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THE USE OF NASTRAN
IN THE
DESIGN OF WIND TUNNEL RESEARCH AIRCRAFT

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SUMMARY

Trends toward more severe test environments and increased demand for test data have resulted in the need for more sophistication in the analysis of wind tunnel research aircraft. The relationship between NASTRAN and the wind tunnel model design process is discussed. Specific cases illustrating the use of NASTRAN for static, heat transfer, dynamic, and aeroelastic analyses are presented. Advantages and disadvantages of using NASTRAN are summarized.

INTRODUCTION

Dynamic Engineering, Inc. (DEI) is a world leader in the design and fabrication of wind tunnel research aircraft.

In past years, wind tunnel models were conservatively designed. This led to exceedingly strong and reliable models which were simple and inexpensive to analyze.

More recently, the design requirements for wind tunnel models have become increasingly complex. Models today must survive severe environments while gathering more data. Time schedules and program costs dictate that models yield more data at faster rates than ever before. Models are designed to have sophisticated electronics, instrumentation, and machinery built into a specified envelope.

For instance, the advent of high reynolds number wind tunnels, such as Langley Research Center's National Transonic Facility (NTF) require that some models survive cryogenic environments. High reynolds numbers can be obtained by decreasing viscous forces while keeping inertial forces constant. In order to reduce viscous forces, liquid nitrogen is injected into the tunnel air-stream. Consequently, the air temperature, and the research model temperature drops to minus 260 degrees fahrenheit.

Turboprop models are exceedingly elaborate propulsion model systems that are enjoying recent attention. What began as a set of propellers attached to a motor has evolved into a system of long counter-rotating shafts and sophisticated gear boxes. Often scale turboprop models must achieve rotor speeds in excess of 15000 rpm. Complicated shafting can lead to subcritical shaft modes that are difficult to damp. Whirl modes compound the problem. Mating these systems to wind tunnel supports can introduce other dynamic considerations.

Scaled helicopter systems offer the greatest challenge to the designer. DEI recently built a dynamically scaled model of the most sophisticated helicopter ever designed, the celebrated X-Wing helicopter. The research model had an intricate network of valves that open and close to allow air to pass into the rotating blades at the appropriate azimuth.

Dynamically scaled helicopter rotor blades are frequently fabricated from composite materials. Stiffness and mass distributions are carefully defined and must be closely matched. Natural frequencies and mode shapes of sample blades are measured to prove analysis and manufacture.

These stringent requirements place higher demands on the model design engineer than ever before. Designers must be well versed in the principles of elasticity, heat transfer, and dynamics. They must have access to state-of-the art structural analysis tools.

DEI management recognized the need to upgrade analysis capability some years ago. After careful consideration and comparison with other analysis packages on the market, DEI obtained COSMIC NASTRAN in 1984. Moreover, DEI management authorized a training session for the design engineering staff in the use of NASTRAN. Well known NASTRAN expert, Tom Butler, was brought in to teach this training session.

NASTRAN is installed on the company's VAX 11/780 computer. The computer is also used to operate the UNIGRAPHICS CAD/CAM system by McAuto.

Part of the UNIGRAPHICS system is a finite element preprocessor module called GFEM. All design engineers are trained in the operation of UNIGRAPHICS. Finite element models are especially easy to generate when much of the geometry data already resides in the CAD system.

The purpose of this paper is to describe the analysis procedures at DEI used in the design of wind tunnel research aircraft.

STATIC ANALYSES

Most finite element analysis models generated at DEI use rigid format one, the static analysis. Load cases usually involve mechanical or aerodynamic pressures and forces, temperature loads, and gravity loads. Very few static analyses use optimization, differential stiffness, or buckling options.

FULL SCALE WING

Not all research models are scale models. DEI designed and built a full scale airplane wing. A new airfoil with a unique contour was to be tested as part of a joint project between NASA and an airplane manufacturer. It had a twenty three foot span and eight foot root chord.

To make a single flight-worthy wing would have been time consuming and costly. Tunnel safety requirements had to be met irregardless of weight. A model wing that maintained the appropriate geometry would be less expensive though heavy. Using estimates of the lift and drag for this new wing design, DEI engineers quickly generated a wing concept which included support tubes inside the wing, and a stressed skin. The wing would be tested in a near vertical position.

A large size means large loads. The full scale wing model must meet stringent safety requirements. Small scale research models can be built stronger with higher safety factors which would allow a more simplified analysis. This large wing would be unwieldy if it were over designed using handbook formulas. This project warranted a more sophisticated analysis.

NASTRAN was used to determine the relative load carrying ability of the skin and the inner support tubes. A detailed NASTRAN finite element model was generated using contour and geometry data that already existed in the CAD/CAM system. The GFEM preprocessor was used to generate the model. The generation of the finite element model took two weeks.

