In the previous presentation, we saw that analytical results compared very well with wind-tunnel tests in the subsonic range. However, in the supersonic range, analysis did not agree as well with test results. In this presentation, we will look at supersonic codes we have recently implemented that might give us better analytical results. In the low hypersonic range, we will look at a finite element capability which allows us to generate Piston Theory aerodynamics. A quasi-steady approach using steady aerodynamics should extend us into the high hypersonic region.

NASP ASCENT TRAJECTORY

UNSTEADY AERODYNAMIC CAPABILITY FOR NASP

Both the Doublet Lattice and ACUNN codes are available and can be used in the subsonic range. In addition to the supersonic ACUNN code, ZONA, a newly implemented supersonic capability, will be discussed. We intend to implement the Potential Gradient Method (PGM), which is a lattice-type code similar to Doublet Lattice and ZONA, when it becomes available from the Air Force Wright Aeronautical Laboratory. With the addition of that code, possibly three supersonic codes could be used for comparison purposes. Also, finite element Piston Theory, which covers the low hypersonic region, will be introduced. We plan to look at a quasi-steady approach which we hope to use to study aeroelastic phenomena in the low to high hypersonic range. More will be said about the quasi-steady approach later.

UNSTEADY AERODYNAMIC CAPABILITY FOR NASP

IMPLEMENTED	DOUBLET LATTICE ⊢————⊣ ATLEE CUNNINGHAM KERNEL FUNCTION ⊢————————⊣ ZONA ⊢————⊣ PISTON THEORY ⊢————⋀⋁————⊣
EXISTING	POTENTIAL GRADIENT METHOD ⊢————⊣
PLANNED	QUASI-STEADY etc? ⊢—⋀⋁————⋀⋁—⊣

0.   1.   2.   3.   10.   25.

MACH NO.

9

ACUNN

ACUNN is a kernel function pressure mode method written by Atlee Cunningham of General Dynamics. It has unsteady and steady subsonic, supersonic, and limited transonic capability and uses a linear, lifting surface approach. Changes were made to the code so that it can be incorporated into the ISAC system of codes and to more easily model control surface and gust aerodynamics. It can be used with arbitrary configurations since it uses a nonplanar kernel. It is, however, very difficult to use unless one has a good knowledge of the aerodynamics involved, especially in the supersonic range. From the table on the right you will notice various types of pressure weighting functions. The engineer needs to decide which combination to use both in the spanwise and chordwise directions for every lifting surface in the analysis. Another difficulty in using the code is choosing the correct order of pressure mode. There are many examples where the highest available order may not give the best results.

ACUNN

Kernel Function-Pressure Mode Aerodynamic Code
Originator: Atlee Cunningham

- **Unsteady subsonic to supersonic aerodynamics**
- **Arbitrary configurations**
- **Requires pressure weight functions**
- **Configuration dependent**

Pressure weighting functions

Spanwise Loadings   Chordwise Loadings

10
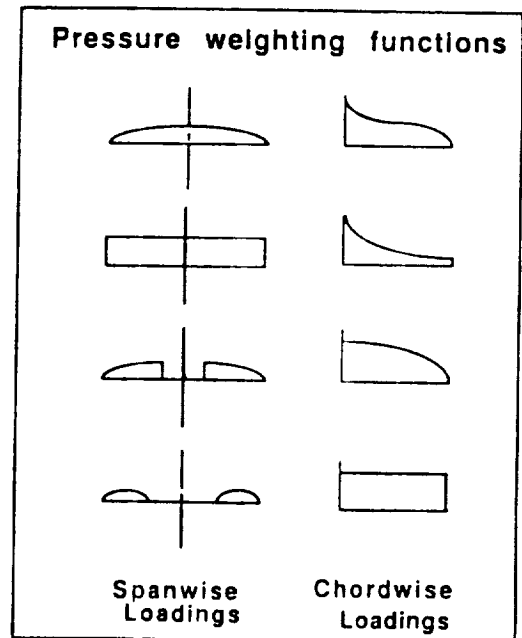
ZONA

ZONA is a Fortran code available in a virtual environment such as VAX
Fortran. This code was made available from Danny Liu of ZONA Technology, Inc.
of Mesa, Arizona. The code is similar to the ACUNN code in that it uses a linear
lifting surface approach for arbitrary configurations. It is different in that it is a lattice
or "finite element" approach similar to Doublet Lattice rather than a pressure mode
approach (thus, it requires no selection of pressure weighting functions). It is
advertised to give better high reduced frequency representation than PGM or
ACUNN which is especially important for wing/fin combinations. The code was
enhanced for in-house use by the addition of a new general surface spline
capability and by making input/output data transfers more compatible to existing
aeroelastic facilities (ISAC system). ZONA is not as sensitive as ACUNN to
changes in aerodynamic modeling.

ZONA

An Unsteady Supersonic Aerodynamic Code for
Aeroelastic Applications   Source: Danny Liu

- Lattice method
- Linear, lifting surface theory
- Arbitrary configurations
- New surface spline capability
- Better aerodynamics with
  wing/fin combination
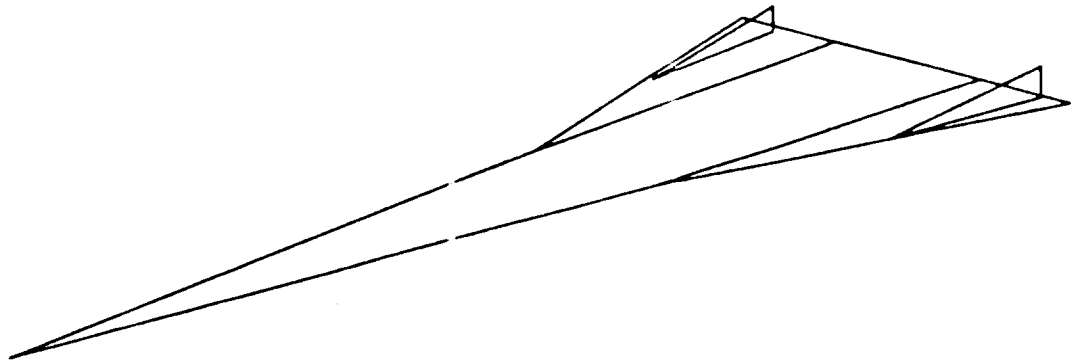
FINITE ELEMENT PISTON THEORY

A second order, linear Piston Theory that can be applied to three-dimensional surfaces has been implemented as part of a finite element code. The same finite element model used for the structure can be extended to be used in generating Piston Theory aerodynamics. As opposed to a lifting surface theory with thickness, the finite element Piston Theory can be easily used with wing-fin-body configurations. Generally, it can be used to Mach number of 10, or where wedge angle is less than the Mach cone angle, or where "local effect" aerodynamics are valid.

