Static and Dynamic Structural-Sensitivity Derivative Calculations in the Finite-Element-Based Engineering Analysis Language (EAL) System

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INTRODUCTION

Researchers at the Langley Research Center are currently developing and applying the latest optimization capability to the multidisciplinary optimization of aircraft and spacecraft (ref. 1). A key part of this effort is to efficiently calculate structural-sensitivity derivatives which quantify the change in a behavior variable with respect to a structural parameter and which are used in the following applications: (1) to act as input to optimization algorithms; (2) to enhance response analysis programs which aid engineering judgment leading to design modifications; (3) to guide the modification of a finite-element model to better correlate analytical and test results; and (4) to approximate structural response by using Taylor series expansions.

The most basic and straightforward approach to sensitivity analysis is the finite-difference method; however, it is computationally slow and its accuracy must be verified by convergence checks. Analytical methods for calculating exact derivatives from the governing equations have been developed (refs. 2 to 10). These methods greatly reduce the computational effort but are somewhat cumbersome to implement for bending-type elements (ref. 4). Most recently, a semianalytical method for calculating derivatives has been developed which has the generality and programming ease of the finite-difference method while retaining much of the efficiency of the analytical method (ref. 11).

The purpose of this paper is to describe the implementation and verification of the aforementioned methods for computing sensitivity derivatives in the structural finite-element computer program currently used in multidisciplinary optimization studies. The program, denoted the Engineering Analysis Language (EAL) System (ref. 12), is similar to its predecessor, SPAR (ref. 13). It is a modular system of individual analysis processors which may be used in any appropriate sequence to perform a variety of analyses. The EAL System differs from SPAR by providing FORTRAN-like commands which permit branching, testing data, looping, and calling runstreams (similar to calling FORTRAN subroutines). These capabilities permit the implementation of sensitivity calculations without changing the basic program or requiring user-written subroutines in separate programs (as in ref. 4). Further, use of the EAL System avoids the need for extensive operating system control commands as used previously (ref. 4) and thus assures machine independence of the resulting system.

This paper draws on results from references 4, 8, and 11 for the basic methodology and presents EAL input runstreams which calculate derivatives of displacements, stresses, vibration frequencies and mode shapes, and buckling loads and mode shapes with respect to structural variables in the model. The variables are sectional properties including thicknesses, cross-sectional areas, and moments of inertia. Results are presented and comparisons are made among analytical, semianalytical, and finite-difference methods for the following four structural configurations: a swept wing, a box beam, a stiffened cylinder with a cutout, and a space radiometer-antenna truss.
SYMBOLS AND ABBREVIATIONS

\( A \) cross-sectional area
\( E \) modulus of elasticity
\( \{F\} \) pseudo load vector
\( [F] \) matrix of pseudo load vectors (eq. (21))
\( f \) applied load
\( \{f\} \) applied load vector
\( [G] \) matrix which relates stresses and temperatures (eq. (26))
\( [I] \) identity matrix
\( I_1, I_2 \) moments of inertia
\( J_o \) polar moment of inertia
\( [K] \) stiffness matrix
\( [K_g] \) geometric stiffness matrix
\( [M] \) mass matrix
\( P_j \) structural definition parameter
\( \{Q\} \) particular solution of equation (35)
\( r \) independent design variable for tube element (eq. (40))
\( r_i, r_o \) inner and outer radii of tube element
\( [S] \) stress-displacement matrix
\( T \) temperature
\( T_o \) stress-free temperature
\( t_i \) element thickness
\( u, v, w \) displacements in x, y, and z directions, respectively
\( \{u\} \) displacement vector
\( \{v\} \) vector of independent design variables
\( \{v\} \) vector of dependent design variables
\( x, y, z \) Cartesian coordinates
\( \{\alpha\} \) vector of linear thermal expansion coefficients
\{\lambda, \omega^2\} \text{ vectors of buckling loads and vibration frequencies, respectively}

\nu \text{ Poisson's ratio}

[\Phi], [\phi] \text{ matrices of buckling and vibration mode shapes, respectively}

\rho \text{ density}

\{\sigma\} \text{ stress vector}

Superscripts:

\text{n} \text{ new (perturbed)}

\text{o} \text{ original (unperturbed)}

Abbreviations:

\text{NDDV} \text{ number of dependent design variables}

\text{NIDV} \text{ number of independent design variables (NDV in computer listing)}

\text{NPOL} \text{ degree of polynominal used in linking (eq. (1))}

\text{NSDP} \text{ number of structural definition parameters}

\text{DESCRIPTION OF THE ENGINEERING ANALYSIS LANGUAGE (EAL) SYSTEM}

The EAL finite-element analysis system (ref. 12) evolved from the SPAR computer program (ref. 13). As indicated in figure 1(a), the EAL System contains individual processors which communicate through a data base consisting of one or more libraries of data sets. The data sets typically contain data describing the finite-element model of the structure (e.g., node point coordinates and material properties) as well as response information such as displacements and stresses. All data base communications between processors are in terms of data sets. A set of data-handling utilities transfers data between the processors in central memory of the computer and the data base on auxiliary storage (ref. 14). Contents of individual data sets for SPAR are compiled and listed in reference 15. (In some instances these data sets may be slightly different from corresponding EAL data sets.)

A list of the EAL processors is shown in the uppermost block of figure 1(a). The functions of the various processors are described in table 1. The processors may be executed in any appropriate sequence. A sequence of processor executions is denoted a runstream and may be defined and stored in the data base as a runstream data set. Runstreams and runstream data sets may be nested within an input file.

The EAL system differs from SPAR in its use of a set of flexible FORTRAN-like statements, denoted executive control system (ECS) commands, which allow branching, testing data, looping, and calling runstreams (similar to calling FORTRAN subroutines). The ECS commands are always preceded by an asterisk (*) and are used to execute processors; for example, the ECS command to execute the TAB processor is *XQT TAB. A list of the ECS commands and their functions is given in table 8-1 of reference 12. The ECS commands are also used to test variables (denoted registers). Registers may be input data, output data, or simple variables defined and manipulated
by the EAL user. If the value of a register is regarded as a variable which changes during an EAL analysis, the current value of the register is defined as a surrogate. A surrogate is always enclosed in quotation marks. Registers and surrogates are defined and manipulated by the use of register action commands (RAC). A RAC is always preceded by an exclamation point (!) in the EAL input. For example, \( !A = \text{ABS("STR")} \) assigns the absolute value of the surrogate "STR" to register A. A complete list of the register action commands is given in table 7.3-1 of reference 12.

The makeup of a sample EAL input file is illustrated in figure 1(b). The file begins with an ECS command to execute processor TAB using appropriate input data following the command; second, there is a call to execute runstream data set CHNG DV; third, there is execution of processor ELD using appropriate input data; and finally, there is execution of processors of K and INV, neither of which require user input.

The makeup of the sample runstream data set CHNG DV is shown in figure 1(c). The function of this runstream is to loop over the membrane elements in the model (looping is controlled by the JLZ command), extract the membrane thicknesses from data set DV DFN and store them in register DV (using the DS register action command), and finally update that part of the input file in which the membrane thicknesses are defined. The updated portion of the file follows the SA identifier and contains the membrane element numbers ("NI") and the corresponding thicknesses ("DV"). Following the satisfaction of the loop and the arrival at LABEL 2, control returns to the calling runstream by means of the RETURN command.

**SCOPE OF CAPABILITY FOR CALCULATING STRUCTURAL-SENSITIVITY DERIVATIVES**

**Methods Used and Overall Capability**

In the present work, structural behavior quantities include displacements \( \{u\} \), stresses \( \{\sigma\} \), buckling loads and mode shapes \( \{\lambda\} \) and \( \{\phi\} \), and vibration frequencies and mode shapes \( \{\omega^2\} \) and \( \{\phi\} \). Structural variables include element thicknesses, cross-sectional areas, and moments of inertia. The following methods for calculating derivatives of structural behavior quantities have been implemented: (1) an analytical method, (2) a semianalytical method (also called the indirect method in refs. 11 and 16), and (3) a finite-difference method (also called the direct method in ref. 11). A list of applicable EAL finite elements is given in table 2. The analytical method was not implemented for the elements which include bending deformation (E32, E33, E42, and E43) because of the algebraic complexity (discussed in the following section).

**Design-Variable Definition**

Structural modifications are specified as changes to certain structural quantities called design variables, which are related to section properties or mass properties of the finite-element model. A structural definition parameter (ref. 4) is defined to be a parameter which has a linear contribution to the stiffness matrix or the mass matrix, or both, of individual finite elements in the structural model. The design variables can be identical to or have a one-to-one relationship to the structural definition parameters. For example, the cross-sectional area of a rod element is a structural definition parameter, and the areas of several elements in the structure could be equal to a single design variable. In some instances, there is a non-linear relationship between the structural definition parameters and the design
variables, for example, when the moment of inertia per unit width of a plate $I_1 = t^3/12$ is a structural definition parameter and the plate thickness $t$ is a design variable. Finally, in some optimization techniques (e.g., ref. 3), design-variable linking is used to reduce the number of independent design variables. In this instance independent design variables can be linearly or nonlinearly related to the dependent design variables, which in turn can be linearly or nonlinearly related to the structural definition parameters. Chain-rule partial differentiation is then used to compute the required derivatives (ref. 4).

