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ADVANCED SUBSTRUCTURING TECHNIQUES

FINAL REPORT

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by

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FOREWORD

Lockheed Missiles & Space Company's Huntsville Research & Engineering Center submits this report in partial fulfillment of the requirements of contract NAS8-30520, Advanced Substructuring Techniques. The report describes work performed for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. The contract was administered under the direction of the Aero-Astrodynamics Laboratory, NASA-MSFC, with Mr. Larry Kiefling as Contracting Officer Representative.

A magnetic tape containing the computer programs developed under the contract is being submitted separately to fulfill contract requirements.

Advanced substructuring techniques and associated computer programs were developed during this study under the supervision of W. D. Whetstone.

The methods incorporated in the study were formulated jointly by W. D. Whetstone and C. E. Jones.

The Substructure Synthesis computer program was developed by C. E. Jones. D. B. Alves developed the most recent version of the Substructure Function Generator program. A previous version of the Function Generator program was developed by R. A. Moore.

SUMMARY

This report describes methods and associated digital computer programs developed for evaluating free undamped modes and frequencies and damped transient responses of structural systems mathematically modeled as assemblages of arbitrary substructures. A Rayleigh-Ritz solution method is incorporated in which the state of each substructure is represented by a set of generalized displacement functions.

Two general purpose computer programs were developed. The Substructure Function Generator program, which is a modification of the dynamics version of the Lockheed-Huntsville Structural Network Analysis Program (SNAP), calculates generalized displacement functions and constructs the corresponding mass and stiffness matrices for substructures mathematically modeled as basic finite element networks. The Substructure Synthesis program forms system mass, stiffness, and damping matrices.

Full-matrix eigenproblem solution routines (Cholesky/Householder) compute system undamped modes and frequencies corresponding to specified constraints on system joint motion components. Transient response is computed using coefficients of undamped system modes as generalized coordinates. A method was developed for constructing a system damping matrix according to the energy dissipation characteristics of the individual substructures. Response calculations are performed by numerically integrating the system equations of motion.

Communication between the Function Generator and Synthesis programs is accomplished by means of substructure data files created by the Function Generator program. Each data file contains a complete substructure description along with a large number of generalized functions of various types. The Synthesis program has provisions for using any prescribed sub-sets of generalized functions from the data files.

Studies were performed of the related topics of substructure number and size and choice of substructure generalized functions.

User's manuals for both the Function Generator and Synthesis programs are included as appendices.

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Section 1
INTRODUCTION

In this study methods and associated computer programs were developed for evaluating the vibrational characteristics of complicated structural systems mathematically modeled as assemblages of arbitrary substructures. Techniques were developed for performing two basic kinds of system analyses: (1) evaluation of the free undamped modes and frequencies; and (2) calculation of damped transient response. A Rayleigh-Ritz formulation is incorporated in which the state of each substructure is represented by a set of generalized displacement functions.

Substructures are mathematically modeled as arbitrary finite element networks. Generalized functions used to represent substructure motions include: (1) rigid body motions, (2) static functions corresponding to independent motion components of boundary nodes (i.e., nodes which connect to other substructures), and (3) arbitrary displacement functions (e.g., vibrational modes) computed subject to specific restraint conditions imposed at the boundary nodes.

A computer program called the Substructure Function Generator program was developed for generating sets of substructure generalized functions. The program also forms mass and stiffness matrices expressing the kinetic and potential energies of substructures as quadratic forms in coefficients of the generalized functions. The Substructure Function Generator program is basically a modification of the dynamic analysis version of the Lockheed/Huntsville-developed Structural Network Analysis Program, SNAP, which performs static and dynamic analyses of structures consisting of various types of finite elements, including beams, triangular and quadrilateral membranes, and plate and shell elements. Detailed accounts are given in Refs. 1 through 4. The Function Generator program creates a substructure data file

containing all the information required to represent a substructure in a system analysis. The data file is automatically stored by the program on magnetic tape, drum or disc units, or punched cards.

The Substructure Synthesis program forms system mass and stiffness matrices based on the contents of the substructure data files and a description of substructure interconnection given by the user via input data cards. System analysis routines are included in the Synthesis program for calculating (1) undamped system modes, and (2) damped transient response.

Each substructure data file created by the Function Generator program contains descriptions of various classes of generalized functions, the number and type of which are controlled by the analyst via input data options. Provisions are included in the Synthesis program for using any sub-set of these functions as generalized coordinates in the system analysis. Accordingly, the effects on overall system modes and response characteristics of different classes of substructure generalized functions can be studied without recreating substructure data files. This feature is also useful if the anticipated motion of a substructure varies according to different system environments such as varying boundary conditions or forcing functions.

The standard mode of operation is to create substructure data files for each substructure with separate executions of the Function Generator program and then to perform a system analysis using the files. This approach is well suited for the types of studies frequently performed early in the design of a system in which it is required to determine the effects on overall system vibrational characteristics of design changes in only a few substructures. In such cases, substructure generalized functions, etc., need be recalculated only for the substructures containing the alterations.

The computer programs developed during this study provide an economical method of performing parametric studies of proposed Space Shuttle launch configurations. For example, the effects of parameters such as orbiter position and interconnection structure stiffness can be readily studied.

Section 2
TECHNICAL APPROACH

2.1 SYSTEM COMPOSITION

In this study a structural system is modeled as an array of interconnected arbitrary multi-node substructures. Joints through which the substructures are interconnected are called "system joints," as illustrated on Fig. 1. Any number of substructures may connect to a given joint.

Substructures are in general modeled as basic finite element networks composed of arrays of nodes interconnected by two, three, and four node beam and shell elements. A specific set of the network nodes in a substructure model are declared "boundary nodes." Each substructure boundary node is attached to some system joint either directly or through a rigid arm. If the location of a boundary node does not coincide with an attached system joint, the connection is accomplished by means of a rigid arm.

As shown on Fig. 1, a local reference frame called the substructure reference frame is associated with each substructure. The position of a substructure in the assembled system is defined by the location of the origin of the substructure reference frame relative to the system reference frame and the orientation of the substructure reference frame axes relative to the system reference frame axes.

2.2 ENERGY FORMS AND GENERALIZED COORDINATES

2.2.1 Substructure Energies

An "intrinsic reference frame," with axes parallel to the arbitrarily selected substructure reference frame, originates at boundary node 1 of each substructure,

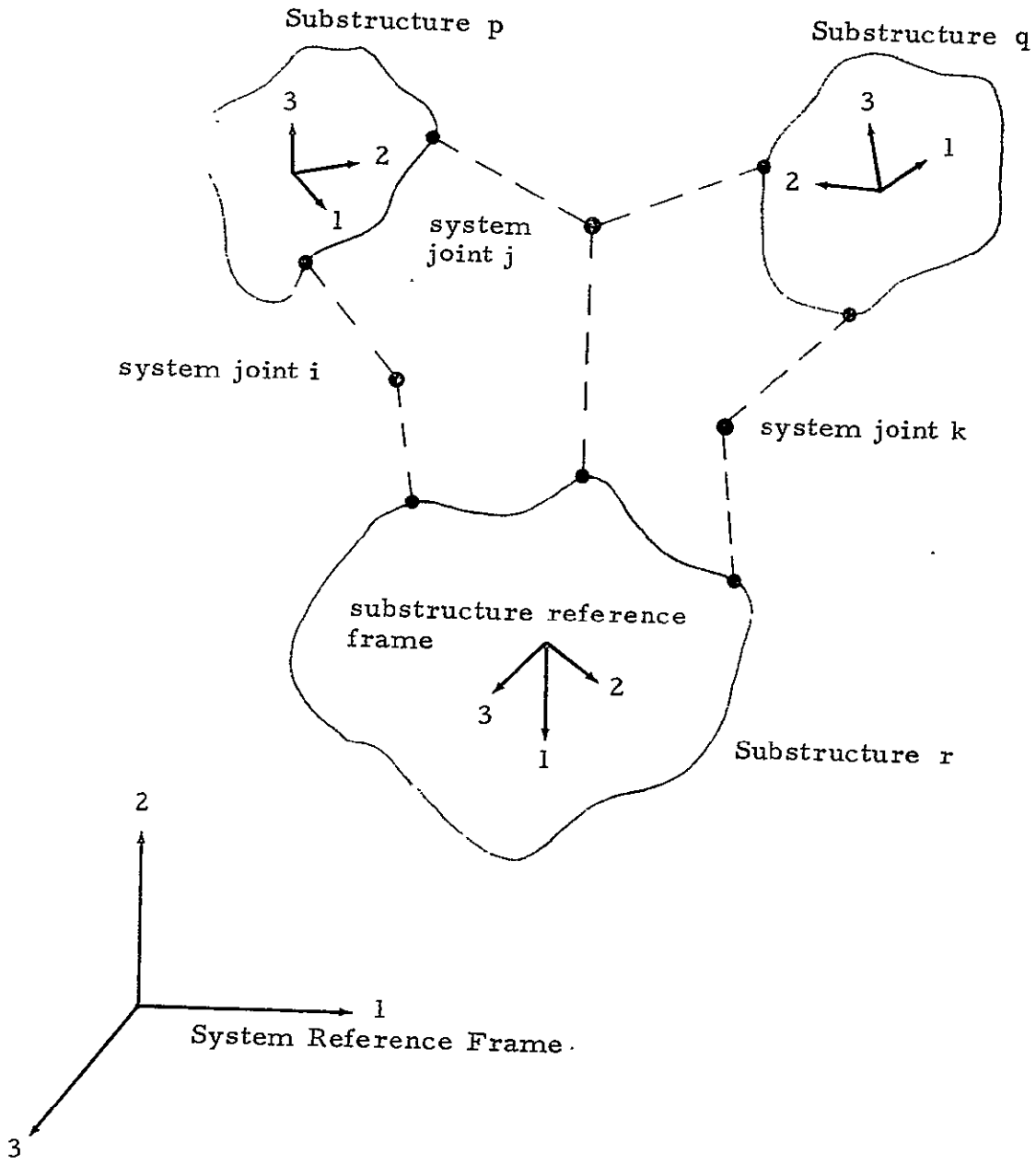


Fig. 1 - System Model

as shown on Fig. 2. Various categories of substructure generalized functions are defined as follows.

Φ_1^i = rigid translation in intrinsic reference frame direction i (for i=1, 2, 3), rigid body rotation about intrinsic frame axis i-3 (for i=4, 5, 6). (1a)

For j=2, 3, . . . , n (n boundary nodes),

Φ_j^i = static displacement function associated with unit value of motion component i (i=1 through 6) of boundary node j. These functions are subsequently called boundary node motion functions. (1b)

For k=1, 2, . . . , m,

ψ_k = arbitrary function, subject to the requirement that all boundary node motion components are identically zero. Specific types of functions are discussed in Section 2.2.3. These functions are subsequently called fixed boundary node functions. (1c)

Total substructure motion is expressed in terms of generalized coordinates as

$$\begin{aligned}\Phi = \; & q_1^1 \Phi_1^1 + q_1^2 \Phi_1^2 + \ldots q_1^6 \Phi_1^6 \\ & + q_2^1 \Phi_2^1 + q_2^2 \Phi_2^2 + \ldots q_2^6 \Phi_2^6 \\ & + \ldots\ldots \\ & + q_n^1 \Phi_n^1 + q_n^2 \Phi_n^2 + \ldots q_n^6 \Phi_n^6 \\ & + p_1 \psi_1 + p_2 \psi_2 + \ldots + p_m \psi_m\end{aligned} \tag{1d}$$

The above equation defines generalized coordinates q_j^i and p_k.

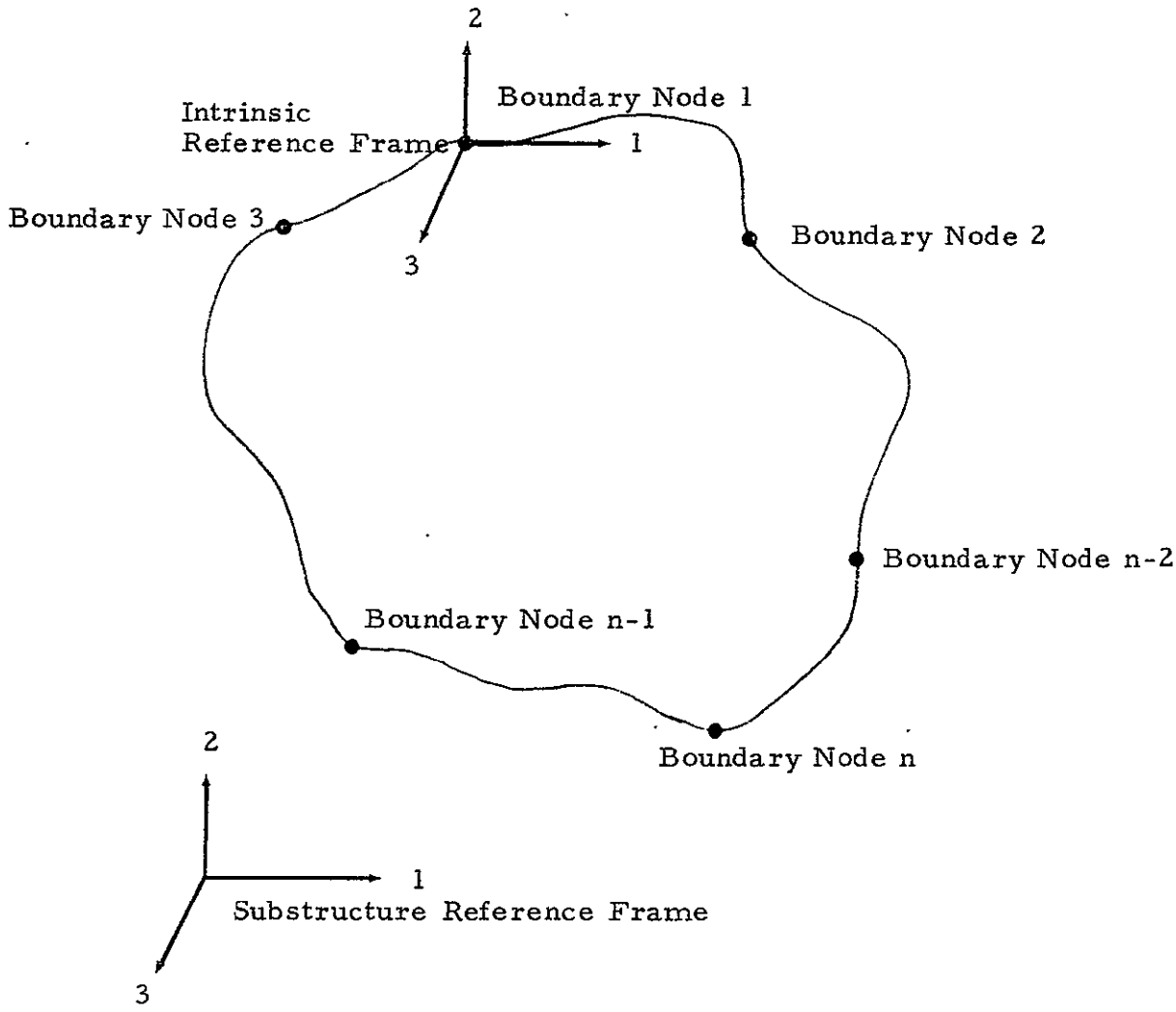


Fig. 2 Substructure Model

If the basic finite element net representing the substructure has s nodes (generally, $s \gg n$), each substructure generalized function is a 6s component vector. The mass and stiffness matrices associated with the basic finite element net will be designated $\widetilde{M}$ and $\widetilde{K}$ (both are 6s x 6s matrices). The substructure kinetic and potential energies are

$$T = \tfrac{1}{2}\dot{\Phi}^* \widetilde{M}\dot{\Phi} \ , \quad \text{and}$$

$$V = \tfrac{1}{2}\Phi^* \widetilde{K}\Phi \ . \tag{2a}$$

Where $$q_i \equiv \left[q_i^1 \ q_i^2 \cdots q_i^6\right] \ ,$$

and

$$Y \equiv \left[q_1 \ q_2 \cdots q_n \ p_1 \ p_2 \cdots p_m\right]^* .$$

Equation (2a) may be rewritten to express the energies in terms of the substructure generalized coordinates, Y, as

$$T = \tfrac{1}{2}\dot{Y}^* M\dot{Y}, \quad \text{and}$$

$$V = \tfrac{1}{2}Y^* KY \ . \tag{2b}$$

If substructure generalized functions corresponding to the i^{th} and j^{th} components of the generalized coordinate vector Y are ψ_i and ψ_j, the associated elements, m_{ij} and k_{ij}, of the substructure mass and stiffness matrices, M and K, are

$$m_{ij} = \psi_i^* \widetilde{M} \psi_j \ , \quad \text{and}$$

$$k_{ij} = \psi_i^* \widetilde{K} \psi_j \ .$$

Terms of this type are readily evaluated after all of the generalized functions have been computed. For example, the "static load vector," F_j, corresponding to each ψ_j is always known (even if ψ_j is a vibrational mode). That is,

$$F_j = \tilde{K}\psi_j \quad .$$

Therefore all k_{ij}'s may be computed as simple inner products, $\psi_i F_j$. Similarly, each vector $\tilde{M}\psi_j$ is readily computed in a sparse-matrix multiplication, then the required m_{ij}'s are computed as inner products, $\psi_i(\tilde{M}\psi_j)$.