FINITE ELEMENT PISTON THEORY

- Applicable to preliminary designs

- Finite element approach

- Wing-Fin-Body applications

- Generally good between Mach numbers 2.5 to 10

- Small disturbance application

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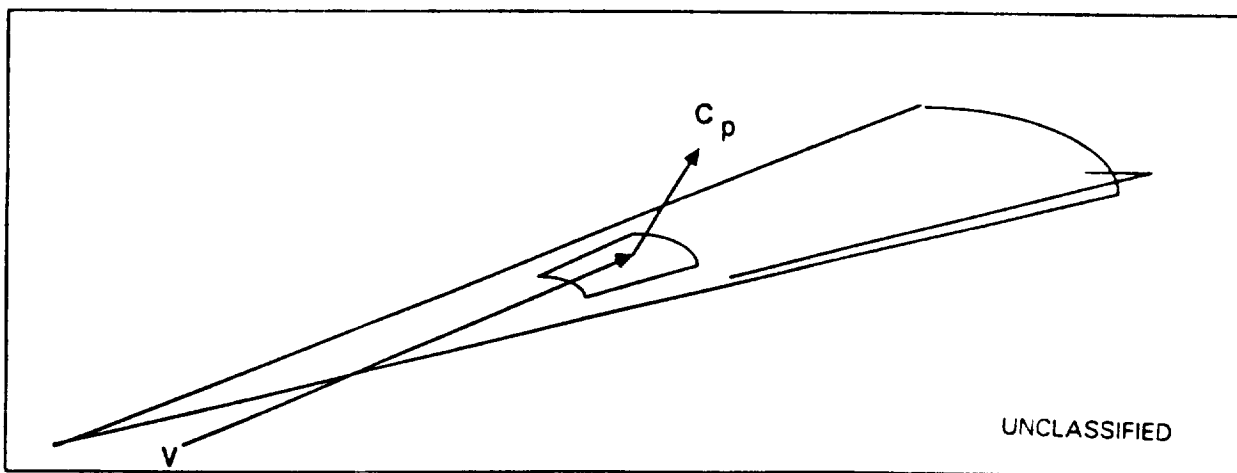
QUASI-STEADY APPROACH

There is little available for analyzing unsteady aeroelastic phenomena at the higher hypersonic speeds, nevertheless, one can take advantage of the physics of high speed flight by examining the equation for reduced frequency on the lower right side. Because the semichord is fixed and structural frequencies change little, reduced frequencies approach the "quasi-steady" range as velocity increases. In this range of reduced frequency, steady aerodynamics codes are available to generate quasi-steady solutions (such as Reynolds Averaged Navier Stokes (RANS), Parameterized Navier Stokes (PNS) or Euler SIMP). In the quasi-steady range, the aerodynamic modeling terms of generalized aerodynamic force coefficients can be shown to simplify to the following form:

$$GAF(S) = A_0 + A_1 \ (s \ b/v)$$

As in Piston Theory aerodynamics, it should be emphasized that these approaches should be used for preliminary design purposes only because there can exist some higher frequency unsteadiness that may not be modeled. We are investigating this concept and will attempt to establish conditions under which it is valid.

QUASI-STEADY APPROACH

- **Generally applicable when aeroelastic model within quasi-steady range of k**

- **Approach good at hypersonic speeds**

- **Simple aero modeling (GAF(s)=A_0+ A_1 sb/v)**

- **Useful with steady aerodynamic codes(k=0)**

Reduced frequency

$$k = \frac{\omega_f \ b}{V_f}$$

2b

13
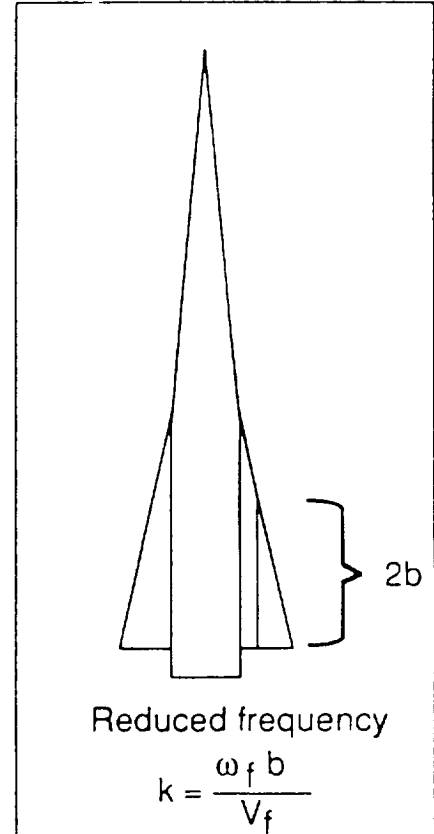
FLUTTER TREND STUDIES OF GENERIC NASP
WING-BODY CONFIGURATIONS

This part of the presentation emphasizes the need to understand various flutter mechanisms and trends which may apply to NASP-type vehicles. Detailed modeling of vehicle designs is extremely time consuming and inefficient for parametric studies, especially when there are many unknowns in material and construction concepts. Informative trend studies can, however, be conducted relatively fast with tools such as those listed.

The model generator creates simple models for use with Engineering Analysis Language (EAL), which is a general purpose finite element program produced by Engineering Information Systems, Inc. The unsteady aerodynamic codes used have been previously described. STABCAR is a program developed at NASA Langley which determines aeroelastic stability characteristics of flexible aircraft.

Some examples of flutter mechanisms and trends for cone body/delta wing configurations will be described.