**Design-Variable Linking**

When linking is used, the number of dependent design variables (NDDV) is larger than the number of independent design variables (NIDV), and the two are related via a mathematical relationship which is often linear (ref. 17). In the present work the following nonlinear design-variable linking algorithm is used:

$$v_i = C_{oi} + \sum_{m=1}^{NPOL} \sum_{k=1}^{NIDV} C_{mk,i} V_k^m$$

where $i = 1, 2, \ldots, NDDV$.

**STIFFNESS AND MASS MATRIX DERIVATIVES**

The derivatives of the stiffness matrix $[K]$ and of the mass matrix $[M]$ with respect to the independent design variable $V_k$ are needed in the subsequent calculations of sensitivity derivatives. Two methods are used for calculating these matrix derivatives: analytical and finite differences.

**Analytical Method**

When the stiffness or the mass matrix of a finite element is linearly related to a design variable, the analytical derivative of the matrix is obtained by simply setting the design variable to unity and calculating the corresponding matrix. When a nonlinear relationship exists between the stiffness or the mass matrix and the design variables or when design-variable linking is used, or both, the situation is more complicated and chain-rule partial differentiation is needed to formulate generalized analytical expressions. For a beam element the stiffness matrix is linearly related to four structural definition parameters ($A, I_1, I_2', J_0$). Analytical
expressions may be written to relate the design variables to these structural definition parameters, and the derivative of the stiffness matrix can be calculated by using

$$\frac{\partial[K]}{\partial v_i} = \frac{\partial[K]}{\partial A} \frac{\partial A}{\partial v_i} + \frac{\partial[K]}{\partial I_1} \frac{\partial I_1}{\partial v_i} + \frac{\partial[K]}{\partial I_2} \frac{\partial I_2}{\partial v_i} + \frac{\partial[K]}{\partial J_o} \frac{\partial J_o}{\partial v_i}$$  \hspace{1cm} (3)

or

$$\frac{\partial[K]}{\partial v_i} = \sum_{j=1}^{\text{NSDP}} \frac{\partial[K]}{\partial P_j} \frac{\partial P_j}{\partial v_i}$$  \hspace{1cm} (4)

where NSDP is the number of structural definition parameters, $\partial[K]/\partial P_j$ is computed by substituting unity for $P_j$, and $\partial P_j/\partial v_i$ is calculated by differentiating the analytical expression relating $v_i$ to $P_j$. The analogous expression for mass matrix derivatives is

$$\frac{\partial[M]}{\partial v_i} = \sum_{j=1}^{\text{NSDP}} \frac{\partial[M]}{\partial P_j} \frac{\partial P_j}{\partial v_i}$$  \hspace{1cm} (5)

If design-variable linking is used, the independent and dependent design variables are related by equation (1) and the expressions for derivatives with respect to the independent design variables are

$$\frac{\partial[K]}{\partial v_k} = \sum_{i=1}^{\text{NDDV}} \sum_{j=1}^{\text{NSDP}} \frac{\partial[K]}{\partial P_j} \frac{\partial P_j}{\partial v_i} \frac{\partial v_i}{\partial v_k}$$  \hspace{1cm} (6)

and

$$\frac{\partial[M]}{\partial v_k} = \sum_{i=1}^{\text{NDDV}} \sum_{j=1}^{\text{NSDP}} \frac{\partial[M]}{\partial P_j} \frac{\partial P_j}{\partial v_i} \frac{\partial v_i}{\partial v_k}$$  \hspace{1cm} (7)

Example of Analytical Derivative of Stiffness Matrix

To crystallize the ideas and terms involved, differentiation of the stiffness matrix for a beam modeled by three E23 channel-section elements (fig. 2) is performed. The structural definition parameters consist of the cross-sectional area $A$ and the moments of inertia $I_1$, $I_2$, and $J_o$. The dependent design variables are the dimensions of the channel $B_1$, $B_2$, and $t$. There are three independent design
variables, each associated with an element and denoted \( V_1 \), \( V_2 \), and \( V_3 \). The dependent design variables are linked to the independent design variables by a 9 × 3 matrix \([C]\). Thus, for the structure in figure 2,

\[
\{p\}^T = \{A \quad I_1 \quad I_2 \quad J\}
\]  

(8)

\[
\{v\}^T = \{B_1P_2t \quad B_1P_2t \quad B_1P_2t\}
\]

Element 1 Element 2 Element 3

(9)

\[
\{v\}^T = \{v_1 \quad v_2 \quad v_3\}
\]  

(10)

\[
\{v\} = [C]\{v\}
\]  

(11)

The structural definition parameters are related to the dependent design variables by equations given in reference 4, as follows:

\[
P_1 = A = (2B_1 + B_2)t
\]

\[
P_2 = I_1 = \frac{B_1(B_2 + 2t)^3}{12} - \frac{(B_1 - t)B_2^3}{12}
\]

\[
P_3 = I_2 = \frac{2tB_1^3}{12} + 2tB_1\left(\frac{B_1}{2} - c\right)^2 + \frac{B_2t^3}{12} + B_2t(c - \frac{t}{2})^2
\]  

(12)

\[
P_4 = J_o = \frac{1}{3}(2B_1 + B_2)t^3
\]

\[
c = \left(\frac{B_1^2t + \frac{B_2t^2}{2}}{A}\right)
\]

From equation (6),

\[
\frac{\partial[K]}{\partial V_k} = \sum_{i=1}^{9} \sum_{j=1}^{4} \frac{\partial[K]}{\partial F_j} \frac{\partial F_j}{\partial V_i} \frac{\partial V_i}{\partial V_k}
\]  

(13)
where

\[
\frac{\partial [K]}{\partial p_j} = [K]_{P_j=1} \quad (j = 1, 2, 3, 4) \tag{14}
\]

\[\frac{\partial P_j}{\partial v_i}\] is obtained from differentiating equations (12) and noting equation (9), and \[\frac{\partial v_i}{\partial v_k}\] is obtained from differentiating equation (11).

**Finite-Difference Method**

The stiffness and mass matrix derivatives can also be computed by finite differences, as follows:

\[
\frac{\partial [K]}{\partial v_k} = \frac{\Delta [K]}{\Delta v_k} = \frac{[K]_k^n - [K]^O}{v_k^n - v_k^O} \tag{15}
\]

\[
\frac{\partial [M]}{\partial v_k} = \frac{\Delta [M]}{\Delta v_k} = \frac{[M]_k^n - [M]^O}{v_k^n - v_k^O} \tag{16}
\]

where \([K]_k^n\) and \([M]_k^n\) are the perturbed stiffness and mass matrices (formed by incrementing the kth independent design variable), \([K]^O\) and \([M]^O\) are the original (unperturbed) stiffness and mass matrices, and \(v_k^n\) and \(v_k^O\) are the perturbed and original values of the kth independent design variable. Since this method operates with the independent design variables directly, it does not require looping over the dependent design variables or the structural parameters indicated by equations (6) and (7).

**Finite Differences With LSK Processor**

In some instances the finite-difference calculation of the stiffness matrix may be improved by use of the LSK processor (table 1). This processor selects appropriate combinations of elements (submatrices) of the global stiffness matrix \([K]\) in a sparse matrix form (called LS-format) and performs the necessary finite differencing. For this case the differencing must be with respect to the dependent design variables, as follows:

\[
\frac{\partial [K]}{\partial v_i} = \frac{\Delta [K]}{\Delta v_i} = \frac{[K]_i^n - [K]^O}{v_i^n - v_i^O} \tag{17}
\]
If design-variable linking is used (eq. (1)),

$$\frac{\partial[K]}{\partial V_k} = \sum_{i=1}^{NDDV} \frac{\partial[K]}{\partial V_i} \frac{\partial V_i}{\partial V_k}$$

(18)

where $\frac{\partial V_i}{\partial V_k}$ is obtained by differentiating equation (1). Using the LSK processor to operate on selected portions of the global stiffness matrix is more efficient than summing and multiplying stiffness matrices having the dimensions of the entire structure. Hence, depending on the ratio of the number of dependent design variables (NDDV) to the number of independent design variables (NIDV), the finite-difference methods of equation (15) or of equations (17) and (18) may be more efficient than the analytical method of equation (6). A large ratio of dependent to independent design variables and a large number of structural parameters needed to specify a particular element favor the use of one of the finite-difference methods for calculating $\frac{\partial[K]}{\partial V_k}$.

