APPLICATIONS OF NASTRAN IN AEROELASTIC ANALYSES AT NORTHROP

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SUMMARY

The NASTRAN finite element program has been actively used at Northrop since 1972 for static and dynamic analyses. Flutter and gust analysis capability was added to NASTRAN by MacNeal-Schwendler Corporation (MSC) under a NASA contract in 1976. The subsonic aeroelastic feature was acquired by the Advanced Structural Computer Methods (ASCM) group at Northrop in 1978 for evaluation. The group has been actively evaluating and exercising the various NASTRAN dynamics analyses features and the aeroelastic package for several months. The integrated NASTRAN flutter analysis is presently being used on several selected projects at the Company. The supersonic aerodynamic package will be evaluated as soon as it is made available to Northrop. This will probably take place in early 1979.

INTRODUCTION

Integrated NASTRAN structural analysis combining static and dynamic analysis, e.g., flutter and gust, is the planned goal at Northrop. In order to achieve this end, a common structural model throughout an engineering project must be used. This practice is also expected to minimize the use of inconsistent structural data and unnecessary data handling among the various engineering disciplines.

The addition of dynamic aeroelastic capability without compromise to the pre-existing structural program of NASTRAN makes it the most powerful flutter analysis tool generally available in industry. Any of the existing NASTRAN structural finite elements can be used to build the structural model for the aeroelastic analysis (Refs. 1, 2 and 3). The structural stiffness, mass and damping matrices are generated from a description of the geometry of the aerodynamic finite elements. The choice of grid points for the aerodynamic model is independent of the location of the structural grid points (Ref. 4).

The most attractive features of the NASTRAN flutter package are:

- Several subsonic and supersonic aerodynamic subroutines available in the library.
- Linear and surface splining techniques to relate the aerodynamic and structural degrees of freedom.

- The aerodynamic forces may be evaluated at a relatively small number of mach numbers and reduced frequencies, and interpolated by means of surface splines at additional values of the independent variables. Linear spline interpolation is also available to obtain the aerodynamic forces at a large number of intermediate reduced frequencies for a given mach number.

- The flutter problem may be solved by any of the three KE(v-g), K and PK methods (Refs. 5 thru 27).

- The capability of coupling servo-systems with structure and aerodynamic forces is also included in NASTRAN, permitting flutter suppression and other active control system analyses.

- In addition to all of the numerical printouts, plots can be made of the structural and aerodynamic elements. The flutter analysis results, in the form of velocity- damping, velocity-frequency and flutter mode shapes, can also be plotted using the Tektronix 4014 terminal.

FLUTTER ANALYSES

Flutter is self-excited aeroelastic instability. In NASTRAN the following set of linear equations of motion is formulated in the modal form in order to perform the K-method of flutter analysis:

$$\{[(2k/\bar{c})^2 M_{hh} + (\rho/2)Q_{hh}]p^2 + [(2k/\bar{c})B_{hh}]p + K_{hh}\}(u_h) = 0 \qquad (1)$$

where

$$p^2 = -V^2/(1 + ig) \qquad (2)$$

In Eq. 1, M_{hh}, B_{hh}, and K_{hh} are the generalized modal mass damping and stiffness matrices, respectively. They are usually diagonal. However, provision is made for the user to add structural changes without recomputing the modes through the DMIG feature of NASTRAN; thus, M_{hh} and k_{hh} need not be diagonal. We also note that k_{hh} is singular when rigid body modes are included. The matrix of $Q_{hh}(k,m)$ is a complex matrix of generalized aerodynamic modal forces and depends on the reduced frequency k ($=\omega\bar{c}/2V$) and the Mach number m. The remaining parameters in Eq. 1 are the circular frequency ,the required artificial structural damping g, the density ρ,the velocity V, the reference chord c, and the vector of modal amplitudes$\{u_h\}$.

An approximation to the root of Eq. 2 for small values of g is

$$p \cong V(g/2 + i) \qquad (3)$$

and is exact at the flutter point, i.e., where $g = 0$. From Eq. 3 we have

$$V = \mathrm{Im}(p) \tag{4}$$

$$g = 2\mathrm{Re}(p)/\mathrm{Im}(p) \tag{5}$$

The flutter analysis is based on a series of values of m, k, and ρ that are supplied by the user. The complex eigenvalue problem of Eq. 3 is solved by the QR-transform method of Ref. 5, as automated in the subroutine ALLMAT (Ref. 6) and modified for NASTRAN. The velocity and damping for each root are computed from equations 4 and 5. The frequency of each root is given by

$$f = \omega/2\pi = kV/\pi\bar{c} \tag{6}$$

Flutter occurs when the required artificial damping is positive, i.e., when $g = 0$ the system is unstable; the flutter speed is the lowest value of V for which $g = 0$.

The primary difference between the above NASTRAN algorithm for the K-method of flutter analysis and the usual K-method is that the mass matrix rather than the stiffness matrix is inverted; secondary differences appear in the approximation of Eq. 3. An advantage of the present formulation is that the user can specify $k = 0$ and solve divergence problems for constrained systems.

The K-method of flutter analysis is a looping procedure. The values of V, g, and f are solved for various values of k, m, and ρ .Plots of V versus g can be used to determine flutter (when g goes through zero to positive values).

A more efficient K-method of flutter analysis is possible if the analyst is willing to neglect viscous damping from all sources, e.g., from the structure or a control system, and to restrict his solution to eigenvalues and not require eigenvectors. Then, many of the operations can be done in core with a consequent increase in efficiency. This efficient K-method algorithm is called the KE-method. With this increase in efficiency, a greater number of points on a flutter stability curve can be obtained for a given cost, and cases with poorly behaved stability curves can be studied more thoroughly. This method gives results similar to those of Ref. 7.

The PK-method of flutter analysis follows the "lined-up" British method as described in Refs. 8 and 9, rather than the procedure suggested in Ref. 10.

The complete flutter analysis by the British method requires a consideration of variations in altitude, h (i.e., density ρ), Mach number, m, and velocity, V. Altitude, Mach number, and velocity are not independent parameters in a standard atmosphere but may be regarded as independent if compressibility effects are secondary, e.g., $m = 0$ is representative of compressibility effects for $0 < m$ 0.4 or 0.5. Velocity and Mach number should be considered as a user input pair, i.e., each value of V has its associated value of m.

The principal advantage of the PK-method over the K-method (or KE-method) is that it produces results directly for given values of Mach number (or speed), whereas the other methods require iteration. In addition, the damping calculated by the method is a better physical approximation of the decay rate than the artificial parameter g in Eq. 5.

