ANALYTICAL METHODS WITH APPLICATION TO THE PATHFINDER I MODEL

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Introduction

The utilization of the high Reynolds number test capability provided by the National Transonic Facility (NTF) requires that models and stings designed and analyzed for operation in a cryogenic environment and in some cases at high dynamic pressures. The combination of high aerodynamic loads and strength limitations on cryogenically acceptable materials will necessitate that model/sting systems be designed to lower safety factors than those which have been used for conventional wind tunnel model/sting systems. This will necessitate that more rigorous and, in some cases, highly sophisticated analyses be performed along with math model verification tests. Also, proof testing may be required for critical applications.

Thermal Analysis

The importance of the thermal analysis for NTF models should not be underestimated. Because of the tunnel transients there will be thermal gradients in the various system components and temperature differences between mating parts. These effects must be evaluated since they can lead to high stresses or loose structural joints.

The cryogenic models will be subjected to various thermal transients. First, there is the initial cooldown period. Also, there will be changes in the tunnel test conditions. In order to make alterations to the models, the tunnel has been designed such that the model and a portion of the sting can be isolated from the cryogenic environment. This is done by enclosing the model in a moveable tube-like structure which passes across the test section. Before model changes can be made, the model must be heated. After model changes are made, the model will be subjected almost instantaneously to the cryogenic environment.

The effects of these transient conditions on the entire model, balance, and sting system must be examined. This means that several thermal math models may need to be developed in order to determine the time-dependent temperature distributions in the various parts. An evaluation of resulting gradients may show the existence of large thermal stresses.

The effects of thermal gradients and temperature changes on the structural joints in each system must be investigated. Since a loss of joint stiffness could lead to divergence or flutter problems, special attention should be given to the model-to-balance joint and to the balance-to-sting joint. For these and other joints, appreciable preloads may be needed in order to avoid joint looseness. When preloading, consideration should be given to both the positive and negative temperature swings so as to avoid over-stressing the joint.

The areas examined on the Pathfinder I model include the temperature distribution in the wing, the dowels in the wing which pass through the tongue and groove joint, the wing/strong back joint, the temperature distribution in the balance, the balance/sting joint, the sting/stub sting joint, the gradient in sting at the rear of the model, the heating requirements for the instrumentation package, and the temperature distribution along the fuselage surface in the region near the instrumentation package. The only design modifications resulting from the thermal analysis were (1) to increase the number and size of the dowels in the wing and (2) to change the eight wing/strong back shoulder bolts from a tight fit to a clearance fit and add two dowels.

Stress Analysis

In view of the potentially high aerodynamic loadings and large thermal gradients, a very thorough stress analysis is required for each model and sting system. The stresses in the various components of the system will probably be evaluated using both finite element and strength of material approaches. The thermal stresses will be studied using finite element models except in instances where the geometry and temperature distribution can be represented by a classical theory of elasticity problem whose solution is known.

Since many models will be designed with small safety factors, much emphasis must be given to stress concentrations. There are numerous reports and handbooks available for determining stress concentration factors. Also, if necessary, stress concentrations can be evaluated by making detailed finite element models of the highly stressed regions.

For the Pathfinder I model, the highest stress is due to the stress concentration around the orifice plugs in the wings. Other sources of stress concentrations are dowels or shear pins such as those incorporated in the Pathfinder I wing. Whenever possible, care should be taken to avoid placement of pins in highly stressed regions. Also, consideration should be given to designing pins to have slight interference fits since this can increase the fatigue life.

Development of Elastic Math Models

The aeroelastic and deformation analyses are dependent upon the development of accurate elastic math models of the model and sting system. For the Pathfinder I model, two different types of math models were used in the analysis: one is a beam representation of the wing and the other is a finite element approach.

It is believed that many high aspect ratio wings such as those of Pathfinder I can be analyzed by treating the wing as a beam. The deformations (bending in two planes, torsion, and extension) are described by twelve first-order differential equations. The static and natural vibration solutions to the equations are obtained using a transfer matrix approach that is based upon Runge-Kutta integration.

The beam approach is a quick and efficient method for calculating stresses, deflections, and frequencies. The solution method easily handles any discontinuities in the cross-sectional properties. Also, the formulation conveniently accommodates displacement-dependent loads as well as direct loads.

A beam math model was used to predict the deformations and stresses for the Pathfinder I wing.

Two finite element models have been developed for analyzing Pathfinder I. One is a detailed model of the wing by itself and the other is a model of the system.

A SPAR model of the wing alone was developed using solid finite elements. SPAR is a general purpose finite element computer program for performing structural and thermal analyses. This model is made up of about 600 elements.

The SPAR program was chosen for modeling the Pathfinder I model/balance/sting system since it is compatible with some of the flutter codes available at the Langley Research Center. The wing was modeled using plate elements. The stiffness and mass properties of the fuselage, balance, and sting were represented by beam elements. The sting was assumed cantilevered at the strut.

The natural frequencies of this plate model wing by itself have been computed. It was found that for the first three nodes, the calculated frequencies agreed within 8 percent with the measured frequencies of a supercritical test wing which is nearly identical to the Pathfinder I wing.

The PATRAN-G computer program, which has been recently leased by the Langley Research Center, appears to be a very useful tool for analyzing wind tunnel models. The program is an expedient method for generating structural finite element models. From an interactive terminal, the user of the program generates a geometric model of the structure. Then, by using the appropriate translator, the finite element model is automatically generated from the geometric model. Translators are currently available for the NASTRAN and EAL finite element programs. The PATRAN-G program was recently used to develop a finite element model of the Pathfinder I wing.