The finite element model consisted of 1722 bar and plate elements (See Figure 1). A pressure distribution that varied over the span and chord was applied to the finite element model. A computer program was written to automate the procedure of assigning pressures to elements, nonetheless, some pressures had to be adjusted manually. Forces and moments were applied to various locations along the trailing edge to represent the lift, drag, and bending effects of flaps and ailerons, which are physically connected at discrete locations for this analysis. The wing was considered to be a cantilever, fixed at the root.

The results showed the force distribution at the root section and the load path the aerodynamic forces took through the structure. In this way the design was verified.

NTF FLAT PLATE

Flow over a flat plate still fascinates people. DEI was given the task of designing a flat plate model to be tested in the NTF. It has an eight foot span and fifteen foot chord. The body is two inch honeycomb aluminum, and it has solid leading and trailing edges. The trailing edge is movable to adjust the flow over the plate. The plate is supported by eight support struts that extend into the tunnel some 40 inches from the tunnel wall. The supports are airfoil shaped.

The test would be useless if the plate deformation was excessive. During the test, the pressure distribution is nearly uniform. But before testing, the airflow must be adjusted and there could be huge leading and trailing edge loads. Furthermore, there are thermal effects to consider.

Because of the non-uniform loading, and discrete support conditions it was decided to analyze the plate using NASTRAN. Due to the symmetry of the problem, only one half of the plate was modeled (**See Figure 2**). It had 793 grid points and 720 quad1 and quad2 elements. The model was quickly generated using the mesh portion of the GFEM preprocessor. A two dimensional interpolator was used to distribute the pressure load over the elements. The scan feature was used to search for the largest stresses. Centerline slopes were plotted externally from NASTRAN.

Contour plots of the stresses were requested, but the presence of the bar elements at right angles to the plate elements seemed to confuse NASTRAN. Spurious plate elements appeared as part of the plate outline.

HELICOPTER ROTOR FORCE TRANSDUCER

DEI designed and built a 600 Hp one half scale helicopter test rig and fuselage. It had a twenty foot diameter rotor section. We also designed the rotor force transducer and instrumentation.

The design of the five component rotor force transducer was quite complicated. The rotor shaft had to go through the force transducer without transferring loads. The force transducer had to have good sensitivity and still maintain good load carrying capability and have natural frequencies beyond the operating range.

A four bar cage concept was used in this model. Simple handbook formulas were used to get ballpark estimates. NASTRAN was used to get detailed distributions of the stress concentrations in each flexure. These were used to locate the position of the strain gauges. Finally, NASTRAN was used to ensure that the natural frequencies were sufficiently high (**See Figure 3**).

DYNAMIC ANALYSES

Most wind tunnel models are not dynamically scaled. For these models dynamics is not a consideration. But for helicopter models, turboprop models, and fixed wing flutter models, the structure must be designed to specific modes and frequencies.

Often, a customer will define stiffness and mass distributions for a model system. The job of the design engineer is to design a system that matches the customers flexibility requirements while maintaining model strength to keep within tunnel safety requirements.

TWO BODY STING

A researcher wanted to study the interference effects between bodies of revolution at high reynolds numbers. DEI engineers were charged with designing a research model that could withstand high dynamic pressures and low temperatures. The concept consisted of an upper body firmly attached to a sting, and a lower body designed to move in discrete intervals relative to the upper body. There were more than 100 distinct combinations of relative positions. A planform view is shown in **Figure 4A,** and an exploded view is shown in **Figure 4B.**

A dynamic analysis was requested to determine natural frequencies and mode shapes. It was considered impractical and unnecessary to analyze for all the combinations of position. Only four extreme configurations were considered which would bound all other modes of vibration.

Because of the complex nature of the geometry of the research model, handbook formulas for frequencies were considered to be too crude. It was decided that a more accurate representation of the geometry would be obtained using finite elements.

A single finite element model of the upper body and four separate models of the lower body were generated. These were done in such a way as to quickly swap grid and connection data for the lower body **(See Figure 5A).**

The upper and lower stings were modeled with bar elements. Special care was given to precisely model changes in geometry. Only structural parts of the connecting blade were modeled with plate elements. Non-structural parts, such as cover plates, were neglected. The bodies of revolution were included as point masses and inertias.

A modal analysis was requested using the inverse power method. To ensure that torsional modes were included properly, the coupled mass option was used. Modes shape data, in three views, was output using the plot capabilities in NASTRAN. **Figure 5B** shows a typical mode shape for one configuration.

COUNTER ROTATING TURBOPROP

There is much interest in turboprop models. An increase of 30 percent in operating efficiency can be obtained with new propeller technology and counter rotating turboprop systems.

Scale turboprop models have interesting dynamics when mounted in a wind tunnel. Long cantilevered shafts are coupled through bearings. Hubs and shrouds are located at the forward most location, adding mass at the most dynamically effective position. High rotation speeds induce gyroscopic effects.