### DISPLACEMENT DERIVATIVES

#### Analytical Method

In the analytical method, derivatives are computed from the governing finite-element equations. For static finite-element structural analysis, the equilibrium equation is

$$[K]\{u\} = \{f\}$$

(19)

where $\{u\}$ is the vector of nodal displacements and $\{f\}$ is the applied load vector. Differentiating equation (19) with respect to the independent design variable $V_k$ gives

$$[K] \frac{\partial\{u\}}{\partial V_k} = \frac{\partial\{f\}}{\partial V_k} - \frac{\partial[K]}{\partial V_k}\{u\} = \{F\}_k$$

(20)

or

$$[K]\frac{\partial\{u\}}{\partial V} = \{F\}$$

(21)

where $\{F\}_k$ is the kth pseudo applied load vector and $[\partial u/\partial V]$ and $[F]$ are, respectively, matrices for which the columns are the displacement derivatives and pseudo load vectors which correspond to individual independent design variables. If
the applied load vector \( \{f\} \) is not a function of the design variables, then the term \( \partial \{f\}/\partial V_k \) is equal to zero.\(^1\) For this case the pseudo load vector becomes

\[
\{P\}_k = - \frac{\partial \{K\}}{\partial V_k} \{u\}
\]  

(22)

The analytical method consists of solving equation (20) for \( \partial \{u\}/\partial V_k \) using analytically computed derivatives for \( \partial \{K\}/\partial V_k \) (eq. (6)). Equation (20) is solved by the same solution algorithm used for solving equation (19), taking advantage of the fact that the factored form of \( \{K\} \) is available from the solution of equation (19). Substitution of equation (6) into equation (20) leads to

\[
[K] \frac{\partial \{u\}}{\partial V_k} = \frac{\partial \{f\}}{\partial V_k} - \sum_{i=1}^{NDDV} \sum_{j=1}^{NSDP} \frac{\partial \{K\}}{\partial P_j} \frac{\partial P_j}{\partial V_i} \frac{\partial v_i}{\partial V_k} \{u\}
\]

(23)

Semianalytical Method

The semianalytical method contains the analytical expression for the displacement derivatives (eq. (20)) with finite-difference derivatives of the stiffness matrix (eq. (15) or eqs. (17) and (18)). If equations (15) and (20) are used, the following expression results:

\[
[K] \frac{\partial \{u\}}{\partial V_k} = \frac{\partial \{f\}}{\partial V_k} - \left( \frac{[K]_k^n - [K]_k^o}{v_k^n - v_k^o} \right) \{u\} = \{P\}_k
\]

(24)

where \( \partial \{f\}/\partial V_k \) can be calculated analytically or by finite differences and the term in parentheses may be obtained by finite differences from equation (15) or by the LSK processor (eqs. (17) and (18)). Derivatives are calculated by creating individual pseudo load vectors \( \{P\}_k \) and solving equation (24) using the factored \( \{K\} \) matrix from equation (19). This formulation is a significant simplification of the analytical approach of reference 4 in that it avoids the need for element-dependent manipulations to handle bending-type elements. It also eliminates the complications in the analytical method when design-variable linking is included (eqs. (1) and (23)).

Finite-Difference Method

The simplest method to implement, but the most time consuming computationally (especially for large finite-element models), is the finite-difference method. In addition, the accuracy of the finite-difference method depends upon the perturbation

\(^1\)One practical case when this term is not zero is when thermal loads are included.
step size. In this method, the original structure is analyzed; the structure is then modified by perturbing a design variable and reanalyzed. The displacement derivative is

$$\frac{\partial \{u\}}{\partial v_k} = \frac{\{u\}^n_k - \{u\}^o}{v^n_k - v^o_k}$$  \hspace{1cm} (25)$$

where $\{u\}^n_k$ is the displacement vector due to a perturbation in the $k$th independent design variable and $\{u\}^o$ is the displacement vector of the original structure.

**STRESS DERIVATIVES**

**Analytical Method**

Element stresses $\{\sigma\}$ are related to joint displacements and element temperatures by the equation

$$\{\sigma\} = [S]\{u\} - [G] \{\alpha\} (T - T_o)$$  \hspace{1cm} (26)$$

where $[S]$ is the stress-displacement matrix, $[G]$ is the stress-temperature matrix, $\{\alpha\}$ is the vector of thermal expansion coefficients, $T_o$ is the stress-free element temperature, and $T$ is the actual element temperature. Upon differentiation with respect to the $k$th independent design variable, the general expression for stress derivatives is

$$\frac{\partial \{\sigma\}}{\partial v_k} = [S] \frac{\partial \{u\}}{\partial v_k} + \sum_{i=1}^{NDDV} \sum_{j=1}^{NSDP} \frac{\partial [S]}{\partial v_i} \frac{\partial P_j}{\partial v_i} \frac{\partial v_i}{\partial v_k} \{u\}$$  \hspace{1cm} (27)$$

Equation (27) neglects any dependence of temperature on the design variables.

For rods (E23), membranes (E31 and E41), and shear panels (E44), the matrix $[S]$ is independent of the section-property design variables; thus, the second term on the right side of equation (27) is zero. For bending-type elements, beams (E21) and plates (E32, E33, E42, and E43), the stress-displacement matrices are dependent on the element cross-sectional geometry, and this dependence must be included in the stress derivative calculations. This was done in reference 4 for the channel-section beam in figure 2 by using specific, user-defined subroutines.

**Semianalytical Method**

In this method (reported in ref. 11), the perturbed displacement vector $\{u\}^n_k$ is approximated by a truncated Taylor series expansion as follows:

$$\{u\}^n_k = \{u\}^o + \frac{\partial \{u\}}{\partial v_k}(v^n_k - v^o_k)$$  \hspace{1cm} (28)$$
where $\partial(u)/\partial V_k$ is calculated with equation (24). The perturbed stress vector is given by

$$\{\sigma\}_k^n = [S]_k^n{u}_k^n - [G]\{\alpha\}[G]\{\alpha\}(T - T_0)$$  \hspace{1cm} (29)

and the derivative is

$$\frac{\partial\{\sigma\}}{\partial V_k} = \frac{\{\sigma\}_k^n - \{\sigma\}_0}{V_k^n - V_k^0}$$  \hspace{1cm} (30)

where

$$\{\sigma\}_0 = [S]\{u\}_0 - [G]\{\alpha\}(T - T_0)$$  \hspace{1cm} (31)

Finite-Difference Method

The stress derivatives are calculated in a manner analogous to the displacement derivatives. The structure is modified and reanalyzed and the derivatives are approximated as

$$\frac{\partial\{\sigma\}}{\partial V_k} = \frac{\{\sigma\}_k^n - \{\sigma\}_0}{V_k^n - V_k^0}$$  \hspace{1cm} (32)

where $\{\sigma\}_k^n$ is the stress vector due to a perturbation in the $k$th independent design variable calculated with equation (29) and $\{\sigma\}_0$ is the original stress vector.

DERIVATIVES OF VIBRATION AND BUCKLING EIGENVALUES AND EIGENVECTORS

Methodologies for calculating derivatives of eigenvalues and eigenvectors have been presented in references 4, 6, 8, and 9. The methods which have been implemented in EAL are an analytical method (ref. 8) and the finite-difference method.

Analytical Method

This method is implemented in EAL using runstreams based on the development in reference 4 and the theory in reference 8. The matrix equation for free vibrations is

$$\left( [K] - \omega_j^2[M] \right)\{\phi\}_j = 0$$  \hspace{1cm} (33)
where \( \{\phi\}_j \) and \( \omega_j \) are, respectively, the vector of the mode shape and the scalar frequency corresponding to vibration mode \( j \), \([M]\) is the mass matrix, and \([K]\) is the stiffness matrix. Normalizing the modes with respect to the mass matrix gives

\[
\{\phi\}^T [M] \{\phi\} = [I]
\]  

(34)

where \([I]\) is the identity matrix. Differentiating equation (33) with respect to \( v_k \) gives

\[
\left( [K] - \omega_j^2 [M] \right) \frac{\partial \{\phi\}_j}{\partial v_k} = \frac{\partial \omega_j^2}{\partial v_k} [M] \{\phi\}_j - \frac{\partial [K]}{\partial v_k} \{\phi\}_j + \omega_j^2 \frac{\partial [M]}{\partial v_k} \{\phi\}_j
\]  

(35)

Premultiplying equation (35) by \( \{\phi\}^T \) and using equations (33) and (34) gives

\[
2 \{\phi\}^T [M] \frac{\partial \omega_j^2}{\partial v_k} = \{\phi\}^T \frac{\partial [K]}{\partial v_k} \{\phi\} - \{\phi\}^T \frac{\partial [M]}{\partial v_k} \{\phi\}_j
\]  

(36)

The value of one component of \( \frac{\partial \{\phi\}_j}{\partial v_k} \) is fixed, yielding a particular solution \( \{Q\}_j \) to equation (35). This is accomplished in EAL by identifying the component of the eigenvector with the largest absolute value and constraining to zero the corresponding component of the eigenvector derivative. The eigenvector \( \{\phi\}_j \) is the complementary solution to equation (35). Thus, the expression for the eigenvector derivative is

\[
\frac{\partial \{\phi\}_j}{\partial v_k} = \{Q\}_j + C \{\phi\}_j
\]  

(37)

The value of the multiplier \( C \) is obtained by substituting the expression for \( \frac{\partial \{\phi\}_j}{\partial v_k} \) from equation (37) into the following:

\[
2 \{\phi\}^T [M] \frac{\partial \{\phi\}_j}{\partial v_k} = \{-\{\phi\}_j^T \frac{\partial [M]}{\partial v_k} \{\phi\}_j
\]  

(38)

Equation (38) is the derivative of the expression for the normalization of modes with respect to the mass matrix (eq. (34)). The resultant equation for \( C \) is

\[
C = \{-\{\phi\}_j^T \frac{[M]}{\partial v_k} \{\phi\}_j - \frac{1}{2} \{\phi\}_j^T \frac{\partial [M]}{\partial v_k} \{\phi\}_j
\]  

(39)
For buckling eigenvalue and eigenvector derivatives, the preceding equations apply directly, with the buckling mode shape $\{\phi\}_j$ and load $\lambda_j$ substituted for the vibration mode shape $\{\phi\}_j$ and frequency $\omega_j^2$ and with the negative of the geometric stiffness matrix $-[K_g]$ substituted for the matrix $[M]$. In the present implementation, derivatives of the matrices $[K]$, $[M]$, and $[K_g]$ were calculated by finite differences.