Verification Testing

It is important that the elastic math models used in the analyses be verified by testing of the actual hardware. This is especially true if the design is marginal. The math models can be confirmed by performing load/displacement tests, measuring natural frequencies, and using strain gage data. Also, joint effects, which are often unpredictable, can be evaluated by testing.

Load/displacement tests have been conducted on supercritical wings which are very similar to the Pathfinder I wings. The test wings have the same airfoil shape and the same planform as the Pathfinder I wings. One of the test wings has a solid cross section and the other has a tongue and groove joint similar to that of the Pathfinder I design. The only significant structural difference between the Pathfinder I wing and the supercritical test wing having the tongue and groove joint is that the Pathfinder I wing is continuous from tip to tip, whereas the test wing is a semi-span wing. The testing of both the solid and the tongue and groove wings was not only beneficial for obtaining data for comparing with calculated results, but showed the effects of the tongue and groove joint on the bending and torsional stiffnesses and on the natural vibration characteristics.

The bending displacements were measured with a machine that is normally used for measuring and checking the coordinates of models. The load was applied using a screw jack and load cell arrangement with the load being monitored with a digital readout. Each wing was bolted to the fixture in the same manner that it is fastened to its fuselage. The wings were loaded at seven equally spaced points along the elastic axis. For each point load, the displacements were measured at a large number of points on the wing's surface. The coordinate measurements made before, during, and after each loading were recorded on punch cards for later data processing.

With the wing mounted to the same fixture, torsional load/displacement tests were also made. The torque was applied through a device which was clamped to the airfoil.

The calculated bending displacements were found to agree very well with the measurements for all seven of the loading conditions. However, the torsional tests indicated that the torsional stiffness of the tongue and groove test wing is only about one-half of that calculated from the cross-sectional data. This stiffness reduction can definitely be attributed to the tongue and groove joint since the tests conducted on the solid wing showed very good agreement between the measured and calculated torsional displacements.

Deformation Analysis

The deformation analysis is essential to the design of highly loaded models. Because of the large deformations, many models will be built with a jig shape such that the model lifting surfaces will have the proper shape when loaded. Thus, it is necessary to be able to predict accurately the deflections of wings under aerodynamic loads. After the beam math model was verified by the load/displacement tests discussed above, the jig shape for the Pathfinder I model was computed for the cruise condition loads (C_L = 0.555 and q = 2800 psf).

Aeroelastic Analyses

The aeroelastic analyses require the development of a math model of the entire model, balance, and sting system. The aeroelastic analyses consist of determining the natural vibration modes, using these modes as displacement functions in the flutter and divergence studies, and performing any needed dynamic response analyses.

It is thought that the flutter analysis, as well as the divergence analysis, must treat the entire system. As might be expected, vibration tests at Langley Research Center have shown appreciable differences in the modes and frequencies of the aforementioned supercritical wing mounted on and off the balance/sting support. These differences reflect the influence of balance/sting flexibility effects on the system model characteristics. Also, since aeroelastic divergence and flutter are of great concern for models that may be tested at high dynamic pressures in the NTF, the analyses must give particular attention to the stiffness of structural joints.

There are various computer codes available at Langley for performing flutter analyses. A system of programs called FAST (flutter analysis system) was used in the analysis of the Pathfinder I model. The unsteady aerodynamics programs in FAST are based on the subsonic kernel function lifting-surface theory.

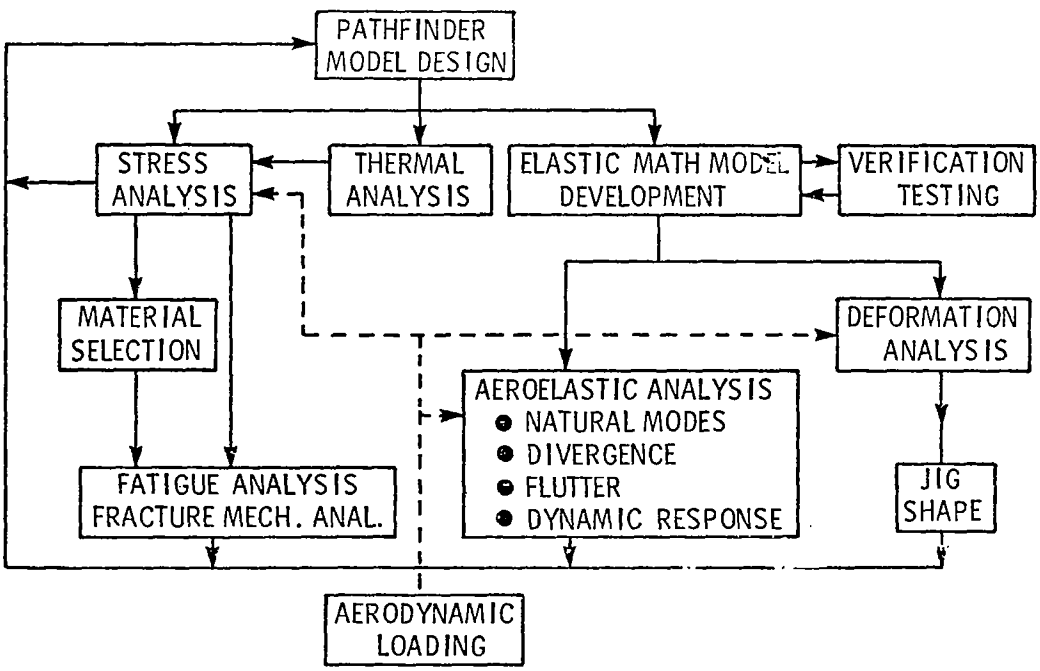
Integrated Computer Program

It is planned that the various elements of the analysis discussed above will eventually be combined into an integrated computer program. Such a program is needed for efficient and systematic evaluation of model/sting systems for the NTF.

