NASTRAN APPLICATIONS TO AIRCRAFT PROPULSION SYSTEMS

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SUMMARY

The use of NASTRAN in propulsion system structural integration analysis is described. Computer support programs for modeling, substructuring and plotting analysis results are discussed. Requirements on interface information and data exchange by participants in a NASTRAN substructure analysis are given. Static and normal modes vibration analysis results are given with comparison to test and other analytical results.

INTRODUCTION

The versatility of NASTRAN makes it an ideal tool for the complex analysis problems associated with aircraft propulsion systems. These systems experience a great variety of loads and environments requiring sophisticated analysis tools for accurate analysis.

A particularly attractive advantage of NASTRAN is its low initial cost of acquisition and its common availability. Thus, it can serve as a unifying structural analysis language in joint engine and airframe company structural integration efforts. This has been the major use of NASTRAN in the Boeing Commercial Airplane Company, although some detailed analysis of engine components has been carried out for risk evaluation. This paper is therefore directed primarily at overall propulsion system structural analysis rather than detailed component analysis.

This paper describes NASTRAN history at Boeing, the various pre and post processors developed for enhanced utilization, propulsion system modeling, substructuring procedures, and various analysis cases with some correlation with test and other analyses.

NASTRAN BACKGROUND

NASTRAN has been operational on Boeing computers since release 8.0 was available in 1969. Currently release 15.5 is running on the IBM 370/168's under HASP and LASP, the IBM 360/65 under OS and the CDC 6600's under KRONOS 2.1. During this time NASTRAN has been used in the analysis of a large number of aerospace and other structures, e.g., MVM, LST, Minuteman, Lunar Rover, Roland, turbine blades, HLH combustor, YC-14 propulsion system, and a large cable-stayed bridge.

To aid in the various analyses and to improve "ease of use" of NASTRAN, various computer programs have been developed. SAIL, SPAN and XFETCH are three such computer programs. Also routines have been developed to provide an overall equilibrium check, to generate multipoint constraints, and to recover multipoint constraint forces.

SAIL II (Structural Analysis Input Language II) (Reference 1) is a language for describing NASTRAN bulk data. Basic finite-element input data such as gridpoints, element connections, and loads are defined in an easy, straightforward manner, using the SAIL II statements. The SAIL II features include looping, data block transformation, and external data generators plus all the capabilities of FORTRAN. The NASTRAN bulk data deck is generated from a relatively small number of SAIL II statements, making it very convenient to incorporate structural and geometry changes into a NASTRAN model.

SPAN (Substructure Partition Automation for NASTRAN) (Reference 2) is a NASTRAN support program that automatically generates the partition vectors required for assembling Phase I matrices during Phase II of a NASTRAN substructure analysis. The partition vectors generated can be based on identical grid or scalar point identifications, identical XYZ coordinates, or specified connection points. User labels can be retained during Phase II to allow loads, constraints, and elements to reference the original grid points. The displacement results are identified by the original gridpoint labels. Structural plots can be produced during Phase II.

SPAN uses the Phase I checkpoint tapes and a small amount of card input to determine the substructure definition. The SPAN output is the NASTRAN Phase II input deck that includes the required partition vectors. Extensive error checks are made to insure proper matrix ordering and consistency.

XFETCH is a subroutine that reads NASTRAN data files from a checkpoint/restart tape. The NASTRAN data can be returned to an incore storage array, or copied and reformatted to data sets easily read by FORTRAN. The copy and reformat feature is useful in applications where the data sets are too large for convenient incore processing. Both tables and matrices can be read.

PROPULSION SYSTEM STRUCTURES BACKGROUND

In the development of aircraft propulsion systems, major structural components are provided by both the engine manufacturer and the airframe manufacture. Typically the strut and nacelle, including inlet, nozzles, reversers, tailcone, cowling and systems equipment - or about 20 percent of the propulsion system below the wing weight - are produced by the airframe manufacturer.

The engine manufacturer ordinarily develops and tests the bare engine on a rigid test stand, exclusive of flight hardware. The airframe manufacturer provides design envelope loads to the engine manufacturer who then determines if the engine will function properly under such loads.

cause the propulsion system is usually not tested on the wing as an inte- ated structure until flight testing begins, it is important that at an rly stage of the engine/airframe development program an integrated structural alysis of the total propulsion system be carried out. A structural integration ol such as NASTRAN can provide this analysis by accurately simulating the al propulsion installation and providing detailed knowledge of internal loads, nning clearances, and total system vibration response. The needs for propul- on system and airframe structural integration are discussed further in Refer- ce 3.