Ideally, the operating speed range should be free of vibration modes. There would be no dynamic problems if all vibration modes were above the operating range of interest. But this is hardly ever the case. The next best situation is to have low frequency modes that can be passed through quickly. However, this may cause static problems. Invariably, subcritical modes plague every design. The best that can be hoped for, then is to damp the subcritical modes so that they may be crossed safely.

Turboprop modal analysis presents a challenge to the model designer. A typical counter rotating turboprop is illustrated in **Figure 6A.** Turboprop design involves long shafts with changing diameters. Bearings and gears provide static coupling. Hubs, shrouds, and instrumentation are sources of point (or locally distributed) mass.

The dynamics of a typical turboprop system quickly becomes too complicated to analyze using classical techniques. Transfer matrix techniques are well suited to solve such problems. Finite elements, too, provide good estimates of the natural frequencies and mode shapes.

NASTRAN is used to determine the natural frequencies of the non-rotating shaft system. (See Figure 6B) Shafts are represented by bar elements, and bearings are modeled with spring elements. The mass effects of hubs and instrumentation are modeled as point masses and inertias. Mode shapes are conveniently output using the NASTRAN plot routines **(See Figure 6C)**.

However, rotating shaft frequencies, such as whirl modes, are not determined (directly) from NASTRAN. Whirl modes depend on the system flexibility. NASTRAN is used to statically determine the flexibility coefficients at various locations. Then, whirl modes are determined external to NASTRAN using standard handbook formulas.

NASTRAN is used to evaluate the effect of damping. Varying magnitudes of viscous damping are input to the finite element model. A frequency response analysis is performed to determine if the damping is useful.

HELICOPTER ROTOR BLADES

Helicopter rotor blades are complicated structures with complicated dynamics. Most scale model blades are fabricated from fiberglass or graphite epoxy composites and have a balsa or foam core.

When a customer is interested in specific blade dynamics, it is the mass and stiffness distributions that are usually specified. The design engineer must optimize the ply orientation of the composite materials to match stiffness and meet strength requirements. Lead or tungsten weights are inserted into the blade to meet mass and center of gravity requirements.

The bending dynamics of a rotating helicopter blade can be complex because strong centrifugal force couples axial with bending and torsion effects. Aeroelastic effects can significant too. The manner in which the blade is connected to the hub can also affect bending dynamics.

NASTRAN is not used to determine rotor blade dynamics. When quick results are needed to evaluate a design concept, NASTRAN is too slow and cumbersome. When very accurate results are important, modeling time is better spent on dedicated blade analysis codes which are easier to use, include specific inputs (such as collective pitch angles and pitch control system stiffness) and have faster turn around.

For some blades, which are beamlike in nature and have relatively constant properties simple handbook calculations give good trends. Classical techniques are used to determine the non-rotating blade frequencies. Beam-column theory can be used to crudely estimate frequencies for rotating blades. Other blades, in which coupling effects, or aerodynamic effects are significant, specialized computer programs are used to determine blade dynamics.

COMPOSITE VERTICAL TAIL

One way to design a flutter model is to build a scale replica. The scaled model must have the correct scaled frequencies and the correct overall contour. This method of design is very expensive.

A particular flutter model built by DEI was fabricated from aluminum, balsa and fiberglass. The model's vertical tail was tested experimentally with our modal analysis equipment. The results showed that the first mode was in good agreement with the design mode, but higher modes were not close enough.

The decision was made to develop a NASTRAN model of the vertical tail to predict the effect of adding or subtracting plys. It is difficult to model composite material properties with NASTRAN. A computer program was developed to establish the in-plane and transverse stiffness of a laminate, given the number of plys, location and orientation, and material properties. Then equivalent orthotopic properties were calculated and the results were output in NASTRAN MAT3 format. Though the measured modes and frequencies were not predicted exactly, trends were useful.

HEAT TRANSFER

As was mentioned earlier, the National Transonic Facility (NTF) is a cryogenic wind tunnel. The temperature of the research models tested in this tunnel drops about 350 degrees Fahrenheit from room temperature. Coupled with air speeds exceeding Mach one this becomes a very severe environment.

There are four distinct temperature phases that a research model must endure in the NTF. They are: 1) cool-down phase, 2) test phase, 3) warm-up phase, and 4) post model maintenance. The time span for each phase is well defined.

It is important to determine the magnitude of the thermal gradients that can exist in a research model. These gradients are caused by uneven cooling of the aircraft structure during the phases listed above. To determine the thermal gradients, a transient heat transfer analysis must be performed.

NASTRAN is not usually used for transient heat transfer analyses. The problem arises from the fact that heat transfer coefficients cannot be specified as functions of time. The heat transfer coefficient at high reynolds numbers depend on temperature, Mach number, pressure, and density, all of which are, directly or indirectly, functions of time.