REQUIRED ANALYSES

- AERODYNAMIC LOADS
- THERMAL ANALYSIS
- STRESS ANALYSIS
- FATIGUE ANALYSIS
- FRACTURE MECHANICS ANALYSIS
- DEFORMATION ANALYSIS
- VIBRATION ANALYSIS
- FLUTTER ANALYSIS
- DIVERGENCE ANALYSIS

DESIGN BY ANALYSIS FLOW DIAGRAM



COMPUTER PROGRAMS BEING USED FOR ANALYZING CRYO MODELS

- EAL/SPAR
  - DEFORMATION ANALYSIS
  - STRESS ANALYSIS
  - NATURAL VIBRATION CHARACTERISTICS
  - THERMAL ANALYSIS
- FAST
  - FLUTTER ANALYSIS
  - DIVERGENCE ANALYSIS
- STING DIVERGENCE PROGRAM
- STING DEFORMATION PROGRAM
- SPECIAL PROGRAMS FOR HIGH ASPECT RATIO WINGS
  - CROSS-SECTIONAL PROPERTIES PROGRAM
  - DISTRIBUTED AERODYNAMIC LOADS PROGRAM
  - WING DEFORMATION PROGRAM
  - WING STRESS PROGRAM
- FRACTURE MECHANICS PROGRAMS