PROPULSION SYSTEM MODELING

r enhanced utilization of NASTRAN, comprehensive modeling procedures have en developed. Because of the axisymmetry or cyclic symmetry of most of the opulsion structure, automation of the modeling is particularly easy.

gure 1 illustrates how the engine structure is modeled utilizing the SAIL II neral purpose input language described earlier. An engine fan frame is shown ereby half of one strut is idealized, then by SAIL II built-in transformation broutines, it is reflected, rotated and joined with other structure to generate e entire fan frame substructure. Where practicable, geometry is digitized irectly from engineering drawings including grid point coordinates, plate sec- ion properties, beam offsets, section properties and orientation grid points.

ne of the most beneficial aids for model checkout has been large size CALCOMP lots identifying grid points and the different element types and their numbers. owever, model checkout is never assumed complete until a successful loads case as been fully executed and results plotted.

igure 2 is a NASTRAN plot of a high bypass ratio, fan jet propulsion system. he models shown are symmetric halves made up essentially of quadrilateral late and beam elements and include a beam-lumped mass representation of the otors. Multipoint constraints simulate the bearing housings as rigid rings hich are coupled to the rotor by scalar spring and damper elements. Direct atrix input is used to input rotor spin stiffening and Coriolis terms when pplicable.

he vibration and dynamic response models are obtained from the static models hown in Figure 2 by the standard methods of Guyan reduction or possibly, ore economically by mass lumping. In either case considerable non-structural ass lumping is required due to the many propulsion system accessories. The ASTRAN generated gross mass matrix has been found useful for manually re- istributing the mass for vibration analysis.

MULTICOMPANY INTEGRATION ANALYSIS

Since NASTRAN is in the public domain and is available to everyone, it is quite straightforward for many companies to join in performing a substructure analysis of the complete structure. Phase I for a particular component is done by the company responsible for the component at its computing facility; Phase II is done at a mutually acceptable computing facility; and Phase III is run at the company responsible for the component. Before a joint effort is undertaken, however, the participating companies should establish the followin ground rules to aid the effort:

1) A basic XYZ coordinate system for the entire structure.
2) Unique grid point numbers for the entire structure so that Phase I grid points instead of scalar points can be used in Phase II.
3) Compatible displacement coordinate system at interface points.
4) Grid point numbers at an interface increasing in the same direction for all substructures.
5) Unique coordinate system numbers for each substructure.
6) Agree on a common buffer size.
7) Compatible user and checkpoint tapes.
8) Unique substructure plot element ID's for Phase II plots.

If SPAN is used, then the ASET degrees of freedom at an interface grid point are required to be the same for all substructures that connect to the interface point.

ANALYTICAL RESULTS - STATICS

NASTRAN models of the type illustrated in Figure 2 have been used to analyze a variety of static loads cases, including thrust, inlet lift, inertia, and gyroscopic moments. Typical loadings and the manner in which they are introduced onto the model are illustrated in Figure 3. A best guess distribution and force balance provided thrust loads which were distributed circumferential at various axial locations. The distributed gravity load is calculated within NASTRAN using the GRAV card. Inlet lift was distributed over the fan case/ inlet attach flange in this early study prior to the availability of an inlet model. Gyroscopic moments, a case requiring antisymmetric boundary conditions were applied at the major inertia locations of the rotor and were based on overall rigid body pitch velocity of the aircraft.

The deflections of the engine structure under load are shown in Figure 4 which were plotted using the standard built in NASTRAN plot capability.

Engine performance depends heavily on maintaining tight running clearances between the rotors and case, particularly in the fan and high pressure compressor. Rubbing increases clearances and decreases engine efficiency causing increased specific fuel consumption. Therefore, detailed knowledge of clearance changes under load is desired. To exhibit change of clearance contours between the engine case and rotors, a NASTRAN postprocessor was written (Reference 4). This postprocessor utilizes XFETCH, previously described, to read NASTRAN restart tapes then plots contour maps for the entire engine under the various loads. Two such plots are shown in Figure 5. Absolute values are not given because of engine proprietary information agreements between the airframe and engine companies.

The accuracy to be expected from NASTRAN analyses for propulsion system type structure has not been determined. The few known correlations with test data indicate it should be within the realm of 5 to 10 percent on peak deflections. The prevalence of bolted flanges in the engine case, slop in the installation system, and non-linear seal interface stiffnesses probably make the analysis less accurate than the 5 percent accuracy usually associated with the finite element methods.

A comparison of test and analysis is shown in Figure 6 for an engine compressor case. The model was produced independently by the airframe company from engine drawings and the analysis run without any knowledge of the tests which were run independently by the engine company. Under such circumstances the correlation should not be considered too bad.

ANALYTICAL RESULTS - VIBRATION

The ability to predict dynamic behavior of the propulsion system is of utmost importance. This includes the response to external gust loads, turbulence, takeoff, maneuver and landing loads in addition to critical rotor speeds and various off design conditions for safety and reliability. The interface problem between the engine and airframe manufacturer is of particular importance here since much of the airframe produced structure is hung at the extremities of the engine, magnifying the dynamic effects.

NASTRAN's dynamics capability provides an excellent tool for propulsion system vibration and dynamic response analysis. The normal modes vibration analysis of a typical high bypass ratio turbine engine is shown in Figure 7. The model shown had 51 lineal masses, 7 rotary inertias and retained 151 freedoms from the static stiffness model. A total of 120 symmetric and 120 antisymmetric modes were extracted, three of which are shown in Figure 7. Mass lumping was used due to excessive computing cost of Guyan reduction which has been found to be typically four times higher than the mass lumping approach.