Finite-Difference Method

The equations for finite-difference derivatives of eigenvalues and eigenvectors are analogous to those previously shown for displacement and stress derivatives (eqs. (25) and (32)). When the finite-difference method is used to obtain derivatives of eigenvectors, careful attention must be paid to accuracy of the eigenvectors. Problems arise because eigenvalue routines generally base convergence on accuracy of the eigenvalues, whereas the associated eigenvectors may not be as accurate. Hence, when differencing the eigenvectors, further errors are introduced which may make the derivatives inaccurate.

IMPLEMENTATION OF DERIVATIVE CAPABILITY IN EAL

An outline of the implementation of the derivative capability in EAL is given in the appendix. For brevity, only the implementation of the semianalytical method is discussed in the appendix, which includes descriptions of the overall procedure, descriptions of the key portions of the EAL runstreams, and a listing of the input for the problem of the box beam.

NUMERICAL EXAMPLES AND RESULTS

Four example problems were investigated to verify the derivative implementation and to compare the methods. The problems were a swept wing, a box beam, a stiffened cylinder with a cutout, and a space radiometer-antenna truss. Comparisons of solution times for the various derivative calculation methods are given, and a convergence study was performed for the wing problem to verify the accuracy of the finite-difference results and to establish an appropriate perturbation in the design variables for the remaining finite-difference calculations. Analytical derivatives (when available) were used to assess the accuracy of the other methods. All numerical calculations were performed on the CDC® CYBER 175 computer under NOS 1.4.

Swept Wing

Optimization of the swept wing shown in figure 3 has been investigated and reported by several researchers (refs. 17 to 19). This example was a moderately complex representation of a wing modeled by rods (E23), triangular membranes (E31), and shear panels (E44). Since bending elements were not used, the calculation of derivatives with the analytical method was straightforward, and the results were used to check the accuracy of the semianalytical and finite-difference methods. The geometry and node numbering are shown in figure 3; nodal coordinates are listed in table 3 and design variables are described in table 4. In this problem, 32 design variables controlled the section properties of 150 elements. The wing was aluminum, had a constrained root, and was subjected to two load conditions. (See table 5.) Load condition 1 was approximately equivalent to a uniform pressure loading of
0.556 psi. Load condition 2 had the same total load, but the distribution was changed to move the center of pressure forward. The wing was symmetric with respect to the x-y plane (u and v displacements were zero on the plane z = 0), and hence only half the wing was modeled. The model consisted of triangular membrane elements for the skin, rod elements for the spar caps, and shear panels for the rib and spar webs. (See fig. 4.) Forty-four transverse rod elements (not shown) were added at the vertical edges of the shear panels to provide the necessary stiffness throughout the depth of the wing. The thicknesses $t_i$ were 0.2 in. for E31 elements 1 to 24, 0.1 in. for E31 elements 25 to 60, and 0.2 in. for all E44 elements. The cross-sectional area $A_i$ was 0.02 in$^2$ for E23 elements 1 to 20 and 0.2 in$^2$ for E23 elements 21 to 64.

A study was performed to determine the perturbation step size needed to obtain sufficiently accurate results for the finite-difference and semianalytical methods. The results are shown in table 6(a). The value of the largest displacement derivative value ($\frac{\partial w}{\partial V_{14}}$ at joint number 41 for load condition 1) was used to judge convergence. As indicated in table 6(a), the finite-difference result, with a 1-percent increment in the design variable, was within 1 percent of the analytical results. Use of perturbations smaller than 0.01 percent led to degradation of accuracy. The semianalytical method was capable of duplicating the analytical result with a 1-percent perturbation in the design variable. Although the acceptable perturbation sizes are generally problem dependent, this dependence was not significant. In all subsequent calculations, perturbations of 1 percent were used.

Comparisons of solution times for displacement derivatives are also presented in table 6(b). The finite-difference method was slowest (700 sec), the semianalytical method required 419 sec without the LSK processor and 161 sec with the LSK processor, and the analytical method required 135 sec. Hence, the use of the LSK processor makes the semianalytical method significantly more effective and makes it competitive with the analytical method.

Box Beam

The next problem was a cantilevered box beam (fig. 5). This example was used to verify displacement derivative runstreams for all the EAL structural elements listed in table 2.

The geometry and joint numbering are shown in figure 5, and elements are illustrated in figure 6. The thickness of all two-dimensional elements was 0.1 in. The cross-sectional area of the rod elements was 1.0 in$^2$, and the beam elements had tube sections with an inner radius of 2.0 in. and an outer radius of 2.5 in. The material was aluminum with the following material properties: $\rho = 0.096$ lb/in$^3$, $E = 10.6 \times 10^6$ psi, and $v = 0.3$. The applied load was composed of 10 000-lb forces in the positive z direction at nodes 27 and 28. The cross-sectional area or thickness of each group of elements was considered to be a separate design variable. The problem had 10 dependent design variables and 9 independent design variables. The inner and outer radii of the tube elements were linked to an independent variable $r$ by the equation

$$
\begin{bmatrix}
  r_i \\
  r_o
\end{bmatrix} = \begin{bmatrix} 1 \\ 1 \end{bmatrix} r + \begin{bmatrix} 0 \\ 0.5 \end{bmatrix}
$$

(40)
Displacement derivatives with respect to each independent design variable were calculated with the finite-difference method and the semianalytical method. Results shown in table 7(a) indicate run times of 133 sec for the finite-difference method and 63 sec for the semianalytical method with the LSK processor. The reduction in solution time for the semianalytical method with LSK over the finite-difference method was smaller for this example than for the swept wing because the swept wing problem had more independent design variables (32 instead of 9). Values shown in table 7(b) reveal which design variables would be most effective to increment to reduce tip deflections. As expected, the upper and lower covers (coupled plate elements E43 and E33) had the greatest effect on limiting tip deflections. In addition, since the E32 and E42 elements had only bending stiffness and the bending loads in the covers were negligible, the derivatives with respect to thickness of these elements were negligible. The results in table 7(b) suggest that derivatives can be used directly to guide improvements in a structural design apart from their use in formal optimization. In some instances substantial improvements may be realized (ref. 20).

Stiffened Cylinder With Cutout

Optimization studies of a cantilevered stiffened cylinder with a cutout (fig. 7) were reported in references 4 and 21. Node point locations are given in table 8. Element types and locations are shown in figure 7(b). The cylinder model had 352 degrees of freedom and was stiffened by 5 equally spaced rings along the length and 16 equally spaced stringers around the circumference. Rotations about the Y-axis at all node points and all translations at node points 1 to 16 were constrained to zero. The rings and stringers were modeled by beam (E21 channel sections) and rod elements (E23). Rectangular panels between rings and stringers were modeled by membrane elements (E41). The cross-sectional area of all rod elements was 0.646 in$^2$, the thickness of the rectangular membranes was 0.0394 in., and the channel-section dimensions are shown in figure 7(b). The material was aluminum alloy with $E = 10.8 \times 10^6$ psi and $v = 0.3$. The independent design variables for this problem included the area of the rods, the thickness of the membrane elements, and a scale factor which controlled the cross-sectional dimensions of the beam elements. The loading consisted of two equal and opposite concentrated axial forces of 20 000 lb applied at the free end.

Derivatives of displacements, stresses, vibration frequencies and mode shapes, and buckling loads and mode shapes were calculated. Computer times for calculating derivatives are presented in table 9. Use of the semianalytical method without the LSK processor for displacement derivatives resulted in a reduction in solution time of about 25 percent over the finite-difference method. Using the semianalytical method with the LSK processor resulted in a reduction in solution time of 28 percent over the finite-difference method. The reason solution times for the semianalytical methods were so similar for this case was that the ratio of the number of independent to the number of dependent design variables was only 3 to 5. As this ratio decreases, the advantage of the LSK processor increases. (In the problem of the swept wing, the ratio was 32 to 150 and the LSK processor had a much larger effect.)

Stress derivatives were calculated by finite differences (122 sec) and semianalytically (95 sec). The savings in solution time for finite differences relative

\[2\text{Derivatives for the membrane and rod elements were computed with the analytical method.}\]
Computer times for calculating derivatives of vibration frequencies, vibration mode shapes, buckling loads, and buckling mode shapes with the finite-difference and analytical methods are also shown in Table 9. For the vibration problem, the analytical method was 57 percent faster than finite differences, and for the buckling problem it was 37 percent faster.