At DEI, we use an in-house developed finite difference code for transient heat transfer analyses. Conduction, convection, and radiation effects are included in this code. There is a user defined subroutine that allows for the time variation in heat transfer coefficient to be calculated from the quantities already mentioned. Temperature time histories, or gradient time histories can be directly plotted.

The disadvantage of the finite difference code is obvious when transferring temperatures to a different structural model. The heat transfer model is necessarily different from the structural model. The transfer process can be time consuming. Two or three dimensional interpolator routines are used to assign temperatures to grid points automatically. Nonetheless, some grid point temperatures must be adjusted manually.

AEROELASTIC ANALYSES

The stability of most aircraft model systems is usually governed by divergence--a static aeroelastic phenomenon. One of the parameters necessary to determine the dynamic pressure at which divergence will occur is the model system structural flexibility. This information is easily obtained from a finite element representation of the model system by applying unit loads individually at various locations and computing the resulting displacements and slopes. NASTRAN is often used to determine model system flexibility coefficients.

Sometimes, a flutter analysis is required for a research model. There exist some simplified analyses in the literature for determining the air speed at which flutter will occur. But these are really intended to illustrate the physical and mathematical nature of the flutter phenomenon - not to solve problems. Usually, the complex geometry and aerodynamic regime of the research model violates assumptions on which the simplified analyses are based. NASTRAN is used to analyze all research models requiring a flutter analysis.

FAA FLUTTER CLEARANCE

DEI has on staff a designated engineering representative (DER) of the Federal Aviation Administration (FAA). This person can certify for the FAA that an aircraft is flight worthy regarding flutter. The aircraft certification process, may require a flutter analysis, a ground vibration test (GVT), or a flight flutter test.

A customer of DEI had a new aircraft design and requested that the aircraft be certified for flutter. NASTRAN was used to perform the flutter analysis.

An example of flutter analysis is briefly described here. The wing, wing flap, and fuselage of the aircraft were modeled with bar elements. Taking advantage of aircraft symmetry, one half of the airplane was modeled **(See Figure 7)**. Symmetric and anti-symmetric vibration modes were computed. The doublet lattice method was used to represent the subsonic aerodynamics. With this relatively simple finite element model, a number of cases were considered. The customer was pleased with the results.

NTF MODEL FLUTTER

Every research model tested in the NTF must be checked for flutter. A customer asked DEI to perform a flutter analysis as part of the total model design. The flutter analysis had not yet been completed at the time this paper was written.

The research model consists of a fuselage, main wing, winglets, and four engine nacelles. There was no vertical or horizontal stabilizers. This was a sting mounted model and included a force transducer as part of the fuselage design.

Since the research model will be tested in various configurations (i.e. with and without winglets, with and without nacelles) the flutter speed of all test configurations must be determined. A detailed finite element model of the wing and winglet was developed using plate elements **(See Figure 8)**. The wing and winglet thickness distributions were computed from contour data already in the CAD system. A two dimensional interpolation routine was used to automatically assign thicknesses to element properties. The mass and inertia effects of the engine nacelles were included. The sting and fuselage were modeled using bar elements. Only one half of the aircraft was modeled taking advantage of the aircraft symmetry. Both symmetric and anti-symmetric vibration modes were computed.

As of this writing, the subsonic aerodynamics was being modeled using double lattice theory.

CONCLUSION

DEI uses NASTRAN for a wide variety of structural analyses.

The advantages of using NASTRAN in the analysis of wind tunnel research models are many. NASTRAN offers a number of analytical capabilities that are needed such as static, dynamic, heat transfer, and aeroelastic analyses.

For many model designs, geometry and contour data is already programmed into the CAD system. This greatly facilitates the generation of finite element models when using the GFEM pre-processor. Finite element data is automatically output in NASTRAN format.

The chief disadvantages of using NASTRAN are summarized below.

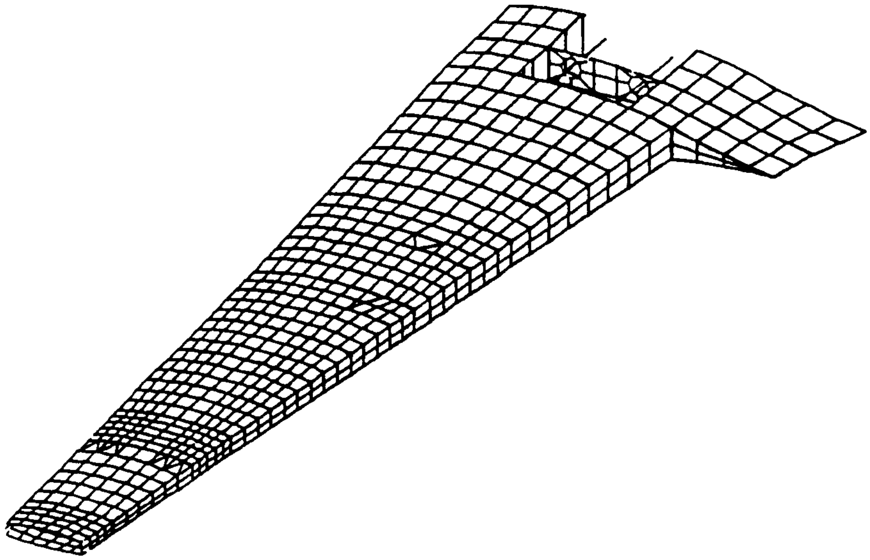
NASTRAN is often too slow and cumbersome to use in the design process. It becomes too difficult or time consuming to alter geometry design parameters with NASTRAN. For this reason, NASTRAN is most often used for a detailed analysis of a final design rather than to evaluate different design concepts.