The versatile plotting capability in NASTRAN is a great help in understanding vibration behavior as illustrated in the mode plots of Figure 7. Correlation has been attempted between NASTRAN normal modes analysis and test data, and with other analyses, i.e., simpler beam-spring-mass simulations.

Certain NASTRAN analysis and test frequencies are very close as indicated in Table I but there is not enough available test data to be sure if the mode shapes correlate. Much the same situation exists in comparing NASTRAN results to the simpler beam-spring-mass simulations, also noted in Table I. A revision of the NASTRAN plot elements and plot viewing angles will be helpful in this regard.

CONCLUSIONS

The success of an engine/airframe structural integration effort depends greatly on the timely exchange of interface information between the engine and airframe manufacturers including not only elementary geometry and loads but also comprehensive finite element models. A good tool for doing this is NASTRAN since it has common availability.

Application of the general purpose finite element programs such as NASTRAN to propulsion system structure is more recent than to airframe structure. More analysis and test correlation is needed to establish better standards for propulsion system modeling and analysis. Experience to date indicates that NASTRAN accuracy for overall engine structures may not be as good as for other more intensively analyzed structures.

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2. Beste, D. L., "SPAN - Substructure Partition Automation for NASTRAN", 10204-003, Boeing Computer Services, Inc., May 1974.

3. Aarnes, M. N. and White, J.L., "Propulsion System and Airframe Structural Integration Program", Journal of Aircraft, Vol. 12, No. 4, April 1975, p. 234.

4. Yantis, T. F., "IFPLOT - Interference Contour Plotter", BCS-G0697, Boeing Computer Services, Inc., July 1975.

TABLE 1 NASTRAN VIBRATION ANALYSIS COMPARED TO TEST AND OTHER ANALYSIS

NASTRAN MODE NO.	NASTRAN FREQUENCY, HZ	ENGINE TEST, HZ	BEAM-SPRING-MASS ANALYSIS, HZ	POSSIBLE CORRELATION
1	11.04		10.9	NO
8	25.2	25		YES
12	38.18	34		YES
13	49.25	51	48	YES
18	76.75	62	62.7	YES