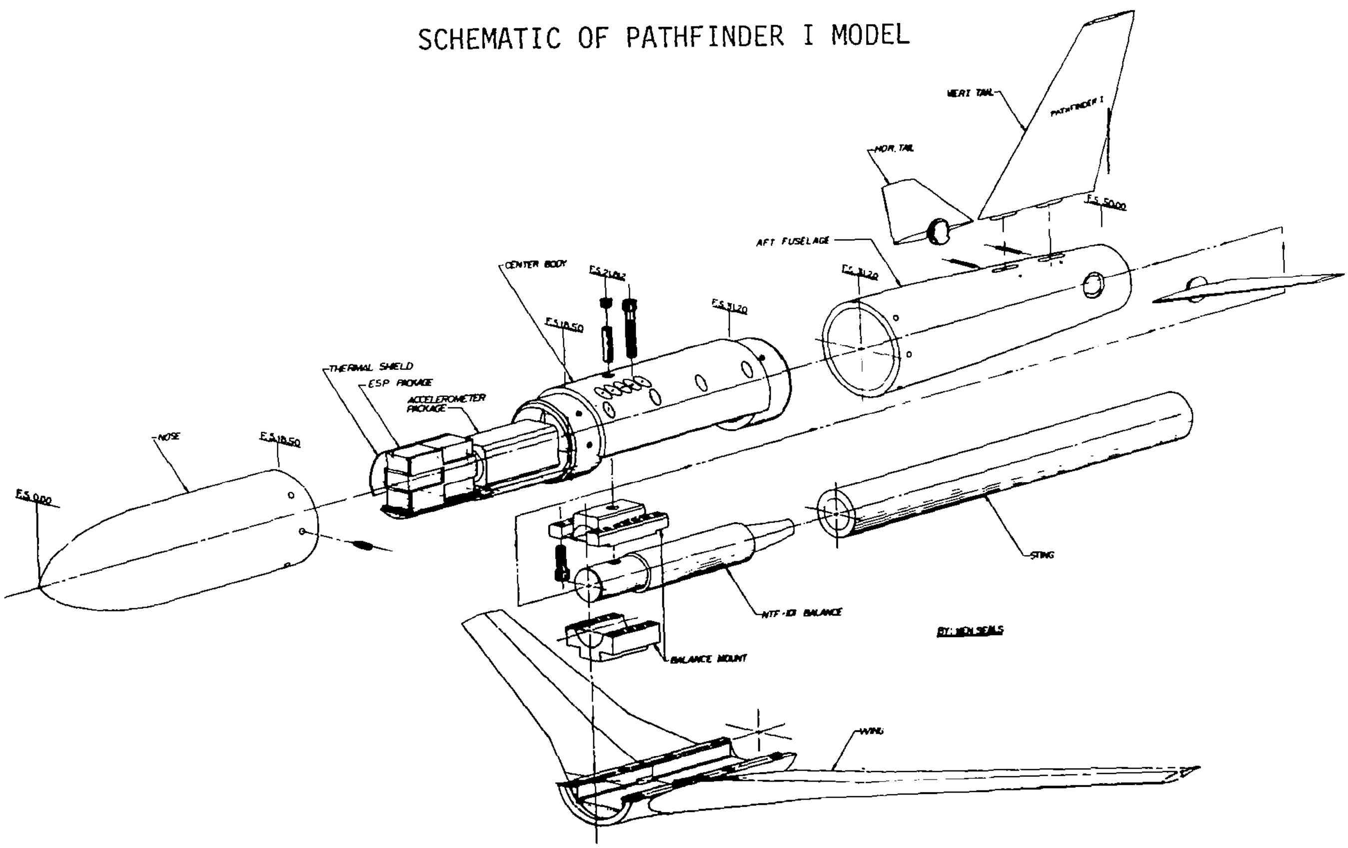
OTHER AVAILABLE COMPUTER PROGRAMS
FOR ANALYZING CRYO MODELS

- PATRAN-G (FEM GENERATOR)
- NASTRAN
  - STRESS ANALYSIS
  - DEFORMATION ANALYSIS
  - NATURAL VIBRATION CHARACTERISTICS
  - THERMAL ANALYSIS
  - FLUTTER ANALYSIS
- MITAS (THERMAL ANALYSIS)

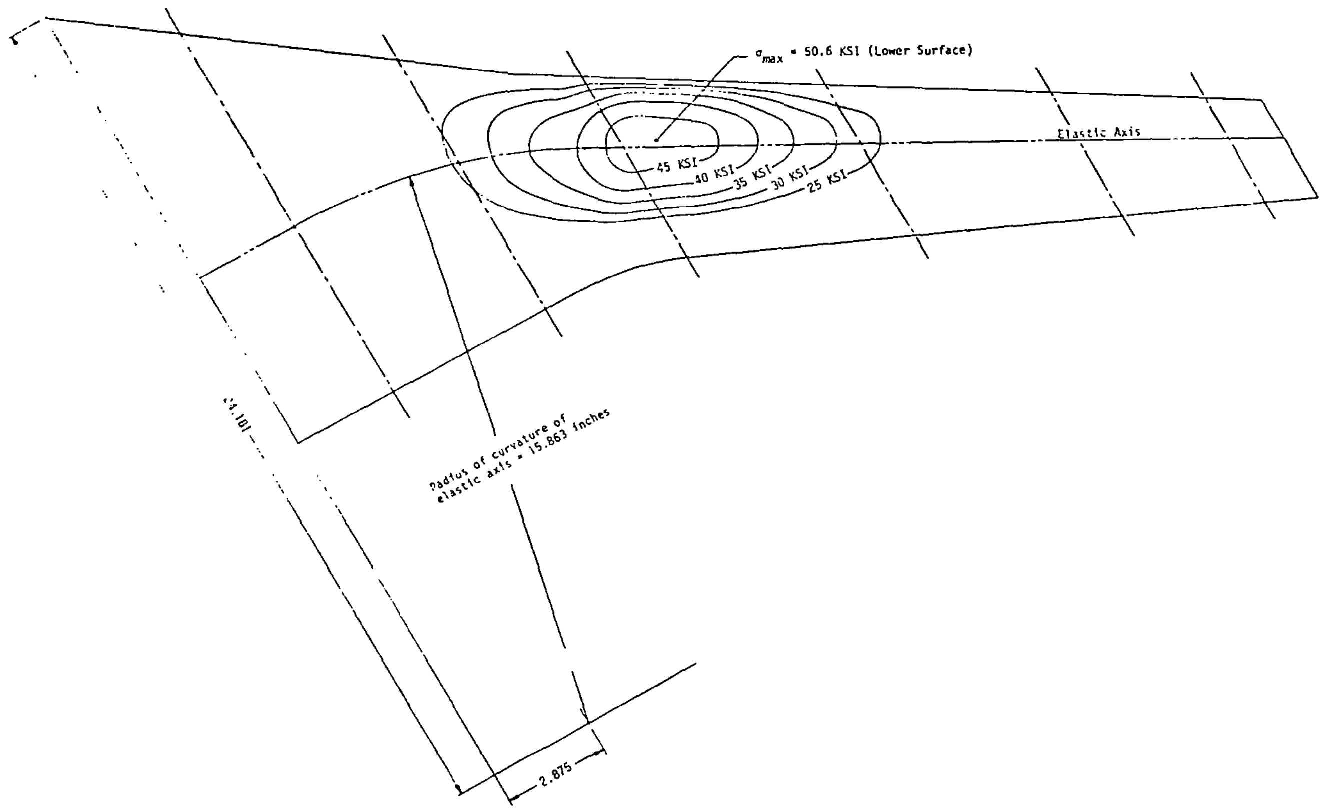
THERMAL ANALYSES

- SOURCES OF TRANSIENT CONDITIONS
  - INITIAL COOLDOWN
  - CHANGE IN TUNNEL TEST CONDITIONS
  - BEFORE AND AFTER MODEL CHANGES
- AREAS TO BE INVESTIGATED
  - THERMAL GRADIENTS
  - TEMPERATURE DIFFERENCE OF MATING PARTS
  - INSULATION OF INSTRUMENTATION PACKAGE
  - TIME TO REACH THERMAL EQUILIBRIUM