Heat transfer coefficients are impossible to describe as a function of time in NASTRAN. Transient heat transfer problems regarding wind tunnel models involve well defined time histories of air temperature, pressure, density and Mach number. The heat transfer coefficient at high Mach numbers is a function of all these parameters, thus indirectly a function of time. This limitation makes the NASTRAN thermal analyzer undesirable for such problems.

NASTRAN is unsuited for the modal analysis of dynamically scaled helicopter rotor blades. Difficulties involved with modeling composite material properties and blade/hub attachments make other dedicated programs more desirable to use.

NASTRAN does not include gyroscopic effects (such as whirl modes) in the dynamic analysis of rotating shafts.

FIGURE 1

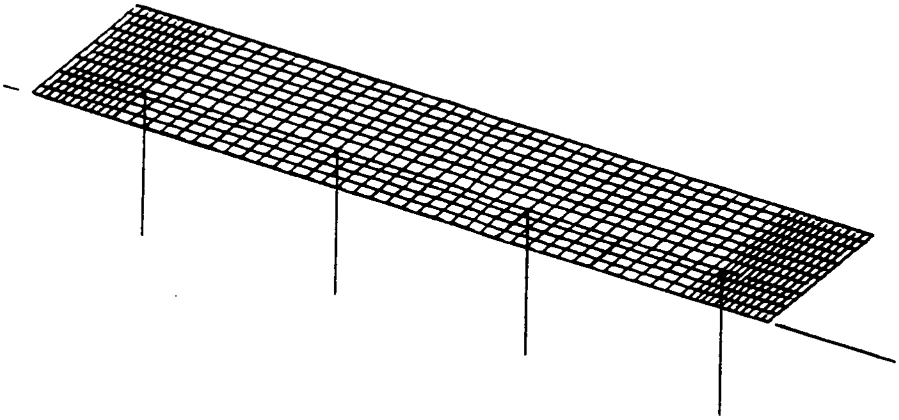


FULL SCALE WING FINITE ELEMENT MODEL

HIDDEN LINE PLOT

- O 23 FOOT SPAN, 8 FOOT CHORD
- O FLAPS AND AILERONS WERE NOT MODELED
- O NON-STRUCTURAL COVERPLATE REMOVED FROM UPPER SURFACE REVEALS ONE OF 18 RIBS AND 2 OF 3 INNER SUPPORT TUBES
- O 1722 BAR AND PLATE ELEMENTS

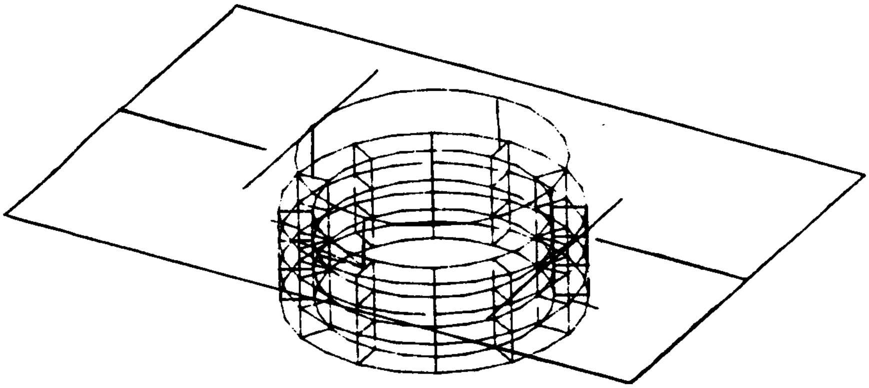
FIGURE 2



NTF FLAT PLATE FINITE ELEMENT MODEL
SYMMETRIC MODEL

- 8 FOOT SPAN, 15 FOOT CHORD
- PRESSURE AND TEMPERATURE LOADS
- 793 GRID POINTS, 720 PLATE ELEMENTS
- SOLID ALUMINUM LEADING AND TRAILING EDGES, HONEYCOMB ALUMINUM BODY