FLUTTER TREND STUDIES OF
GENERIC NASP WING-BODY CONFIGURATIONS

OBJECTIVES-

   TO RAPIDLY ASSESS FLUTTER MECHANISMS AND FLUTTER
   BOUNDARY TRENDS OF VARIOUS NASP WING-BODY CONCEPTS

TOOLS-

   MODEL GENERATOR

   FEM- ENGINEERING ANALYSIS LANGUAGE (EAL)
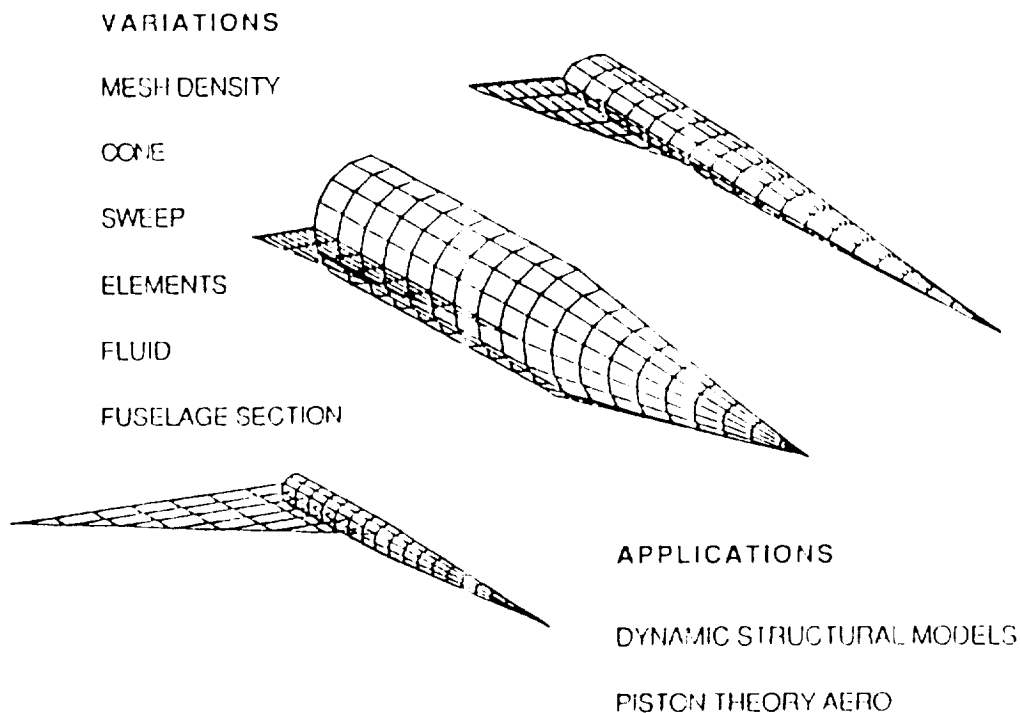
   SUBSONIC AND SUPERSONIC AERO CODES

   STABCAR

EXAMPLE RESULTS- TWO SMALL AND ONE FULL SCALE MODELS

WING-BODY MODEL GENERATOR

A few examples of models created with the model generator are shown. The mesh density, cone angle anywhere along the fuselage,and wing leading-edge sweep can be varied. The skin elements are usually bending-plate/membrane combinations. Fuselage rings consisting of beams may be selected. The wing may be flat plate or upper and lower skins with ribs and spars. Posts connecting the upper and lower skins may also be used. When using upper and lower skins, the leading and trailing edges converge to form knife edges. Another option is to create fluid elements with interface springs to represent fuel mass and stiffness. The fuselage cross section can be either circular or elliptical. The BASIC program will be enhanced as required for various components and configurations.

This capability was used to create the structural models which in turn produced the vibration modes for this study. Piston Theory computations, implemented with an EAL utility processor, were also performed for these models.

WING BODY MODEL GENERATOR

VARIATIONS

MESH DENSITY

CONE

SWEEP

ELEMENTS

FLUID

FUSELAGE SECTION

APPLICATIONS

DYNAMIC STRUCTURAL MODELS

PISTON THEORY AERO

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SMALL MODELS

Two finite element models were formed on a scale compatible with the Hanson Wing 1A discussed by Mike Gibbons. The fuselage was a five-degree circular cone similar to the concept studied at Langley last year and presented at the Third NASP Symposium by Rodney Ricketts ("Aeroelastic Considerations for an Airbreathing Single-Stage-to-Orbit Vehicle" (U)). To eliminate shell or "breathing modes," stiff, weightless fuselage rings were used. The baseline model had a relatively stiff fuselage so that the lower frequency modes would be strictly those of the wing. The fuselage of the second model was intentionally made flexible to allow wing-body modal coupling as was seen in the Langley study.

SMALL MODELS
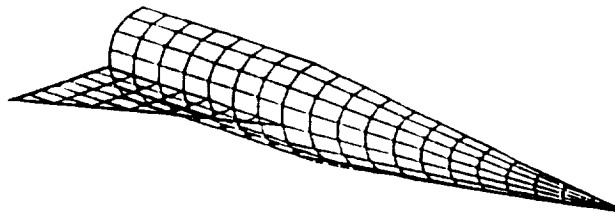
5 DEGREE CONE FUSELAGE SIMILAR TO LANGLEY STUDY
PRESENTED AT THE LAST SYMPOSIUM

SCALED FOR USE WITH HANSON WING 1A (70 DEG LE)

STIFF FUSELAGE RINGS

STIFF FUSELAGE

6 WING MODES, 89 TO 694 HZ

FLEXIBLE FUSELAGE

1 BODY MODE, 51 HZ
5 COUPLED MODES, 89 TO 276 HZ

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DOMINANT FLUTTER MODES

The dominant flutter mechanisms observed during analysis involved the coalescence of two modes, one containing wing-bending and one containing wing-torsion motion as shown. The flexible fuselage version, however, shows a great deal of fuselage motion in the coalescing modes. The result of this is that flutter occurs at a lower speed for the flexible fuselage than for the stiff fuselage.
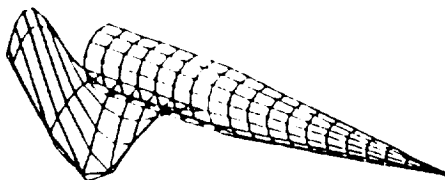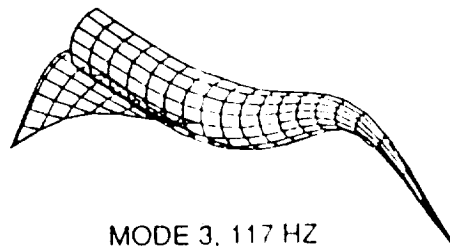
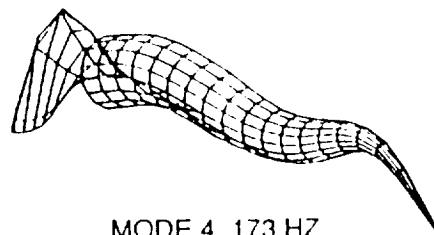# DOMINANT FLUTTER MODES

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STIFF FUSELAGE   FLEXIBLE FUSELAGE
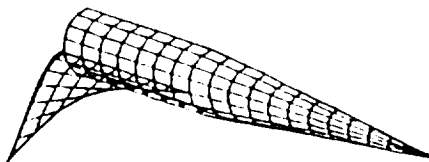
MODE 1, 89 HZ   MODE 3, 117 HZ

MODE 2, 218 HZ   MODE 4, 173 HZ

IMPACT-
LOWERS FLUTTER SPEED

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This slide shows a comparison of the flutter trends predicted by Piston Theory for the baseline and flexible fuselage models over a Mach number range of 3 to 10. The plot on the left gives flutter dynamic pressure as a function of Mach number. Pressure conditions above the line (flutter boundary) indicate flutter while those below are flutter free. The plot on the right shows corresponding flutter frequencies. Included on the plots are two additional points at Mach 3. These points are the Hanson 1A cantilevered test data and the corresponding ACUNN results. The Piston Theory results at Mach 3 appear good because the baseline fuselage behavior would be similar to a rigid support for the wing. Flutter dynamic pressure goes up with Mach number, and the flutter boundary for the flexible fuselage is significantly lower than for the baseline version.