Advantage is taken of the fact that certain components of F_j and ψ_j, etc., are identically zero for specific classes of functions.

2.2.2 System Energies

The kinetic and potential energies of an assembled system composed of N substructures can be expressed as the summation of the energies of the individual substructures, as follows:

$$T = \sum_{r=1}^{N} T_r, \qquad \text{and}$$

$$V = \sum_{r=1}^{N} V_r \,, \tag{3}$$

where T_r and V_r represent the kinetic and potential energies of substructure r as required by Eq. (2b).

In order to perform the energy summations indicated by Eqs. (3), the substructure energies must be expressed in terms of a set of system generalized coordinates that are common to all substructures. In this study, the system generalized coordinate vector, $\overline{X}$, is expressed as

$$\overline{X} = \begin{Bmatrix} Q_1 \\ Q_2 \\ \cdot \\ \cdot \\ \cdot \\ Q_m \\ Q_\psi \end{Bmatrix} \tag{4}$$

Q_i, for i=1, 2, . . . m (m=total number of system joints), is a six component vector containing the motion components of system joint i. As illustrated on Fig. 3, a joint reference frame is associated with each system joint. The origins of the joint reference frames coincide with their associated system joints and the axes of the joint reference frames are arbitrarily oriented relative to the system reference frame axes. Components of Q_i are relative to the i^{th} joint reference frame. Q_ψ represents a vector of coefficients of the individual substructure fixed boundary node functions (see Eq. (1c)).

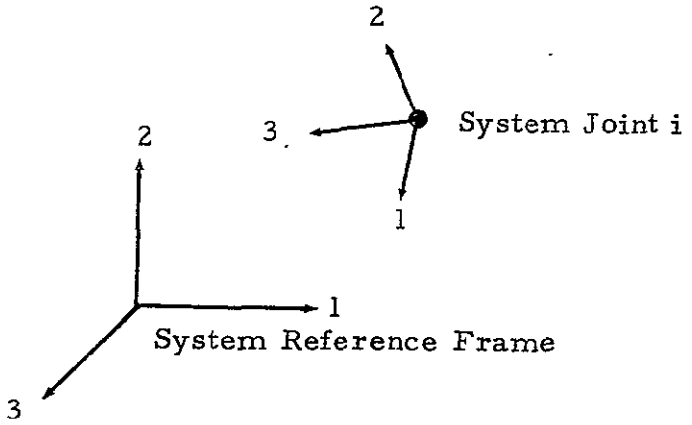


Fig. 3 - Joint Reference Frame

The generalized coordinate vector, Y_r, for substructure r can be expressed in terms of the system generalized coordinate vector, $\overline{X}$, as follows

$$Y_r = \overline{A}_r \overline{X} \quad . \tag{5}$$

Substituting Eq. (5) into Eq. (2b) yields the substructure expressions as quadratic forms in terms of the system generalized coordinates as follows

$$\begin{aligned} T_r &= \tfrac{1}{2}\dot{\overline{X}}^* \overline{M}_r \dot{\overline{X}} , \quad \text{and} \\ V_r &= \tfrac{1}{2}\overline{X}^* \overline{K}_r \overline{X}, \end{aligned} \tag{6}$$

where

$$\begin{aligned} \overline{M}_r &= \overline{A}_r^* M_r \overline{A}_r, \quad \text{and} \\ \overline{K}_r &= \overline{A}_r^* K_r \overline{A}_r \quad . \end{aligned} \tag{7}$$

Substituting Eqs. (6) into Eqs. (3) yields the following expressions for the system kinetic and potential energies:

$$\begin{aligned} T &= \tfrac{1}{2}\dot{\overline{X}}^* \overline{M} \dot{\overline{X}}, \quad \text{and} \\ V &= \tfrac{1}{2}\overline{X}^* \overline{K} \overline{X} \ , \end{aligned} \tag{8}$$

where

$$\begin{aligned} \overline{M} &= \sum_{r=1}^{N} \overline{M}_r, \quad \text{and} \\ \overline{K} &= \sum_{r=1}^{N} \overline{K}_r \end{aligned} \tag{9}$$

The matrix notation used above is symbolic of the actual operations performed by the Substructure Synthesis program to transform the substructure energy expressions from substructure generalized coordinates to the desired system generalized coordinates. Trivial arithmetic operations are avoided by taking advantage of the sparse characteristics of both the transformation and energy matrices. The symmetric properties of M_r, K_r, $\overline{M}_r$, $\overline{K}_r$, M and K are utilized, and only the upper triangular portions are computed. The coordinate transformations indicated by Eqs. (7) are performed in a manner ensuring maximum numerical accuracy and minimum computer execution costs.

2.2.3 Substructure Generalized Functions

As discussed in Section 2.2.1, arbitrary "fixed boundary node functions" represented by the vectors ψ_k of Eq. (1d) are admitted.

The zero boundary node motion requirement does not restrict generalized function choice, since a complete set of boundary node motion functions (Φ_j's) are used. That is, suppose it is desired to use a certain function, f, involving general motion of the boundary nodes. Some linear combination of the Φ_j^i's may be added to f to generate a function for which all boundary node motions are zero.

In this study, the standard types of fixed boundary node functions are:

- Undamped free vibrational mode shapes,
- Arbitrary static displacement functions, and
- Uniform acceleration modes.

Uniform acceleration modes (Whetstone, Ref. 5) are static displacement functions produced by inertia loadings corresponding to six independent uniform accelerations (3 linear, 3 angular). Functions of this type are especially useful if the system consists of a relatively large number of small substructures, since the total motion of most individual substructures will consist

primarily of rigid body motion. Consider, for example, the lateral motion of a beam-like structure for which x is a position coordinate directed along the longitudinal axis. The total lateral motion of points along the substructure is.

$$u(x) = U + Rx + f(x),$$

where U and R are the displacement and rotation of the origin of the x coordinate axis, and f(x) is the deformation of the substructure. Where m(x) is the distributed mass intensity, the lateral inertial forces acting on the substructure are proportional to m(x)u(x). If the predominant motion is rigid body (i.e., f(x) is small compared to U and Rx), the distributed lateral inertia forces are approximately proportional to $m(x)\left[U + Rx\right]$. Accordingly, displacement functions produced by lateral loadings corresponding to static lateral force distributions proportional to (1)m(x), and (2) x m(x) are excellent substructure generalized functions. For a general substructure, six functions of this type are used: three functions corresponding to static displacement fields produced by inertia loadings associated with constant rigid-body acceleration in each of three non-parallel directions, and three similar functions produced by inertia loads associated with constant rigid-body angular acceleration about each of the three non-parallel axes.

During the course of the study, an investigation was conducted to evaluate the relative merits of the substructure generalized functions mentioned above. Examples were executed to compare uniform acceleration modes, static displacement functions, and natural vibrational mode shapes. No general conclusions could be drawn from the results except that generalized functions selection should be governed by the anticipated motion of the substructure in the assembled system. It was determined, however, that in most applications an adequate set of substructure coordinates were the rigid body functions and the functions associated with boundary node motions along with uniform acceleration modes. In almost all comparisons, uniform acceleration modes represented substructure behavior as well as, if not better than, natural vibrational modes. Since uniform acceleration modes can be generated at a much lower cost than

natural modes, it was concluded that they should always be included in a substructure generalized function repertoire.

2.3 SYSTEM CONSTRAINTS

Using the complete set of system generalized coordinates represented by Eq. (4) to characterize the motions of the assembled system implies that all system joints are free to execute six independent motions. The Substructure Synthesis program includes provisions for imposing constraints upon selected system joint motion components. Two types of constraints are permitted:

- Complete restraint of explicit system joint motion components, and
- Relative constraints among sets of system joint motion components.

For each explicit system joint motion restraint, the order of the system mass and stiffness matrices, M and K of Eqs. (8), is reduced by one, and the corresponding term of the system generalized coordinate vector is eliminated.

Relative joint motion constraints are provided for imposing linear relations among various joint motion components. For example, consider a set of eight system joints lying in a circular plane as shown on Fig. 4a. If motion is confined to the plane of the circle, 24 coordinates (two displacements and one rotation of each of the eight joints) would be required to represent all possible joint motions. Through the use of joint motion relative constraints, however, the total number of system degrees of freedom can be substantially reduced (e.g., Fig. 4b - 4e), provided that expected system motion is adequately represented. This is often of considerable value in systems containing substructures having large numbers of boundary nodes.

2.4 UNDAMPED EIGENVALUE ANALYSIS

After the system energy expressions appearing in Eq. (8) are modified according to the constraint conditions imposed upon system joint motion

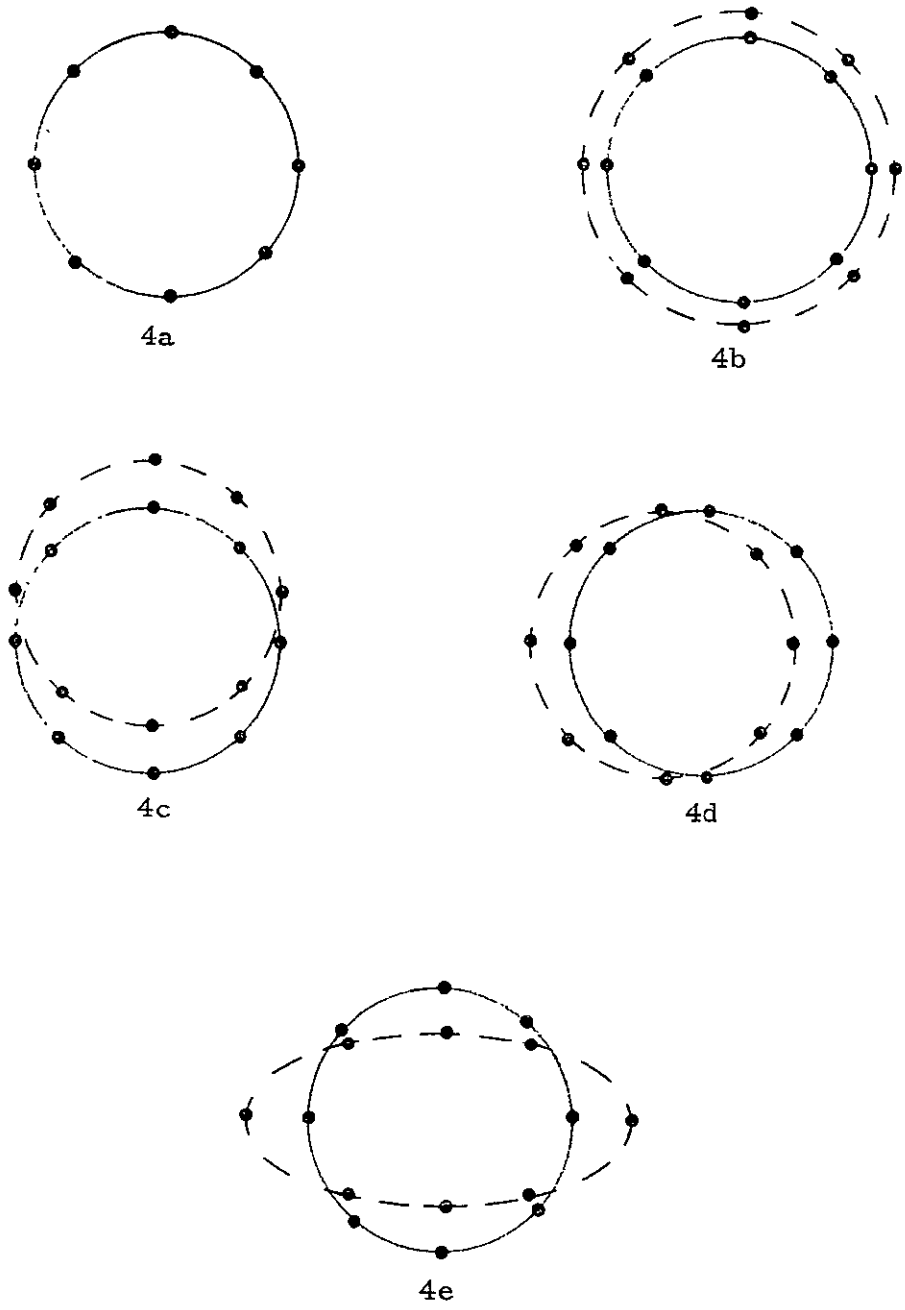


Fig. 4 - Relative Joint Motion Constraint Example

components, the final form of the system kinetic and potential energies are expressed as

$$T = \tfrac{1}{2}\dot{X}^{*} M \dot{X}, \quad \text{and}$$
$$V = \tfrac{1}{2}X^{*} K X \ . \tag{10}$$

In the absence of dissipative effects and externally applied forces, the Lagrange equations yield

$$M \ddot{X} + K X = 0 . \tag{11}$$

Assuming solutions of the form $X = Z \sin\omega t$ yields the usual linear vibrational eigenproblem

$$\omega^2 M Z - K Z = 0 \ . \tag{12}$$

Since an arbitrary selection of generalized coordinate functions occasionally results in a dependent set of system equations of motion, a solution procedure is incorporated for solving Eq. (12) that eliminates the problem of coordinate dependence by automatically "collapsing" the mass and stiffness matrices of the system. For instance, if during the eigensolution process it is discovered that the N^{th} coordinate function is a linear combination of coordinates 1 through N-1, the N^{th} row and column of the system mass and stiffness matrices are automatically eliminated, thereby reducing the order of the eigenproblem by one. The solution is then continued, eliminating any subsequently encountered dependence in a similar manner.

2.5 DAMPED FORCED RESPONSE ANALYSIS

The energy dissipation function for a viscously damped assembled system is

$$F = \tfrac{1}{2}\dot{X}^{*} D \dot{X} \ , \tag{13}$$

where D is the system damping matrix, and as discussed in Section 2.4, X is the vector of coefficients of the system generalized functions.

In this study, the forced transient response of an assembled system is evaluated using a specified set of the undamped system modes as generalized functions. Where q is a vector of coefficients of undamped system modes, the transformation from response coordinates to modal coordinates is

$$X = E\,q \quad . \tag{14}$$

Columns of E are the particular system modes used as generalized functions.

Substitution of Eq. (14) into Eqs. (10) and (13) yields the following expressions:

$$\begin{aligned} T &= \tfrac{1}{2}\dot{q}^{*}\,\hat{M}\,\dot{q} \quad , \\ V &= \tfrac{1}{2}q^{*}\,\hat{K}\,q, \quad \text{and} \\ F &= \tfrac{1}{2}\dot{q}^{*}\,\hat{D}\,\dot{q} \quad , \end{aligned} \tag{15}$$

where

$$\begin{aligned} \hat{M} &= E^{*}\,M\,E \quad , \\ \hat{K} &= E^{*}\,K\,E \quad , \quad \text{and} \\ \hat{D} &= E^{*}\,D\,E \quad . \end{aligned} \tag{16}$$

Where q_i is the i^{th} term of q, the generalized force associated with q_i is equal to

$$\frac{d}{dt}\frac{\partial T}{\partial \dot{q}_i} + \frac{\partial F}{\partial \dot{q}_i} + \frac{\partial V}{\partial q_i} \quad .$$

Accordingly from Eqs. (15),

$$\hat{M}\,\ddot{q} + \hat{D}\,\dot{q} + \hat{K}\,q = G \tag{17}$$

where G is the vector of generalized forces.