Antenna Truss

A finite-element model of a 180-ft radiometer-antenna reflector is shown in Figure 8. The reflector, described in Reference 22, was made up of tetrahedral truss modules, and the model consisted of 109 structural node points (Table 10) and 420 rod elements. The structure was composed of graphite-epoxy composite with an effective modulus of elasticity of $10.6 \times 10^6$ psi and a coefficient of thermal expansion of $0.13 \times 10^{-6}$ per degree Fahrenheit. The antenna was subjected to thermal loading corresponding to Earth orbit at an altitude of 216 miles in an Earth-facing orientation. The thermal loading consisted of a combination of solar, Earth-reflected (albedo), and Earth-emitted heat flux. A transient thermal analysis of the structure for a complete orbit was performed (Ref. 23) and node point temperature differences from a worst-case condition (largest temperature gradients, Table 11) were used for the present calculations. Three design variables were used for this problem. They were the cross-sectional area of the elements in the upper surface (0.2530 in$^2$), the area of the diagonal elements joining the upper and lower surfaces (0.1741 in$^2$), and the area of the elements in lower surface (0.2530 in$^2$). Both stress and displacement derivatives were calculated, and for this problem the applied load vector $\{f\}$ was a function of the design variables. (See Eq. (20).)

Solution times for displacement and stress derivatives are summarized in Table 12(a). The semianalytical method was 39 percent faster than the finite-difference method for displacement derivatives and 29 percent faster for stress derivatives for this problem. As indicated by the tabulated derivatives in Table 12(b), the most effective way to reduce the center deflection of the reflector would be to decrease the areas of the upper-surface elements.

CONCLUDING REMARKS

A capability for computing structural-sensitivity derivatives has been implemented in the general purpose, finite-element computer program denoted the Engineering Analysis Language (EAL) System. This paper presented the development of runstreams which calculate derivatives of displacements, stresses, vibration frequencies and mode shapes, and buckling loads and mode shapes with respect to structural variables which include thicknesses, areas, and moments of inertia. Linear and nonlinear design-variable linking representations were included. Three methods for computing the derivatives were documented: analytical (which calculates exact structural-sensitivity derivatives from the governing equations), semianalytical (which combines finite-difference derivatives of mass, stiffness, and geometric stiffness matrices with analytical expressions for derivatives), and finite differences. The derivative capability was demonstrated for the following four structures: a swept wing, a box beam, a stiffened cylinder with a cutout, and a space radiometer-antenna truss. Comparisons of solution times for the various methods were described. A convergence study was performed for the swept wing to...
verify the accuracy of the finite-difference results and to establish an appropriate increment in the design variables for use in the subsequent finite-difference calculations. Analytical derivatives of displacements for the wing and of vibration frequencies of the cylinder served as benchmarks to assess the accuracy and efficiency of the finite-difference and semianalytical methods. Results indicated that the semianalytical method for calculating displacement and stress derivatives was efficient, general, and straightforward to implement. Further, the semianalytical method was not adversely affected by the presence of bending elements or design-variable linking.

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APPENDIX

SYSTEM OF EAL RUNSTREAMS FOR CALCULATING STRUCTURAL-SENSITIVITY DERIVATIVES WITH SEMIANALYTICAL METHOD

Overall Procedure

This appendix describes a system of EAL runstreams used to calculate structural-sensitivity derivatives with the semianalytical method. A flowchart for the overall system is shown in figure 9. Runstreams or groups of runstreams presented at the end of this appendix are keyed by numerals to specific portions of flowcharts shown in figures 10 to 12. The semianalytical method uses equations (15) and (16) to calculate derivatives of the stiffness and mass matrices and uses equations (24) and (28) to (30) to calculate the displacement and stress derivatives.

As shown in figure 10, derivatives of the stiffness, mass, and geometric stiffness matrices are calculated by finite differences. The procedure is as follows: loop over the independent design variables, perturb a design variable, link design variables to form vector of dependent design variables, loop over the dependent design variables and modify the structure, calculate new stiffness and mass matrices and geometric stiffness matrix (if appropriate), differentiate the resulting matrices, and restore the original value of independent design variable $V_k$. The numerals beside specific boxes correspond to runstreams described subsequently.

Displacement derivatives (fig. 11) are calculated by looping over the independent design variables, building a pseudo load matrix (eq. (20)) and solving equation (24). The acquired displacement derivatives are then used to approximate a perturbed displacement vector $\{u\}^R_k$ (eq. (28)) and then to approximate a perturbed stress vector (eq. (29)). The stress derivatives are then calculated by finite differences (eq. (30)).

The flowchart which illustrates the calculation of derivatives of vibration and buckling eigenvalues is shown in figure 12. The outer loop is on the mode for which derivatives are required. The two inner loops are both over the independent design variables. The first inner loop calculates the derivatives of the vibration frequencies and buckling loads with equation (36) and then builds a pseudo load vector (right-hand side of eq. (35)). A particular solution of equation (35) is calculated and used in the second inner loop to calculate derivatives of the eigenvectors with equations (37) and (39).

Descriptions of the key runstreams used in the system of figures 9 to 12 (particularly those which are problem dependent) are given in the following table:
<table>
<thead>
<tr>
<th>Runstream name</th>
<th>Identification no. in figs. 9 to 12</th>
<th>Description</th>
</tr>
</thead>
</table>
| DRIV GRD4     | 1                                | Driver runstream which calculates derivatives semianalyti-
|               |                                  | cally; the entire system can be run by the statement
|               |                                  | *DCALL (DRIV GRD4) |
| INIT MODL     | 2                                | Sequence of EAL processors (TAB, ELD, TAN, and AUS) which
|               |                                  | describes the initial structural model and load cases; the
|               |                                  | example shown in the runstream listing is for the box beam |
| SET PARA      | 3                                | Initializes following parameters used by system to determine
|               |                                  | specifics of derivative information required: |
|               | NLST Number of load sets          |             |
|               | MODT Number of modes for which derivatives are computed by method of reference 8 |
|               | NODE Same as MODT                 |             |
|               | OLIB Output library for intermediate buckling and vibration derivatives |
|               | OTIB Output library for intermediate stress or displacement derivatives |
|               | NPOL Degree of polynomial used in linking design variables (eq. (1)) |
|               | DISP If equal to 1, displacement derivatives are calculated |
|               | STRD If equal to 1, stress derivatives are calculated |
|               | BUCD If equal to 1, buckling load and mode shape derivatives are calculated; if equal to 2, only buckling load derivatives are calculated |
|               | VIRD Same as BUCD for vibration derivative |
|               | NJ Number of joints in model      |             |
|               | NIV Number of independent design variables | |
|               | NDIV Number of dependent design variables | |
|               | NDVA Number of rod and membrane dependent design variables (E23, E31, E41, E44) | |
|               | NHDV Number of beam dependent design variables (E21) | |
|               | NPDV Number of plate dependent design variables (E32, E33, E42, E43) | |
|               | NDVX Number of shape-dependent design variables | |
|               | DR Incrementing factor for design variables for finite-difference calculations | |
|               | DE21, DE23,                     | Number of dependent design variables for each element |
|               | ..., DE44                       |             |
|               | NE21, NE23,                     | Number of independent design variables for each element |
|               | ..., NE44                       |             |
|               | MODE NUM TABLE                  | Name of table of mode numbers for which derivatives are taken |
### APPENDIX

<table>
<thead>
<tr>
<th>Runstream name</th>
<th>Identification no. in figs. 9 to 12</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DESV DFN</td>
<td>4</td>
<td>Set up tables denoted DVA DFN, DVP DFN, and DVB DFN which define membrane, plate, and beam dependent design variables, respectively; element types are defined by a numeral: E23-1, E31-2, E32-3, E33-4, E41-5, E42-6, E43-7, E44-8, and E21-9; the type of beam used in EAL in section 3.1.9 of reference 12 is denoted by a code as follows: TUBE = 1, BOX = 2, TEE = 3, ANG = 4, WFL = 5, CHN = 6, ZEE = 7, GIVN = 8, DSY = 9; beam design variable numbers are designated by the following codes: b_1 = 1, t_1 = 2, b_2 = 3, t_2 = 4, b_3 = 5, t_3 = 6, b_4 = 7, t_4 = 8, b_5 = 9, t_5 = 10, b_6 = 11, t_6 = 12, b_7 = 13, t_7 = 14, b_8 = 15, t_8 = 16, b_9 = 17, t_9 = 18, b_10 = 19, each of the variables shown is described in section 3.1.9 of reference 12; the order in which the dependent design variables are listed (starting with the membrane, then plate, and then beam design variables) are the actual locations of each design variable in the dependent design variable vector (see INTL DESV); the only restriction is that the structural parameters of beams with the same section property number must be listed together in the DVB DFN table; this permits the linking of several section properties of a beam; this could be used to facilitate the scaling of an entire beam cross section by one design variable or scale factor.</td>
</tr>
<tr>
<td>INTL DESV</td>
<td>5</td>
<td>Initializes design variables by forming a table of initial design variables called DESV CNMN whose only limitation is that when linked it will produce the same structural parameters as the initial structural model (see INIT MODL).</td>
</tr>
<tr>
<td>COEF LINK</td>
<td>6</td>
<td>Series of tables which define the coefficients for nonlinear design-variable linking as expressed by equation (1) and rewritten as ( {v} = {C_0} + {C_1} {v} + {C_2} {v^2} + \ldots + {C_m} {v^m} ), where ( {C_0} ) is represented as table COEF DV 1 0, ( {C_1} ) is COEF DV 1 1, ( {C_2} ) is COEF DV 1 2, \ldots, ( {C_m} ) is COEF DV 1 M; each block of the above tables represents a column in the ( {C} ) matrices; this runstream must be included in the system of runstreams even if linking is not used.</td>
</tr>
</tbody>
</table>
This section of the appendix contains a listing of the EAL runstreams used to calculate derivatives of displacement, stress, and vibration and buckling eigenvalues and eigenvectors with the semianalytical method.