EVALUATION OF THE NASTRAN AEROELASTIC PACKAGE

The evaluation of the NASTRAN aeroelastic package is divided into the following tasks:

1. Flutter Analysis
2. Flutter Analysis with Servo-Elastic Interaction
3. Gust Response and Ride Quality Analyses with Servo-Elastic Interaction.

To date, the first task, Flutter Analysis, has been rigorously tested. The testing involved:

- Wing structure represented by beam elements and aerodynamics by doublet-lattice elements
- Finite element representation of a composite fin structure with doublet-lattice aerodynamics
- Total airplane structure represented by elastic beam elements and the aerodynamics by doublet-lattice lifting surface, slender body and interference elements.

T-38 Wing Flutter Analysis

The T-38 wing and the fuselage structure were modeled by elastic beam elements as shown in Figure 1. The horizontal and vertical stabilizers are lumped into the fuselage as point masses.

The wing was represented by the doublet-lattice lifting surface elements. No interference effect with the fuselage or the fuselage slender body aerodynamics was considered. The wing was subdivided into 6 chordwise and 11 spanwise boxes as shown in Figure 2. A linear spline function was used to relate the aerodynamic and structural degrees of freedom.

Eight free free symmetric vibration modes were used to generalize the aerodynamic forces. In this problem the forces were initially evaluated for mach .9 and three reduced frequencies. Forces at 17 additional reduced frequencies were evaluated by means of a linear spline interpolation.

The results of the KE or V-g method of flutter analysis for $M = .9$ at sea level are presented in Figure 3. Indicated on the figure, in addition to NASTRAN results, are the results of analysis performed by another flutter program. A slightly higher flutter speed obtained by the complete NASTRAN approach is due to the consideration of camber effect along the streamwise chords of the wing. This detail is ignored in the other program.

Typical Vertical Stabilizer Flutter Analysis

A fin with rudder was modeled by means of the membrane, shear, bending, rod, CELAS, GENEL and rigid elements available in NASTRAN as shown in Figure 4. The surface is made of graphite composite. In this model the NASTRAN GENEL is a general element representing the fuselage support to the fin at six of its root fittings.

The fin/rudder aerodynamics was represented by the doublet-lattice elements arranged in 14 chordwise and 13 spanwise boxes as shown in Figure 5. The interpolation between the structural and aerodynamic degrees of freedom is based on the theory of surface splines. Ten surface patches on the fin and four on the rudder were used for the spline fit, in conjunction with 101 structural degrees of freedom normal to the surfaces. Seven cantilevered vibration modes were used to generalize the aerodynamic forces. In this problem the forces were initially evaluated for mach .9 and three reduced frequencies. The forces at 27 additional reduced frequencies were evaluated by means of a linear spline interpolation. Flutter results are shown in Figure 6.

A Complete Aircraft Flutter Analysis

A beam element NASTRAN model of a complete airplane was used next to checkout the NASTRAN flutter analysis. The airplane with a tip store, launcher rail, wing, flaperon, fuselage, fin with rudder and horizontal stabilizer was modeled as finite beam elements as shown in Figure 7. The store and launcher rail assembly was tied to the wing tip by rigid elements which may be modified to possess elastic properties. The wing root and fin root flexibilities were modeled by lumped springs, which may be made more complex as the finite element model of the airplane is developed. The horizontal stabilizer root stiffness is a general element accounting for the spindle and the actuator assembly flexibilities. Mass properties were input on lumped mass element cards.

A doublet-lattice finite element program was used to represent the aerodynamics of the vehicle as shown in Figure 8. The wing with the launcher rail, fin with the rudder and horizontal stabilizer are represented as lifting surface elements. The fuselage and the tip missile are represented as slender body elements. In the present analysis the aerodynamic induction effect among all the elements is considered. The wing, horizontal stabilizer and fin are divided into 125, 57 and 53 micro lifting surface elements, respectively. The fuselage and the store each are divided into 14 slender body elements. There are 11 and 7 interference elements on the fuselage and store, respectively.

A complicated network of linear spline functions is used to relate the modal deflections to each of the aerodynamic element deflections. Five distinct splines were used for the wing, rail and flaperon panels, two for the horizontal stabilizer, three for the fin with rudder, two for the fuselage and one for the store.

In order to compute the generalized aerodynamic forces 3 rigid body and 22 free-vibration modes were used for either symmetric or antisymmetric flutter analyses. Forces were initially evaluated for mach .9 and six reduced frequencies. The forces at 29 additional reduced frequencies were evaluated by means of a linear spline interpolation.

Typical results of the NASTRAN flutter analyses for mach .9 at sea level are presented in Figures 9 and 10.

CONCLUSIONS

The subsonic flutter capability of NASTRAN has been tested at Northrop. The results of the flutter analysis of the T-38 wing and a cantilevered fin are in good agreement with the existing Northrop analyses. The complete airplane analysis performed by NASTRAN is very complex. The accuracy and complexity of the mode interpolation scheme between the structural grid and the aerodynamic grid for branched beams (Figure 7) cannot be duplicated by the existing programs. However, good agreement with other methods of flutter analysis results is obtained in the complete airplane analysis by making the aerodynamic model, shown in Figure 8, slightly less complex.

In the case of a swept beam representation of the wing structure, the camber effect along the streamwise chord is automatically accounted for in each vibration mode for the aerodynamic calculation. For a plate-like structure, the available surface spline fit between the aero and structural degrees of freedom yields a more accurate generalized aerodynamic force computation than most conventional flutter analysis programs.

The advantage of the integrated NASTRAN flutter analysis is that a common structural model for various engineering disciplines may be used, thereby saving a large number of man-hours in duplicated efforts and unnecessary transmittal of data between groups. When a common structural model is used by the various groups, the updates in the model are instantaneously available to other users. The use of obsolete data due to the time lag in communication between the groups is minimized and nearly eliminated completely in some cases. A considerable saving in elapsed time and data handling is also accomplished by the integrated NASTRAN analysis.