The transformations of Eqs. (16) yield diagonal matrices for $\hat{M}$ and $\hat{K}$ in which the i^{th} diagonal terms correspond to the generalized mass and stiffness of the system mode associated with the i^{th} term of q. The damping matrix $\hat{D}$ is not diagonal unless D is constructed as a linear combination of M and K.

In many cases the damping properties of individual substructures can be obtained more readily than those of the assembled system. Accordingly, the system damping matrix, D, is constructed on the basis of the damping characteristics of individual substructures, and the resulting matrix $\hat{D}$ is, in general, not diagonal.

The system response is evaluated by numerically integrating equations of motion in the form of Eq. (17).

2.5.1 System Damping Matrix

The total energy dissipation of an assembled system composed of m substructures is expressed as the summation of the energy dissipation of the individual substructures, as follows:

$$F = \sum_{r=1}^{m} F_r , \tag{18}$$

where F_r is the dissipation function of substructure r.

$$F_r = \dot{Y}_r^{*}\, D_r\, \dot{Y}_r , \tag{19}$$

where D_r is the damping matrix for substructure r, and Y_r is the vector of coefficients of substructure generalized functions as discussed in Section 2.2.1.

The damping matrix for substructure r is expressed as a linear combination of the individual substructure mass and stiffness matrices, as follows:

$$D_r = \alpha_1 M_r + \alpha_2 K_r , \tag{20}$$

where α_1 and α_2 are constants to be determined, and M_r and K_r are the substructure mass and stiffness matrices as defined in Section 2.2.1.

Substitution of Eq. (20) into Eq. (19) yields the following expression for the substructure energy dissipation:

$$F_r = \dot{Y}_r^* (\alpha_1 M_r + \alpha_2 K_r) \dot{Y}_r . \tag{21}$$

It is assumed at this point that the generalized damping, a_1 and a_2, associated with two specific substructure generalized coordinate vectors, φ_1 and φ_2, are known. Accordingly, from Eq. (21), the following simultaneous equations are derived for α_1 and α_2:

$$\begin{aligned} \alpha_1 A_1 + \alpha_2 B_1 &= a_1 \\ \alpha_1 A_2 + \alpha_2 B_2 &= a_2 \end{aligned} \tag{22}$$

where, for j=1, 2,

$$\begin{aligned} A_j &= \varphi_j^* M_r \varphi_j, \quad \text{and} \\ B_j &= \varphi_j^* K_r \varphi_j . \end{aligned} \tag{23}$$

Solving Eq. (22) for α_1 and α_2, and substituting into Eq. (20), yields the substructure damping matrix, D_r.

In the Substructure Synthesis program, the coordinate vectors, φ_1 and φ_2, may correspond to any two designated substructure vibrational modes calculated by the program relative to a specified set of boundary node constraint conditions. Individual eigenvalue analyses are performed for each substructure contributing to the system damping. Consequently, the terms A_1, A_2, B_1, and B_2 of Eq. (22) correspond to the generalized mass associated with φ_1 and φ_2, and the generalized stiffness associated with φ_1 and φ_2, respectively.

The substructure coordinates may be transformed to system coordinates by the following expression

$$Y_r = A_r X \,, \tag{24}$$

where A_r is determined from $\bar{A}_r$ of Eq. (5), according to the constraint conditions imposed upon system joint motion components.

Substitution of Eq. (24) into Eq. (19) yields

$$F_r = \dot{X}^* \bar{D}_r \dot{X} \,, \tag{25}$$

where

$$\bar{D}_r = A_r^* D_r A_r \,.$$

Accordingly, substituting Eq. (25) into Eq. (18) and comparing with Eq. (13) yields the system damping matrix,

$$D = \sum_{i=1}^{m} \bar{D}_i \,. \tag{26}$$

2.5.2 Numerical Integration Method

Determination of the system response involves integration of matrix equations of the form

$$\hat{M}\,\ddot{q} + \hat{D}\,\dot{q} + \hat{K}\,q = G \quad , \tag{27}$$

where q is the system coordinate vector representing coefficients of free undamped system vibrational modes. As discussed in Section 2.3, $\hat{M}$ and $\hat{K}$ are diagonal matrices and $\hat{D}$ is, in general, completely full.

The numerical integration procedure used in the program is a matrix Taylor series expansion method developed by Whetstone (Ref. 6), which has been used in a number of structural dynamics applications in recent years. The basis of this procedure is outlined below.

Matrix series expansions of the vectors q and $\dot{q}$ in powers of the time increment Δ are:

$$\begin{aligned} q(t+\Delta) &= q(t) + \Delta\,\dot{q}(t) + \frac{\Delta^2}{2}\,\ddot{q}(t) + \ldots \\ \dot{q}(t+\Delta) &= \dot{q}(t) + \Delta\,\ddot{q}(t) + \frac{\Delta^2}{2}\,\dddot{q}(t) + \ldots \quad . \end{aligned} \tag{28}$$

Equation (27) may be rewritten as

$$\ddot{q} = A\,\dot{q} + B\,\dot{q} + \eta \quad , \tag{29}$$

where

$$A = -\hat{M}^{-1}\hat{D},\quad B = -\hat{M}^{-1}\hat{K},\quad \text{and}\quad \eta = \hat{M}^{-1}G \tag{30}$$

From Eq. (29), higher derivatives of q may be expressed in terms of q, $\dot{q}$ and η.

$$\ddot{q} = A\ddot{q} + B\dot{q} + \dot{\eta}$$

$$= A\,(A\dot{q} + Bq + \eta) + B\dot{q} + \dot{\eta}$$

$$= (A^2 + B)\dot{q} + AB\,q + A\eta + \dot{\eta}$$

$$\dddot{q} = (A^2 + B)\,(A\dot{q} + Bq + \eta) + AB\,\dot{q} + A\dot{\eta} + \ddot{\eta}$$

$$= \left[(A^2 + B)\,A + AB\right]\,\dot{q} + (A^2 + B)\,Bq + (A^2 + B)\eta + A\dot{\eta} + \ddot{\eta},$$

etc. In general,

$$q^{(n)} = R_n q + P_n \dot{q} + P_{n-1}\,\eta + P_{n-2}\dot{\eta} + \ldots + P_1 \eta^{(n-2)} \tag{31}$$

Since

$$q^{(n+1)} = R_n \dot{q} + P_n(A\dot{q} + Bq + \eta) + P_{n-1}\,\dot{\eta} + P_{n-2}\,\ddot{\eta} + \ldots + P_1 \eta^{(n-1)},$$

The recursion formulae for P and R are

$$P_{n+1} = P_n A + R_n$$

$$R_{n+1} = P_n B, \tag{32}$$

beginning with

$$P_1 = I \text{ (identity matrix)}$$

and

$$R_1 = 0 \text{ (zero matrix).} \tag{33}$$

Substitution of Eq. (31) into (28) yields:

$$\begin{aligned}
q(t+\Delta) = {} & q(t) + \Delta\dot{q}(t) \\
& + \frac{\Delta^2}{2}\left[R_2 q(t) + P_2\dot{q}(t) + P_1\eta(t)\right] \\
& + \frac{\Delta^3}{3!}\left[R_3 q(t) + P_3\dot{q}(t) + P_2\eta(t) + P_1\dot{\eta}(t)\right] \\
& + \frac{\Delta^4}{4!}\left[R_4 q(t) + P_4\dot{q}(t) + P_3\eta(t) + P_2\dot{\eta} + P_1\ddot{\eta}(t)\right] + \ldots . \\
\dot{q}(t+\Delta) = {} & \dot{q}(t) \\
& + \Delta\left[R_2 q(t) + P_2\dot{q}(t) + P_1\eta(t)\right] \\
& + \frac{\Delta^2}{2}\left[R_3 q(t) + P_3\dot{q}(t) + P_2\eta(t) + P_1\dot{\eta}(t)\right] \\
& + \frac{\Delta^3}{3!}\left[R_4 q(t) + P_4\dot{q}(t) + P_3\eta(t) + P_2\dot{\eta}(t) + P_1\ddot{\eta}(t)\right] + \ldots .,
\end{aligned} \tag{34}$$

or, for an ℓ-term expansion,

$$\begin{Bmatrix} q(t+\Delta) \\ \dot{q}(t+\Delta) \end{Bmatrix} = \begin{bmatrix} W_{11} & W_{12} \\ W_{21} & W_{22} \end{bmatrix} \begin{Bmatrix} q(t) \\ \dot{q}(t) \end{Bmatrix}$$

$$\begin{bmatrix} N_{10} & N_{11} \cdots N_{1,\,\ell-2} \\ N_{20} & N_{21} \cdots N_{2,\,\ell-2} \end{bmatrix} \begin{Bmatrix} Q(t) \\ \dot{Q}(t) \\ \vdots \\ (\ell-2) \\ Q(t) \end{Bmatrix} \tag{35}$$

where

$$W_{11} = I + \sum_{n=2}^{\ell} \frac{\Delta^n}{n!} R_n, \qquad W_{12} = \sum_{n=1}^{\ell} \frac{\Delta^n}{n!} P_n,$$

$$W_{21} = \sum_{n=1}^{\ell-1} \frac{\Delta^n}{n!} R_{n+1}, \qquad W_{22} = I + \sum_{n=1}^{\ell-1} \frac{\Delta^n}{n!} P_{n+1},$$

and, for $j=0, 1, 2, \ldots, \ell-2$,

$$N_{1j} = \left[\sum_{n=j+2}^{\ell} \frac{\Delta^n}{n!} P_{n-j-1} \right] M^{-1},$$

$$N_{2j} = \left[\sum_{n=j+1}^{\ell-1} \frac{\Delta^n}{n!} P_{n-j} \right] M^{-1}. \tag{36}$$

Since the W and N matrices are not functions of time, they need be evaluated only once (at the beginning of the solution process); provided that a constant time interval, Δ, is used. Equation (35) can then be used to calculate the solution step-by-step in time. One advantage of this method is that it permits economical use of high-order approximations, which allows relatively long time increments. That is, unless the higher derivatives of Q become very complicated to evaluate, the time required to carry out an integration step using a sixth order approximation (i.e., ℓ=6) is typically only about 50% greater than the time required to effect one step of a third order approximation (ℓ=3). In the Substructure Synthesis program, the forcing function, G, is assumed to be a piece-wise linear function in time, so that all derivatives of G higher than $\dot{G}$ vanish. Consequently, high-order approximations may be used to accurately evaluate W and N matrices with no increase in the time required to perform the integration step.

Section 3
COMPUTER PROGRAMS

3.1 SUBSTRUCTURE FUNCTION GENERATOR PROGRAM

An accurate representation of the characteristics of individual substructures is probably the single most important factor in the analysis of a complicated system. During this study a digital program was developed for calculating generalized coordinate functions for substructures modeled as networks of basic finite elements. The program, which is a modification of the dynamic analysis version of the Lockheed developed Structural Network Analysis Program, SNAP (Refs. 1 - 4), provides an extremely fast and accurate means of computing any desired set of static or dynamic generalized functions for a substructure composed of basic finite elements. The program constructs substructure mass and stiffness matrices expressing the kinetic and potential energies as quadratic forms in coefficients of the generalized functions.

For substructure modeling the program contains the following finite element formulations:

- General symmetrical and non-symmetrical Timoshenko beam elements including shear and torsional effects,
- Isotropic, orthotropic, and aeolotropic triangular and quadrilateral membrane and bending elements.

The computer execution costs achieved by the basic solution routines of the program are very close to the minimum that can possibly be attained using direct solution procedures. This factor is extremely important in generating functions of large complicated substructures. The program's

"size" capacity, e.g., the allowable number of degrees of freedom, etc., is extremely large (approximately 12,000 d. o. f.), and the number of finite elements is virtually unlimited. Detailed checks of the numerical accuracy associated with the evaluation of every displacement vector are automatically executed. There are three checks: (1) a strain energy-external work comparison; (2) a total applied force/reaction comparison; and (3) an equilibrium check at all joints. The results of these checks should be carefully analyzed in all executions, since significant numerical error (usually the result of some elements having certain terms in their stiffness matrices much larger than corresponding terms in stiffness matrices of elements to which they are connected) is not an uncommon occurrence and may not be apparent from inspection of the displacements or energy arrays alone. Options are included for automatically executing an iterative accuracy improvement procedure and for using double precision arithmetic as means of overcoming accuracy problems.

The Function Generator program has three optional procedures for calculating terms of the substructure mass matrix, M_r, of Eq. (1). The available options are: (1) the lumped mass method, with distributed structural and nonstructural mass lumped automatically by the program; (2) the consistent mass matrix method (available only for beams and certain membrane elements); and (3) a "pseudo-consistent" mass matrix method which is more economical computer-wise, but less accurate than the consistent mass matrix method (this method is sufficiently accurate in most applications). Nonstructural lumped masses are also allowed.

The generalized function repertoire created automatically by the Function Generator program includes

- Rigid body functions. Six rigid body functions are created as discussed in Section 2.2.1.
- Boundary node motion functions. For a substructure with n boundary nodes, 6(n-1) functions of this type are created. Each function is calculated by applying a unit motion to the appropriate boundary node with all other boundary node motions identically equal to zero.

- Uniform acceleration modes. Six functions of this type are automatically generated by the program as discussed in Section 2.2.3 with all boundary node motion components identically equal to zero.

Also included (optionally) are fixed boundary node functions corresponding to arbitrary static loadings and/or undamped vibrational modes.

The user's manual for the Substructure Function Generator program is included in Appendix A.

3.2 SUBSTRUCTURE SYNTHESIS PROGRAM

As discussed in Section 2, the Substructure Synthesis program contains provisions for: (1) determining the undamped modes and frequencies of the assembled system, (2) constructing a system damping matrix based on the energy dissipation characteristics of individual substructures, and (3) performing a damped transient response analysis of the system. The program is arranged in a modular fashion, so that routines can be added for handling substructure representations in formats other than those supplied via data files created by the Function Generator program (e.g., from test data).

The matrix notation used in Section 2.2.2 only symbolically represents the computations performed by the Synthesis program in forming system mass and stiffness matrices. The transformation matrix, A_r, of Eq. (5) is never created in its entirety. Only the non-zero parts of the upper triangular portions of the substructure mass and stiffness matrices are used in transforming from individual substructure coordinates to system coordinates. During the processing of substructure data, individual terms of the system mass and stiffness matrices are accumulated in a core-buffer file and eventually stored on a secondary storage unit (drum, disc, or magnetic tape) as the buffer is filled. Consequently, the degree-of-freedom limitation of the program is imposed only by the full-matrix eigenproblem solution routines incorporated in the program (Cholesky/Householder). The program is arranged such that these routines can be easily replaced, if necessary, by routines with a larger size capacity.

Development of response routines to accommodate a wide variety of types of forcing functions was beyond the scope of this study. Forcing functions used in the response analysis are limited to point forces and moments, specified as piecewise linear functions of time, acting at system joints. The routines developed for performing the numerical integration procedure outlined in Section 2.5.2 are specialized for this type of forcing function. However, the program can readily be modified to accommodate virtually any forcing function form. All information required to handle distributed loading is available in existing internally-generated data files.

All matrix transformations performed by the Substructure Synthesis program are carried out in double precision to insure maximum accuracy.

A user's manual for the Substructure Synthesis program is included in Appendix B.

3.3 SUBSTRUCTURE DATA FILES

Communication between the Substructure Function Generator and Synthesis programs is accomplished by means of substructure data files which are created by the Function Generator program and read as input by the Synthesis program. These data files contain all the information required to represent the substructures in a system analysis. Magnetic tape, drum or disc units, or punched cards may be used to store a substructure data file.