* CHAR $!M!Z
* ECHU 1,2,3,4
* ABORT 1
* QUIT U1

$(DRV DRD4) ENDDG4
$DRIVER PROGRAM TO CALCULATE DU/DCAPV BY THE SEMI-ANALYTICAL METHOD
*DCALL(INIT MOL)
*QUT DCU
DUPLICATE 1 2
DUPLICATE 1 3
DUPLICATE 1 4
DUPLICATE 1 5
*DCALL(SET PARA)
*DCALL(DESV DFN)
*DCALL(INL DESV)
*DCALL(COEF LINK)
*DCALL(CALC GRD4)
*DCALL(PRT SUB)
*RETURN

$ ENDDG4

$ (INIT MOL) ENDDGM
$ INITIAL MODEL STRUCTURAL DEFINITION
$ TITLE 'BOX BEAM GRADIENT CALCULATION
$ START 28
$ DESCRIPTION OF A BOX-BEAM WHICH USES E21, E23, E31, E32, E33, E41, E42, E43, AND E44 ELEMENTS
JLOC
1 0.0, 0. 0, 10.0, 2.17
2 60.0, 0. 0, 60.10, 0.
15 0.0, 0. 10.0, 10.0, 2.17
2 60.0, 0. 60.10, 0.
$SPECIFY MATERIAL PROPERTIES
$ MATERIAL CONSTANTS
1 10.6E6 .3 .096
$DESCRIBE MATERIAL REFERENCE FRAME
$MREF
$FORMAT=2
1,1,1000,0,1000.
2,1,1000,0,1000.
$BEAM ELEMENT SECTION PROPERTIES
$BA
$TUBE 1.25, 3
$ROD ELEMENT AREAS
dC
1,1.
$MEMBRANE AND PLATE ELEMENT THICKNESSES
$SA
$MAT=1
1,1E31 ELEMENTS
2,1E32 ELEMENTS
3,1E33 ELEMENTS
4,1E41 ELEMENTS
5,1E42 ELEMENTS
6,1E43 ELEMENTS
$SHEAR PANEL THICKNESSES
$SB
1,1
$CONSTRAINT DEFINITION
APPENDIX

CON=1
ZERO 1,2,3,4,5,6;1,2
ZERO 1,2,4,5,6,15,16
*XQT ELD
*BEAM ELEMENT DEFINITION
E21
NMAT=1
NSECTION=1
KREF=1
1 3 1 6
15 17 1 6
KREF=2
2 4 1 6
16 18 1 6
*ROD ELEMENT DEFINITION
E23
NMAT=1
NSECTION=1
1 15 1 17 2
2 16 1 17 2
*TRIANGULAR MEMBRANE ELEMENT DEFINITION
E31
NMAT=1
NSECTION=1
8 10 7
7 9 10
9 11 10
10 12 11
12 14 11
11 13 14
*UNCOPLED TRIANGULAR PLATE ELEMENT DEFINITION
E32
NMAT=1
NSECTION=2
8 10 7
7 9 10
9 11 10
10 12 11
12 14 11
11 13 14
*UNCOPLED TRIANGULAR PLATE ELEMENT DEFINITION
E33
NMAT=1
NSECTION=3
1 3 2
2 4 3
4 6 3
3 5 6
5 7 6
6 8 7
*QUADRILATERAL MEMBRANE ELEMENT DEFINITION
E41
NMAT=1
NSECTION=4
21 23 24 22 1 3 1
*UNCOPLED QUADRILATERAL PLATE ELEMENT DEFINITION
E42
NMAT=1
NSECTION=5
21 23 24 22 1 3 1
*UNCOPLED QUADRILATERAL PLATE ELEMENT DEFINITION
E43
NMAT=1
NSECTION=6
15 17 18 1 6 1
*SHENAR PANEL DEFINITION
E44
NMAT=1
NSECTION=1
1 3 17 19 1 6 1
2 4 10 16 1 6 1
*XQT TAN
*APPLIED LOADS DEFINITION
*XQT AUS
SYSVEC=APPLIED FORCE 1
1=3;4=27;28; 10000. 10000.
*RETURN
APPENDIX

ENDDM

$----------------------------------------------- 3$

*(SET PARA) ENDPAR

$** SET CONTROL PARAMETERS

ILST=1& NUMBER OF LOAD SETS
ILCAS=1& NUMBER OF LOAD CASES
IMODT=2& TOTAL NUMBER OF MODES
IOLIB=15 OUTPUT LIBRARY FOR INTERMEDIATE DYNAMIC DERIVATIVES
ITLIB=15 OUTPUT LIBRARY FOR INTERMEDIATE STRESS OR DISP. DERIVATIVES
IMOD=2

INPOL=15 DEGREE OF POLYNOMIAL LINKING
IDISP=15 DISPLACEMENT DERIVATIVES
ISTRI=15 STRESS DERIVATIVES
IBUCD=15 BUCK DERIVS. (LOAD & FREQUENCY)
IVBD=15 VIB. DERIVS. (LOAD & FREQUENCY)
INJ=28 NO. OF JOINTS
INDV=9 NO. OF INDEPENDENT DESIGN VARIABLES
INDO=9

INDX=1NO. OF DEPENDENT SHAPE VARIABLES TO BE LINKED
INDVA=4 NO. OF DEPENDENT MEMBRANE-TYPE DESIGN VARIABLES TO BE LINKED

INLK=10 NO. OF LINKED DESIGN VARIABLES
INLV=9

INPV=25 NO. OF PLATE DEPENDENT DESIGN VARIABLES TO BE LINKED
INPS=5 NO. OF PLATE DEPENDENT DESIGN VARIABLES TO BE LINKED
INPDV=NO. NO. OF E2 MAMDEPENDENT DESIGN VARIABLES TO BE LINKED
INDV=NO. JOUNS+NDV+NDV+NDV

*INDV=NDV

IDK=0.01% FACTOR FOR INCREMENTING DESIGN VARIABLE

1DE23=18 NO. OF E23 D.V. * S
1DE31=1# NO. OF E31 D.V. * S
1DE32=1# NO. OF E32 D.V. * S
1DE33=1# NO. OF E33 D.V. * S
1DE41=1# NO. OF E41 D.V. * S
1DE42=1# NO. OF E42 D.V. * S
1DE43=1# NO. OF E43 D.V. * S
1DE44=1# NO. OF E44 D.V. * S
1DE21=2# NO. OF E21 D.V. * S

INZ1=1

INX1=DS4,1,11,11,JDF1,1TAB1,18

INX2=DS5,1,11,11,JDF1,1TAB1,18

INX3=DS6,1,11,11,JDF1,1TAB1,18

INX4=DS7,1,11,11,JDF1,1TAB1,18

INX5=DS8,1,11,11,JDF1,1TAB1,18

INX6=DS9,1,11,11,JDF1,1TAB1,18

$ STABLE OF MODE NUMBERS $

*XOT AUS

TABLE(RM=2*TYPE=0,N1=1,NJ="MODE");MODE
J=11
J=212

$ STABLE OF UNCONSTRAINED DEGREES OF FREEDOM $

TABLE(RM=2*TYPE=0,N1=1,NJ=6);IN EX
J=11;"INX1"
J=21;"INX2"
J=31;"INX3"
J=41;"INX4"
J=51;"INX5"
J=61;"INX6"

INX1=FREE()

INX2=FREE()

INX3=FREE()

INX4=FREE()

INX5=FREE()

INX6=FREE()

*RETURN

ENDPAR

$----------------------------------------------- 4$

*(DESVD DFN) ENDDVD

** $ DEPENDENT DESIGN VARIABLE DEFINITION

*XOT AUS

24
$MEMBRANE-TYPE DESIGN VARIABLES
TABLE(RMODE=2,TYPE=0,NI=4,NJ=NDVA) JOIN DVF DFN
J=1,NDVA$ELEMENT TYPE GROUP NO. NO. OF ELEM. SECT. NO.
1 1 12 1
2 1 6 1
3 1 3 4
8 1 12 1

$PLATE-TYPE DESIGN VARIABLES
TABLE(RMODE=2,TYPE=0,NI=4,NJ=NPDV) JOIN DVP DFN
J=1,NPDV$ELEMENT TYPE GROUP NO. NO. OF ELEM. SECT. NO.
3 1 6 2
4 1 6 3
5 1 3 5
7 1 3 6

$BEAM-TYPE DESIGN VARIABLES
TABLE(RMODE=2,TYPE=0,NI=5,NJ=NBVDV) JOIN DVP DFN
J=1,NBDV$ELEMENT TYPE GROUP NO. NO. OF ELEM. SECT. NO. D.V. NO.
1 1 1 24 1 1
1 1 24 1 2

*RETURN
ENDDVD

*(INTL DESV)
ENDIND

$(INITIAL DESIGN VARIABLES
*XT AUS
TABLE(NJ=NDVA); DESV CNMN$DATA SET CONTAINING INITIAL VALUE OF DESIGN VARIABLES
J=1;1.
J=2;8;1.
J=9;23.
RETURN
ENDIND