APPLICATIONS OF NASTRAN IN AEROELASTIC ANALYSIS AT NORTHROP

NASTRAN IN USE AT NORTHROP SINCE 1972

AEROELASTIC PACKAGE WAS ADDED IN 1976

ADVANTAGES OF NASTRAN AEROELASTIC ANALYSIS

- COMMON STRUCTURAL MODEL
- INTEGRATED NASTRAN ANALYSIS
- ENABLES DYNAMICIST TO PARTICIPATE IN STRUCTURAL DESIGN PHASE

AEROELASTIC PACKAGE EVALUATION

- SUBSONIC FLUTTER ANALYSIS - COMPLETED
- SUPERSONIC FLUTTER ANALYSIS
- FLUTTER ANALYSIS WITH ACTIVE CONTROL
- GUST ANALYSIS WITH ACTIVE CONTROL

SUBSONIC FLUTTER PACKAGE EVALUATION

NO COMPROMISE TO THE PRE EXISTING STRUCTURAL PROGRAM

THE FLUTTER PROBLEM CAN BE SOLVED BY KE, K AND PK METHODS

SEVERAL AERODYNAMIC SUBROUTINES IN THE LIBRARY

SEVERAL EIGENVALUE ROUTINES ARE AVAILABLE

DIRECT MATRIX INPUT FEATURE