# FLUTTER TRENDS FOR SMALL MODELS USING PISTON THEORY
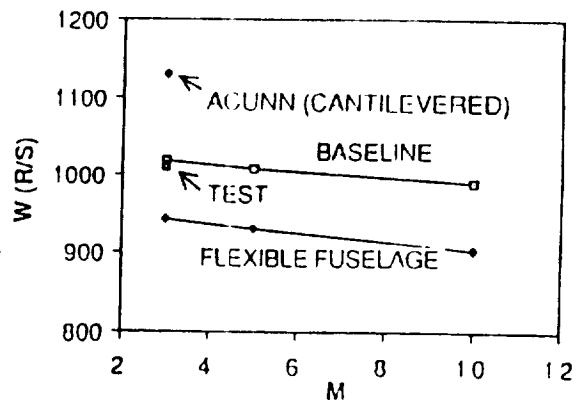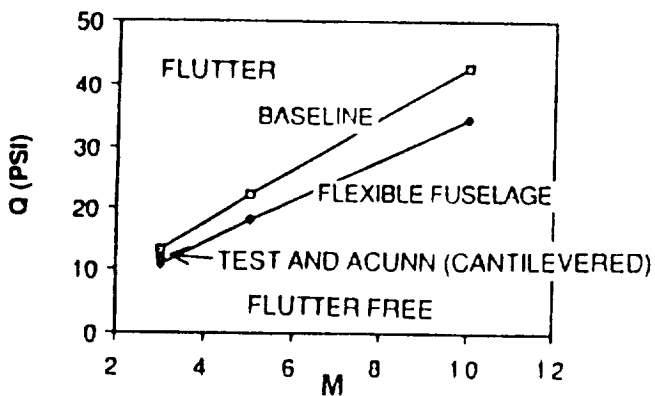
COMPARISON OF FLUTTER BOUNDARIES PREDICTED BY VARIOUS METHODS

The flutter results from ZONA, ACUNN, and Piston Theory are compared on this slide. For the stiff fuselage model, ZONA predicted the same flutter mechanism throughout the Mach range, while ACUNN indicated two lower "Q" flutter mechanisms at M=2.5. At all other conditions, ACUNN agreed reasonably well with the other methods. Piston Theory agreed well with ZONA at M=2.5 and 3.0. The test points were from similar conditions for Wing 1A in the Hanson data.

For the flexible fuselage, ZONA and ACUNN showed good agreement, and both indicated a mechanism shift (to the dominant mechanism described), between M=2.5 and 3.0. Piston Theory agreed well with the others after the shift but did not predict the lower "Q" flutter at M=2.5. Where the codes predicted the same mechanisms, the flutter conditions agreed well. Where the mechanism differed, poor agreement on flutter "Q" resulted.

COMPARISON OF FLUTTER BOUNDARIES PREDICTED BY VARIOUS METHODS


BASELINE
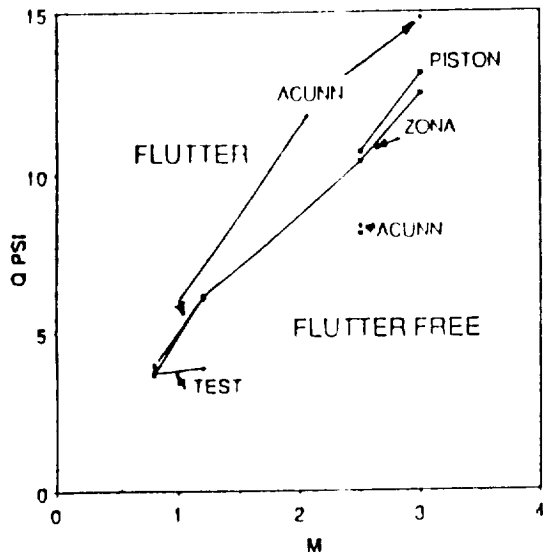
FLEXIBLE FUSELAGE
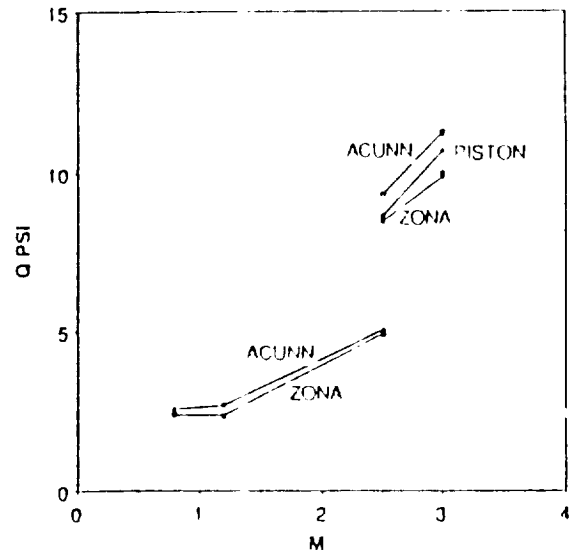
IMPORTANCE OF 3-D REPRESENTATION

The importance of thickness or three-dimensional representation is emphasized in some of the literature pertaining to hypersonic flight and was found to be relevant here. The implementation of Piston Theory in a finite element code allows three-dimensional directionality for the pressure calculations, and consequently, for the generalized aerodynamic forces. In this study the impact of 3-D representation did not become apparent until the Mach number exceeded 5. This slide shows the change in modal damping as density is increased. Negative damping indicates flutter. The plots on top are for the flexible fuselage model except that the fuselage is represented as flat with zero thickness, which is typical of classical methods. The bottom plots include the full 3-D representation. The plots on the left are for M=5, while those on the right are for M=10. Although there is little difference in the flutter point for the primary mechanism between the flat and 3-D models, there is dramatic change in modal damping for the 3-D model at M=10. It would be reasonable to expect that for certain configurations and flight conditions 3-D representation could be critical in predicting flutter.