*(COEF LINK)
ENDCLK

$(MATRIX OF COEFFICIENTS FOR LINKING
*XT AUS
TABLE(NJ=NDVA); COEF DVF 1 1
BLOCK 1
I=1;J=1;1.
BLOCK 2
I=1;J=2;1.
BLOCK 3
I=1;J=3;1.
BLOCK 4
I=1;J=4;1.
BLOCK 5
I=1;J=5;1.
BLOCK 6
I=1;J=6;1.
BLOCK 7
I=1;J=7;1.
BLOCK 8
I=1;J=8;1.
BLOCK 9
I=1;J=9;1.
I=1;J=10;1.
TABLE(NJ=NDVA); COEF DVF 1 0
J=1;910.
J=10;99.
RETURN
ENDCLK

*(CALC GRD04)
ENDG04

$(CALCULATE DERIVATIVES OF U W.R.T. DESIGN VARIABLES USING THE SEMI-ANALYTICAL METHOD
*CALL(CALC KI)
*CALL(DKDV DMDV)
*JNZ(DISP,262)
*JNZ(STRD,262)
*JUMP 265
*LABEL 262
*CALL(CALC DUDV)
*LABEL 264
*JZ(STRD,265) TEST TO SEE IF STRESS DERIVATIVES ARE REQUIRED
APPENDIX

*DCALL(STAS DERVS)CALCULATE STRESS DERIVATIVES
*LABEL 265
*TEST TO SEE IF BUCKLING DERIVATIVES ARE REQUIRED
*JZ(BUCD$266)
IN=UUCD
*JNZ,-1(N,267)
INAM9=*BUCK
INAM7=*BKVL
INAM8=*BKMD
*DCALL(NELS METH)
*JUMP 266
*LABEL 267
*JNZ,-1(N,269)
INAM9=*BUCK
INAM7=*BKVL
INAM8=*BKMD
*DCALL(NELS MET2)
*LABEL 269
*JNZ,-1(N,273)
INAM9=*BUCK
INAM7=*BKVL
INAM8=*BKMD
*DCALL(MODL METH)
*JUMP 266
*LABEL 273
*JNZ,-1(N,285)
INAM9=*BUCK
INAM7=*BKVL
INAM8=*BKMD
*DCALL(NELS METH)
*JUMP 266
*LABEL 285
*QX EXIT
*LABEL 266
*JZ(VIBD$268)*TEST TO SEE IF VIBRATION DERIVATIVES ARE REQUIRED
IN=VIB
*JNZ,-1(N,270)
INAM9=*VIBK
INAM7=*VBVL
INAM8=*VBMD
*DCALL(NELS METH)
*JUMP 268
*LABEL 270
*JNZ,-1(N,271)
INAM9=*VIBK
INAM7=*VBVL
INAM8=*VBMD
*DCALL(NELS MET2)
*JUMP 268
*LABEL 271
*JNZ,-1(N,274)
INAM9=*VIBK
INAM7=*VBVL
INAM8=*VBMD
*DCALL(MODL METH)
*JUMP 264
*LABEL 274
*JNZ,-1(N,275)
INAM9=*VIBK
INAM7=*VBVL
INAM8=*VBMD
*DCALL(MODL METH)
*JUMP 268
*LABEL 275
*QX EXIT
*LABEL 268
*RETURN
*
ENDGD4
$
$------------------------------------------------------------------- 8$
$
*(CALC KM) ENDCM$PERFORM STATIC AND/OP DYNAMIC ANALYSES OF INITIAL STRUCTURE
*QX E
*QX EKS
*QX K
*JNZ(DISP$156)
*JNZ(STRO$156)
*JUMP 157
APPENDIX

*LABEL 156
*XQT RSI
IA=NLST
*LABEL 5666
*JLZ=-1(A,J6667)
INNST*KLST=A
*XQT SSL$CALCULATE DISPLACEMENTS
RESET SET=*NNST"
*JUMP 5666
*LABEL 5667
IA=FREE()
INNST=FREE()
*LABEL 157
*XQT U1
INN3=TOC,N3(1,K,SPAR,MA$K,MA$K)
INN4=TOC,N4(1,K,SPAR,MA$K,MA$K)
*JZ(STRO,150)
IA=NLST
*LABEL 7666
*JLZ=-1(A,7667)
INNST=KLST=A
INAM1=STAT
INAM2=DISP
INAM3="NNST"
INAM4=1
IGLIB=1
IN1=1000 $SET N1=1000 FOR UNPERTURBED STRESS CALCULATIONS
*OCALL(CALC STRS)CALCULATE STRESSES
*JUMP 7666
*LABEL 7667
IA=FREE()
INNST=FREE()
INAM1=FREE()
INAM2=FREE()
INAM3=FREE()
INAM4=FREE()
IGLIB=DISP
*LABEL 150
*JNZ(DISP,193)
*JNZ(STR0,193)
*XQT RSI
*XQT SSL
*LABEL 193
*JZ(BI$D,151)
*XQT GS$F
RESET EMBED=1
*XQT KG
*XQT EIG$PERFORM BUCKLING ANALYSIS
RESET CONV=1.-10
RESET PKB=BUCK
RESET INIT="MMDB",NREQ="MRQB"
RESET NDY=20
*XQT EIG
RESET CONV=1.-10,PKB=BUCK,NREQ="MRQB",NDY=20
*LABEL 151
*JZ(VIB0,152)
*XQT E4$PERFORM VIBRATION ANALYSIS
RESET NMODE="MMDD",NREQ="MREQ"
*LABEL 152
*XQT DC$U
*JNZ(DISP,159)
*JNZ(STR0,159)
*JUMP 158
*LABEL 159
IA=NLST
*LABEL 6666
*JLZ=-1(A,6667)
INNST=NLST=A
$RENAME ALL DATA SETS AS INDICATED BELOW
CHANGE 1 STAT DISP "NNST" 1,PREV DISP "NNST" 1
*JUMP 6666
*LABEL 6667
*LABEL 159
IA=FREE()
INNST=FREE()
*LABEL 150
CHANGE 1 REM DIAG 0 O,DEMP DIAG 0 0
CHANGE 1 K SPAR "NN3" "NN4",KP SPAR "NN3" "NN4"
APPENDIX

CHANGE 1 INV K 1 0, INV KP 1 0
CHANGE 1 XINV K 1 0, XINV KP 1 0
*JZI(BUCD, 154)
INNN=N2D, M31, KG, SPAR, MASK, MASK
INN3=N4(1, KG, SPAR, MASK, MASK)
CHANGE 1 KG SPAR "INNN" "INN4", KG SPAR "INNN" "INN4"
CHANGE 1 BUCK EVAL 1 1, PREV BKVL 1 1
CHANGE 1 BUCK MODE 1 1, PREV BKMD 1 1
*LABEL 154
*JZI(VIBD, 155)
CHANGE 1 VIBR EVAL 1 1, PREV VBVL 1 1
CHANGE 1 VIBR MODE 1 1, PREV VBMD 1 1
*LABEL 155
*RETURN
*
ENDCKM

*----------------------------------------------- 9
*
*DKDV DMD
ENDCKM CALCULATE DK/DV, OM/DV, AND DKG/DV
III=0
IIEV=NDV
*LABEL 800
*JZI(IIEV, 804)*LOOP OVER DESIGN VARIABLES
III=IIV+1
IDV=DS, S1, "IIV", 15, DESV, CMN3, MASK, MASK
IDV=DR*DVP*DVP
IAQ=1, JDR
IAQ=AO*DVP
IIO=1, #AJ
*XQ AT AUS
TABLE(U=INV"NDV"), DESV CMN3 INCREMENT DESIGN VARIABLE
UPMASTER S XSUM
J="IIV"*MDV"
*DCALL(TRNS DESV)
*UCALL(LINK POLY)
*XQ AT DCU
PRINT 1 LNK DV
*XQ AT TAB
UPDATE=1
*JZI(NDVA, 800)
IIEV=NDV
*DCALL(DVA FDO)* UPDATES ALL MEMBRANE PROPS. TO CURRENT VALUE
*LABEL 800
*JZI(HPDV, 801)
IIEV=NPDV
*DCALL(DV*FDO)* UPDATES ALL PLATE PROPS. TO CURRENT VALUES
*LABEL 801
*JZI(BDV, 802)
IIEV=NBDV
*DCALL(DVA FDO)* UPDATES ALL BEAM PROPS. TO CURRENT VALUES
*LABEL 802
INNN=TDC, A3(1, KP, SPAR, MASK, MASK)
*XQ AT E
*XQ AT EK
*XQ AT K
KESET OUTLIB = "OLIO"
*XQ AT AUS
DEFINE KN = "OLIO" K SPAR
DEFINE KD=1 KP SPAR
UK*SUM("AO", KN, "BQ") KD
DEFINE A*DEMP DIAG 0 0
DEFINE B*DEMP DIAG 0 0
OMDV DIAG 0 "IIV"*SUM("AO", B, "BQ" A)
*XQ AT DCU
SPRINT 15 K SPAR
SPRINT 1 KP SPAR
CHANGE 1 UK MASK MASK MASK, DKDV SPAR "INNN" "IIV"
SPRINT 1 DKDV SPAR "INNN" "IIV"
*JZI(BUCD, 294)
*XQ AT RSI
RESET NUK="OLIO"
*XQ AT S5JL
RESET KLIB="ULIB"
KESET KLIB=1
*XQ AT GSF
RESET EMBED=1
*LABEL 292
*JZI(GUCD, 293)
APPENDIX