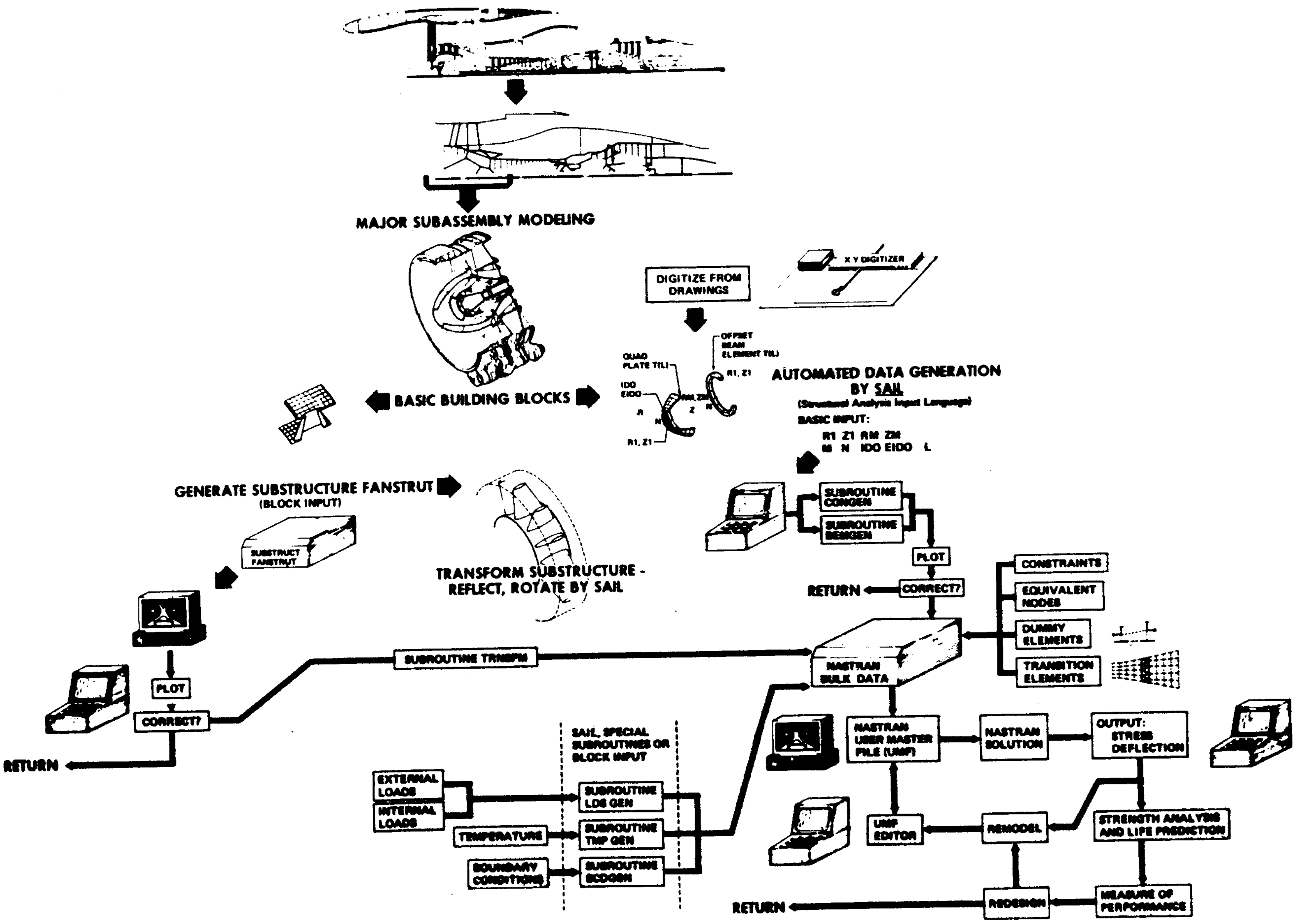


Figure 1.- Propulsion system modeling.

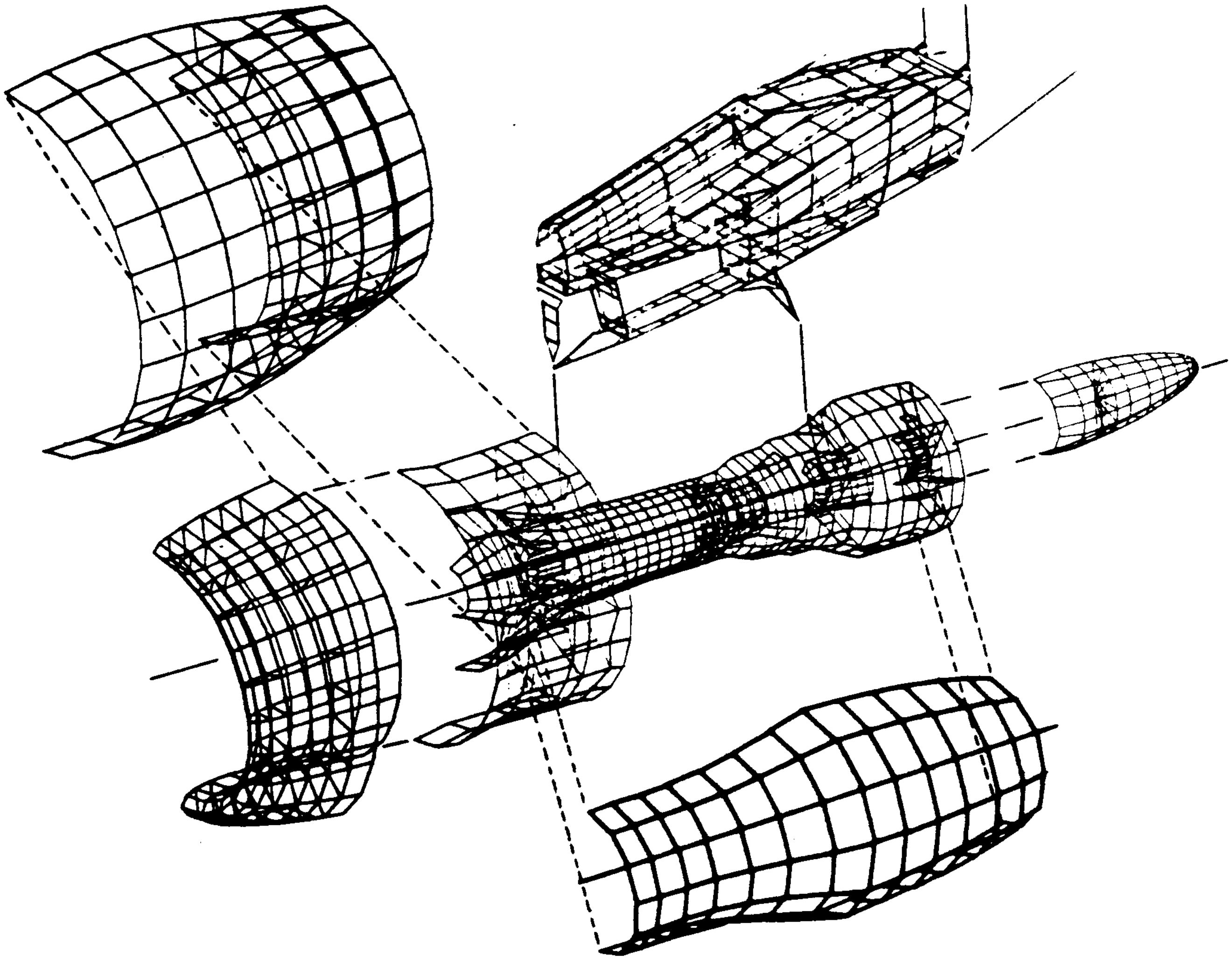


Figure 2.- Propulsion system substructures.