The content of a substructure data file is outlined below:

- An alphanumeric description of the substructure. This description is used to identify the substructure throughout the Synthesis program printout,
- The total number of nodes in the substructure,
- The number of and identification of boundary nodes,
- The number of fixed boundary node functions,
- Position coordinates relative to the substructure reference frame of all nodes,

- Nodal displacement vectors associated with the six rigid body functions,
- Nodal displacement vectors associated with the boundary node motion functions,
- Nodal displacement vectors associated with the six uniform acceleration modes,
- Nodal displacement vectors associated with the other fixed boundary node functions,
- The upper triangular portion of the substructure mass matrix, and
- The upper triangular portion of the substructure stiffness matrix.

Section 4
RESULTS

A magnetic tape containing the Substructure Function Generator and Synthesis programs was delivered to the NASA Contracting Officer Representative. The programs are coded in Fortran IV and are compatible with the MSFC Univac 1108 system. The tape contains complete files of the symbolic, relocatable, and absolute elements for the programs. Also included are several example problem data elements which demonstrate proper program usage.

A lengthy presentation of numerical solutions computed with the programs is not within the scope of this report. Execution of the data elements included on the tape will produce several complete numerical examples. However, results for one typical example are presented below. An early Space Shuttle launch configuration is illustrated on Fig. 5. Each vehicle was a substructure in the system model. Two system joints interconnected the two substructures. The forward joint lies on the symmetry plane, and the aft joint lies off the symmetry plane. A half-model on one side of the symmetry plane was used to obtain the symmetric modes of the system. The fifteen generalized coordinates used to characterize system motion were:

- Three motion components (2 displacements, 1 rotation) of the forward system joint,
- Six motion components of the aft system joint, and
- Coefficients of the first three symmetric vibrational modes of each substructure, corresponding to zero boundary node motion.

Table 1 presents a comparison of the frequencies of the first five symmetric elastic modes obtained with the Substructure Synthesis program with results obtained with the SNAP/Dynamics program.

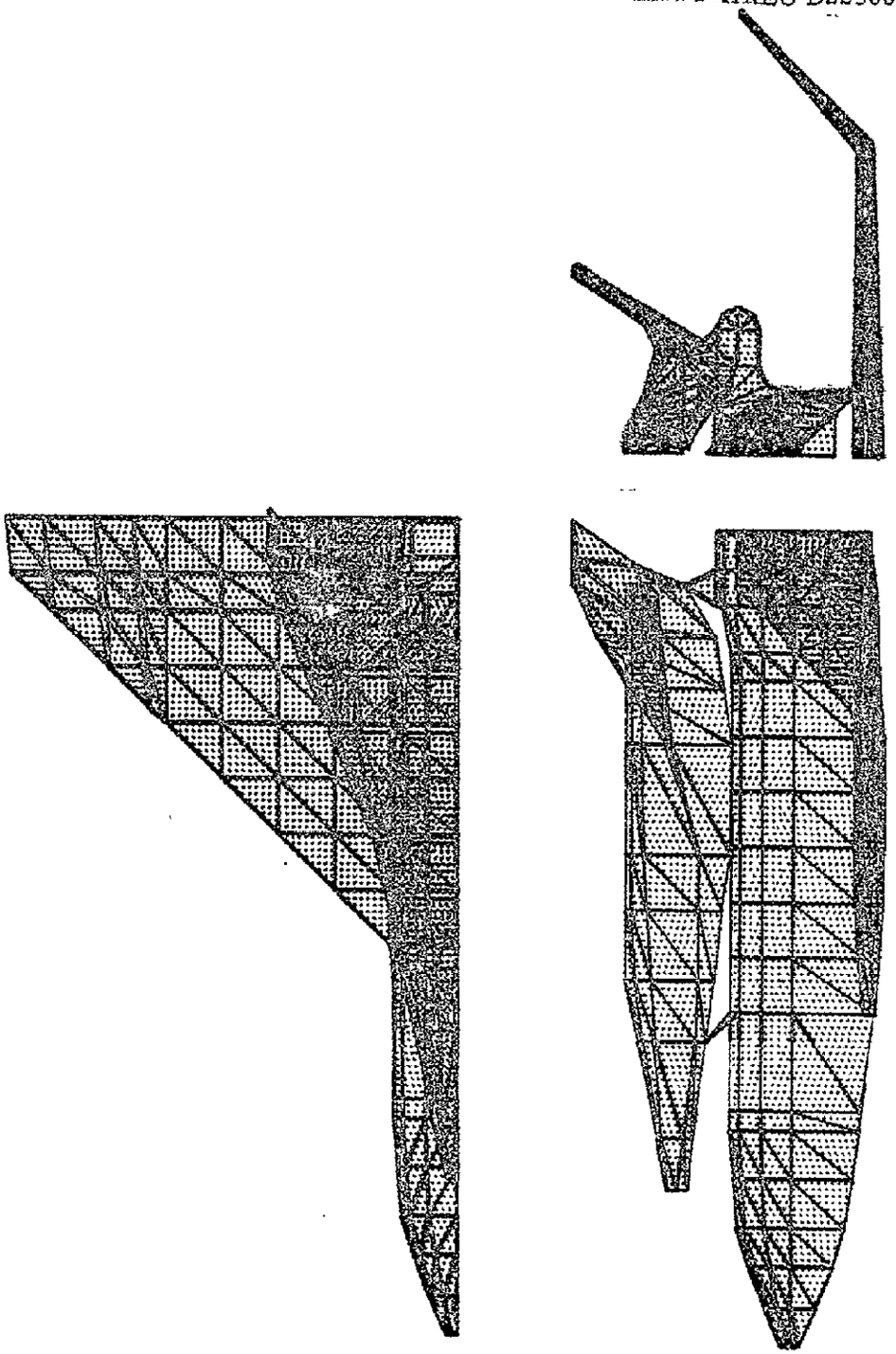


Fig. 5 - Space Shuttle Launch Configuration

Table 1
FREQUENCY COMPARISON

Elastic Mode	Substructure Frequency	SNAP/Dynamics Frequency
1	2.3179 cps	2.3329 cps
2	2.6994 cps	2.6488 cps
3	4.1891 cps	3.8209 cps
4	4.4330 cps	4.2454 cps
5	6.9777 cps	6.2128 cps

The fact that the first mode computed by the Synthesis program is slightly lower than that computed by the SNAP/Dynamics program is attributed to some small differences in the basic finite element nets employed in the two analyses.

The effects of substructure number and size and substructure generalized function selection were investigated during the course of the study. As discussed in Section 2.2.3, no general conclusions could be drawn from the results. Models composed of a small number of large substructures require more generalized functions per substructure than models composed of a large number of small substructures. It is generally best to use as many substructures as possible. If small substructures are used, it is often sufficient to use only uniform acceleration modes as substructure fixed boundary node functions, avoiding the expense of computing vibrational modes. In almost all comparisons, uniform acceleration modes represented substructure behavior as well as, if not better than, vibrational modes. Since uniform acceleration modes can be computed at a much lower cost than vibrational modes, they are always included in the substructure data files generated by the Function Generator program.

Section 5
REFERENCES

1. Whetstone, W. D., "Computer Analysis of Large Linear Frames," Journal of the Structural Division, ASCE, Vol. 95, No. ST11, Proc. Paper 6897, November 1969, pp. 2401-2417.

2. Whetstone, W. D., and C. E. Jones, "Vibrational Characteristics of Linear Space Frames," Journal of the Structural Division, ASCE, Vol. 95, No. ST10, Proc. Paper 6821, October 1969, pp. 2077-2091.

3. Whetstone, W. D., "Structural Network Analysis Program User's Manual, Static Analysis Version V70E," LMSC-HREC D162812, Lockheed Missiles & Space Company, Huntsville, Ala., December 1970.

4. Whetstone, W. D., "Structural Network Analysis Program User's Manual, Dynamic Analysis Version V70E," LMSC-HREC D225101, Lockheed Missiles & Space Company, Huntsville, Ala., May 1971.

5. Whetstone, W. D., "Substructure Uniform Acceleration Modes," Unpublished internal report, Lockheed Missiles & Space Company, Huntsville, Ala., 1967.

6. Whetstone, W. D., "A Numerical Solution Method for Systems of Ordinary Differential Equations," Unpublished internal report, Lockheed Missiles & Space Company, Sunnyvale, Calif., 1962.

Appendix A
SUBSTRUCTURE FUNCTION GENERATOR PROGRAM
USER'S MANUAL

PART 1

GENERAL PROGRAM INFORMATION

THIS MANUAL DESCRIBES THE INPUT DATA REQUIREMENTS FOR THE LOCKHEED/HUNTSVILLE DEVELOPED SUBSTRUCTURE FUNCTION GENERATOR PROGRAM. THE PROGRAM IS A MODIFICATION OF THE V70E VERSION OF THE LOCKHEED SNAP/DYNAMICS PROGRAM, AND THE INPUT DATA DESCRIBED HEREIN ONLY SUPPLEMENTS THE DATA REQUIRED BY SNAP/DYNAMICS AS DESCRIBED IN THE SNAP/DYNAMICS USER'S MANUAL, REF. 4. THE PROGRAM IS INTENDED FOR USE ONLY BY PERSONS FAMILIAR WITH THE FORMULATIONS AND TECHNIQUES UPON WHICH BOTH THE SNAP/DYNAMICS AND SUBSTRUCTURE ANALYSES ARE BASED.

THIS MANUAL ONLY DESCRIBES THE INPUT DATA WHICH MUST BE SUPPLIED IN ADDITION TO (AND IN SOME INSTANCES, IN PLACE OF) THE DATA REQUIRED BY THE SNAP/DYNAMICS PROGRAM, AND IT CANNOT BE USED WITHOUT A COPY OF THE SNAP/DYNAMICS USER'S MANUAL AT HAND.

THE PURPOSE OF THE FUNCTION GENERATOR PROGRAM IS TO CREATE AND STORE ON A DATA FILE INFORMATION THAT IS SUBSEQUENTLY USED BY THE SUBSTRUCTURE SYNTHESIS PROGRAM TO CHARACTERIZE SUBSTRUCTURE BEHAVIOR IN AN ASSEMBLED SYSTEM. THE SUBSTRUCTURE INFORMATION PRIMARILY CONSISTS OF A SET GENERALIZED DISPLACEMENT FUNCTIONS AND A MASS AND STIFFNESS MATRIX EXPRESSING THE KINETIC AND POTENTIAL ENERGIES OF THE SUBSTRUCTURE AS QUADRATIC FORMS IN COEFFICIENTS OF THE GENERALIZED FUNCTIONS.

A SUBSTRUCTURE REFERENCE FRAME IS ASSOCIATED WITH THE SUBSTRUCTURE AND IS REFERRED TO AS THE GLOBAL REFERENCE FRAME THROUGHOUT THE SNAP/DYNAMICS USER'S MANUAL.

A SUB-SET OF THE SUBSTRUCTURE'S NODES ARE DECLARED BOUNDARY NODES BY THE ANALYST THROUGH INPUT CARDS. BOUNDARY NODES ARE THE NODES THROUGH WHICH THE SUBSTRUCTURE IS CONNECTED TO OTHER SUBSTRUCTURES BY THE SUBSTRUCTURE SYNTHESIS PROGRAM (SEE APPENDIX B).

THE FUNCTION GENERATOR PROGRAM GENERATES FIVE DISTINCT GROUPS OF SUBSTRUCTURE GENERALIZED FUNCTIONS. SOME OF THE GROUPS ARE GENERATED AUTOMATICALLY, AND SOME ARE OPTIONALLY COMPUTED ACCORDING TO INPUT DATA. THE FIVE GROUPS OF FUNCTIONS ARE LISTED BELOW IN THE ORDER THEY ARE COMPUTED BY THE PROGRAM. EACH FUNCTION GROUP IS REFERRED TO BY ITS CORRESPONDING GROUP NUMBER IN SUBSEQUENT INPUT DATA

GROUP NO.	FUNCTION TYPE
1	RIGID BODY FUNCTIONS. SIX FUNCTIONS ARE AUTOMATICALLY COMPUTED, THREE RIGID BODY DISPLACEMENTS IN DIRECTIONS PARALLEL TO THE AXES OF THE SUBSTRUCTURE REFERENCE FRAME, AND THREE RIGID BODY ROTATIONS ABOUT THE AXES OF THE SUBSTRUCTURE INTRINSIC REFERENCE FRAME (THE ORIGIN OF THE INTRINSIC REFERENCE FRAME IS LOCATED AT BOUNDARY NODE ONE AND ITS AXES ARE PARALLEL TO THE AXES OF THE SUBSTRUCTURE REFERENCE FRAME).

2 BOUNDARY NODE MOTION FUNCTIONS. FOR A SUBSTRUCTURE WITH N BOUNDARY NODES, 6*(N-1) FUNCTIONS ARE COMPUTED AUTOMATICALLY. THE FUNCTIONS CORRESPOND TO THREE UNIT DISPLACEMENTS AND THREE UNIT ROTATIONS APPLIED SEPARATELY TO BOUNDARY NODES 2 THRU N WITH ALL OTHER BOUNDARY NODE MOTIONS IDENTICALLY EQUAL TO ZERO.

3 UNIFORM ACCELERATION MODES. SIX FUNCTIONS ARE COMPUTED AUTOMATICALLY WITH ALL BOUNDARY NODE MOTIONS IDENTICALLY EQUAL TO ZERO. A DESCRIPTION OF UNIFORM ACCELERATION MODES IS PRESENTED IN SECTION 2.2.3 OF THE MAIN TEXT.

4 STATIC FUNCTIONS (COMPUTED WITH ALL BOUNDARY NODES FIXED). FOR EACH FUNCTION, A LOADING CORRESPONDING TO POINT FORCES AND MOMENTS ACTING THROUGH SUBSTRUCTURE NODES MUST BE SUPPLIED BY CARD INPUT.

5 VIBRATIONAL MODES (COMPUTED WITH ALL BOUNDARY NODES FIXED). AS IN THE SNAP/DYNAMICS PROGRAM, THE VIBRATIONAL MODES ARE CALCULATED USING A METHOD ANALOGOUS TO THE STODOLA METHOD OF BEAM ANALYSIS. A RAYLEIGH-RITZ ANALYSIS IS PERFORMED TO OBTAIN THE INITIAL APPROXIMATIONS FOR THE SUBSTRUCTURE MODES. GENERALIZED FUNCTIONS USED IN THE RAYLEIGH-RITZ ANALYSIS ARE OBTAINED FROM TWO SOURCES, (1) ANY OF THE FUNCTIONS APPEARING IN GROUPS 1,2,3,OR 4 MAY BE USED IN ADDITION TO, (2) STATIC DISPLACEMENT FUNCTIONS COMPUTED BY THE PROGRAM, BASED ON STATIC LOADINGS SUPPLIED BY THE USER.

PART 2

INPUT REQUIREMENT DIFFERENCES BETWEEN SNAP/DYNAMICS AND FUNCTION GENERATOR PROGRAMS

A FUNCTION GENERATOR PROGRAM DATA DECK IS IDENTICAL TO A V70E SNAP/DYNAMICS DATA DECK THROUGH THE 'PLOT SPECIFICATION DECK' (PARAGRAPH E, PAGE 1-9, SECTION 1 OF SNAP/DYNAMICS V70E USER'S MANUAL), WITH THE FOLLOWING EXCEPTION.

ADDITIONAL DRUM UNIT ASSIGNMENTS ARE REQUIRED. THE FOLLOWING CARD SHOULD APPEAR IN THE DATA DECK IMMEDIATELY FOLLOWING THE TWO CARDS DEFINING THE 17 DRUM UNITS REQUIRED BY SNAP/DYNAMICS.

```
LIST= (NUNIT(I),I=18,21)
FORMAT(4I5)
```

USAGE OF THE ADDITIONAL UNITS IS SUMMARIZED BELOW. NUNIT(I) IS THE LOGICAL UNIT NUMBER ASSIGNED TO 'UNIT' I.