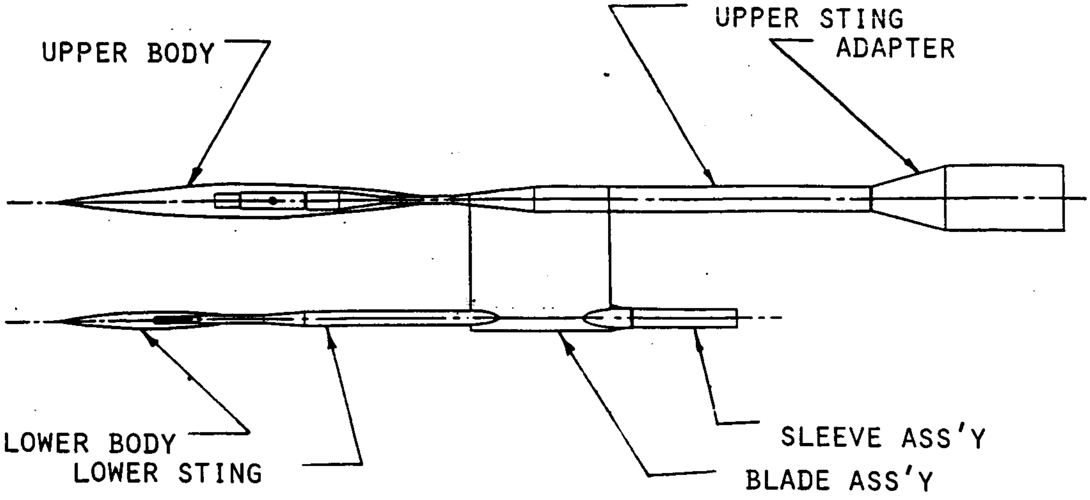
FIGURE 3



FORCE TRANSDUCER FINITE ELEMENT MODEL

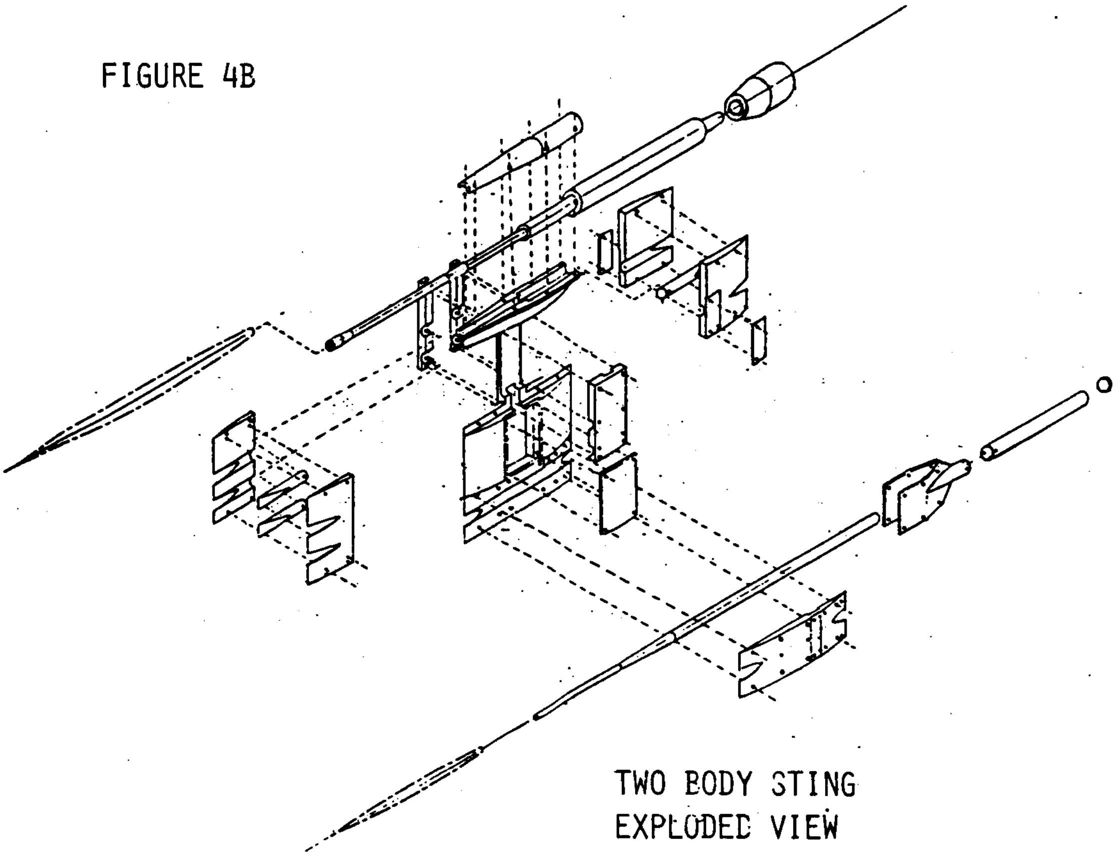
- O FIVE LOAD CONDITIONS REPRESENT THRUST, DRAG, SIDE FORCE, PITCHING MOMENT, AND ROLLING MOMENT
- O FOUR TAPERED FLEXURES ARE REPRESENTED BY BAR ELEMENTS. THEY CONNECT THE THIN UPPER RING MODELED WITH BAR ELEMENTS, TO THE THICK LOWER RING MODELED WITH SOLID ELEMENTS.