LINEAR AND SURFACE SPLINING TECHNIQUES

COUPLING OF THE SERVO-SYSTEMS WITH AERODYNAMIC FORCES

PLOTTING CAPABILITY

EQUATIONS

RESULTS

CONCLUSIONS

NASTRAN FLUTTER ANALYSIS

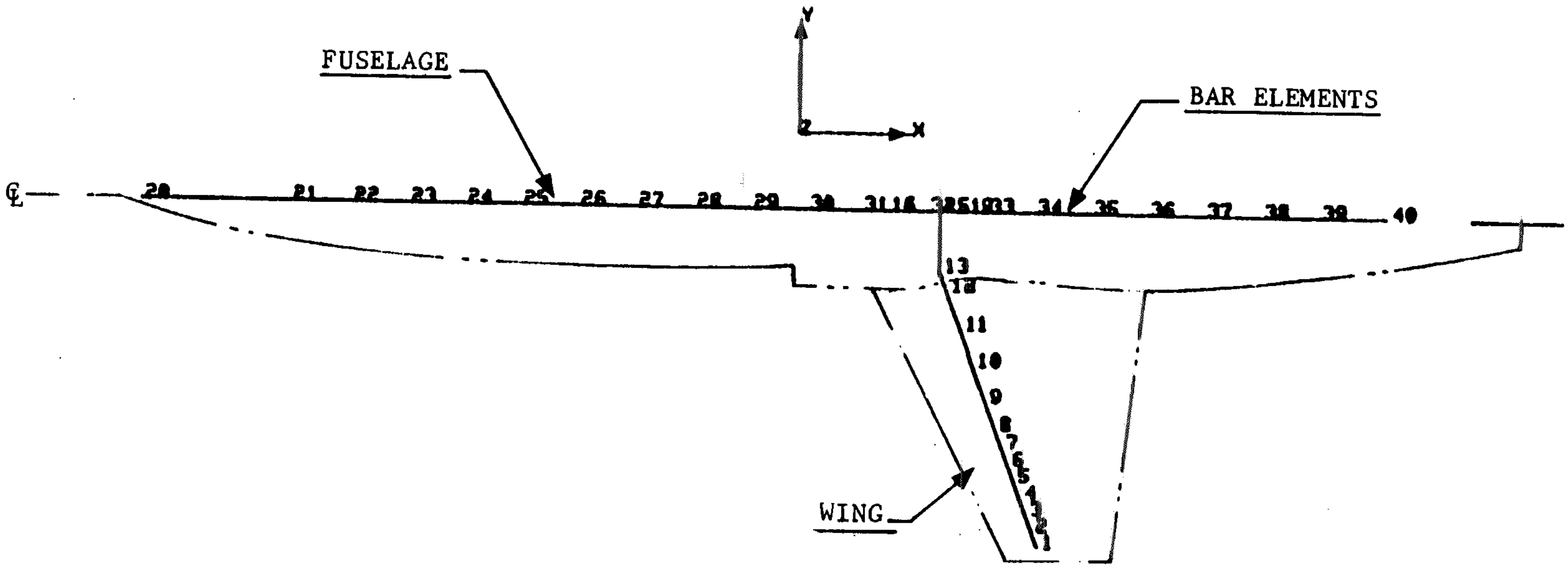

Figure 1. T-38 Wing and Fuselage Structural Model - NASTRAN

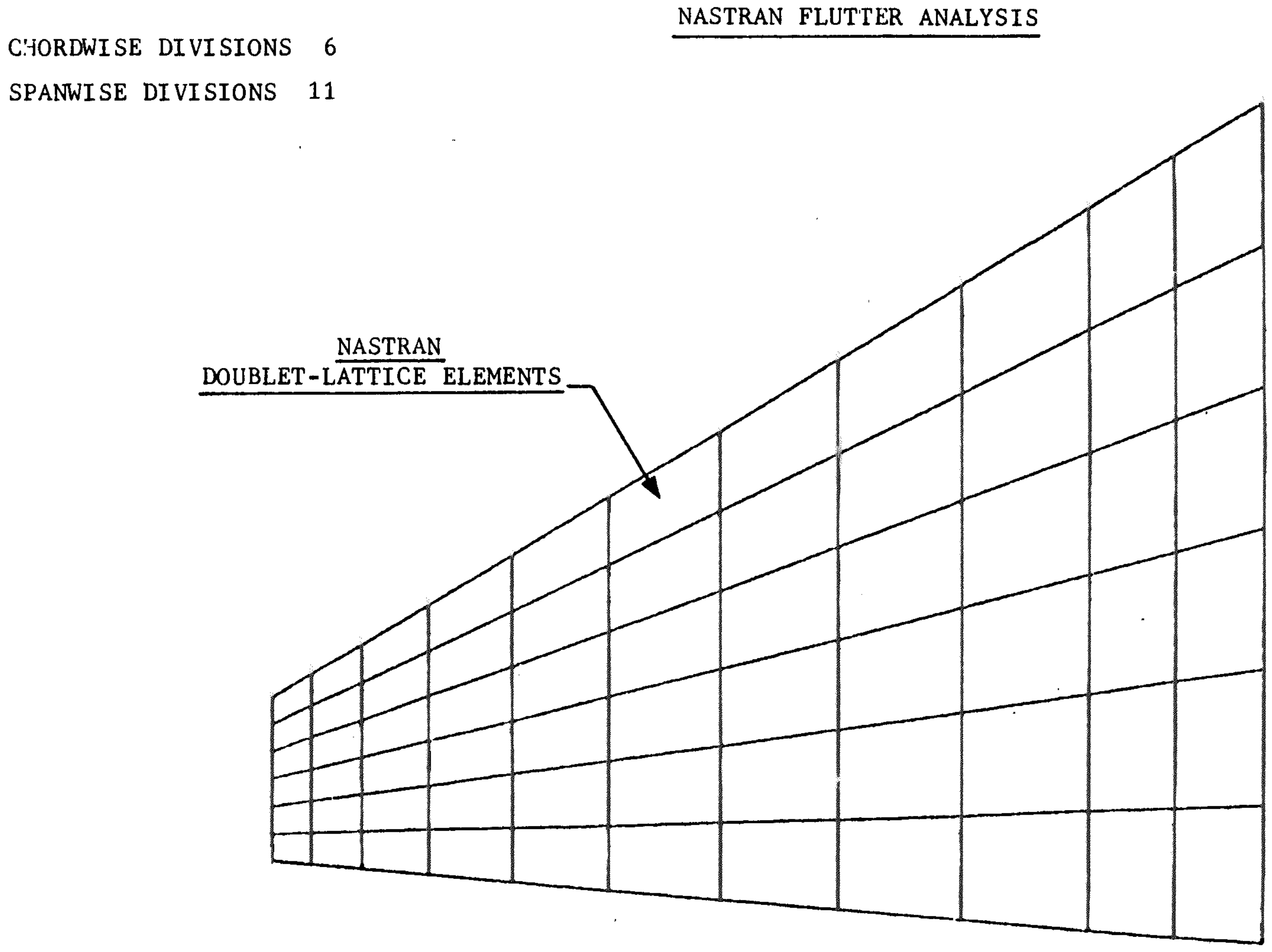

Figure 2. T-38 Wing Aerodynamic Model - NASTRAN

NASTRAN FLUTTER ANALYSIS