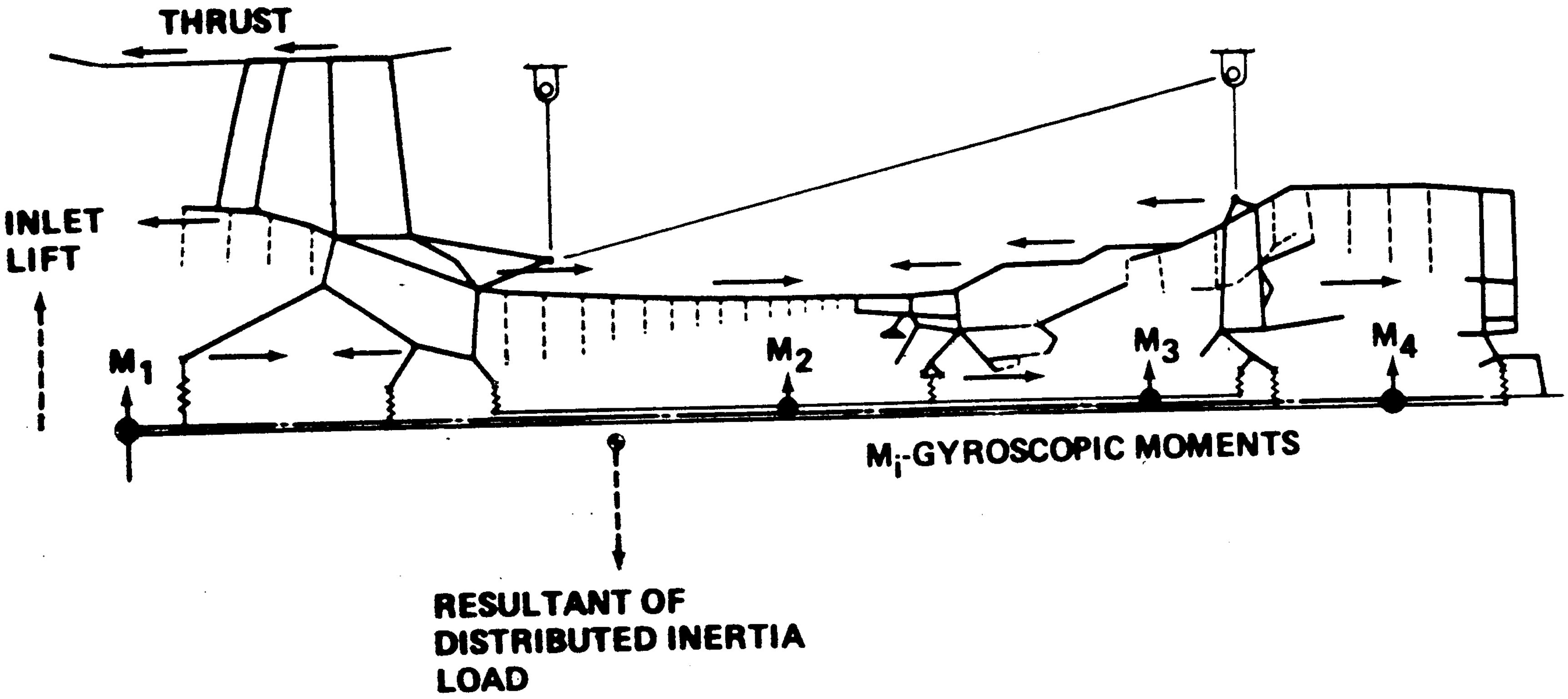


Figure 3.- Propulsion system static loads simulation.