IMPORTANCE OF 3-D REPRESENTATION

FLEXIBLE FUSELAGE

20
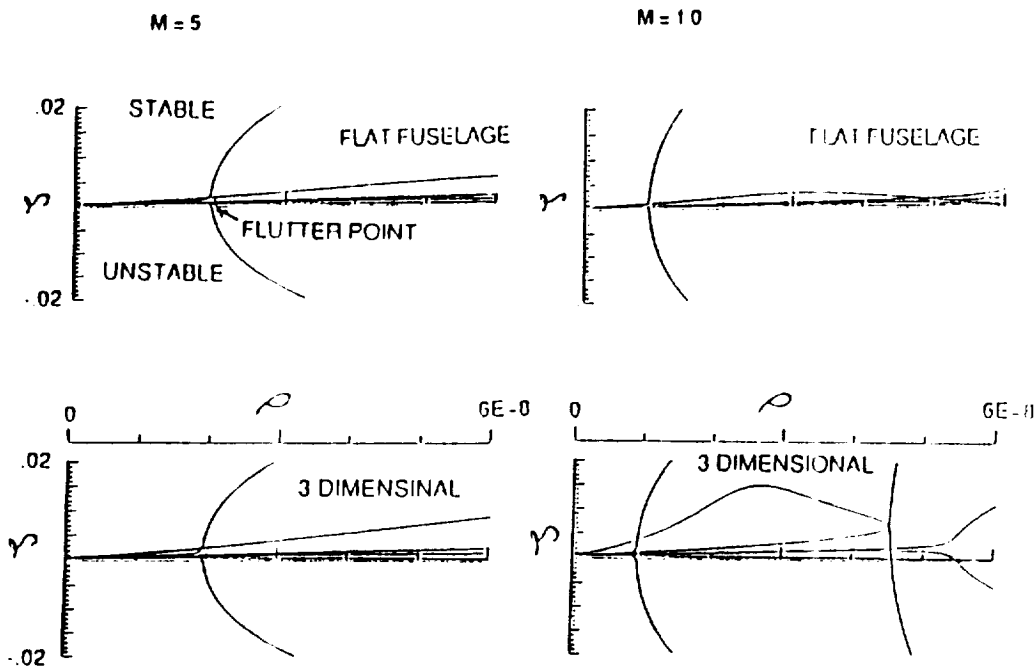
FULL-SCALE CONCEPT

In order to approximate behavior of a full-scale vehicle, the geometry of the small models was scaled up and the mass and frequencies were tuned to be similar to that of the Langley study referenced earlier. The six flexible modes used in the analysis were similar to the flexible fuselage in shape and ranged from 2.1 to 10.8 Hz. An atmospheric altitude variation flutter analysis was conducted, and the flutter mechanism was similar to the flexible fuselage model. The plot shows flutter altitude for M=3 to 10. The 2000 psf dynamic pressure line (possible ascent trajectory) is safely removed from the flutter boundary.

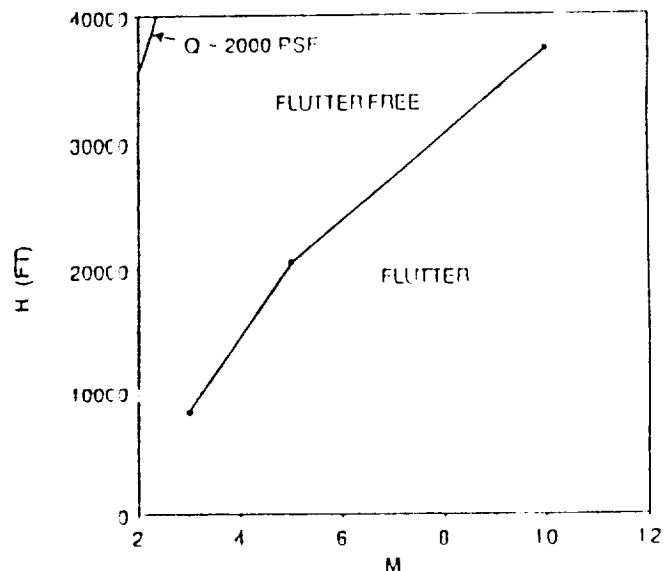# FULL SCALE CONCEPT

FULL SCALE MODEL

GEOMETRY SCALED UP
FROM SMALL MODELS

SIZE, MASS AND STIFFNESS
SIMILAR TO "90 DAY ATTACK"
CONCEPT

6 FLEXIBLE MODES FROM
2.1 TO 10.8 HZ

FLUTTER MECHANISM SIMILAR
TO FLEXIBLE FUSELAGE SMALL
MODEL

FLUTTER BOUNDARY

TRENDS

Trends indicated by this analysis are listed on the slide. Validation of these and other phenomena require testing. Following is a description of the work relating wing leading edge sweep to the ease of experimentally identifying the flutter boundary.

TRENDS

- FLUTTER Q TRENDS UP WITH M FOR THESE CONFIGURATIONS

- FLUTTER MECHANISMS AND TRENDS MAY CHANGE WITH
  FLIGHT CONDITION

- FLEXIBLE FUSELAGE AFFECTS FLUTTER

- THE IMPORTANCE OF 3D SHAPE (AS OPPOSED TO PLANFORM)
  INCREASES WITH M

FLUTTER ANALYSIS OF DELTA WINGS WITH LEADING EDGE SWEEP VARIATION

The purpose of this study was to examine how a variation in leading edge sweep angle for a delta wing may affect flutter sensitivity. The motivation for this analysis came from wind-tunnel tests conducted on a flat-plate aluminum model in which the onset of flutter was difficult to detect. Future wind-tunnel tests are planned based upon this analysis.

- DETERMINE THE EFFECT THAT VARIATION IN LEADING EDGE SWEEP ANGLE HAS ON FLUTTER SENSITIVITY

- MOTIVATION FOR THIS ANALYSIS FROM WIND TUNNEL TESTS OF FLAT PLATE DELTA WING MODEL IN WHICH THE ONSET OF FLUTTER WAS DIFFICULT TO DETECT

- CONSTANT AREA FOR EACH MODEL WITH THICKNESS VARIED IN ORDER TO OBTAIN FLUTTER POINTS AT CONSTANT DYNAMIC PRESSURE

- ACUNN CODE USED TO CALCULATE THE AERODYNAMICS, STABCAR USED FOR THE FLUTTER ANALYSIS

- FUTURE TESTS ARE PLANNED FOR THE TRANSONIC DYNAMICS TUNNEL AT LANGLEY RESEARCH CENTER TO VERIFY THIS STUDY

- ONCE THIS PROBLEM WITH SIMPLE MODELS HAS BEEN DEALT WITH, MORE COMPLEX MODELS WILL BE TESTED FOR FLUTTER

WIND-TUNNEL MODEL

Pictured is the wind-tunnel model which had been tested in the Transonic Dynamics Tunnel at NASA Langley Research Center prior to this study. It was a flat-plate aluminum model and was cantilevered at the root chord. The test was made using a density variation with freon as the medium.