NOTE: NASTRAN ANALYSIS INCLUDES STREAMWISE CAMBER EFFECT IN THE AERODYNAMICS

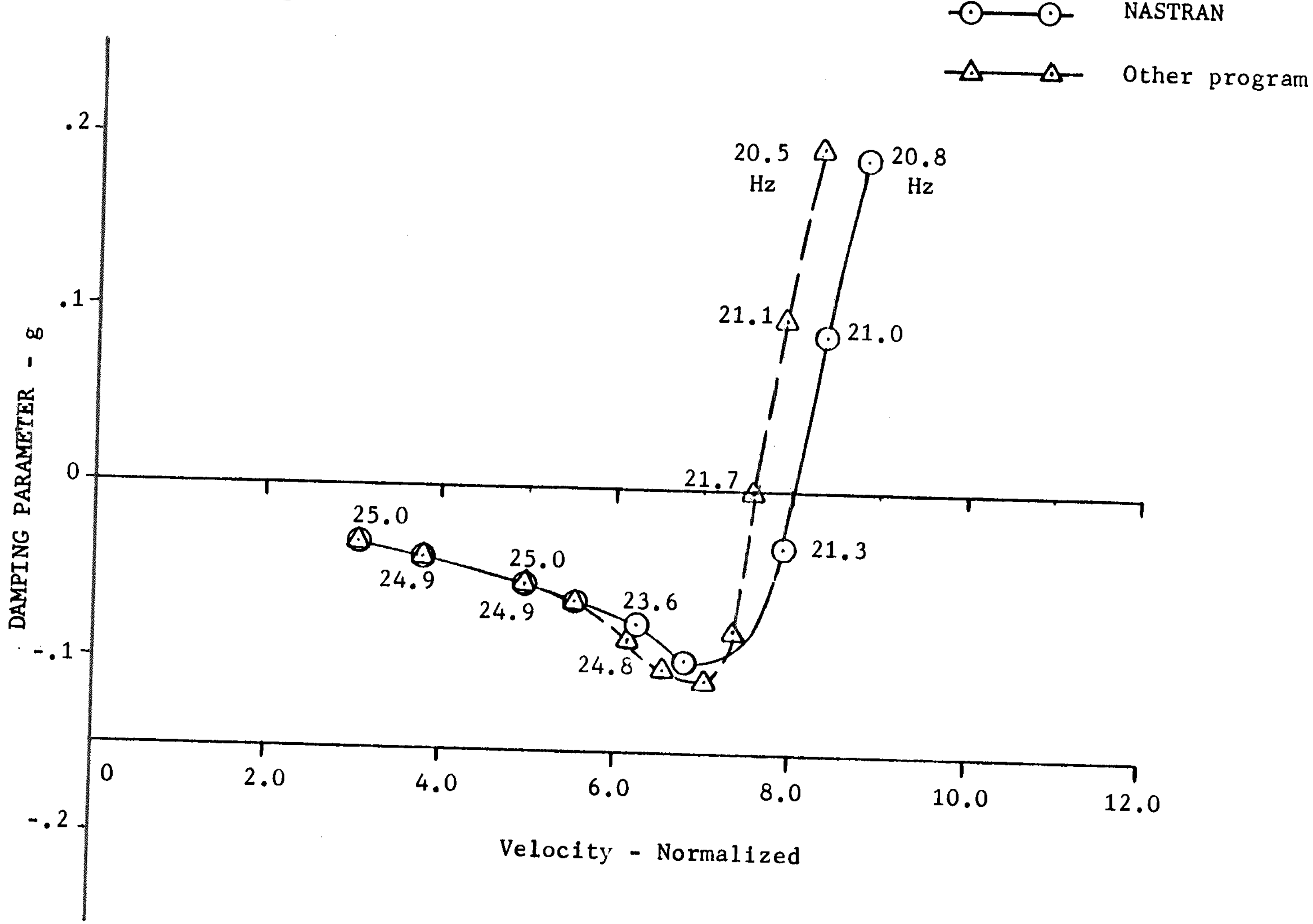

Figure 3. T-38 Wing Flutter Results for M = 0.90 at Sea Level

NASTRAN FLUTTER ANALYSIS

Number of elements - 1,490
Number of grids - 650
Vibration DOF - 88

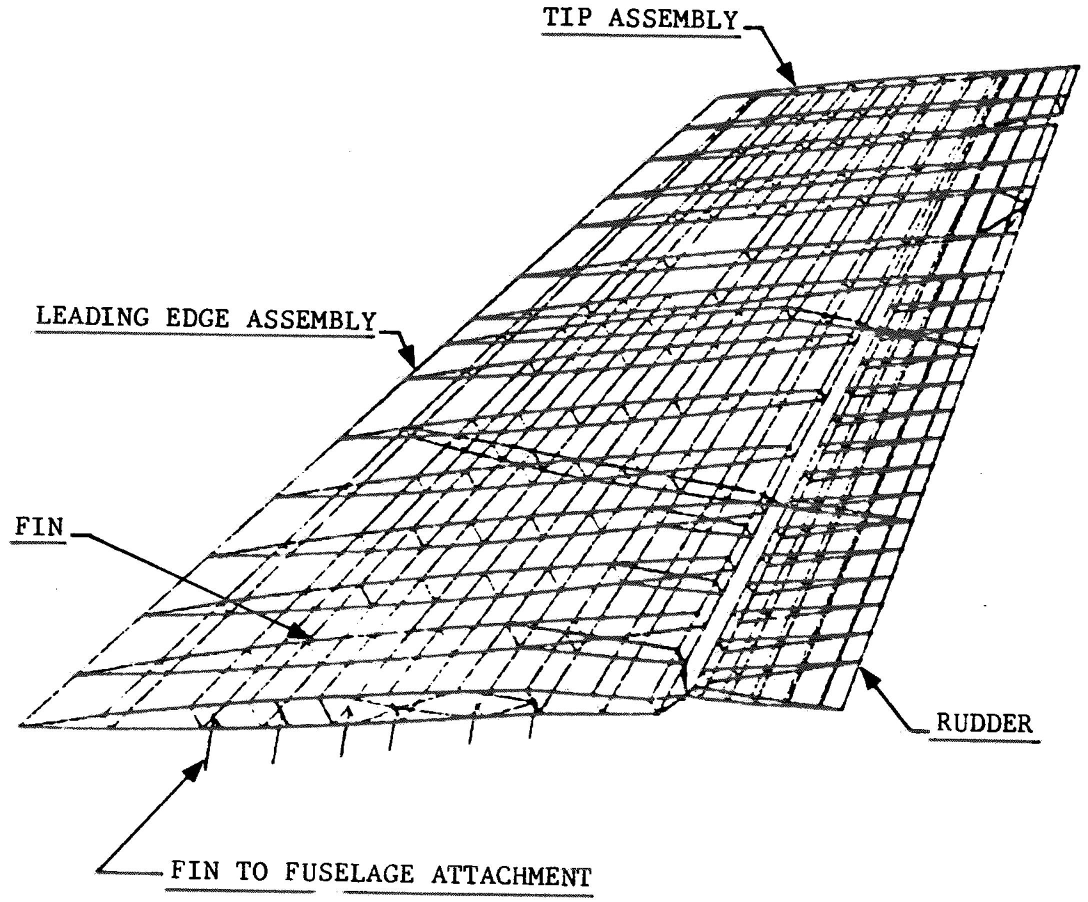

Figure 4. Fin Structural Model - NASTRAN

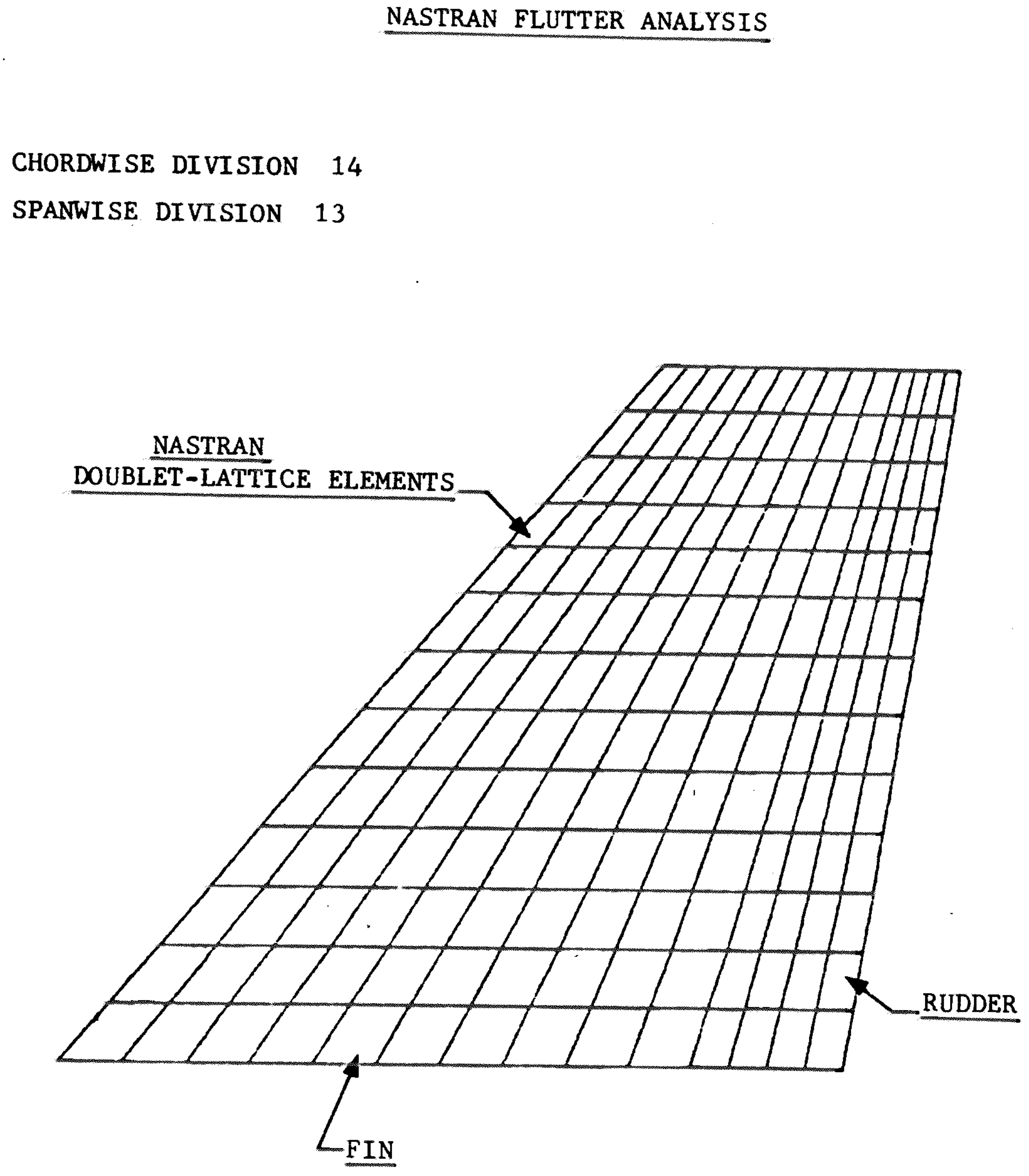