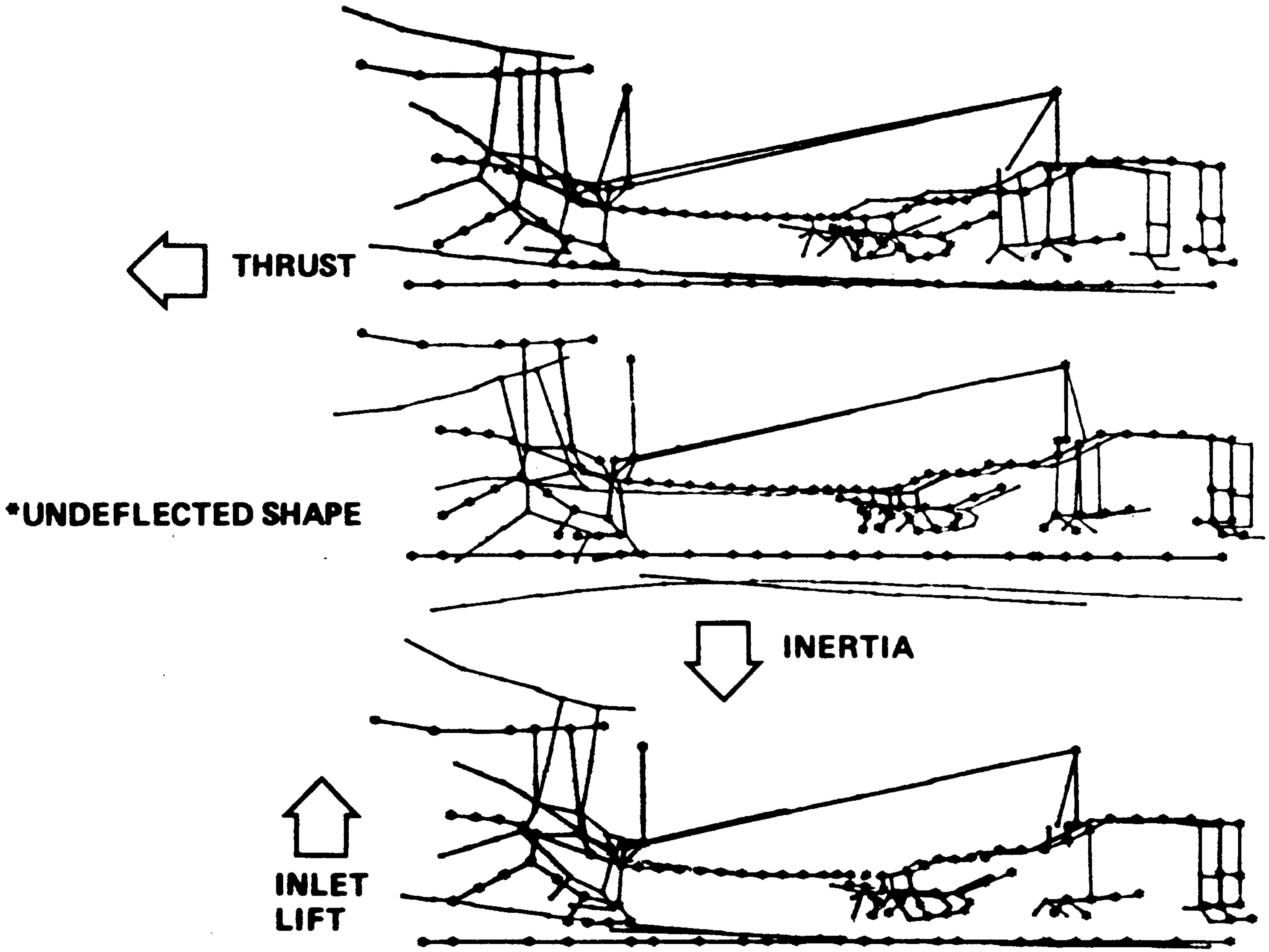
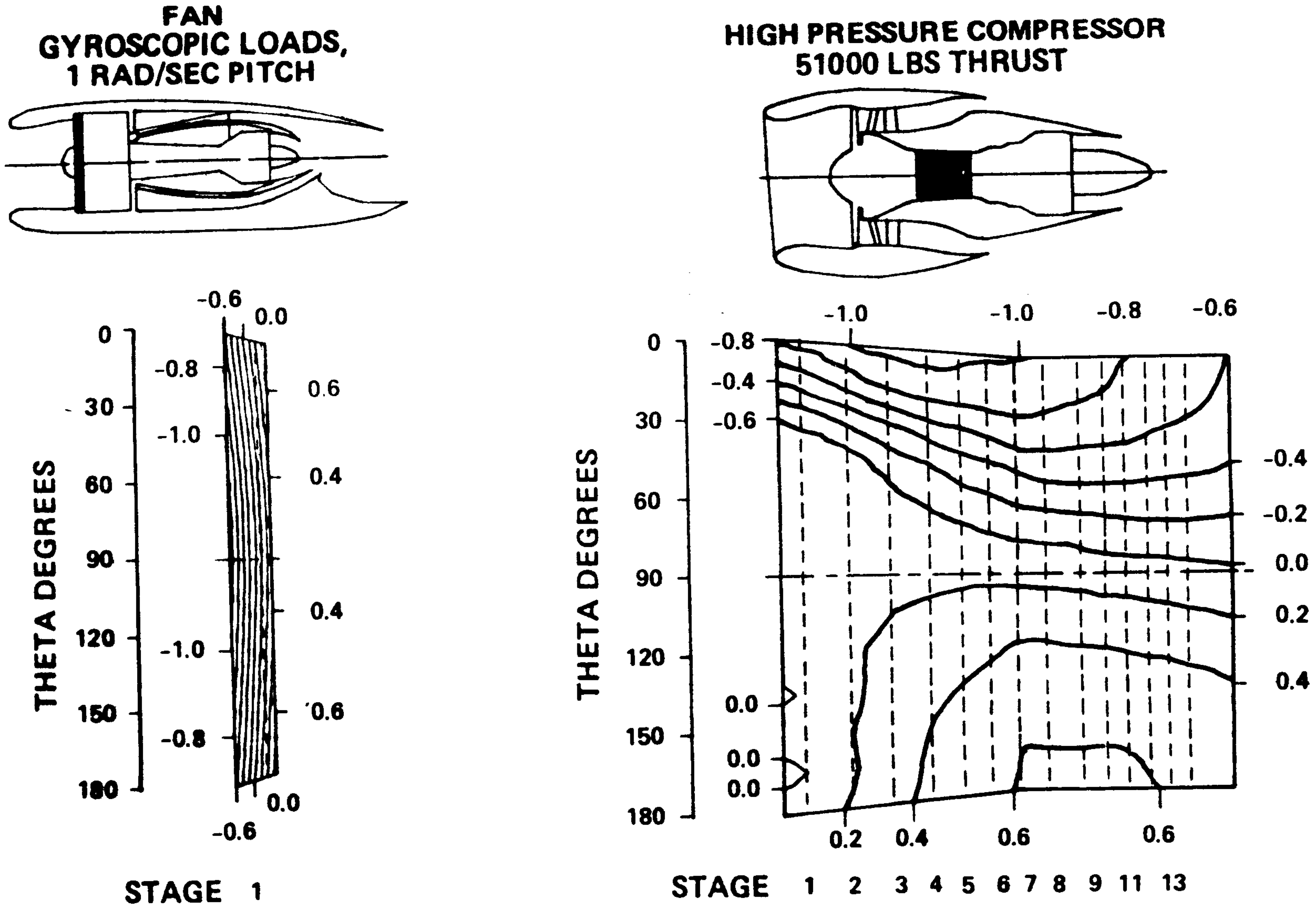