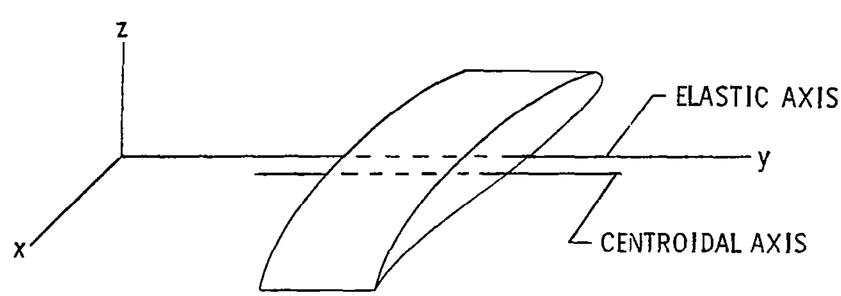
SCHEMATIC OF PATHFINDER I MODEL



BENDING STRESS DISTRIBUTION
FOR C_L = 1.0, Q = 2800 PSF



BEAM MODEL OF WING

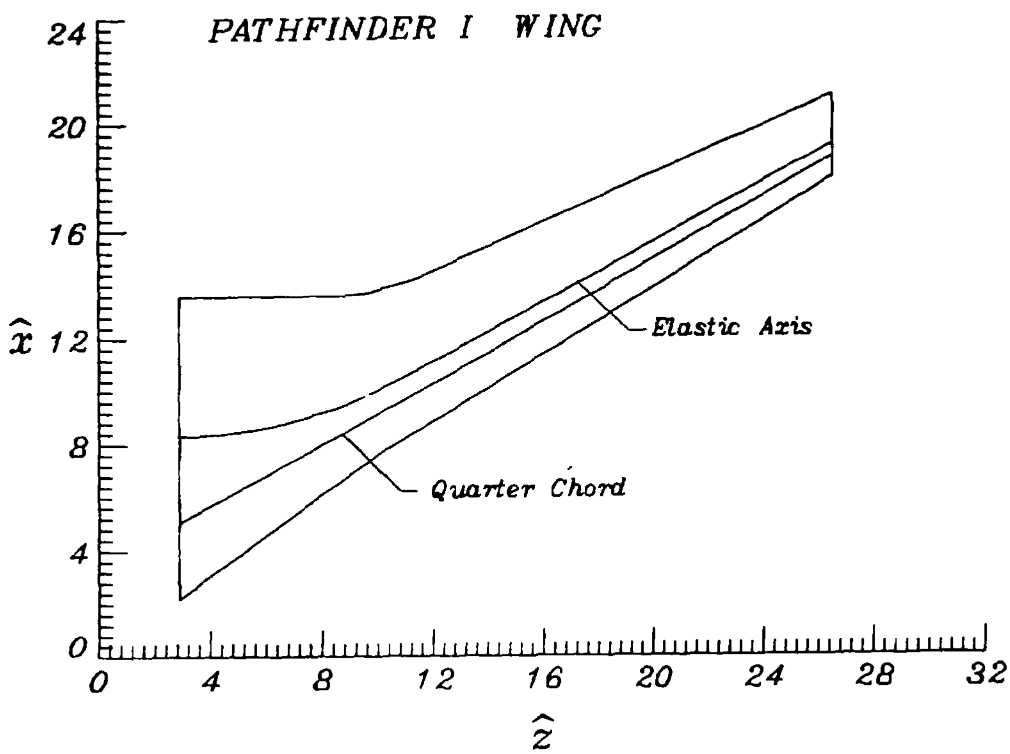


ASSUMPTIONS

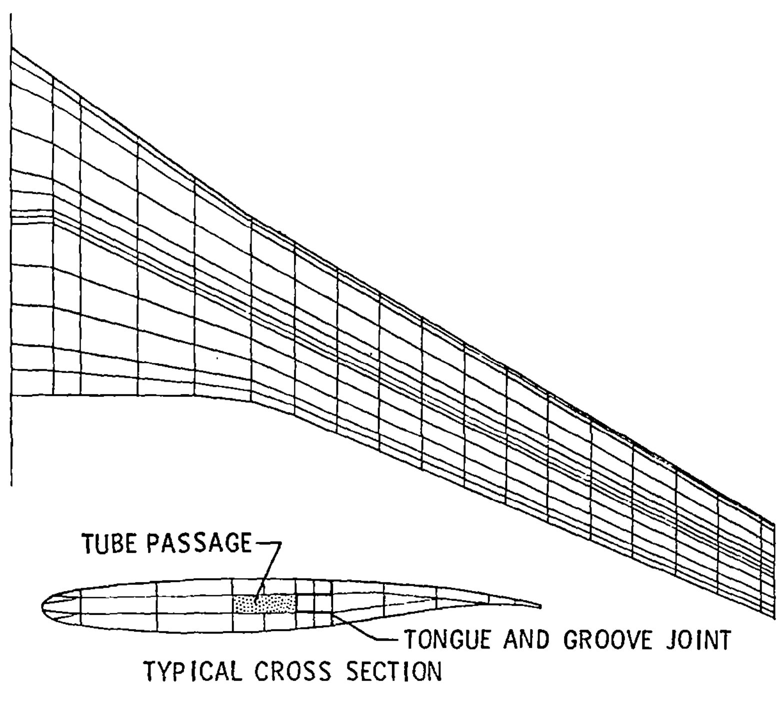
- TWISTED CANTILEVERED BEAM
- UNSYMMETRICAL CROSS-SECTION
- BENDING IN TWO PLANES, TORSION, EXTENSION