FIGURE 4A



TWO BODY STING PLANFORM

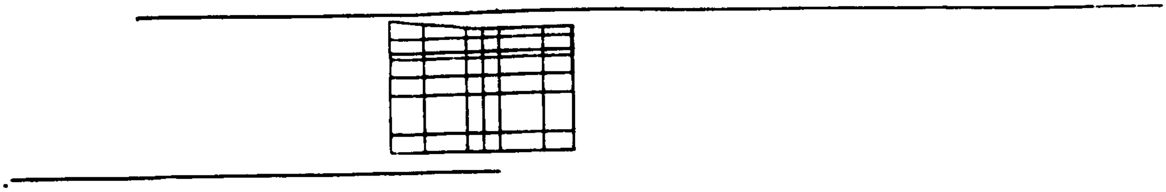
FIGURE 4B



TWO BODY STING
EXPLODED VIEW

C - 3

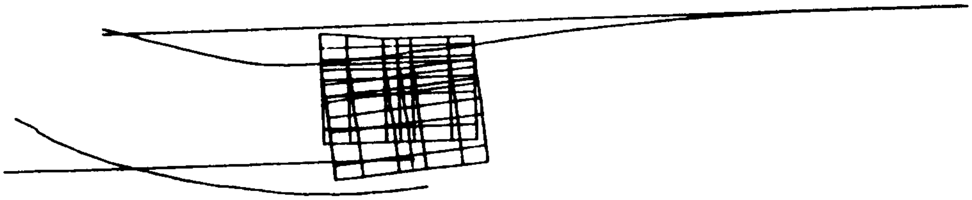
FIGURE 5A



TWO BODY STING FINITE ELEMENT MODEL
ONE OF FOUR CONFIGURATIONS

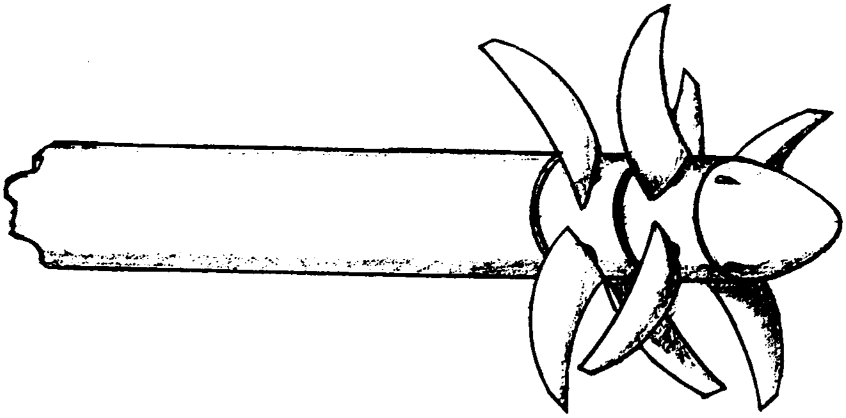
- O BODIES OF REVOLUTION INCLUDED AS POINT MASSES
- O UPPER AND LOWER STINGS CONNECTED BY RIGID ELEMENTS