UNIT	USAGE
18	FORCE VECTOR FILE. LENGTH= 6*JT*NGEN, WHERE JT IS THE TOTAL NUMBER OF JOINTS, AND NGEN IS THE NUMBER OF GENERALIZED FUNCTIONS TO BE COMPUTED.
19	DISPLACEMENT VECTOR FILE AND TEMPORARY MATRICES STORAGE. SIZE REQUIREMENTS WILL BE THE LARGEST OF 6*JT*NGEN OR NGEN*(NGEN+1).
20	ELEMENT DEFORMATION FILE (USED ONLY IF DIAGONAL MASS MATRIX OPTION IS NOT IN EFFECT). LENGTH= NGEN*(13*N2+ 19*N3+ 25*N4), WHERE N2, N3, AND N4 ARE THE NUMBER OF 2, 3, AND 4-NODE ELEMENTS IN THE SUBSTRUCTURE MODEL.
21	FILE USED FOR TEMPORARY STORAGE OF MASS AND STIFFNESS MATRICES. LENGTH= NGEN*(NGEN+1).

PARAGRAPH F, PAGE 1-9, SECTION 1 OF THE SNAP/DYNAMICS V70E USER'S MANUAL IS REPLACED BY THE FOLLOWING

F. FUNCTION GENERATOR OUTPUT OPTIONS ARE SPECIFIED NEXT

```
LIST= (KOPT(I),I=1,3)
FORMAT(3I5)
```

THE OUTPUT INDICATED BELOW IS CAUSED BY VALUES GREATER THAN ZERO OF THE ASSOCIATED OPTIONS.

I RESULTING OUTPUT IF KOPT(I).GT.0

1 JOINT DISPLACEMENT VECTORS AND ASSOCIATED FORCE VECTORS ARE DISPLAYED AT THE END OF THE PROGRAM PRINTOUT FOR ALL GENERATED FUNCTIONS.

2 THE SUBSTRUCTURE MASS MATRIX IS PRINTED.

3 THE SUBSTRUCTURE STIFFNESS MATRIX IS PRINTED.

G. IDENTIFICATION OF THE NUMBER AND TYPE OF GENERALIZED FUNCTIONS TO BE COMPUTED FOLLOWS

LIST= NSTATIC, NMODES, NBOUND, NAPROX
FORMAT(4I5)

NSTATIC IS THE NUMBER OF STATICALLY LOADED FUNCTIONS TO BE INCLUDED IN FUNCTION GROUP 4. NMODES IS THE NUMBER OF VIBRATIONAL MODES COMPUTED IN THE STODOLA ANALYSIS TO BE INCLUDED IN THE GENERALIZED FUNCTION GROUP 5. NBOUND IS THE NUMBER OF SUSTRUCTURE NODES TO BE SUBSEQUENTLY DECLARED BOUNDARY NODES. NAPROX IS THE NUMBER OF GENERALIZED FUNCTIONS TO BE USED IN THE RAYLEIGH-RITZ ANALYSIS FOR DETERMINING INITIAL APPROXIMATIONS FOR THE VIBRATIONAL MODES. IF NMODES=0, NAPROX IS AUTOMATICALLY SET EQUAL TO ZERO. NAPROX SHOULD TYPICALLY ASSUME A VALUE OF AT LEAST 2*NMODES.

H. THREE COMPONENTS OF A PROBLEM DEFINITION DECK ARE READ NEXT AS SUMMARIZED BELOW, IN THE ORDER IN WHICH THEY APPEAR IN THE DATA DECK.

SECTION IN WHICH FORMAT IS DEFINED	DESCRIPTION
3.1	OUTPUT CONTROL
3.2	FUNCTION CONTROL (NOTE THE COMMENTS DISCUSSED IN PART 3 CONCERNING SECTION 3.2 OF THE SNAP/DYNAMICS USERS MANUAL)
3.3	LUMPED MASS DATA

I. IDENTIFICATION OF THE BOUNDARY NODES IS READ NEXT ACCORDING TO THE FOLLOWING LIST AND FORMAT.

LIST= (NODBND(I), I=1,NBOUND)
FORMAT(14I5)

NODBND(I) IS THE JOINT NUMBER IDENTIFIED AS THE I-TH BOUNDARY NODE. NBOUND WAS PREVIOUSLY INPUT ACCORDING TO PARAGRAPH G ABOVE.

J. NSTATIC FORCING FUNCTIONS ARE READ NEXT. THE CORRESPONDING DISPLACEMENT FUNCTIONS MAKE UP THE GENERALIZED FUNCTION GROUP 4. IF NSTATIC=0, NO CARDS APPEAR FOR THIS DATA. THE LIST AND FORMAT REQUIRED FOR EACH STATIC LOADING IS DISCUSSED IN SECTION 3.4 (NOTE THE COMMENTS DISCUSSED IN PART 3 CONCERNING SECTION 3.4 OF THE SNAP/DYNAMICS MANUAL).

K. IDENTIFICATION OF THE FUNCTIONS USED AS GENERALIZED COORDINATES IN THE INITIAL APPROXIMATION RAYLEIGH-RITZ ANALYSIS APPEARS NEXT. IF NMODES AND/OR NAPROX IS SPECIFIED ZERO ACCORDING TO PARAGRAPH G ABOVE, NO INITIAL APPROXIMATION DATA IS READ. ANY OF THE PREVIOUSLY COMPUTED SUBSTRUCTURE GENERALIZED FUNCTIONS BELONGING TO GROUPS 1 THRU 4 CAN BE USED AS RAYLEIGH-RITZ FUNCTIONS ALONG WITH ADDITIONAL FUNCTIONS CORRESPONDING TO STATIC LOADINGS SUPPLIED BY THE ANALYST VIA INPUT DATA CARDS. FUNCTIONS BELONGING TO GROUPS 1 AND 2 (RIGID BODY AND BOUNDARY NODE MOTION FUNCTIONS) SHOULD NOT BE USED AS RAYLEIGH-RITZ GENERALIZED FUNCTIONS, HOWEVER, FUNCTIONS BELONGING TO GROUPS 3 AND 4 (UNIFORM ACCELERATION MODES AND STATIC FUNCTIONS) MAY BE USED EXTENSIVELY. THE LIST AND FORMAT IDENTIFYING THE RAYLEIGH-RITZ FUNCTIONS FOLLOWS.

```
LIST= (NF(I),NG(I),I=1,NAPROX)
FORMAT(14(I3,I1))
```

FUNCTION NF(I) OF GROUP NG(I) WILL BE USED AS THE I-TH RAYLEIGH-RITZ FUNCTION. FOR INSTANCE, IF NF(4)=2 AND NG(4)=3, THE SECOND UNIFORM ACCELERATION MODE WILL BE USED AS THE 4TH FUNCTION. IF NG(I)=0, THE I-TH FUNCTION IS CALCULATED ACCORDING TO A STATIC LOADING SUPPLIED VIA INPUT DATA CARDS.

A SET OF STATIC LOADING DEFINITION DECKS FOLLOW. ONE DECK MUST APPEAR FOR EACH ZERO VALUE SPECIFIED ABOVE FOR NG(I). THE LIST AND FORMAT REQUIRED FOR EACH STATIC LOADING IS DISCUSSED IN SECTION 3.4 (NOTE THE COMMENTS DISCUSSED IN PART 3 CONCERNING SECTION 3.4 OF THE SNAP/DYNAMICS MANUAL).

L. THE STODOLA PROCESS CONTROL CARDS DISCUSSED IN SECTION 3.5 ARE READ NEXT. THESE CARDS APPEAR ONLY IF NMODES DISCUSSED IN PARAGRAPH G IS GREATER THAN ZERO.

M. THE LAST TWO CARDS OF THE DATA DECK ARE READ NEXT.

```
LIST= KTAPE
FORMAT(I5)
```

KTAPE IS THE LOGICAL UNIT NUMBER ASSIGNED TO THE SUBSTRUCTURE DATA FILE. KTAPE CAN IDENTIFY A MAGNETIC TAPE, DRUM UNIT, OR PUNCHED CARDS (KTAPE=7 FOR PUNCHED OUTPUT).

```
LIST=(SUBID(I),I=1,12)
FORMAT(12A6)
```

SUBID IS AN ALPHA-NUMERIC IDENTIFICATION OF THE SUBSTRUCTURE. IT IS PLACED AT THE BEGINNING OF THE SUBSTRUCTURE DATA FILE AND USED TO IDENTIFY THE SUBSTRUCTURE THROUGHOUT THE SUBSTRUCTURE SYNTHESIS PROGRAM PRINTOUT.

PART 3

COMMENTS CONCERNING
PROPER PROGRAM USAGE

THE FOLLOWING COMMENTS ARE PERTINENT TO THE USE OF THE SNAP/DYNAMICS USER'S MANUAL IN PREPARING A DATA DECK FOR THE SUBSTRUCTURE FUNCTION GENERATOR PROGRAM. THE COMMENTS ARE ARRANGED BELOW ACCORDING TO THE SECTION OF THE SNAP/DYNAMICS USER'S MANUAL TO WHICH THEY PERTAIN.

SECTION 2.4.

NON-ZERO VALUES OF JREF ARE NOT ALLOWED FOR JOINTS THAT ARE USED AS SUBSTRUCTURE BOUNDARY NODES. IT IS ASSUMED IN THE SUBSTRUCTURE SYNTHESIS PROGRAM THAT THE BOUNDARY NODE MOTION FUNCTIONS CORRESPOND TO DISPLACEMENTS AND ROTATIONS IN DIRECTIONS PARALLEL TO THE SUBSTRUCTURE REFERENCE AXES.

SECTION 2.5.

ALL BOUNDARY NODES MUST BE RESTRAINED WITH A (KC(K)=2,K=1,6) SPECIFICATION. THIS TYPE RESTRAINT IS REQUIRED FOR CALCULATION OF THE BOUNDARY NODE MOTION FUNCTIONS.

SECTION 3.2.

GMASS IS THE VALUE OF GENERALIZED MASS CONTROLLING NORMALIZATION OF ALL GENERALIZED DISPLACEMENT FUNCTIONS.

KESTOD, IAPROX, AND NFREE ARE IGNORED BY THE FUNCTION GENERATOR PROGRAM. KERITZ GOVERNS THE KINETIC ENERGY REPRESENTATIONS FOR ALL CALCULATIONS. A RAYLEIGH-RITZ ANALYSIS IS ALWAYS PERFORMED TO OBTAIN INITIAL APPROXIMATIONS FOR THE VIBRATIONAL MODES, AND THE NATURE OF THE FUNCTIONS CALCULATED BY THE PROGRAM PRECLUDES ANY SPECIFICATION FOR NFREE.

SECTION 3.4.

THE ONLY PART OF SECTION 3.4 PERTINENT TO THE FUNCTION GENERATOR PROGRAM ARE THE LIST AND FORMAT CONTROLLING INPUT OF ONE STATIC LOADING DEFINITION. ANY NUMBER OF CARDS, EACH IN THE FORMAT INDICATED IN SECTION 3.4, MAY APPEAR IN A STATIC LOADING DECK. EACH DECK IS TERMINATED BY A BLANK CARD. IN THE FUNCTION GENERATOR PROGRAM, APPROPRIATE DATA IS READ DEFINING THE NUMBER OF STATIC LOADING DEFINITION DECKS TO BE READ. CONSEQUENTLY, A BLANK CARD DOES NOT FOLLOW THE LAST DECK.

THE COMMENTS IN SECTION 3.4 PERTAINING TO RESTARTED RUNS DO NOT APPLY TO THE FUNCTION GENERATOR PROGRAM.

SECTION 3.5.

THE NUMBER OF VIBRATIONAL MODES INCLUDED IN A SUBSTRUCTURE DATA FILE MAY BE LESS THAN THE NUMBER OF MODES CALCULATED BY MEANS OF THE STODOLA ANALYSIS. THE VARIABLE NMODES DISCUSSED IN PARAGRAPH G OF PART 3 DEFINES THE NUMBER OF MODES TO BE INCLUDED IN THE DATA FILE. THESE MODES WILL BE EXTRACTED FROM THOSE COMPUTED IN THE STODOLA ANALYSIS, SO THAT THE NUMBER OF STODOLA PROCESS CONTROL CARDS MUST AT LEAST EQUAL NMODES.

SECTION 4.

FUNCTION GENERATOR PROGRAM RUNS CANNOT BE RESTARTED IN THE SAME MANNER AS SNAP/DYNAMICS RUNS. THE DATA DISCUSSED UNDER PART 'A' OF SECTION 4 IS THE ONLY INFORMATION WRITTEN ON A RESTART TAPE BY THE PROGRAM. CONSEQUENTLY, ALL DATA BEGINNING WITH THAT DISCUSSED UNDER PARAGRAPH F OF PART 2 OF THIS MANUAL MUST APPEAR IN A FUNCTION GERERATOR PROGRAM DATA DECK.

SECTION 5.

SOLUTION DATA OUTPUT TAPES ARE NORMALLY NOT REQUESTED IN A FUNCTION GENERATOR PROGRAM RUN. IF THE TAPE IS CREATED, THE INFORMATION DISCUSSED IN SECTION 5 IS WRITTEN ON THE TAPE ONLY FOR THE VIBRATIONAL MODES COMPUTED DURING THE FUNCTION GENERATION.

SECTION 6.6

THIS SECTION IS NOT APPLICABLE TO THE FUNCTION GENERATOR PROGRAM.

APPENDIX A.

ADDITIONAL TAPE AND DRUM ASSIGNMENTS ARE REQUIRED AS FOLLOWS

```
'ASG,T 26,T,XXXXX        . SOLUTION DATA TAPE (KTAPE)
'REWIND 26
'ASG,T 27,F2/1/TRK/500   . TEMPORARY DATA FILE
'ASG,T 28,F2/1/TRK/500   . TEMPORARY DATA FILE
'ASG,T 29,F2/1/TRK/500   . TEMPORARY DATA FILE
'ASG,T 30,F2/1/TRK/500   . TEMPORARY DATA FILE
```

THE ADDITIONAL TEMPORARY DATA FILE ASSIGNMENTS CORRESPOND TO THE FOLLOWING INTERNAL UNIT DESIGNATIONS (SEE PART 3)

I	NUNIT(I)
18	27
19	28
20	29
21	30

APPENDIX B.

ADDITIONAL DRUM UNIT ASSIGNMENTS ARE REQUIRED, AND A CARD MUST BE INSERTED IMMEDIATELY AFTER THE SNAP/DYNAMICS DRUM UNIT ASSIGNMENTS AS FOLLOWS

```
LIST= (NUNIT(I),I=18,21)
FORMAT(4I5)
```

PARAGRAPH F, PAGE B-4 IS REPLACED BY THE FOLLOWING

F. FUNCTION GENERATOR OUTPUT OPTIONS

```
LIST= (KOPT(I),I=1,3)
FORMAT(3I5)
```

G. GENERALIZED FUNCTION CONTROL

```
LIST= NSTATIC, NMODES, NBOUND, NAPROX
FORMAT(4I5)
```

H. NORMAL SNAP/DYNAMICS DATA (SEE PARAGRAPH F, PAGE B-4 OF THE SNAP/DYNAMICS MANUAL)

1. OUTPUT OPTIONS (SEE TOPIC 1, PARAGRAPH F)

2. FUNCTION CONTROL (SEE TOPIC 2, PARAGRAPH F)

3. LUMPED MASS DATA (SEE TOPIC 3, PARAGRAPH F)

I. BOUNDARY NODE IDENTIFICATION

```
LIST= (NODBND(I),I=1,NBOUND)
FORMAT(14I5)
```

J. STATIC FORCING FUNCTIONS

```
LIST= JO, K, QO, NI, IINC, DQI, NJ, JINC, DQJ
FORMAT(I4,I2,E14.5,2I5,E10.3,2I5,E10.3)
```

TERMINATE EACH DECK WITH A BLANK CARD.
NSTATIC DECKS ARE PRESENT

K. RAYLEIGH-RITZ COORDINATE IDENTIFICATION

```
LIST= (NF(I),NG(I),I=1,NAPROX)
FORMAT(14(I3,I1))
```

ONE STATIC FORCING FUNCTION DECK IS READ FOR EACH ZERO VALUE SPECIFIED FOR NG(I). LIST AND FORMAT FOR EACH FORCING DECK IS GIVEN IN PARAGRAPH J ABOVE.