Figure 5. Fin Aerodynamic Model - NASTRAN

NASTRAN FLUTTER ANALYSIS

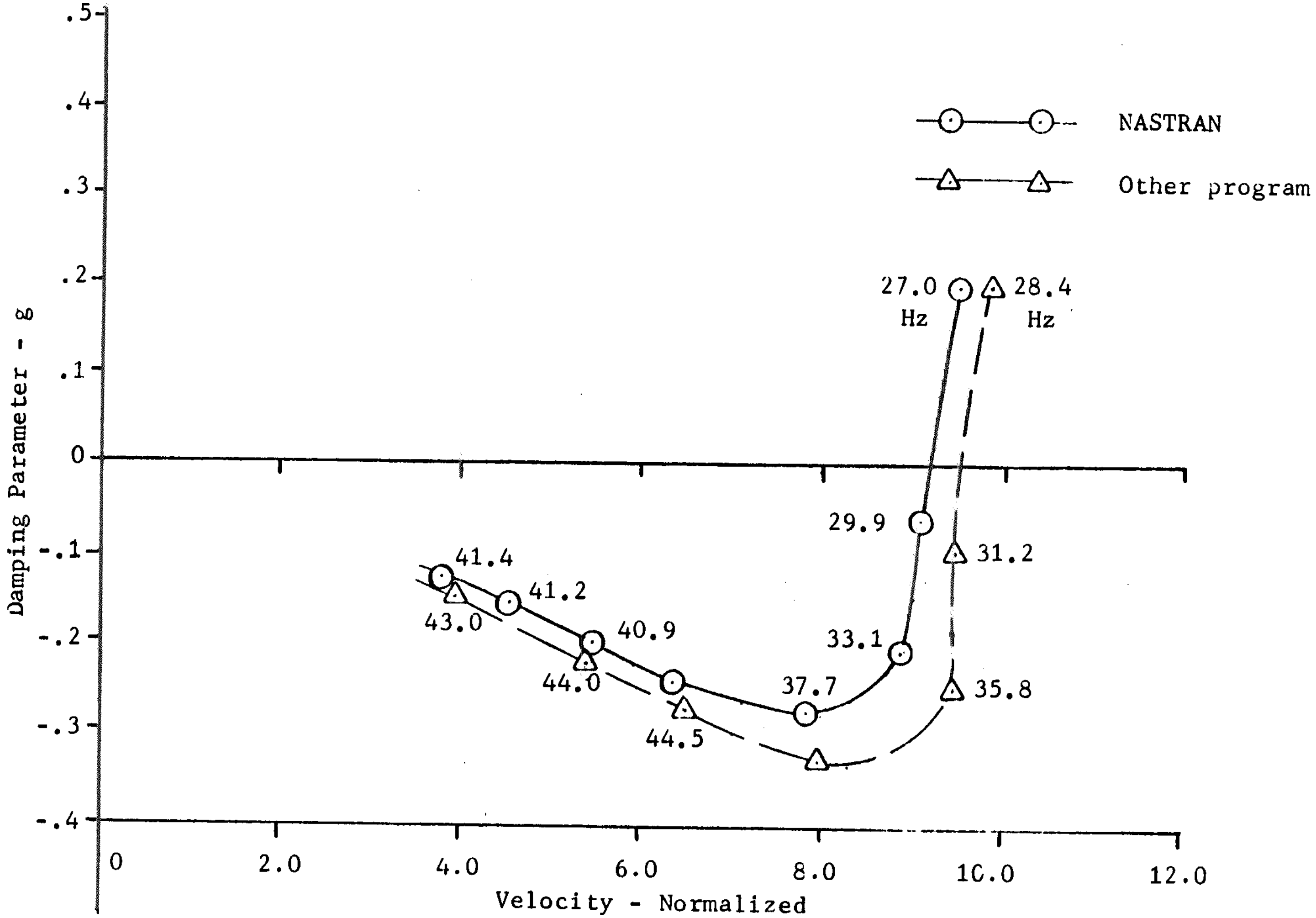

Figure 6. Fin Flutter Result for M = 0.90 at Sea Level

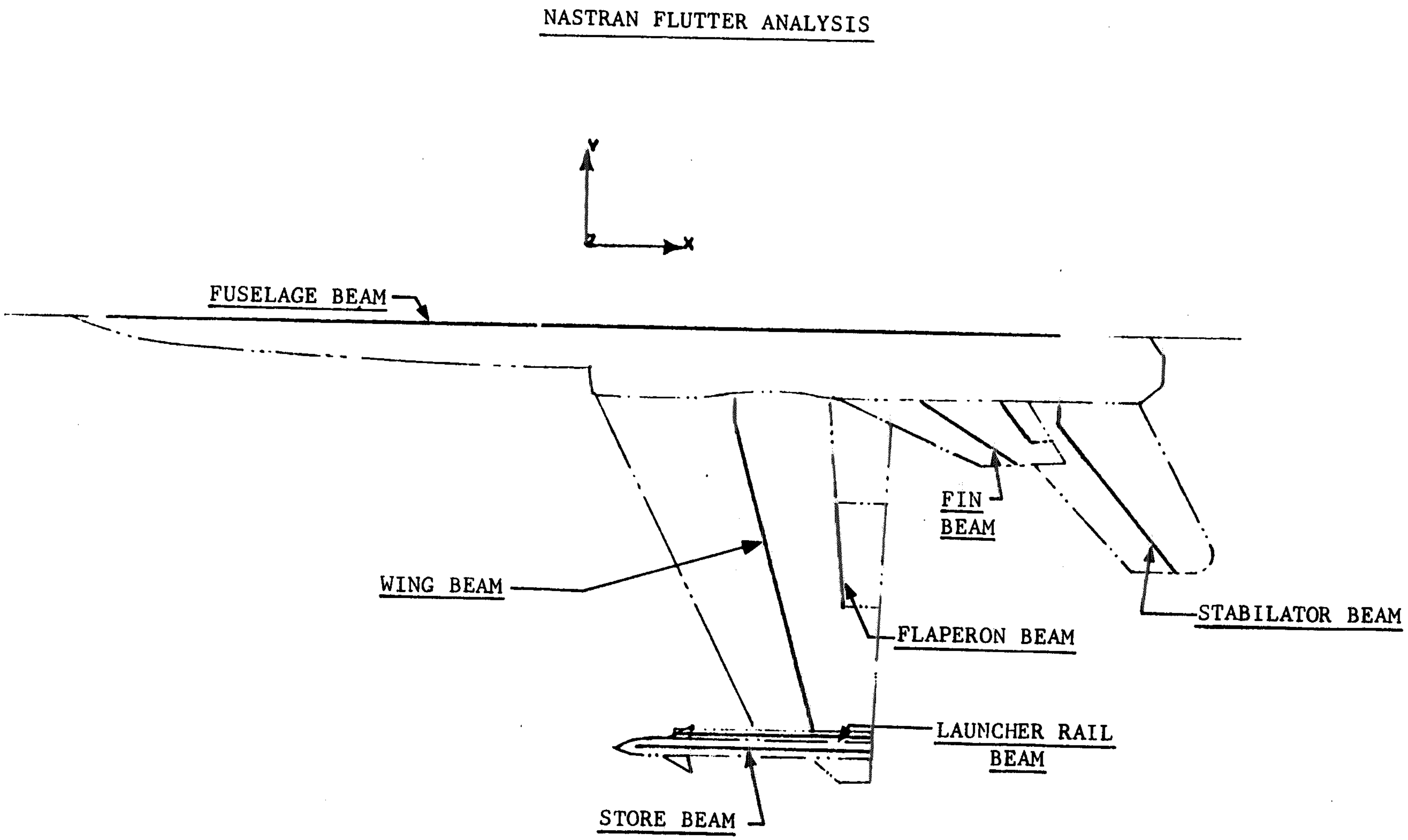

Figure 7. Complete Airplane Structural Model - NASTRAN

NASTRAN FLUTTER ANALYSIS

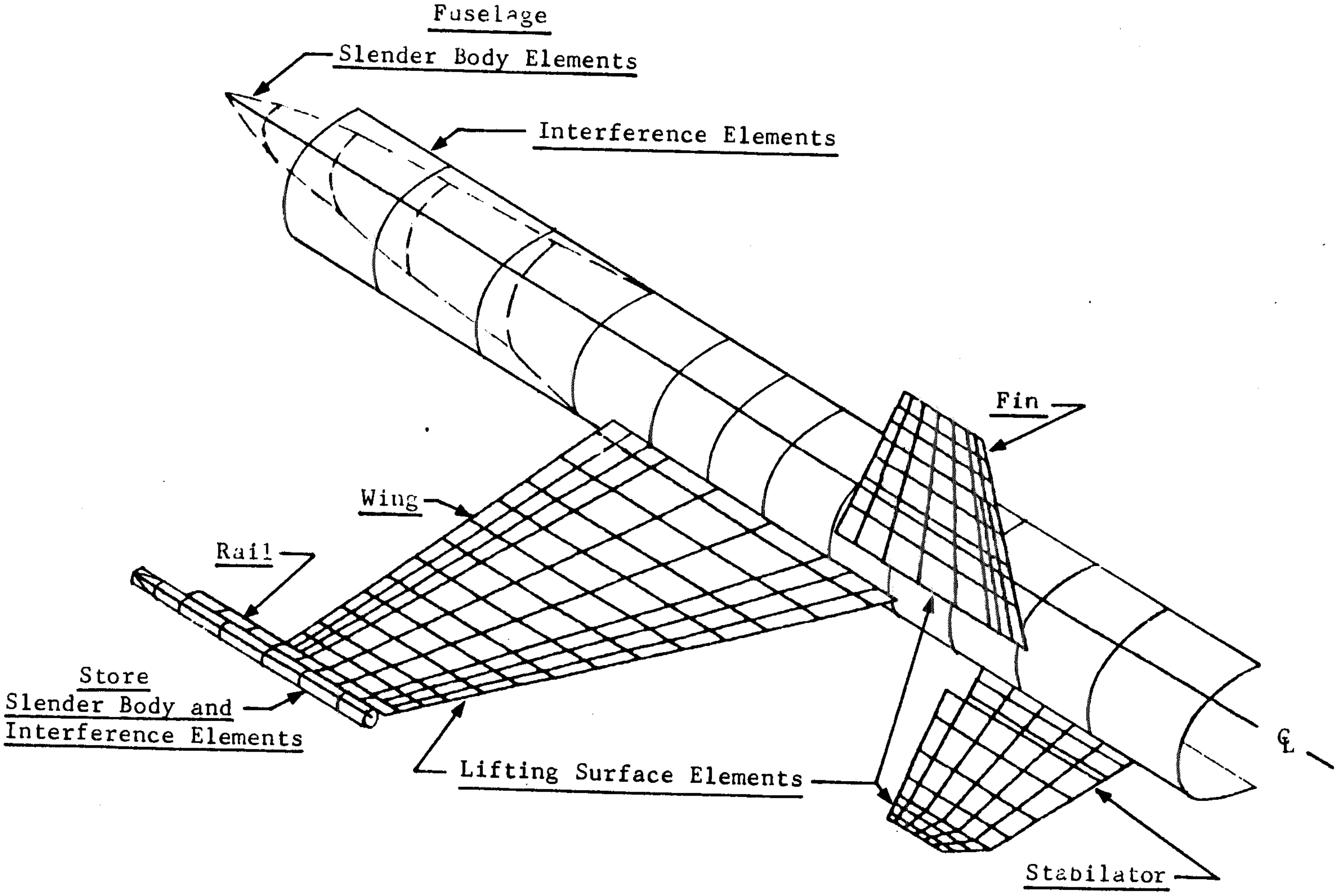

Figure 8. Complete Airplane Aerodynamic Model - NASTRAN