WIND TUNNEL MODEL

72°   V
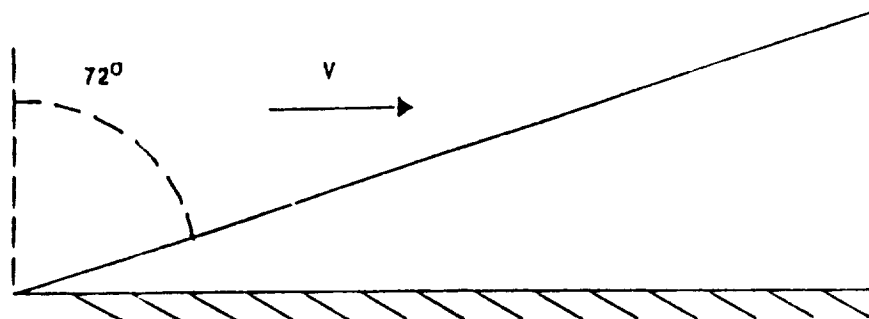
- FLAT PLATE ALUMINUM
- 72 DEGREE SWEEP ANGLE
- DENSITY VARIATION USING FREON AS THE MEDIUM
- RUN IN THE TRANSONIC DYNAMICS TUNNEL AT NASA LANGLEY RESEARCH CENTER

WIND-TUNNEL RESULTS

Strain gage measurements taken from the wind-tunnel test were used to plot the inverse deflection amplitude of the model versus increasing dynamic pressure. This technique is used to project where flutter will occur. As can be seen below by the dotted line, the tunnel test data has been extrapolated to this point, which is where analysis had predicted that flutter would occur. However, the test data shows a bend in the curve occurred and the point at which flutter started was not clearly defined.

WIND TUNNEL RESULTS

CALCULATED FLUTTER POINT

1 / AMPLITUDE

DYNAMIC PRESSURE (PSF)
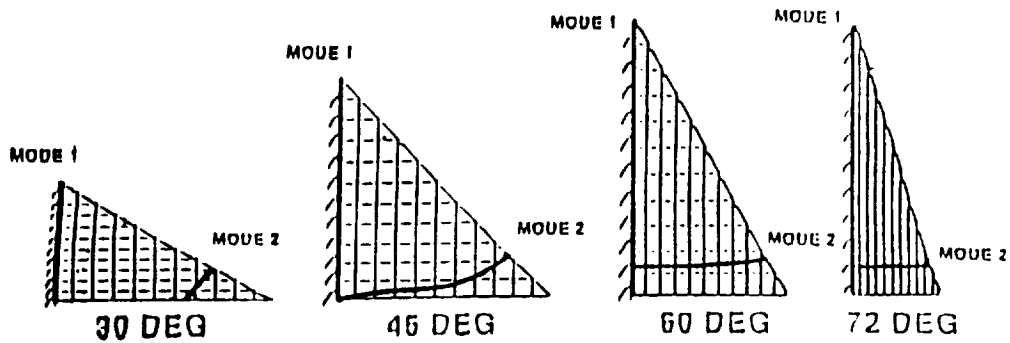
100   140   180
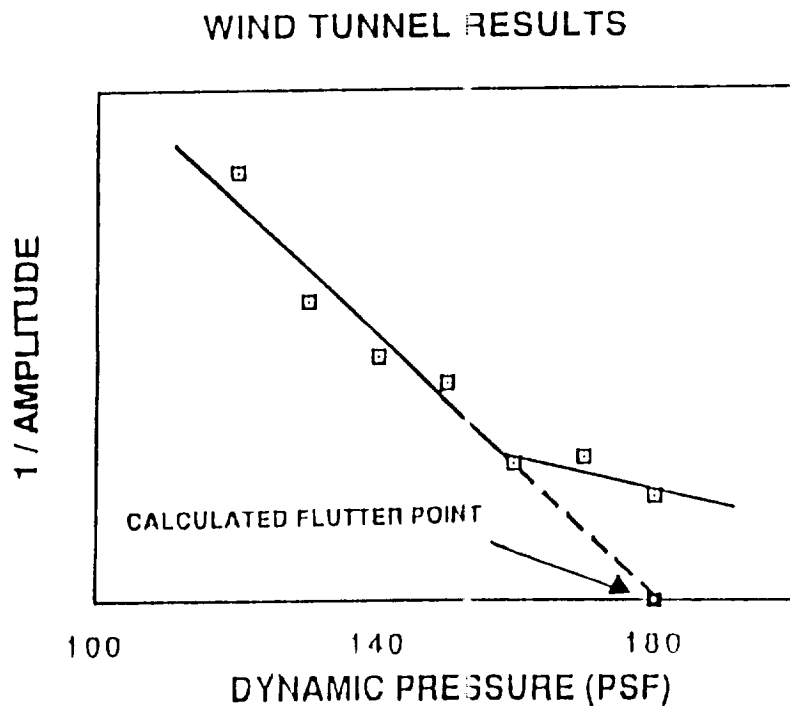
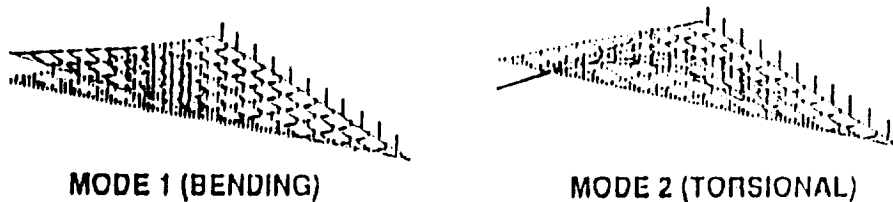# VIBRATION CHARACTERISTICS WITH WING SWEEP VARIATION

Pictured are the four models which were analyzed. Each of the four models had the same area. The node lines are on each model for the first two modes. The first two mode shapes are shown for the 60-degree model. The first mode for each model was a bending mode at the root chord. The second mode for the 30-degree model was a cross between a second bending and first torsion. The second mode for the other three models was basically a torsion mode.

VIBRATION CHARACTERISTICS WITH WING SWEEP VARIATION

### NODE LINES

MODE 1			
MODE 1			
MODE 1	MODE 1	MODE 1	MODE 1
MODE 2	MODE 2	MODE 2	MODE 2
30 DEG	45 DEG	60 DEG	72 DEG

MODE SHAPES

MODE 1 (BENDING)   MODE 2 (TORSIONAL)

FREQUENCY AND DAMPING VERSUS DENSITY
60-DEGREE MODEL

As seen below, there is a coalescence of modes one and two at the point where flutter occurs. Flutter takes place with the first crossing of a mode into the negative damping region. Flutter sensitivity will be defined here as the slope of the line at this crossing.