L. STODOLA PROCESS CONTROL

```
LIST= N, IAPROX, ITER, CONVRG
FORMAT(3I5,F15.8)
```

```
M. SUBSTRUCTURE DATA FILE TAPE

     LIST= KTAPE
     FORMAT(I5)

N. SUBSTRUCTURE IDENTIFICATION

     LIST= (SUBID(I),I=1,12)
     FORMAT(12A6)
```

Appendix B

SUBSTRUCTURE SYNTHESIS PROGRAM USER'S MANUAL

PART 1

GENERAL PROGRAM FUNCTION

THIS MANUAL DESCRIBES INPUT DATA REQUIRED BY THE SUBSTRUCTURE SYNTHESIS PROGRAM. IT IS INTENDED FOR USE ONLY BY PERSONS THOROUGHLY FAMILIAR WITH THE MAIN TEXT OF THIS REPORT.

BEFORE DEFINING SPECIFIC INPUT DATA FORMATS, CERTAIN RELEVANT TERMINOLOGY WILL BE SUMMARIZED.

A SUBSTRUCTURE REFERENCE FRAME IS ASSOCIATED WITH EACH SUBSTRUCTURE. THE LOCATION OF THE SUBSTRUCTURE RELATIVE TO THIS FRAME IS DEFINED BY THE ANALYST IN EXECUTING THE FUNCTION GENERATOR PROGRAM (SEE APPENDIX A).

THE LOCATION WITHIN THE SYSTEM OF EACH SUBSTRUCTURE IS DEFINED IN THE INPUT DATA BY SPECIFYING THE POSITION AND ORIENTATION OF THE CORRESPONDING SUBSTRUCTURE REFERENCE FRAME, RELATIVE TO THE SYSTEM REFERENCE FRAME.

EVERY BOUNDARY NODE OF A SUBSTRUCTURE CONNECTS TO SOME SYSTEM JOINT. ANY NUMBER OF SUBSTRUCTURES MAY CONNECT TO A PARTICULAR JOINT. INTERCONNECTION DETAILS ARE DEFINED BY SPECIFYING, FOR EACH SUBSTRUCTURE, THE SYSTEM JOINTS TO WHICH ITS BOUNDARY NODES ARE ATTACHED.

IF A SYSTEM JOINT DOES NOT COINCIDE GEOMETRICALLY WITH EVERY SUBSTRUCTURE BOUNDARY NODE CONNECTED TO IT, THE LOCATION OF THE JOINT MUST BE GIVEN EXPLICITLY IN THE INPUT DATA, AND THE PROGRAM WILL ASSUME THAT THE CORRESPONDING JOINT-BOUNDARY NODE INTERCONNECTIONS ARE EFFECTED THROUGH MASSLESS RIGID LINKS.

PART OF THE INPUT TO THE SYNTHESIS PROGRAM CONSISTS OF A SEQUENCE OF SUBSTRUCTURE DATA FILES (ONE FOR EACH SUBSTRUCTURE) GENERATED BY THE FUNCTION GENERATOR PROGRAM (APPENDIX A). THESE FILES MAY BE STORED ON DRUM, MAGNETIC TAPE, OR DATA CARDS. THE INFORMATION CONTAINED IN A SUBSTRUCTURE DATA FILE INCLUDES THE POSITION COORDINATES OF ALL SUBSTRUCTURE JOINTS RELATIVE TO THE SUBSTRUCTURE REFERENCE FRAME, DESCRIPTIONS OF A SET OF GENERALIZED FUNCTIONS USED TO CHARACTERIZE THE SUBSTRUCTURE MOTIONS, MASS AND STIFFNESS MATRICES EXPRESSING THE KINETIC AND POTENTIAL ENERGIES OF THE SUBSTRUCTURE AS QUADRATIC FORMS IN COEFFICIENTS OF THE GENERALIZED FUNCTIONS, AND IDENTIFICATION OF THE SUBSTRUCTURE BOUNDARY NODES.

TYPICALLY, A SUBSTRUCTURE DATA FILE CONTAINS MANY INDIVIDUAL SUBSTRUCTURE GENERALIZED DISPLACEMENT FUNCTIONS. INCLUDED AMONG THESE ARE SIX UNIFORM ACCELERATION MODES, AND ANY NUMBER OF STATIC DEFORMATIONS AND NATURAL MODES. PROVISIONS ARE INCLUDED IN THE SYNTHESIS PROGRAM FOR SELECTING ANY PRESCRIBED SUB-SET OF THESE FUNCTIONS FOR USE IN ANALYZING THE ASSEMBLED SYSTEM.

SYSTEM GENERALIZED COORDINATES CONSIST OF MOTION COMPONENTS OF THE SYSTEM JOINTS AND COEFFICIENTS OF INDIVIDUAL SUBSTRUCTURE FIXED BOUNDARY NODE GENERALIZED FUNCTIONS (SEE MAIN TEXT, SECTION 2.2.3).

ANY SET OF SYSTEM JOINT MOTION COMPONENTS MAY BE SET IDENTICALLY EQUAL TO ZERO. ALSO, LINEAR RELATIONS MAY BE IMPOSED AMONG SPECIFIED SYSTEM JOINT MOTION COMPONENTS. THIS IS TERMED RELATIVE JOINT MOTION CONSTRAINT, WHICH IS ESPECIALLY USEFUL IN HANDLING SYSTEMS CONTAINING A LARGE NUMBER OF JOINTS.

AFTER FORMING THE SYSTEM MASS AND STIFFNESS MATRICES AND SOLVING FOR THE UNDAMPED SYSTEM MODES AND FREQUENCIES, THE PROGRAM WILL OPTIONALLY FORM A SYSTEM DAMPING MATRIX AND EXECUTE TRANSIENT RESPONSE CALCULATIONS. THE SYSTEM DAMPING MATRIX IS FORMED BY SUMMING THE CONTRIBUTIONS TO SYSTEM ENERGY DISSIPATION OF ALL DAMPED SUBSTRUCTURES.

THE DAMPING CHARACTERISTICS OF AN INDIVIDUAL SUBSTRUCTURE ARE DEFINED IN THE INPUT DATA BY SPECIFYING THE DAMPING FACTORS ASSOCIATED WITH ANY TWO SUBSTRUCTURE VIBRATIONAL MODES, FOR ANY PRESCRIBED BOUNDARY NODE CONSTRAINT CONDITIONS.

SUPPOSE, FOR EXAMPLE, THAT THE ANALYST PRESCRIBES THAT THE DAMPING FACTORS FOR THE FIRST TWO FREE-FREE MODES OF A CERTAIN SUBSTRUCTURE ARE .005 AND .01. THE PROGRAM WILL COMPUTE THE SUBSTRUCTURE'S FREE-FREE MODES, USING GENERALIZED FUNCTIONS STORED IN THE SUBSTRUCTURE DATA FILE, AND PROCEED AS OUTLINED IN SECTION 2.5.1 OF THE MAIN TEXT OF THE REPORT.

THE MAXIMUM NUMBER OF SYSTEM DEGREES OF FREEDOM ALLOWED IN THE UNDAMPED EIGENVALUE ANALYSIS IS 75. THE MAXIMUM NUMBER OF SYSTEM DEGREES OF FREEDOM ALLOWED IN THE RESPONSE ANALYSIS IS 60. THE NUMBER OF SUBSTRUCTURES MAKING UP THE SYSTEM IS UNLIMITED.

NJREF= THE NUMBER OF LOCAL REFERENCE FRAME ORIENTATION SPECIFICATIONS TO BE READ.

NOSUB= THE NUMBER OF SUBSTRUCTURES INCLUDED IN THE SYSTEM MODEL.

MAXJT= LARGEST NUMBER OF JOINTS IN ANY SUBSTRUCTURE.

MAXBND= LARGEST NUMBER OF BOUNDARY NODES APPEARING IN ANY SUBSTRUCTURE.

MAXFCN= LARGEST NUMBER OF INDIVIDUAL GENERALIZED FUNCTIONS CREATED FOR ANY SUBSTRUCTURE BY THE FUNCTION GENERATOR PROGRAM. THIS INCLUDES ALL NATURAL NODES, UNIFORM ACCELERATION MODES, AND STATIC FUNCTIONS.

NRELTV= THE NUMBER OF RELATIVE JOINT MOTION COORDINATES TO BE INCLUDED.

THE KCGEN ARRAY IS USED TO IMPOSE A GENERAL CONSTRAINT TO ALL SYSTEM JOINTS. IF ALL DIRECTION-I DISPLACEMENT COMPONENTS (WITH RESPECT TO JOINT REFERENCE FRAMES) ARE ZERO, SET KCGEN(I)=1. IF ALL DIRECTION-I ROTATION COMPONENTS ARE ZERO, SET KCGEN(I+3)=1. ANY SUBSEQUENT CONSTRAINT OR CONSTRAINT RELEASE SPECIFIED FOR A SYSTEM JOINT OVERRIDES THE KCGEN SPECIFICATION FOR THAT JOINT.

WITH THE EXCEPTION OF KCGEN, ALL THE VARIABLES APPEARING ON THE GENERAL CONTROL CARD ARE USED TO ALLOCATE CORE STORAGE FOR VARIOUS ARRAYS REQUIRED DURING CONSTRUCTION OF THE SYSTEM MASS AND STIFFNESS ARRAYS.

E. SUBSTRUCTURE DATA FILE UNIT ASSIGNMENTS

LIST= (ITAPE(I),I=1,NOSUB)
FORMAT(14I5)

ITAPE(I) IS THE LOGICAL UNIT NUMBER ASSIGNED AS THE DATA FILE UNIT FOR SUBSTRUCTURE I. THIS UNIT IS ASSUMED TO CONTAIN THE DATA FILE CREATED FOR SUBSTRUCTURE I BY THE FUNCTION GENERATOR PROGRAM. IF ITAPE(I)=5, THE DATA FILE WILL BE READ FROM PUNCHED CARDS. OTHERWISE, ITAPE(I) DEFINES EITHER A DRUM UNIT OR MAGNETIC TAPE.

PART 2

INPUT DATA FORMAT

THE NOMINAL U-1108/ EXEC 8 VERSION OF THE PROGRAM USES 30000 CORE LOCATIONS FOR MAIN DATA STORAGE, ALLOWING APPROXIMATELY 75 DEGREES OF FREEDOM FOR REPRESENTING SYSTEM MOTIONS. THE DEGREE OF FREEDOM LIMITATION IS IMPOSED BY THE EIGENVALUE SOLUTION ROUTINES, AND, SINCE THE PROGRAM IS ASSEMBLED IN A MODULAR FASHION, THESE ROUTINES CAN BE REPLACED, IF NECESSARY, BY ROUTINES WITH A LARGER SIZE CAPACITY.

THE COMPONENTS OF A PROBLEM DEFINITION DECK ARE OUTLINED BELOW.

A. DRUM UNIT ASSIGNMENTS AND BUFFER DIMENSIONS.

THE FIRST TWO CARDS IN THE DATA DECK SPECIFY DRUM UNIT ASSIGNMENTS AND BUFFER DIMENSIONS, RESPECTIVELY, AS DESCRIBED IN PARTS 2.1 AND 2.2.

B. TITLE CARDS (AT LEAST ONE MUST APPEAR).

ANY NUMBER OF TITLE CARDS MAY BE USED. INFORMATION APPEARING IN COLUMNS 2 THROUGH 73 OF THESE CARDS WILL APPEAR AT THE BEGINNING OF THE PRINTED OUTPUT. THE LAST TITLE CARD MUST HAVE A BLANK IN COLUMN 1. ALL PRECEEDING CARDS (IF ANY) MUST HAVE A NON-ZERO INTEGER IN COLUMN 1.

C. OUTPUT OPTIONS.

A CARD SPECIFYING THE PRINTOUT OPTIONS IS READ NEXT AS DISCUSSED IN PART 2.3.

D. GENERAL CONTROL CARD

```
LIST= JT, NX, NJREF, NOSUB, MAXJT, MAXBND, MAXFCN,
      NRELTV, (KCGEN(I),I=1,6)
FORMAT(8I5,4X,6I1)
```

JT= TOTAL NUMBER OF SYSTEM JOINTS

NX= THE NUMBER OF SYSTEM JOINTS FOR WHICH THE POSITION COORDINATES ARE TO BE EXPLICITLY DEFINED BY CARD INPUT. IF A SYSTEM JOINT DOES NOT GEOMETRICALLY COINCIDE WITH ALL ATTACHED BOUNDARY NODES, ITS POSITION MUST BE SPECIFIED IN THE INPUT DATA. AS DISCUSSED IN PART 1, IF POSITION COORDINATE DATA IS NOT READ FOR A SYSTEM JOINT, IT IS ASSUMED TO COINCIDE WITH ALL SUBSTRUCTURE BOUNDARY NODES TO WHICH IT IS ATTACHED.

F. A SEQUENCE OF DECKS SPECIFYING VARIOUS PARTS OF THE PROBLEM DEFINITION APPEAR NEXT, IN THE FOLLOWING ORDER.

PART IN WHICH INPUT FORMAT IS DISCUSSED	DECK NAME
3.1	SYSTEM JOINT CONSTRAINTS
3.2	SYSTEM JOINT POSITION COORDINATES (THIS DECK APPEARS ONLY IF NX.GT.0)
3.3	LOCAL REFERENCE FRAME ORIENTATION SPECIFICATION DECK (THIS DECK APPEARS ONLY IF NJREF.GT.0)
3.4	RELATIVE JOINT MOTION CONSTRAINT SPECIFICATIONS (THIS DECK APPEARS ONLY IF NRELTV.GT.0)
3.5	SUBSTRUCTURE DATA DECKS (ONE DECK APPEARS FOR EACH SUBSTRUCTURE)
3.6	DIRECTLY SPECIFIED SYSTEM MATRIX ENTRIES

G. DAMPED RESPONSE CONTROL CARD

THE NEXT CARD IN THE DATA DECK MAY CONTAIN ANY ALPHA-NUMERIC LIST IN COLUMNS 1 THRU 72. IF THE CHARACTERS 'STOP' APPEAR IN THE FIRST FOUR COLUMNS, THE SOLUTION WILL TERMINATE WITH THE EIGENVALUE ANALYSIS, AND NO FURTHER DATA IS REQURIED. OTHERWISE, THE RESPONSE OF A DAMPED SYSTEM IS COMPUTED, AND THE INFORMATION APPEARING ON THE CARD WILL APPEAR IN THE PRINTOUT AT THE BEGINNING OF THE DAMPED RESPONSE OUTPUT.

H. DAMPING CHARACTERISTICS. THE INPUT REQUIREMENTS FOR THIS DECK ARE DESCRIBED IN PART 4.

I. FORCED RESPONSE PROBLEM DEFINTION. THE INPUT REQUIREMENTS FOR THIS DECK ARE DESCRIBED IN PART 5.

PART 2.1 DRUM UNIT ASSIGNMENTS

DRUM (OR OTHER SECONDARY DATA STORAGE) UNIT ASSIGNMENTS ARE SPECIFIED ACCORDING TO THE FOLLOWING LIST AND FORMAT.

```
LIST= (NUNIT(I),I=1,10)
FORMAT(10I5)
```

NUNIT(I) IS THE LOGICAL UNIT NUMBER ASSIGNED TO 'UNIT' I. NUNIT(1) AND NUNIT(10) ARE NOT USED BY THE CURRENT VERSION OF THE PROGRAM. USAGE OF THE OTHER UNITS IS SUMMARIZED BELOW.

UNIT	USAGE
2	TEMPORARY FILE USED DURING EIGENVALUE ANALYSES. ALSO USED AS TEMPORARY STORAGE FOR FORCING FUNCTION DATA.
3	SUBSTRUCTURE PROPERTY FILE
4	TEMPORARY FILE USED TO STORE ENTRIES TO THE SYSTEM MASS AND STIFFNESS MATRICES.
5	SUBSTRUCTURE COORDINATE DISPLACEMENT VECTOR FILE. CONTAINS ALL THE DISPLACEMENT VECTORS USED TO REPRESENT INDIVIDUAL SUBSTRUCTURE MOTIONS.
6	SUBSTRUCTURE DISPLACEMENT VECTORS ASSOCIATED WITH THE UNDAMPED SYSTEM MODES.
7	TEMPORARY FILE USED TO STORE ENTRIES TO THE SUBSTRUCTURE MASS AND STIFFNESS MATRICES USED IN SUBSTRUCTURE DAMPING CALCULATIONS.
8	SUBSTRUCTURE DAMPING MATRIX FILE.
9	RESPONSE FILE USED TO ACCUMULATE NUMERICAL INTEGRATION RESULTS.