FEATURES

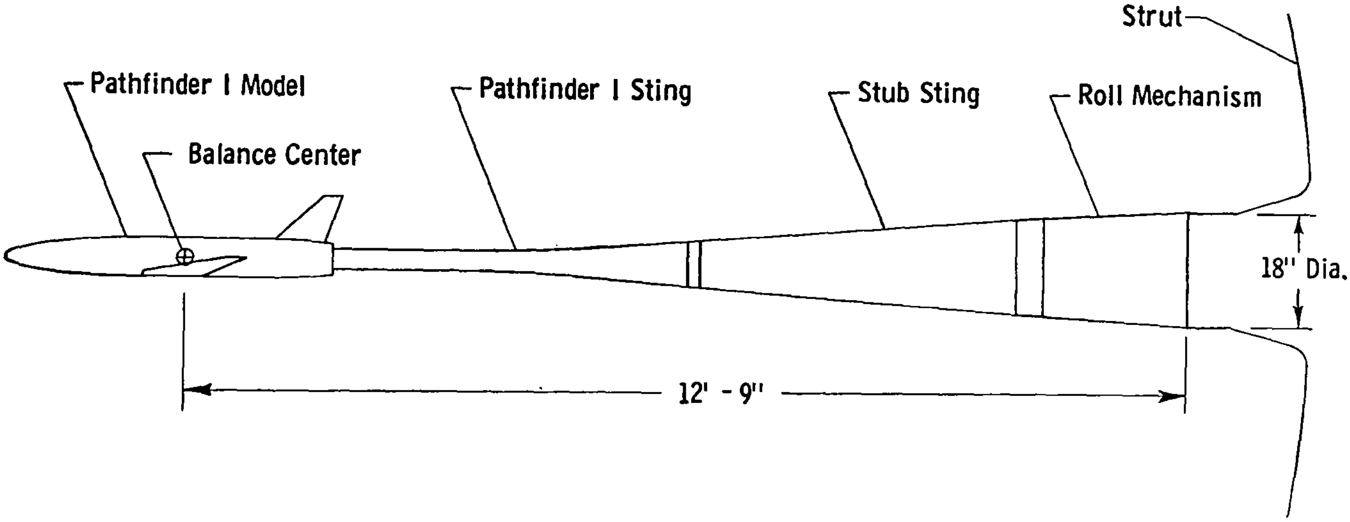
- QUICK AND EFFICIENT
- HANDLES STRUCTURAL DISCONTINUITIES
- HANDLES DISPLACEMENT DEPENDENT LOADS
- STREAMWISE AERODYNAMICS ON SWEPT WING