FREQUENCY & DAMPING VS DENSITY
60 DEGREE MODEL
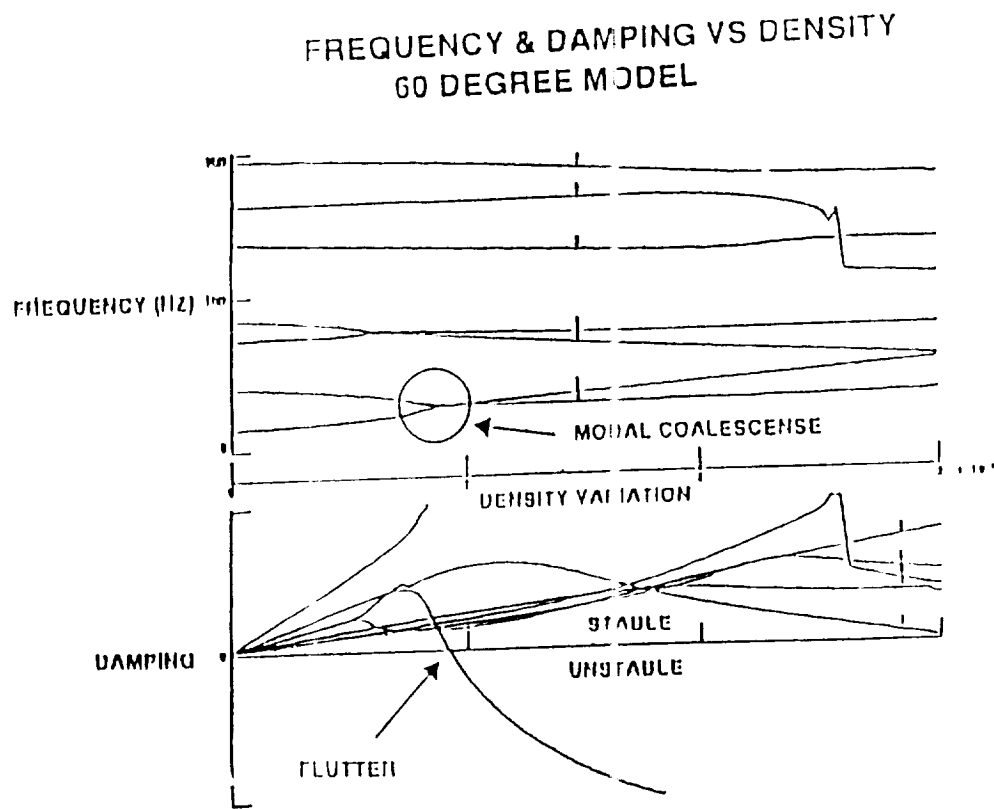
FLUTTER Q VARIATION WITH INCREASING SWEEP ANGLE

This plot was obtained by using the same thickness for each model. It shows how the flutter q increases with increasing sweep angle. The next step was to change the thickness of the 30-, 45-, and 60-degree models in order to obtain the same flutter q for each of those as the 72-degree model.

FLUTTER Q VARIATION WITH SWEEP ANGLE

SUBSONIC, M=0.8
CONSTANT THICKNESS

FLUTTER Q (PSF)