FIGURE 5B



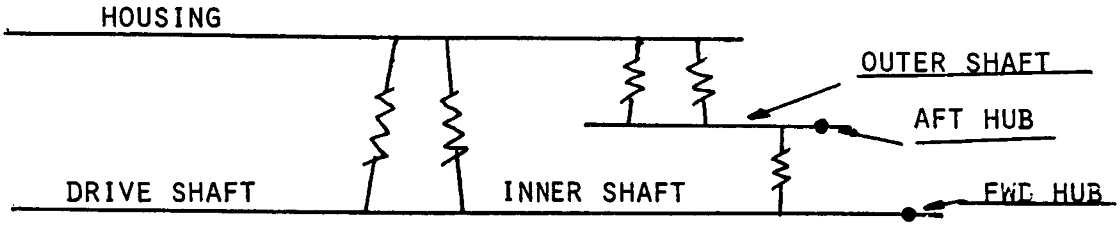
TYPICAL MODE SHAPE FROM TWO BODY STING FINITE ELEMENT MODEL

FIGURE 6A



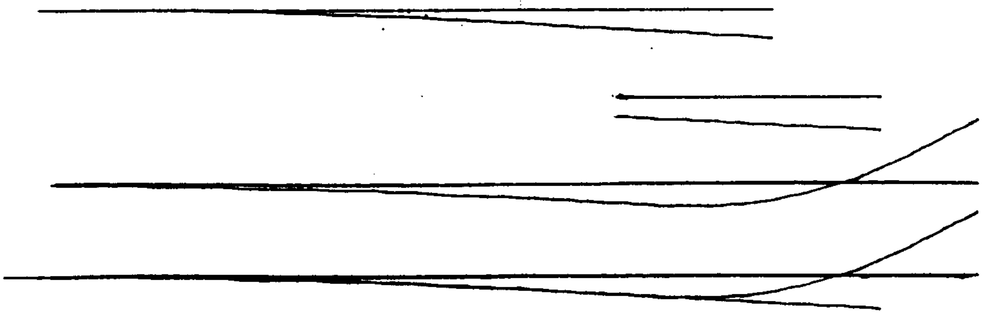
COUNTER ROTATING TURBOPROP CONCEPT

FIGURE 6B



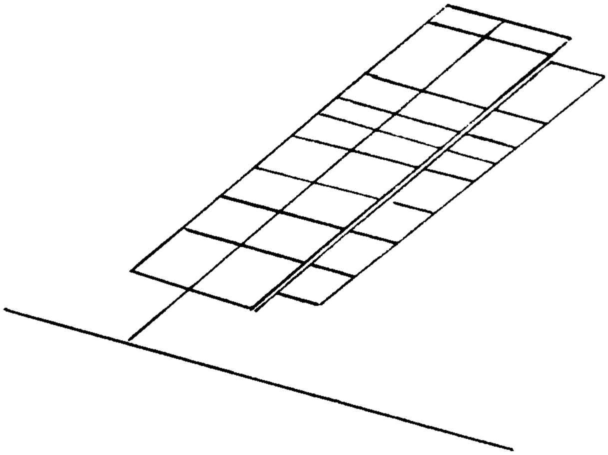
SCHEMATIC REPRESENTATION OF TURBOPROP

FIGURE 6C



TYPICAL REPRESENTATION OF TURBOPROP MODE SHAPE

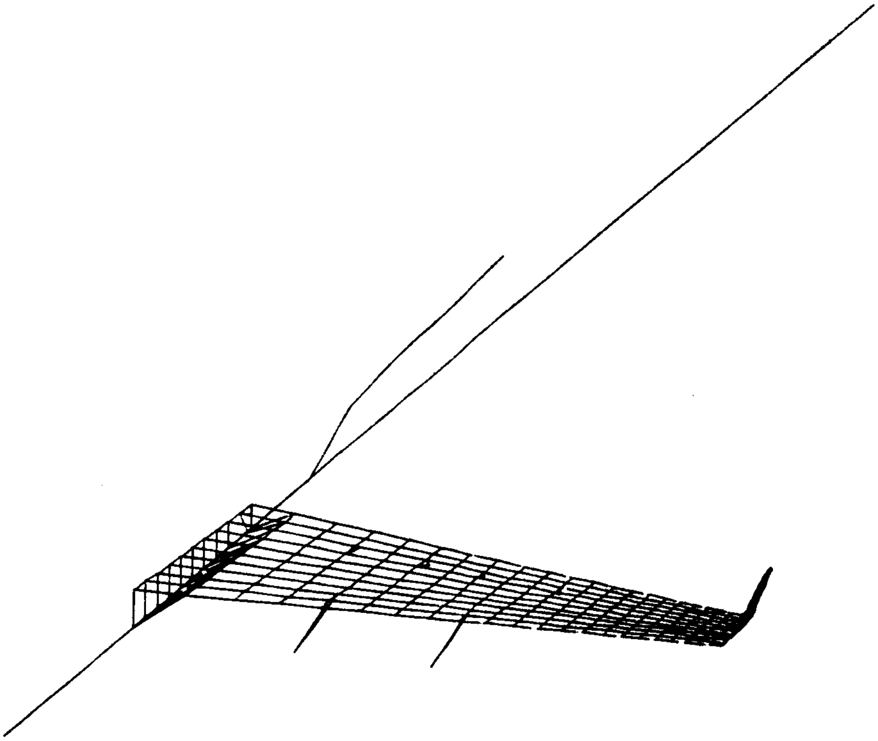
FIGURE 7



FINITE ELEMENT MODEL FOR FAA FLUTTER CERTIFICATION

- O SYMMETRIC MODEL
- O BAR ELEMENTS REPRESENT FUSELAGE, WING, AND FLAP
- OSUBSONIC AERODYNAMICS

FIGURE 8



FINITE ELEMENT MODEL FOR FLUTTER ANALYSIS

- O SYMMETRIC MODEL
- O BAR ELEMENTS REPRESENT FUSELAGE AND STING
- O PLATE ELEMENTS REPRESENT WING AND WINGLET
- O NACELLES REPRESENTED BY POINT MASSES AND INERTIAS
- O SUBSONIC AERODYNAMICS