NASTRAN FLUTTER ANALYSIS

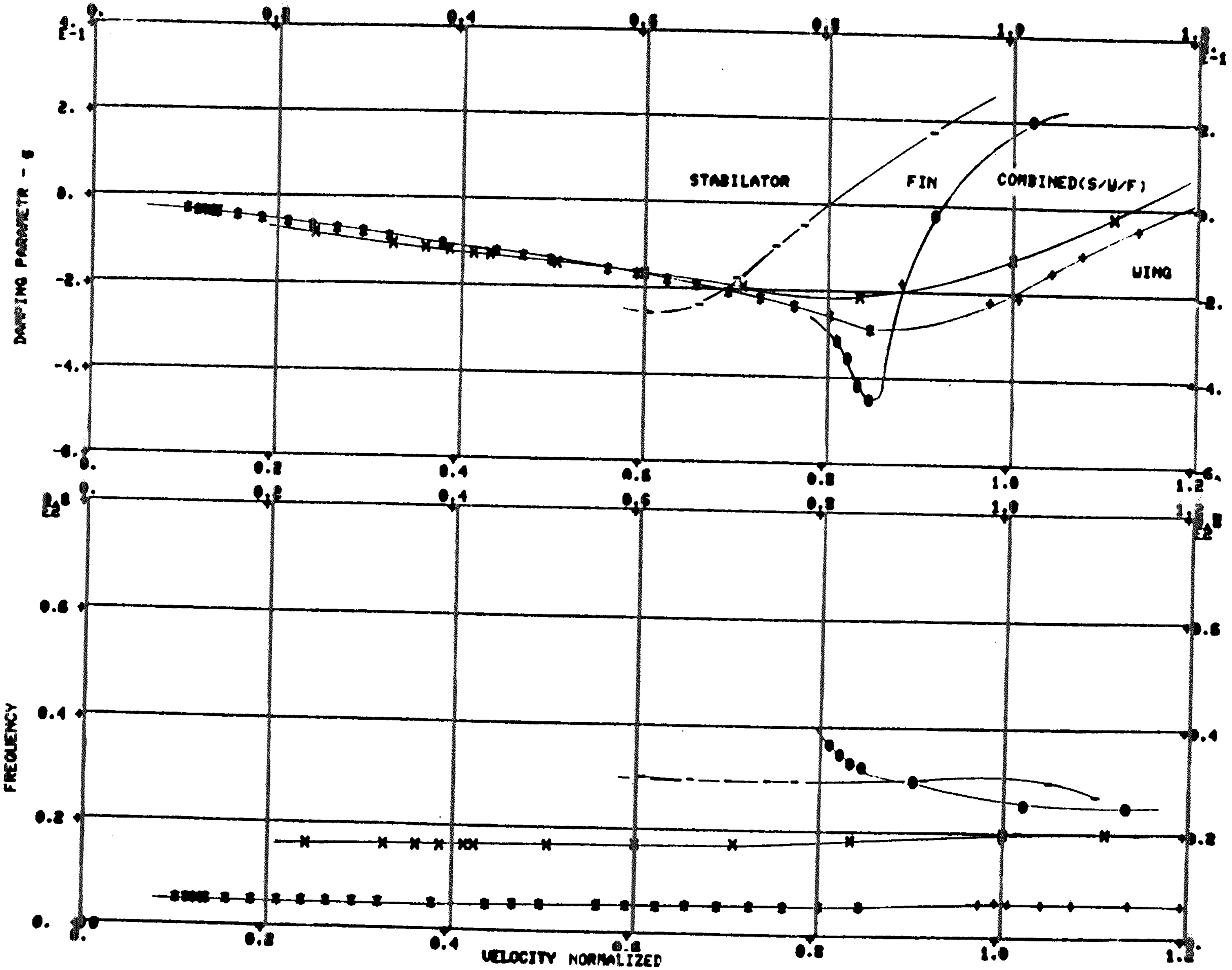

Figure 9. Complete Airplane Flutter Result for M = 0.90 at Sea Level - Symmetric

NASTRAN FLUTTER ANALYSIS

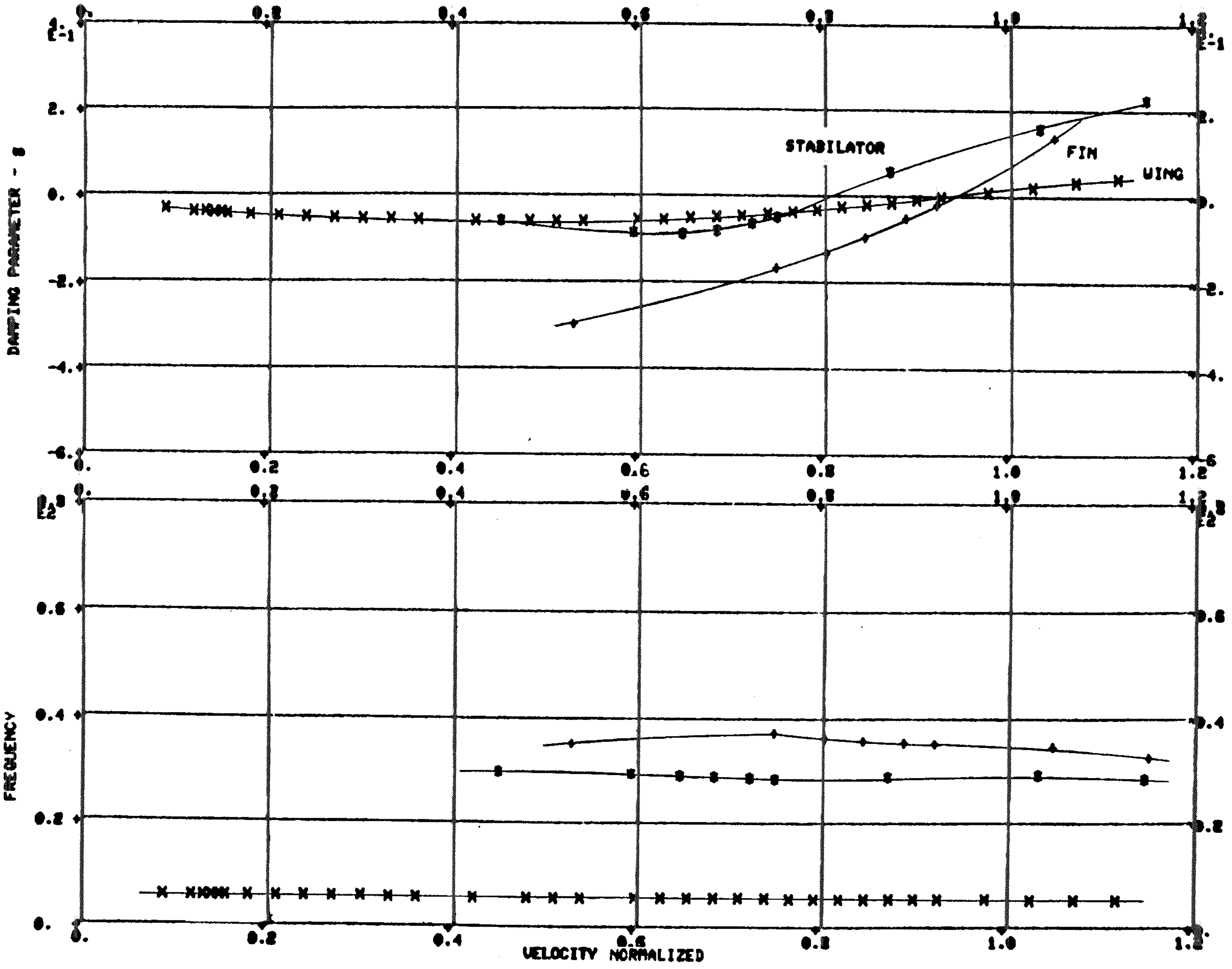

Figure 10. Complete Airplane Flutter Result for M = 0.90 at Sea Level - Antisymmetric

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