SWEEP (DEG)
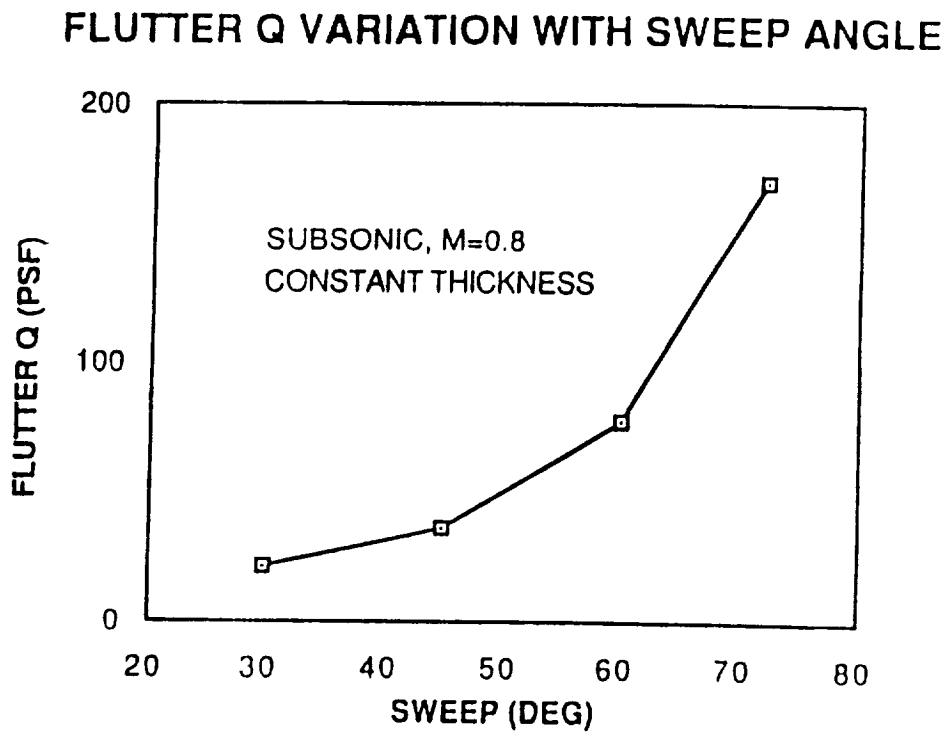
SIZING MODELS FOR CONSTANT FLUTTER Q

Flutter calculations were made with varying thickness for the 30-, 45-, and 60-degree models to obtain the family of curves shown. The 72-degree model flutter q for a particular thickness was then traced across these curves. The design thickness for each model was obtained at the junction of the model's curve with the design q line.
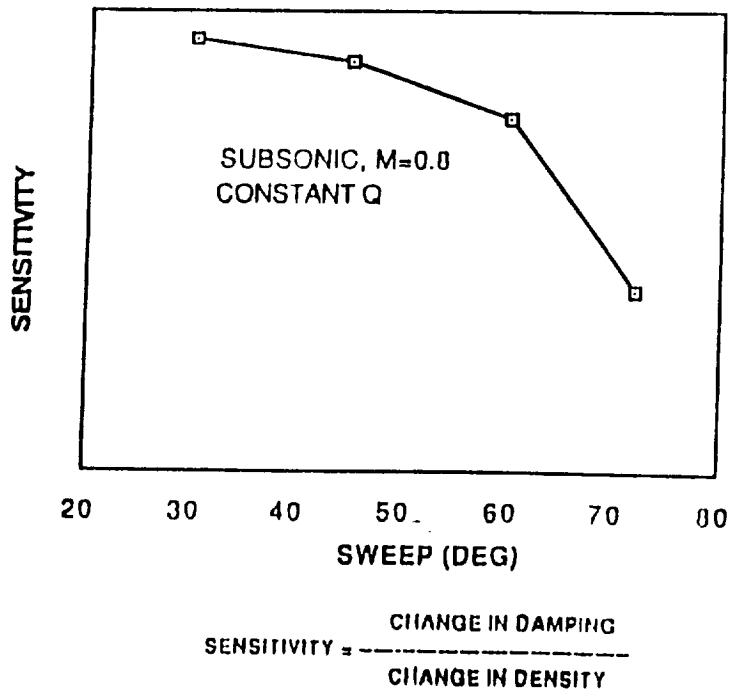
SIZING MODELS FOR CONSTANT FLUTTER Q
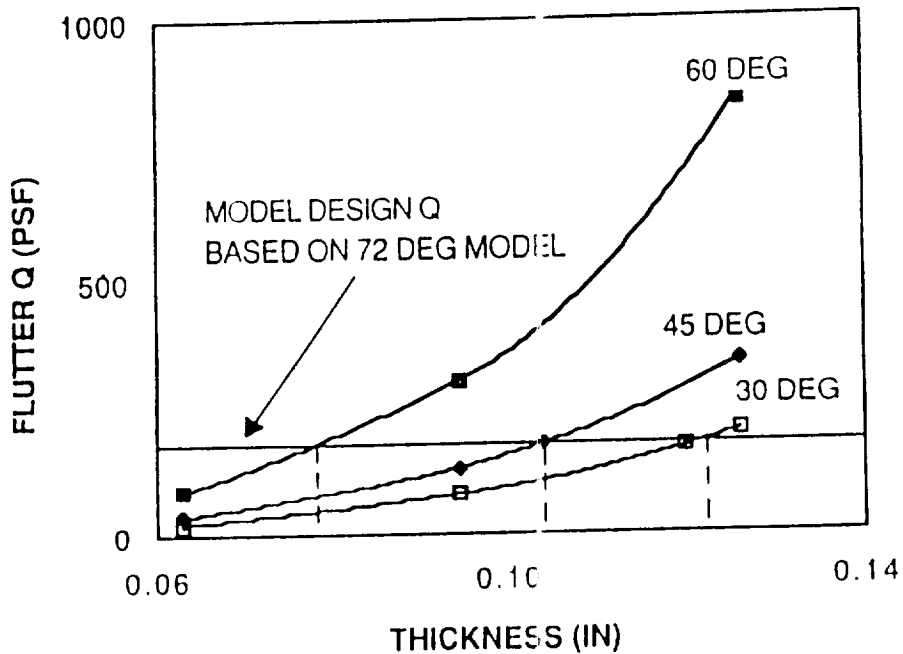
DECREASING FLUTTER SENSITIVITY WITH INCREASING SWEEP ANGLE

This plot indicates the trend of decreasing flutter sensitivity as the leading edge sweep angle is increased. In particular, there is quite a drop-off in flutter sensitivity between the 60- and 72-degree models. It is felt that the difficulty in identifying flutter points with the 72-degree wind-tunnel model may be attributed to this decrease in flutter sensitivity for highly swept delta wings.

DECREASING FLUTTER SENSITIVITY WITH INCREASING SWEEP ANGLE

SUBSONIC, M=0.8
CONSTANT Q

SENSITIVITY

SWEEP (DEG)

20   30   40   50.   60   70   80

$$\text{SENSITIVITY} = \frac{\text{CHANGE IN DAMPING}}{\text{CHANGE IN DENSITY}}$$

SWEEP SENSITIVITY RESULTS

       Analysis indicates that flutter for delta wing models occurs as the first bending and first torsional modes coalesce. For the low leading edge sweep angles, i.e., 30- to 60- degrees, the flutter sensitivity is substantially higher than for models with leading edge sweep angles greater than 60 degrees. This may be the cause of the inability to identify flutter points in the wind tunnel with the 72-degree model. Wind-tunnel tests based upon this study have been planned to determine the nature of these delta wing flutter models experimentally. Once this has been nailed down, more complex models will be tested.

SWEEP SENSITIVITY RESULTS

- ANALYSIS SHOWS THAT FLUTTER OCCURS AS THE 1ST BENDING AND 1ST TORSIONAL MODES COALESCE

- INCREASING THE SWEEP ANGLE ON A DELTA WING CONFIGURATION DECREASES THE FLUTTER SENSITIVITY

- FUTURE WIND TUNNEL TESTS ARE TO BE CONDUCTED BASED UPON THIS ANALYSIS

CONCLUSION

This slide shows major conclusions from these studies.

CONCLUSION

- Analysis showed good agreement with existing wind-tunnel test results in the subsonic range, but mixed agreement in the supersonic range.

- Unsteady aerodynamic methods are being developed and evaluated to give better analytical results in the supersonic range and develop new and improved capabilities in the hypersonic range.

- Trend studies using simple models and approximate aerodynamic methods are valuable in conceptual design.

- Results based on leading edge sweep flutter sensitivity studies will be used to guide and evaluate future wind-tunnel testing of delta wing configurations.

PLANS

Our plans are to continue developing capabilities and perform analysis and testing in support of NASP with emphasis on those areas listed on the slide. Of particular interest at this time is the integration of thermal effects into the aeroelastic analysis process. Work has been initiated to determine the best approach for calculating temperature distributions and the associated changes to a NASP vehicle encountering hypersonic heating while carrying cold liquid hydrogen fuel. These temperature gradients affect internal stresses, material properties, and aerodynamic shape, all of which have an impact on aeroelastic behavior.

PLANS

MODELING-   VARIOUS CONFIGURATIONS
CONTROL SURFACES AND FINS
RIGID BODY , ANTISYMMETRIC AND BREATHING MODES
FLUID BEHAVIOR

METHODS-   EFFECTS OF HEATING
ADDITIONAL AERO CODES

ANALYSIS-   AEROELASTIC TRIM
GUST RESPONSE
AEROTHERMO ELASTICITY
AEROSERVO ELASTICITY

TESTING-   AEROELASTIC WIND TUNNEL MODELS

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16. Abstract

This report documents a presentation provided at the Fourth National Aerospace Plane Technology Symposium held in Monterey, California, during February 1988. The objective of the presentation was to provide current results of ongoing investigations to develop a methodology for predicting the aerothermoelastic characteristics of NASP-type (hypersonic) flight vehicles. Several existing subsonic and supersonic unsteady aerodynamic codes applicable to the hypersonic class of flight vehicles that are generally available to the aerospace industry are described. These codes were evaluated by comparing calculated results with measured wind-tunnel aeroelastic data. The agreement was quite good in the subsonic speed range but showed mixed agreement in the supersonic range. In addition, a future endeavor to extend the aeroelastic analysis capability to hypersonic speeds is outlined. An investigation to identify the critical parameters affecting the aeroelastic characteristics of a hypersonic vehicle, to define and understand the various flutter mechanisms, and to develop trends for the important parameters using a simplified finite element model of the vehicle is summarized. This study showed the value of performing inexpensive and timely aeroelastic calculations using simplified structural and aerodynamic models. Finally, ongoing and proposed aeroelastic wind-tunnel tests to expand the experimental data base required for code validation using simple to complex models that are representative of the NASP configurations and root boundary conditions are discussed.

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