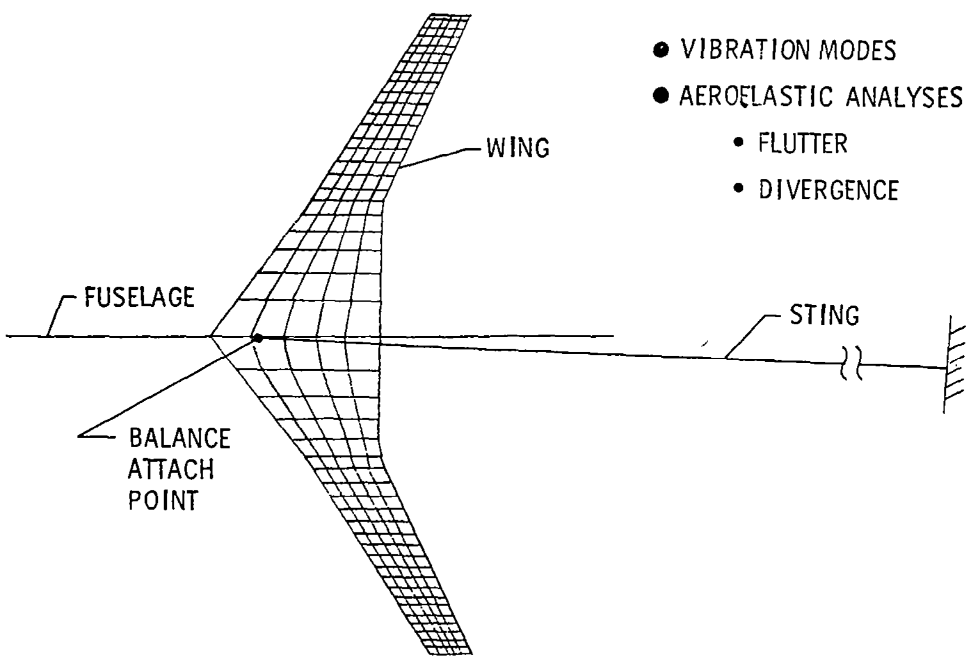
SPAR FINITE ELEMENT MODEL PATHFINDER I WING



PATHFINDER I STING CONFIGURATION

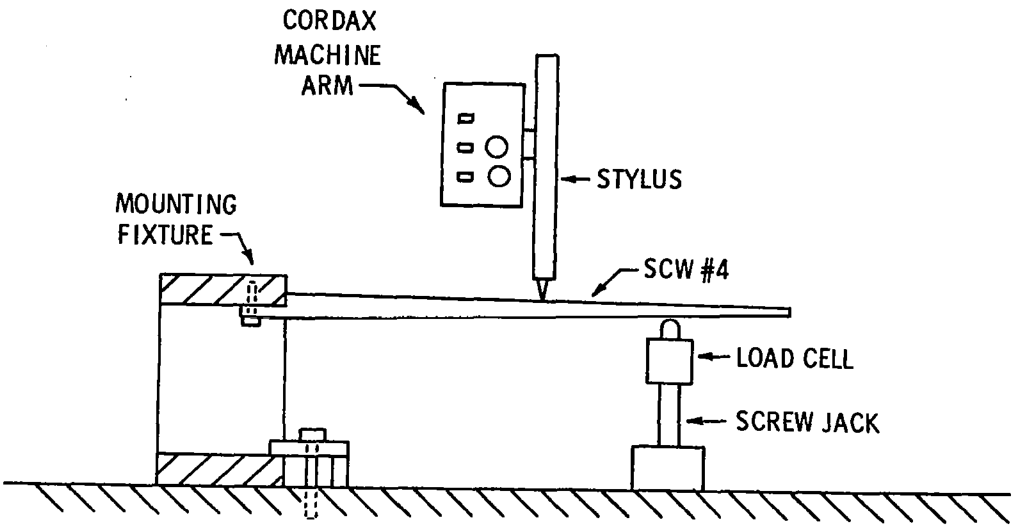


AEROELASTIC FINITE ELEMENT MODEL OF PATHFINDER I

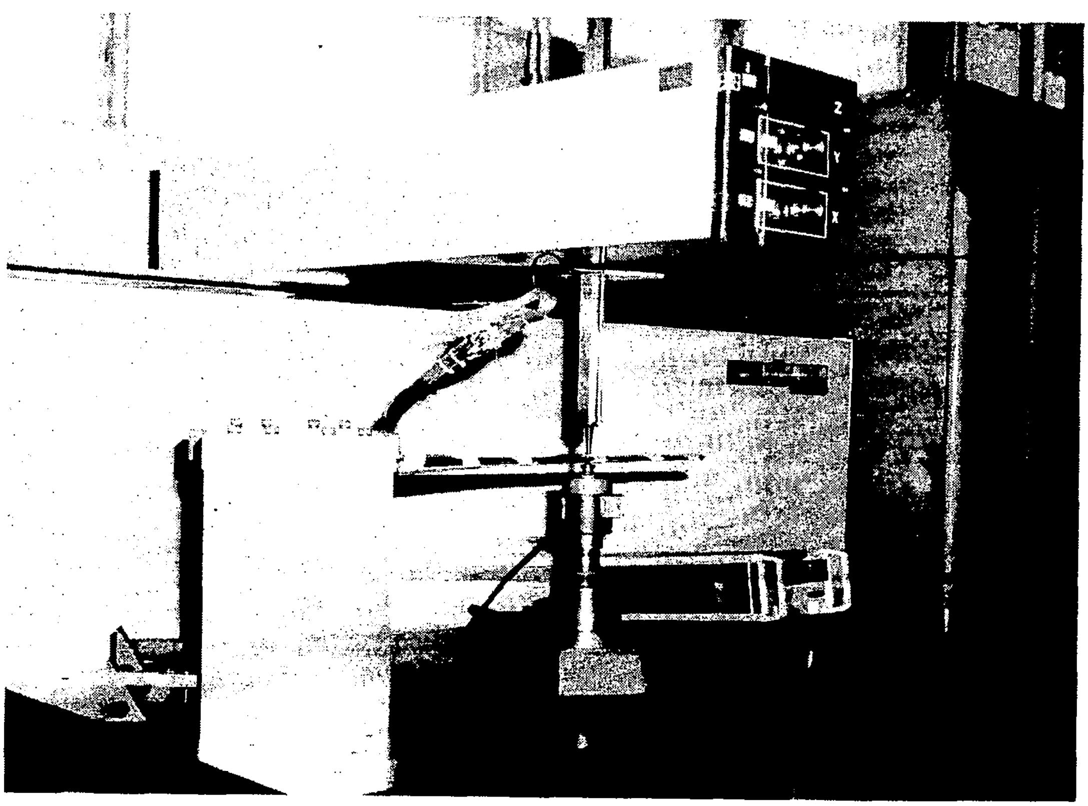


- VIBRATION MODES
- AEROELASTIC ANALYSES
  - FLUTTER
  - DIVERGENCE

SCHEMATIC OF SUPERCRITICAL WING
LOAD / DISPLACEMENT MEASUREMENTS



SUPERCRITICAL WING LOAD/DISPLACEMENT MEASUREMENTS



COMPARISON OF MEASURED AND COMPUTED BENDING DISPLACEMENTS FOR SCW#4 (INSTRUMENTED WING)

z, in.	Displacement, in., for 100 lb at z = 30 in.		Displacement, in., for 150 lb at z = 27 in.		Displacement, in., for 200 lb at z = 24 in.		Displacement, in., for 250 lb at z = 21 in.	
	Measured	Computed	Measured	Computed	Measured	Computed	Measured	Computed
6.0	0.004	0.004	0.005	0.005	0.006	0.006	0.007	0.006
9.0	.009	.009	.011	.011	.013	.013	.014	.014
12.0	.017	.017	.022	.022	.025	.025	.027	.027
15.0	.033	.032	.042	.042	.047	.047	.049	.048
18.0	.061	.059	.076	.076	.084	.084	.083	.081
21.0	.101	.100	.125	.124	.133	.132	.125	.122
24.0	.155	.154	.187	.186	.191	.189	.167	.165
27.0	.223	.221	.258	.258	.249	.248	.209	.207
30.0	.303	.302	.331	.332	.307	.307	.251	.250