Figure 4.- Propulsion system static deflections.



FAN
GYROSCOPIC LOADS,
1 RAD/SEC PITCH

HIGH PRESSURE COMPRESSOR
51000 LBS THRUST

Figure 5.- Rotor/case change of clearance under load.

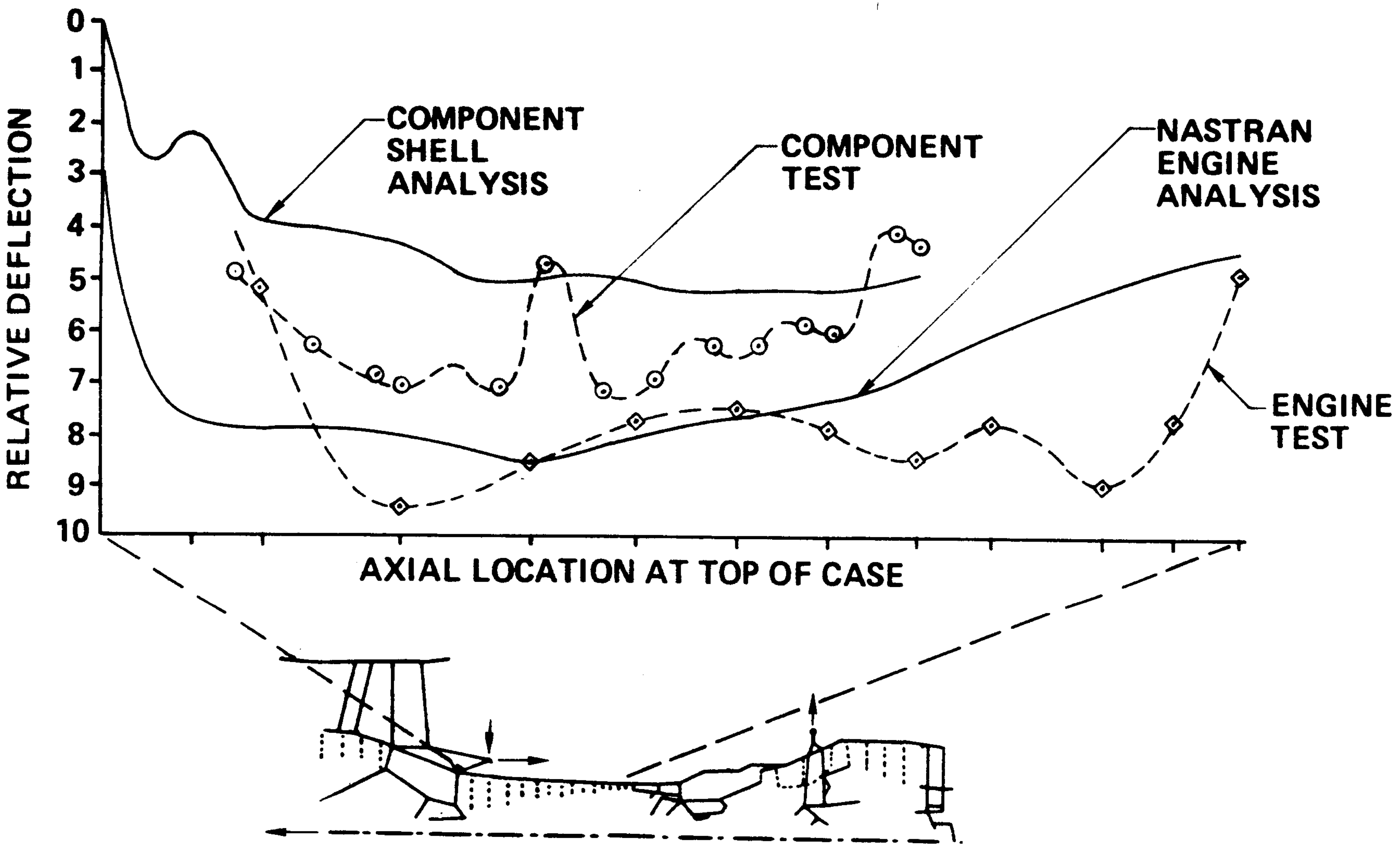


Figure 6.- Comparison of test and analysis results for engine case deflections under thrust load.

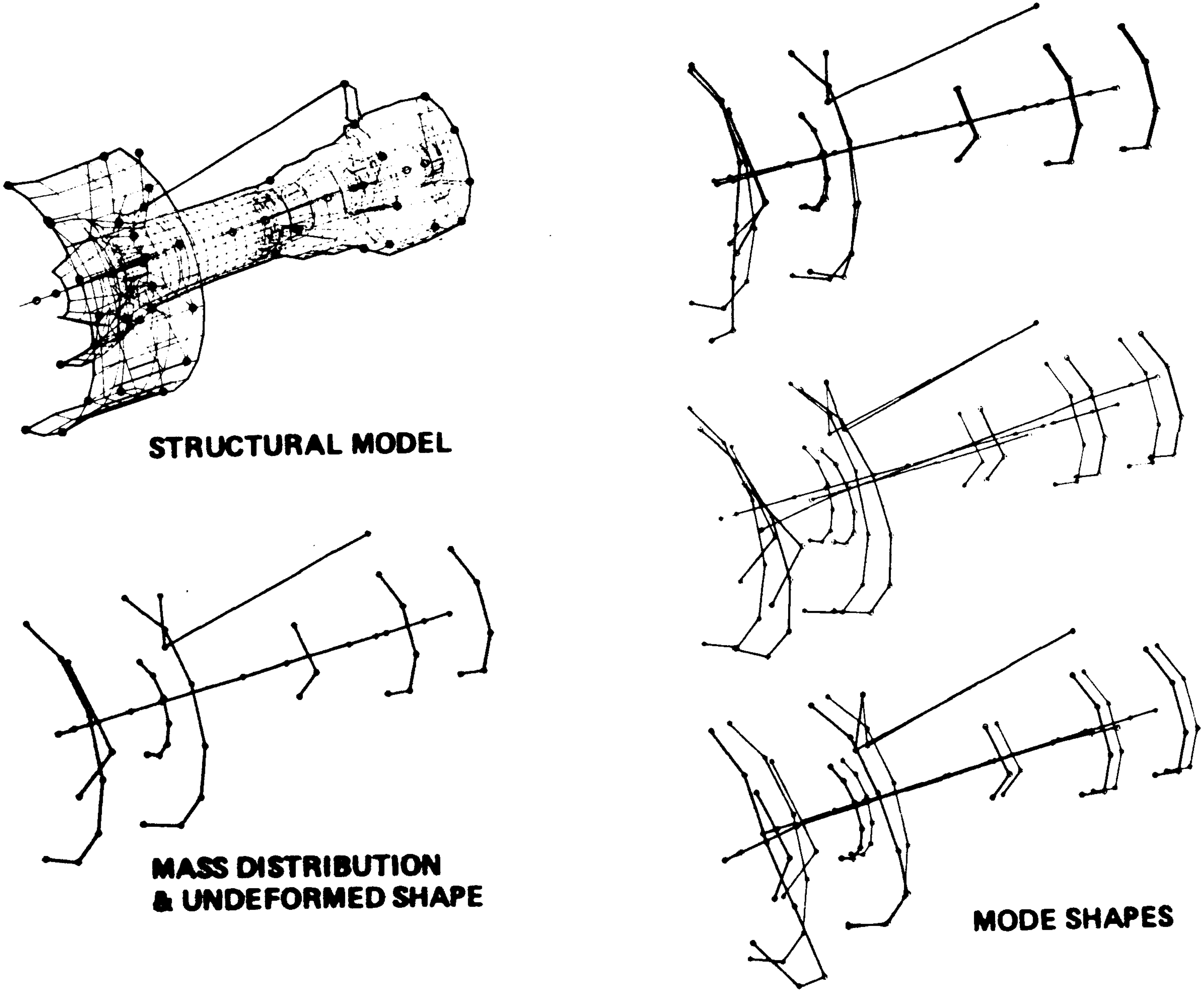


Figure 7.- Engine vibration analysis.