FIVE UNIQUE ASSIGNMENTS ARE REQUIRED FOR THE SECONDARY STORAGE UNITS. FOR THE ASSIGNMENTS SHOWN BELOW, ND1, ND2, ND3, ND4, AND ND5 ARE UNIQUE DRUM UNIT LOGIC NUMBERS.

I	NUNIT(I)
2	ND1
3	ND2
4	ND3
5	ND4
6	ND5
7	ND3
8	ND5
9	ND4

A MAGNETIC TAPE MAY BE USED FOR NUNIT(9) FOR STORAGE OF THE RESPONSE FILE.

PART 2.2 BUFFER DIMENSIONS

THE LENGTHS OF TEN BUFFER STORAGE AREAS ARE SPECIFIED AS FOLLOWS

```
LIST= (LREC(I),I=1,10)
FORMAT(10I5)
```

NORMALLY SET LREC(3)=2000, LREC(7)=1000, LREC(9)=1000, WITH ALL OTHERS EQUAL TO ZERO. THE PROGRAM AUTOMATICALLY ALLOCATES ALL OTHER BUFFERS ACCORDING TO AVAILABLE CORE.

PART 2.3 OUTPUT OPTIONS

TEN PROGRAM OUTPUT OPTIONS ARE SPECIFIED AS FOLLOWS

```
LIST= (OPT(I),I=1,10)
FORMAT(10I3)
```

THE OUTPUT INDICATED BELOW IS CAUSED BY NON-ZERO VALUES OF THE ASSOCIATED OPTIONS.

OPT	RESULTING OUTPUT
1	SYSTEM JOINT INFORMATION INCLUDING JOINT CONSTRAINTS, POSITIONS, AND REFERENCE FRAME SPECIFICATIONS
2	SUBSTRUCTURE DEFINITION DATA INCLUDING BOUNDARY NODE POSITION COORDINATES AND DESCRIPTIVE TITLES IDENTIFYING THE NUMBER AND TYPES OF FUNCTIONS APPEARING IN THE SUBSTRUCTURE DATA FILE.
3	INDIVIDUAL SUBSTRUCTURE ENERGY MATRICES. THIS OUTPUT IS NORMALLY NOT REQUESTED AND IS OF LITTLE OR NO VALUE TO ANYONE WHO IS NOT FAMILIAR WITH THE TERMINOLOGY INTERNAL TO THE PROGRAM.
4	SYSTEM MASS AND STIFFNESS MATRICES USED IN THE UNDAMPED EIGENVALUE ANALYSIS.
6	ACCURACY CHECKS FOR THE UNDAMPED EIGENVALUE ANALYSIS
7	UNDAMPED EIGENSOLUTION INFORMATION IN TERMS OF SUBSTRUCTURE COORDINATES, INCLUDING NODE MOTIONS RELATIVE TO LOCAL SUBSTRUCTURE REFERENCE FRAMES AND ENERGY BREAKDOWNS SHOWING THE CONTRIBUTION OF EACH SUBSTRUCTURE TO THE TOTAL SYSTEM KINETIC AND POTENTIAL ENERGIES.
8	NOT APPLICABLE TO THIS PROGRAM VERSION
9	FORCED RESPONSE NUMERICAL RESULTS ARE STORED ON NUNIT(9). THIS OUTPUT IS FOR EXTERNAL USE ONLY AND IS NORMALLY NOT REQUESTED.

OPT(5) AND OPT(10) MUST ASSUME SPECIFIC VALUES AS FOLLOWS.

OPT	VALUE	RESULTING OUTPUT
5	N	FREQUENCIES AND EIGENVECTORS FOR THE FIRST N UNDAMPED SYSTEM MODES
5	-1	FREQUENCIES AND EIGENVECTORS FOR ALL SYSTEM MODES
10	N	NUMERICAL INTEGRATION RESPONSE RESULTS ARE PRINTED FOR EVERY N-TH TIME STEP.

PART 3.1 SYSTEM JOINT CONSTRAINTS

THE FIRST CARD IN THE CONSTRAINT DECK SPECIFIES THE NUMBER OF EXPLICIT CONSTRAINT CONDITIONS THAT DIFFER FROM THE GENERAL CONSTRAINT (KCGEN) SPECIFIED ON THE MAIN CONTROL CARD.

```
LIST= NCONST
FORMAT(I5)
```

NCONST SETS OF CONSTRAINT SPECIFICATIONS FOLLOW. IF NCONST=0, NO CONSTRAINTS ARE READ. THE LISTS AND FORMAT OF EACH OF THE NCONST SPECIFICATIONS FOLLOW

```
LIST= (KC(I),I=1,6),N
FORMAT(6I1,I4)

LIST= (JNT(I),I=1,N)
FORMAT(14I5)
```

THE KC ARRAY INDICATES THE CONSTRAINT STATE OF JOINTS JNT(1),...JNT(N). IF THE DIRECTION-K DISPLACEMENT OF THE JOINT IS IDENTICALLY ZERO, SET KC(K)=1. OTHERWISE, SET KC(K)=0 OR LEAVE BLANK. KC(K+3) SIMILIARLY DEFINES DIRECTION-K ROTATIONS (FOR K=1,2,3).

THE LAST CONSTRAINT OR CONSTRAINT RELEASE SPECIFIED FOR A JOINT REPLACES ALL CONSTRAINTS PREVIOUSLY DEFINED FOR THAT JOINT.

2

PART 3.2 SYSTEM JOINT POSITION COORDINATES

THIS DECK IS PRESENT ONLY IF THE VARIABLE NX ON THE MAIN CONTROL CARD IS GREATER THAN ZERO. THE DECK IS COMPOSED OF NX CARDS EACH OF WHICH IS DEFINED BY THE FOLLOWING LIST AND FORMAT

```
LIST= JNT, (X(I),I=1,3)
FORMAT(I5,3E15.8)
```

X(I) SPECIFIES THE I-TH POSITION COORDINATE RELATIVE TO THE SYSTEM REFERENCE FRAME OF SYSTEM JOINT JNT. POSITION COORDINATES NEED BE DEFINED ONLY FOR EACH SYSTEM JOINT THAT DOES NOT COINCIDE WITH ALL SUBSTRUCTURE BOUNDARY NODES CONNECTED TO IT. OTHERWISE, THE LOCATIONS OF THE BOUNDARY NODES AUTOMATICALLY LOCATE THE SYSTEM JOINT. ANY SUBSTRUCTURE NODE SUBSEQUENTLY CONNECTED TO JOINT JNT IS ASSUMED TO BE CONNECTED TO JNT BY MEANS OF A RIGID ARM.

PART 3.3 LOCAL REFERENCE FRAME ORIENTATION SPECIFICATION DECK

THE PROGRAM USES THE DATA SPECIFIED IN THIS DECK TO CONSTRUCT A 'LIBRARY' OF 3 BY 3 ORTHOGONAL TRANSFORMATION MATRICES. THESE MATRICES DEFINE THE ORIENTATIONS OF VARIOUS LOCAL REFERENCE FRAMES RELATIVE TO THE SYSTEM REFERENCE FRAME. THE LOCAL REFERENCE FRAMES ARE ASSOCIATED WITH SUBSTRUCTURES AND/OR SYSTEM JOINTS. THE NUMBER OF LOCAL REFERENCE FRAME SPECIFICATIONS TO BE READ IS DEFINED BY THE VARIABLE NJREF ON THE MAIN CONTROL CARD. THE CARDS REQUIRED FOR EACH OF THE NJREF SPECIFICATIONS ARE READ ACCORDING TO THE FOLLOWING LISTS AND FORMATS.

LIST= J1,Q(3,J1),J2,Q(3,J2),J3SIGN,NL,NG,NSGN,Q(NL,NG),NOJNTS
FORMAT(I5,E15.5,I5,E15.5,I5,6X,2I1,I2,E15.5,I5)

IN THE DISCUSSION THAT FOLLOWS, 'GLOBAL FRAME' REFERS TO THE SYSTEM REFERENCE FRAME.

ENTRIES TO THE REFERENCE FRAME LIBRARY ARE IDENTIFIED BY THE ORDER IN WHICH THEY ARE READ. THEREFORE, THE K-TH REFERENCE SPECIFICATION DEFINES THE K-TH MATRIX. THE Q MATRIX (3 BY 3) INDICATES ORIENTATION RELATIVE TO THE GLOBAL FRAME. Q(I,J) IS THE COSINE OF THE ANGLE BETWEEN THE I-TH AXIS OF THE LOCAL FRAME AND THE J-TH AXIS OF THE GLOBAL FRAME (RIGHT-HAND, RECTANGULAR).

J1, Q(3,J1), J2, Q(3,J2), AND J3SIGN SPECIFY THE ORIENTATION OF THE 3-AXIS OF THE LOCAL FRAME. Q(3,J1) AND Q(3,J2) ARE ANY TWO DISTINCT ELEMENTS IN THE THIRD ROW OF Q, AND J3SIGN (+1 OR -1) GIVES THE SIGN OF THE THIRD ELEMENT.

Q(NL,NG) MAY GENERALLY BE ANY ELEMENT IN THE FIRST TWO ROWS OF Q. NSIGN (+1 OR -1) GIVES THE SIGN OF Q(3-NL,NG).

IN CHOOSING NL AND NG, CARE MUST BE TAKEN TO ENSURE A UNIQUE SPECIFICATION. FOR EXAMPLE, IF THE 3-AXIS OF THE LOCAL FRAME WERE CHOSEN TO BE PARALLEL TO THE GLOBAL 2-AXIS (EG J1=1,J2=3, Q(3,J1)=.0, Q(3,J2)=.0,J3SIGN= +1), THEN THE ORIENTATION OF THE LOCAL 1 AND 2 AXES IS NOT UNIQUELY DETERMINED BY SPECIFICATION THAT Q(1,2) OR Q(2,2) IS ZERO.

NOJNTS INDICATES THE NUMBER OF SYSTEM JOINTS FOR WHICH THE ORIENTATION OF THE LOCAL REFERENCE FRAME IS DEFINED BY THIS DIRECTION COSINE MATRIX. IF NOJNTS IS GREATER THAN ZERO, THE FOLLOWING CARD OR CARDS INDICATE WHICH SYSTEM JOINT REFERENCE FRAMES ARE ORIENTED IN THIS MANNER.

LIST= (IJNTS(I),I=1,NOJNTS)
FORMAT(14I5)

THIS SPECIFICATION IS ONLY REQUIRED FOR THOSE JOINTS WITH LOCAL REFERENCE FRAMES THAT ARE NOT PARALLEL TO THE GLOBAL SYSTEM REFERENCE FRAME.

PART 3.4 RELATIVE JOINT MOTION CONSTRAINT SPECIFICATIONS

THE DATA DESCRIBED IN THIS SECTION APPEAR ONLY IF THE VARIABLE NRELTV ON THE MAIN CONTROL CARD IS GREATER THAN ZERO. IF NRELTV IS GREATER THAN ZERO, THERE ARE NRELTV INDEPENDENT LINEAR RELATIONS IMPOSED AMONG VARIOUS JOINT MOTION COMPONENTS. EACH SUCH RELATIVE CONSTRAINT IS DEFINED BY AN ARBITRARY NUMBER OF CARDS, EACH OF WHICH SPECIFIES COEFFICIENTS FOR ONE OR MORE JOINT MOTIONS. A BLANK CARD TERMINATES EACH RELATIVE CONSTRAINT SPECIFICATION. EACH CARD OF A SPECIFICATION IS READ ACCORDING TO THE FOLLOWING LIST AND FORMAT.

```
LIST=K,JNT,JDEL,COEF,CDEL,N
FORMAT(3I5,2E15.8,I5)
```

EACH CARD DEFINES THE COEFFICIENT OF THE DIRECTION K MOTION OF N SYSTEM JOINTS. FOR K=1,2,3, THE CARD DEFINES DISPLACEMENTS PARALLEL TO THE K-TH AXIS OF THE LOCAL JOINT REFERENCE FRAME. FOR K=4,5,6, THE CARD DEFINES ROTATIONS ABOUT JOINT REFERENCE FRAME AXIS K-3. FOR I=1,N, THE COEFFICIENT OF THE DIRECTION-K MOTION OF JOINT JNT+(I-1)*JDEL IS SET EQUAL TO COEF+(I-1)*CDEL.

SUPPOSE THE J-TH RELATIVE CONSTRAINT IS DEFINED BY A CARD CONTAINING THE FOLLOWING DATA

K=2, JNT=3, JDEL=2, COEF=1.0, CDEL=1.0, N=3

THE TABLE BELOW ILLUSTRATES THE RESULTING JOINT MOTION COEFFICIENTS

JOINT	COEFFICIENT OF DIR-2 DISPLACEMENT
3	1.0
5	2.0
7	3.0

THE ABOVE EXAMPLE IMPLIES THAT THE DIRECTION-2 DISPLACEMENTS OF JOINTS 3,5,AND 7 OCCUR IN A 1-2-3 PROPORTION.

PART 3.5 SUBSTRUCTURE DATA DECK

THE FOLLOWING DATA DECK IS READ FOR EACH SUBSTRUCTURE IN THE SYSTEM. SUBSTRUCTURES ARE IDENTIFIED BY THE ORDER IN WHICH THESE DATA DECKS ARE READ. THE SUBSTRUCTURE DEFINED BY THE K-TH DATA DECK IS REFERRED TO AS THE K-TH SUBSTRUCTURE.
THE FIRST CARD IN A SUBSTRUCTURE DECK IS READ AS FOLLOWS

```
LIST= NBOUND,NINTR
FORMAT(2I5)
```

NBOUND IS THE NUMBER OF BOUNDARY NODES IN THE SUBSTRUCTURE MODEL. THIS NUMBER MUST AGREE WITH THE NUMBER OF BOUNDARY NODES USED BY THE FUNCTION GENERATOR PROGRAM TO CREATE THE SUBSTRUCTURE GENERALIZED FUNCTIONS. IF NBOUND DOES NOT AGREE WITH THE NUMBER OF BOUNDARY NODES IN THE SUBSTRUCTURE DATA FILE, A PROGRAM STOP OCCURS. NINTR CONTROLS PRINTOUT OF SUBSTRUCTURE JOINT MOTIONS.

THE NEXT CARD IN A SUBSTRUCTURE DATA DECK IDENTIFIES THE SYSTEM JOINTS TO WHICH THE SUBSTRUCTURE BOUNDARY NODES ARE ATTACHED, EITHER DIRECTLY OR VIA RIGID ARMS.

```
LIST= (JTCON(I),I=1,NBOUND)
FORMAT(16I5)
```

JTCON(I) IS THE SYSTEM JOINT TO WHICH THE I-TH SUBSTRUCTURE BOUNDARY NODE IS CONNECTED. IF NO EXPLICIT POSITION COORDINATE WAS SPECIFIED FOR JTCON(I), IT IS ASSUMED TO COINCIDE WITH BOUNDARY NODE I. EVERY BOUNDARY NODE IN THE SUBSTRUCTURE MUST BE CONNECTED TO SOME SYSTEM JOINT. IF JTCON(I) IS SPECIFIED LESS THAN 1 OR GREATER THAN JT, A PROGRAM STOP OCCURS. THE INDEX I REFERS TO THE SUBSTRUCTURE JOINT THAT WAS DECLARED TO BE THE I-TH BOUNDARY NODE IN THE SUBSTRUCTURE FUNCTION GENERATOR ANALYSIS.

IF NINTR IS GREATER THAN ZERO, A LIST OF SUBSTRUCTURE JOINTS APPEARS NEXT

```
LIST= (JTINTR(I),I=1,NINTR)
FORMAT(16I5)
```

MOTION COMPONENTS OF THE SUBSTRUCTURE JOINTS REFERENCED ABOVE WILL BE INCLUDED (ALONG WITH ALL BOUNDARY NODE MOTIONS) IN THE PRINTOUT OF THE EIGENVALUE SOLUTION.