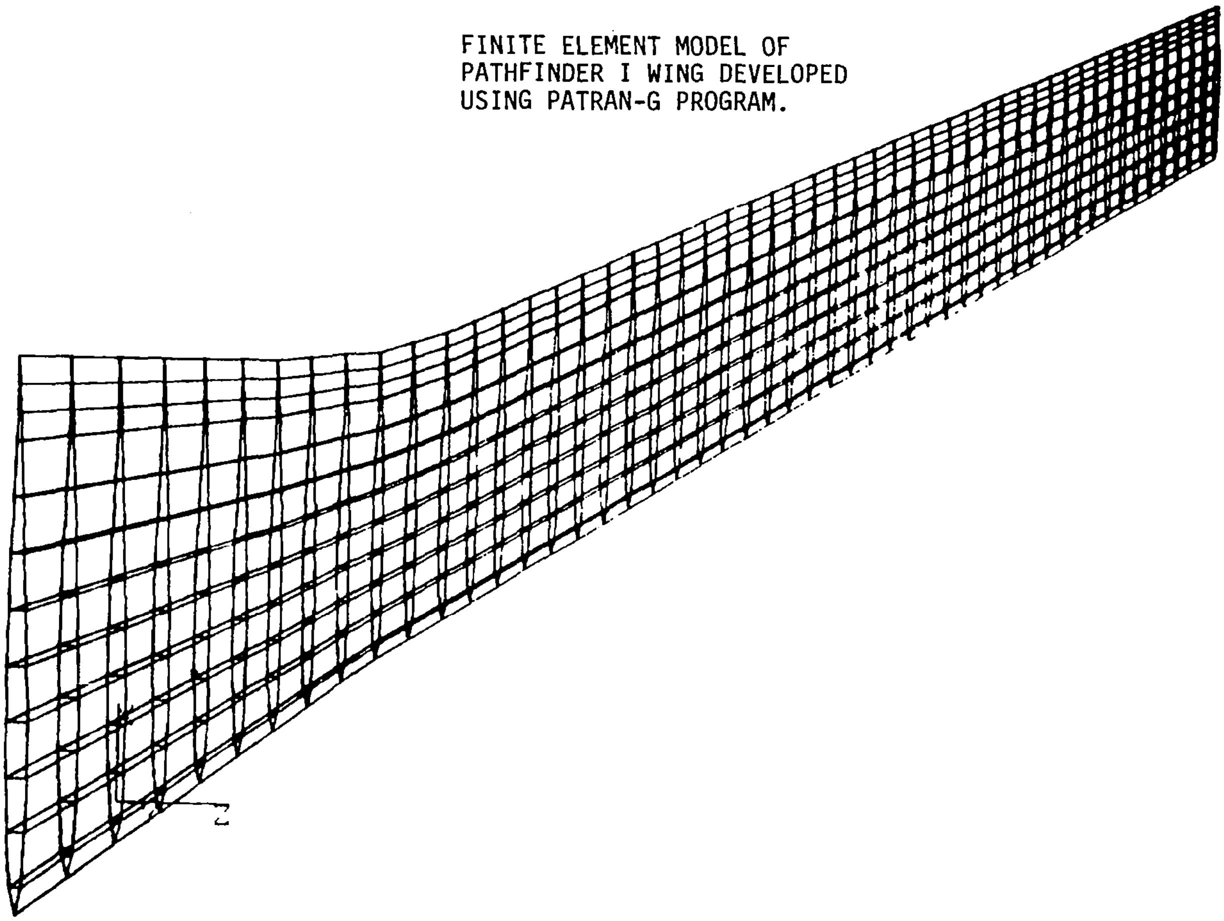
z, in.	Displacement, in., for 400 lb at z = 18 in.		Displacement, in., for 500 lb at z = 15 in.		Displacement, in., for 500 lb at z = 12 in.	
	Measured	Computed	Measured	Computed	Measured	Computed
6.0	0.009	0.008	0.009	0.008	0.007	0.006
9.0	.019	.019	.018	.018	.014	.013
12.0	.034	.034	.033	.033	.023	.023
15.0	.060	.059	.053	.053	.033	.033
18.0	.094	.094	.074	.074	.043	.043
21.0	.130	.130	.095	.096	.053	.053
24.0	.166	.165	.115	.117	.063	.063
27.0	.201	.201	.135	.139	.072	.073
30.0	.236	.237	.155	.160	.082	.083

DEFORMATIONS FOR CRUISE CONDITION LOADINGS: $C_L = 0.555$, Q = 2800 PSF

TIP DISPLACEMENT = 0.594 INCHES

TIP ROTATION = 1.191 DEGREES (Leading Edge Down)

FINITE ELEMENT MODEL OF
PATHFINDER I WING DEVELOPED
USING PATRAN-G PROGRAM.



SUMMARY

- PATHFINDER I ANALYSIS
    - STRESS - BEAM THEORY
    - DEFORMATION - BEAM THEORY
    - THERMAL - SPAR
    - VIBRATION - SPAR
    - FLUTTER - FAST
    - DIVERGENCE - SPECIAL PROGRAM
- CONTINUING DEVELOPMENT AND INVESTIGATION OF OTHER ANALYTICAL TOOLS. COMPUTER PROGRAMS TO BE DOCUMENTED.
- GOAL IS TO DEVELOP AN INTEGRATED COMPUTER PROGRAM FOR ANALYZING WIND TUNNEL MODELS.