THE NEXT CARD IN THE SUBSTRUCTURE DATA DECK DEFINES THE LOCATION AND ORIENTATION OF THE SUBSTRUCTURE.

```
LIST= IDOREF,(XORIGN(I),I=1,3)
FORMAT(I5,3F15.8)
```

IDOREF IDENTIFIES THE ORIENTATION OF THE LOCAL SUBSTRUCTURE REFERENCE FRAME RELATIVE TO THE SYSTEM REFERENCE FRAME. THE AXES OF THE SUBSTRUCTURE REFERENCE FRAME ARE PARALLEL TO THE AXES OF THE IDOREF-TH ENTRY IN THE LIBRARY OF LOCAL REFERENCE FRAME ORIENTATION SPECIFICATIONS. IDOREF MUST BE GREATER THAN ZERO. IF THE AXES OF THE SUBSTRUCTURE REFERENCE FRAME ARE PARALLEL TO THE AXES OF THE SYSTEM REFFRENCE FRAME, IDOREF SHOULD REFERENCE A Q MATRIX THAT IS A 3 BY 3 IDENTITY MATRIX. XORIGN(I),I=1,3 ARE THE POSITION COORDINATES, RELATIVE TO THE SYSTEM REFERENCE FRAME, OF THE ORIGIN OF THE SUBSTRUCTURE REFERENCE FRAME.

THE NEXT CARD IDENTIFIES THE INDIVIDUAL SUBSTRUCTURE FIXED BOUNDARY NODE MOTION FUNCTIONS TO BE USED AS SYSTEM COORDINATES.

```
LIST= (IMODE(I),I=1,20), (IUFAC(I),I=1,20),.(ISTAT(I),I=1,20)
FORMAT(20I1,10X,20I1,10X,20I1)
```

IF IMODE(I)=0 OR BLANK, THE I-TH SUBSTRUCTURE NATURAL MODE WILL BE USED AS A SYSTEM COORDINATE. IF IT EQUALS 1, THE I-TH MODE WILL NOT BE USED. IN A SIMILAR MANNER, IUFAC AND ISTAT IDENTIFY THE UNIFORM ACCELERATION MODES (FIXED BOUNDARY NODE) STATIC FUNCTIONS TO APPEAR AS SYSTEM COORDINATES. SINCE ONLY SIX UNIFORM ACCELERATION MODES ARE POSSIBLE, IUFAC(7) THRU IUFAC(20) ARE IGNORED.

THE DATA FILE CREATED BY THE FUNCTION GENERATOR PROGRAM IS READ NEXT. IF THE DATA FILE IS ON PUNCHED CARDS, INSERT THE DECK HERE. IF THE FILE IS ON MAGNETIC TAPE, IT IS READ AUTOMATICALLY, AND NO DATA CARDS ARE REQUIRED.

PART 3.6 DIRECTLY SPECIFIED SYSTEM MATRIX ENTRIES

EACH CARD IN THIS DATA DECK DEFINES AN EXPLICIT ENTRY TO THE SYSTEM MASS AND/OR STIFFNESS MATRICES. THE DECK IS TERMINATED BY A BLANK CARD. IF NO DATA OF THIS TYPE IS TO BE USED, A SINGLE BLANK CARD SHOULD BE USED FOR THE DECK. EACH CARD IS READ ACCORDING TO THE FOLLOWING LIST AND FORMAT.

```
LIST= NI, NJ, K, A, B
FORMAT(3I5,2E15.8)
```

THE DIRECTION-K MOTION (IF K.LE.3, DIRECTION K DISPLACEMENT, IF K.GT.3, DIRECTION K-3 ROTATION) OF SYSTEM JOINTS NI AND NJ ARE COUPLED IN THE MASS MATRIX BY THE QUANTITY A AND COUPLED IN THE STIFFNESS MATRIX BY THE QUANTITY B. IF NI=NJ THE QUANTITIES A AND B ARE ADDED TO DIAGONAL MATRIX TERMS. OTHERWISE THEY APPEAR AS OFF-DIAGONAL QUANTITIES.

AS AN EXAMPLE, ASSUME THAT THE DIRECTION-2 DISPLACEMENTS OF SYSTEM JOINTS 7 AND 9 ARE ELASTICALLY RELATED BY A MASSLESS LINEAR SPRING OF STIFFNESS 5.0E+06. THREE DATA CARDS WOULD BE REQUIRED TO CHARACTERIZE THE SPRING.

```
CARD 1.   NI=7, NJ=7, K=2, A=0.0, B=+5.0E+06
CARD 2.   NI=7, NJ=9, K=2, A=0.0, B=-5.0E+06
CARD 3.   NI=9, NJ=9, K=2, A=0.0, B=+5.0E+06
```

NOTE THAT IT IS NOT NECESSARY TO DEFINE ELEMENTS THAT APPEAR BELOW THE MATRIX DIAGONAL.

PART 4

DAMPING CHARACTERISTICS

A SYSTEM DAMPING MATRIX IS GENERATED ON THE BASIS OF SPECIFIED DAMPING CHARACTERISTICS OF INDIVIDUAL SUBSTRUCTURES. SUBSTRUCTURE DAMPING CHARACTERISTICS ARE SPECIFIED BY DEFINING DAMPING FACTORS FOR TWO UNDAMPED SUBSTRUCTURE NATURAL MODES. THE SUBSTRUCTURE MODES ARE CALCULATED ACCORDING TO ANY SPECIFIED BOUNDARY NODE CONSTRAINT CONDITIONS. THE MODES ARE COMPUTED IN A RAYLEIGH-RITZ ANALYSIS USING AS GENERALIZED FUNCTIONS AN APPROPRIATE SET OF FUNCTIONS FROM THE SUBSTRUCTURE DATA FILE.

ANY SUBSET OF THE SYSTEM'S SUBSTRUCTURES MAY CONTRIBUTE TO THE DAMPING MATRIX. A DECK COMPOSED OF ONE OR MORE CARDS IS REQUIRED FOR EACH SUBSTRUCTURE CONTRIBUTING TO THE SYSTEM DAMPING. A BLANK CARD TERMINATES ALL DAMPING DATA. THE LISTS AND FORMATS FOR A SINGLE SUBSTRUCTURE DAMPING SPECIFICATION ARE AS FOLLOWS.

```
LIST= NSUB, IPRNT, (KCGEN(I),I=1,6), NCNSTR, (MODE(I),ALFA(I),I=1,2)
FORMAT(2I5,4X,6I1,I5,2(I5,E15.8))
```

NSUB INDICATES THAT THE NSUB-TH SUBSTRUCTURE CONTRIBUTES TO THE SYSTEM DAMPING. VALUES OF NSUB APPEARING ON SUCCESSIVE CARDS MUST BE IN ASCENDING ORDER.

IPRNT CONTROLS PRINTOUT OF THE EIGENVALUE SOLUTION USED TO COMPUTE THE SUBSTRUCTURE MODES.

```
IPRNT=0, NO PRINTOUT
IPRNT.GT.0, MASS AND STIFFNESS MATRICES, EIGENVALUES,
            AND EIGENVECTORS
IPRNT.LT.0, MASS AND STIFFNESS MATRICES, EIGENVALUES,
            EIGENVECTORS, AND ACCURACY CHECKS
```

THE KCGEN ARRAY IS USED TO IMPOSE A GENERAL CONSTRAINT TO ALL SUBSTRUCTURE BOUNDARY NODES. IF ALL DIRECTION-I DISPLACEMENTS (WITH RESPECT TO THE LOCAL SUBSTRUCTURE REFERENCE FRAME) ARE ZERO, SET KCGEN(I)=1. IF ALL DIRECTION-I ROTATIONS ARE ZERO, SET KCGEN(I+3)=1. ANY SUBSEQUENT CONSTRAINT OR CONSTRAINT RELEASE SPECIFIED FOR A BOUNDARY NODE OVERRIDES THE KCGEN SPECIFICATION FOR THAT NODE.

NCNSTR IS THE NUMBER OF CONSTRAINT SPECIFICATIONS TO FOLLOW THAT DIFFER FROM KCGEN.

ALFA(I) IS THE DAMPING FACTOR ASSUMED FOR THE COMPUTED UNDAMPED SUBSTRUCTURE MODE, MODE(I). IF GM REPRESENTS THE GENERALIZED MASS OF MODE(I), AND GS REPRESENTS THE GENERALIZED STIFFNESS, THE ENERGY DISSIPATION CONSTANT FOR MODE(I) IS

```
2.0*ALFA(I)*SQRT(GM*GS)
```

DAMPING FACTORS NORMALLY RANGE FROM .001 TO .05. A DAMPING FACTOR OF .01 WOULD CONSTITUTE ONE PERCENT OF 'CRITICAL DAMPING'.

IF NCNSTR IS GREATER THAN ZERO, NCNSTR ADDITIONAL BOUNDARY NODE CONSTRAINTS ARE READ. EACH CONSTRAINT SPECIFICATION IS READ ACCORDING TO THE FOLLOWING LISTS AND FORMATS

```
LIST= (KC(I),I=1,6), N
FORMAT(6I1,4X,I5)

LIST= (NOD(I),I=1,N)
FORMAT(16I5)
```

THE KC ARRAY DEFINES THE CONSTRAINT OF BOUNDARY NODES NOD(1),...,NOD(N). IF THE DIRECTION-K DISPLACEMENT OF THE NODE IS IDENTICALLY ZERO, SET KC(K)=1. OTHERWISE SET KC(K)=0 OR LEAVE BLANK. KC(K+3) SIMILIARLY DEFINES DIRECTION-K ROTATIONS (FOR K=1,2,3). THE LAST CONSTRAINT SPECIFIED FOR A BOUNDARY NODE REPLACES ALL CONSTRAINTS PREVIOUSLY DEFINED FOR THAT NODE.

PART 5

FORCED RESPONSE PROBLEM DEFINITION DATA

UNDAMPED SYSTEM MODES ARE USED AS GENERALIZED FUNCTIONS IN THE FORCED RESPONSE ANALYSIS. THE FIRST TWO CARDS IN THE RESPONSE DATA IDENTIFY THE MODES TO BE USED AND DEFINE CERTAIN NUMERICAL INTEGRATION PARAMETERS.

```
LIST= NMODES, NTERMS, ADEL, TIMEND
FORMAT(2I5,2E15.8)

LIST=(MODEID(I),I=1,NMODES)
FORMAT(16I5)
```

THE UNDAMPED MODES USED AS GENERALIZED FUNCTIONS ARE

```
MODEID(1), MODEID(2),....,MODEID(NMODES)
```

NTERMS IS THE NUMBER OF TERMS TO INCLUDE IN THE TAYLOR SERIES EXPANSIONS FOR CALCULATING THE NUMERICAL INTEGRATION COEFFICIENT MATRICES. NTERMS=6 IS USUALLY SUFFICIENT. IF NTERMS IS LESS THAN OR EQUAL TO ZERO A PROGRAM STOP WILL OCCUR.

ADEL IS USED TO COMPUTE THE NUMERICAL INTEGRATION TIME STEP. THE TIME STEP IS CALCULATED BY DIVIDING THE PERIOD ASSOCIATED WITH THE HIGHEST FREQUENCY SYSTEM MODE USED AS A RESPONSE COORDINATE INTO ADEL PARTS. ADEL IS USUALLY SET EQUAL TO 10.

TIMEND IS THE TIME AT WHICH THE NUMERICAL INTEGRATION PROCESS IS TO TERMINATE.

FORCING FUNCTIONS CONSIST OF POINT FORCES AND MOMENTS DEFINED AS PIECEWISE LINEAR FUNCTIONS OF TIME. ANY NUMBER OF POINT LOADS MAY BE SPECIFIED ACCORDING TO THE FOLLOWING LIST AND FORMAT. A BLANK CARD IS USED TO TERMINATE FORCING FUNCTION DATA.

```
LIST= JNT, K, NPTS
FORMAT(3I5)
```

IF K.LE.3, THE FORCING FUNCTION WILL BE APPLIED AS A POINT FORCE IN DIRECTION K AT JOINT JNT. IF K.GT.3, THE FUNCTION WILL BE APPLIED AS A POINT MOMENT IN DIRECTION K-3 AT JOINT JNT. NPTS IS THE NUMBER OF POINTS IN TIME AT WHICH THE FORCING FUNCTION IS DEFINED. THE FUNCTION IS ASSUMED TO VARY LINEARLY BETWEEN TIME POINTS.

THE FOLLOWING CARDS DEFINE THE TIME AND THE MAGNITUDE OF THE LOADING AT EACH TIME STATION. THE CARDS ARE READ IN PAIRS (ONE TIME CARD AND ONE LOADING CARD) WITH EIGHT POINTS BEING DEFINED BY EACH CARD PAIR UNTIL ALL NPTS TIME POINTS ARE DEFINED. THE LIST AND FORMAT CONTROLLING INPUT OF A SINGLE PAIR OF CARDS FOLLOWS.

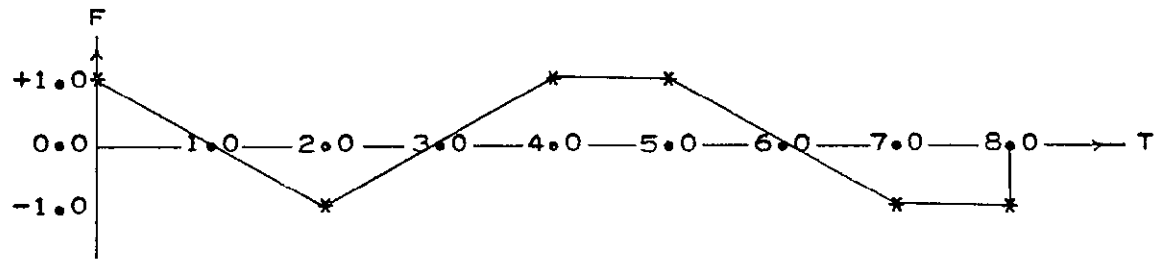
```
LIST= (T(I),I=1,8)
FORMAT= (8E10.6)

LIST= (F(I),I=1,8)
FORMAT= (8E10.6)
```

F(I) IS THE MAGNITUDE OF THE POINT LOAD APPLIED AT JOINT JNT IN DIRECTION K AT TIME T(I). THE LAST PAIR OF CARDS IN THE T AND F SPECIFICATION MAY DEFINE LESS THAN EIGHT TIME STATIONS. SUPPOSE THAT NPTS=13. TWO CARD PAIRS WOULD BE REQUIRED. THE FIRST DEFINING TIME STATIONS 1 THRU 8, AND THE SECOND DEFINING TIME STATIONS 9 THRU 13.

FOR EXAMPLE, SUPPOSE THE FOLLOWING DATA WAS READ FOR NPTS=7.

I=	1	2	3	4	5	6	7
T(I)=	0.0	2.0	4.0	5.0	7.0	8.0	8.0
F(I)=	1.0	-1.0	1.0	1.0	-1.0	-1.0	0.0

A TIME PLOT OF THE RESULTING LOADING FOLLOWS.



THE NON-ZERO INITIAL CONDITION SPECIFICATIONS ARE READ NEXT. UNLESS SPECIFIED OTHERWISE BELOW, THE INITIAL STATE OF A COORDINATE AND ITS FIRST TIME DERIVATIVE ARE SET EQUAL TO ZERO. A BLANK CARD TERMINATES THE INITIAL CONDITION DECK. EACH NON-ZERO SPECIFICATION IS READ ACCORDING TO THE FOLLOWING LIST AND FORMAT.

```
LIST= I, Q, QDOT
FORMAT= (I5,2E15.8)
```

Q DEFINES THE INITIAL STATE OF THE I-TH SYSTEM COORDINATE. QDOT DEFINES THE INITIAL DERIVATIVE OF Q WITH RESPECT TO TIME. THE I-TH SYSTEM COORDINATE IS IDENTIFIED AS THE UNDAMPED SYSTEM MODE MODEID(I) AS DISCUSSED PREVIOUSLY IN THIS SECTION.