*JNZ(V180, 293)
*JUMP 294
*LABEL 293
*XOT KG
*XOT AUS
DEFINE KG*KG SPAR "NNN3" "NNN4"
DEFINE KG*KG SPAR "NNN3" "NNN4"
DG*KG*SUM("AO" KG, "BQ" KG)
*XOT DCU
CHANGE I OK SPAR "NNN3" "NNN4", OK SPAR "NNN3" "NNIV"
*LABEL 294
*XOT AUS
TABLED(NZ="NOV") J:DESU CMN% SET ORIGINAL VALUE OF DESIGN VARIABLE
QPER*XSUM
J="NNIV":"POVP"
INIEV=II EV
*JNZ(INIEV, 805)
*DCALL(TPNS DESV)
*DCALL(LINK POLY)
*LABEL 805
*DCALL(DCU EFIL)
*JUMP 803
*LABEL 804
ID1=FREE()
ID2=FREE()
ID3=FREE()
ID4=FREE()
ID5=FREE()
ID6=FREE()
ID7=FREE()
ID8=FREE()
ID9=FREE()
ID10=FREE()
ID11=FREE()
ID12=FREE()
ID13=FREE()
ID14=FREE()
ID15=FREE()
ID16=FREE()
ID17=FREE()
ID18=FREE()
ID19=FREE()
ID20=FREE()
ID21=FREE()
ID22=FREE()
ID23=FREE()
ID24=FREE()
ID25=FREE()
*RETURN
*
ENDDKM

$----------------------------------------------- 10$

*(CALC QUDV) ENDDUV$CALCULATE DU/OCAPV
I=A=NLST
*LABEL 5666
*JLZ=-1(I-A, 5667) $LOOP OVER LOAD SETS
INNST=NLST-A
IIIV=O
IIIEV=NOV
*LABEL 7777
*JLZ=-1(IIIEV, 7778) $LOOP OVER DESIGN VARIABLES
IIIV=IIIV+1
INNST
*XOT AUS
DEFINE U*PRE Disp "NNST" 1
DEFINE DK1=OKDV SPAR "NN3" "IIIV"
DK1=PROD(DK5, U)
*XOT DCU
$PRINT 1 DKU MASK
$PRINT 1 PRE Disp "NNST" 1
*XOT AUS
IS=IIIV-1
*JGZ(I5, 825)
APPL FORCE 50=UNION(-1, DKU)
*XOT DCU
*JUMP 826
*LABEL 829
DEFINE AF2=APPL FORCE 50
APPENDIX

AF2 TMP=UNION(AF2,=) DKU
*QUIT DCU
CHANGE 1 AF2 TMP 1,APPL FORC 50 1
*PRINT 1 APPL FORC 50 1
*LABEL 126
*JUMP 7777
*LABEL 7778
*QUIT S SUL
RESET SET=50
RESULT **KP
*QUIT DCU
TOC 1
CHANGE 1 STAT DISP 50 MASK,DUOV CAPV "NNST" 1
*JNZ(0DISP,263)
*JNZ(STRD,263)
*JUMP 265
*LABEL 263
*JUMP 5666
*LABEL 5667
*RETURN
ENDDUV

*LINK POLY)
ENDLPK

$**NONLINEAR POLYNOMIAL LINKING
ILL1=0
ILL2=0
INPL=NPOL$POWER OF POLYNOMIAL
INSEQ=0
*QUIT AUS
*XX=TOCJ,N1(1,CQEF,DV1,0),NSEQ
*JLZ(INSEQ,1301)
ILL2=ILL2+1
DEFINE C=CQEF DV1 0
LNK DV=UNION(CL)
*LABEL 1301
*JLZ=-1(INPL,1300)
ILL1=ILL1+1
INSEQ=0
*XX=TOCJ,N1(1,CQEF,DV1,"ILL"),NSEQ
*JLZ(INSEQ,1301)
ILL1=ILL2+1
DEFINE V=DESV TMP
DEFINE C=CQEF DV1 "ILL"
INILI=ILL1+0.
Z=POWER(V,"NIL1")
JVN=CBR(N,2)
TABLE(NJ="NUVD")TMP1
TRANSFER(SOURCE=DVNC,1ILM="NDV")
INL2=IL2
*JNZ,-1(INL2,1302)
LNK DV=UNION(TMP1)
*JUMP 1301
*LABEL 1302
LNK DV=SUM(TMP1,LNK DV)
*JUMP 1301
*LABEL 1300
ILL1=FREE()
ILL2=FREE()
INPL=FREE()
IXX=FREE()
INILI=FREE()
INL2=FREE()
*RETURN

ENDLPK

30
APPENDIX

ENDFDS UPDATE ALL MEMBRANE DESIGN VARIABLES
INIV=IEV
*LABEL 900
*JL2=1(IEV,901)
INIV=INIV=IEV
ITYP=DS,1,"NNIV",1(1,DVA,DFN,MASK,MASK)
ISECT=DS,4,"NNIV",1(1,DVA,DFN,MASK,MASK)
IUDVP=DS,1,"NNIV",1(1,LNK,DV,MASK,MASK)
IRR=DDVP
*DCALL(FO LP1)
*JUMP 900
*LABEL 901
ITYP=FREE()
IRR=FREE()
IDDVP=FREE()
INIV=FREE()
*RETURN
ENDFDS

ENDFDL

UPDATE MEMBRANE AND ROD ELEMENT PROPERTIES TO VALUE RR WHICH IS DETERMINED PREVIOUSLY
INTYP="TYP"
*JNZ=1(INTYP,1802)*TEST IF E23 ELEMENT
$SET ROD SECTION PROPERTIES
E23 SECTION PROPERTIES
"SECT" "RR"
*JUMP 1803
*LABEL 1802
INTYP="TYP"
*JNZ=2(INTYP,1804)*TEST IF E31 ELEMENT
$SET MEMBRANE SECTION PROPERTIES
SA
"SECT" "RR"
*JUMP 1803
*LABEL 1804
INTYP="TYP"
*JNZ=5(INTYP,1807)*TEST IF E41 ELEMENT
$SET MEMBRANE SECTION PROPERTIES
SA
"SECT" "RR"
*JUMP 1803
*LABEL 1807
INTYP="TYP"
*JNZ=8(INTYP,1810)*TEST IF E44 ELEMENT
$SET SHEATH PANEL PROPERTIES
SB
"SECT" "RR"
*JUMP 1803
*LABEL 1810
*EXIT
*LABEL 1803
*RETURN
ENDFDL

ENDFDP UPDATE ALL PLATE DESIGN VARIABLES
INIV=IEV
*LABEL 902
*JL2=1(IEV,903)
INIV=INIV=IEV
ITYP=DS,1,"NNIV",1(1,DVP,DFN,MASK,MASK)
ISECT=DS,4,"NNIV",1(1,DVP,DFN,MASK,MASK)
IUDVP=DS,1,"NNIV",1(1,LNK,DV,MASK,MASK)
IRR=DDVP
*DCALL(FO LP2)
*JUMP 902
*LABEL 903
INIV=FREE()
ITYP=FREE()
APPENDIX

I$ECT=FREE()
INRI V=FREE()
IDDV P=FREE()
IKR=F R E ()
RETURN $)
#(F D LP2) E NODP
#(I NTPy "TYP"
#(I2=3 (NTYP600) TEST IF E32 ELEMENT
#(I2=1(NTYP600) TEST IF E33 ELEMENT
#(I2=2 (NTYP600) TEST IF E42 ELEMENT
#(I2=1(NTYP600) TEST IF E43 ELEMENT
#X T Y P
#L A B E 500
#DCALL(SA TY P)
#RETURN $)
#(SA TY P) E NOSAT
S A
"S ECT" "RR"
RETURN $)
#(S E C T "RR"
#(AVP F DD) E N O D B$ U P D A T E ALL BEAM DESIGN V A R I A B L E S
$S E C L =0
$N I I V =1E V
#L A B E 904
#JLZ=1 (N I I V, 905)
$N I I V=N I I V=1E V
$N I I V=N I I V=1E V
$I D D V P=0 $S1, "N N I V", 111, L N K, D V, M A S K, M A S K)
$I R R=0 D V P
#U C A L L (B A T Y P2)
$J U M P 904
#L A B E 905
$S E L 1=FREE()
$N I I V=FREE()
$N I I V=FREE()
$S E C T=FREE()
$N I I V=FREE()
$I D D V P=FREE()
$I K R=FREE()
#E T A N
#E N O D B
$#(B A T Y P2) E N D B A 2$ U P D A T E S BEAM DESIGN V A R I A B L E S
$S E C L =S E C T=S E C 1
#(S E C 2=S E C 1, 1000)
#D 12=0 S, 26, 1, "S E C T" (1, B A, B T A B, M A S K, M A S K)
#D 13=0 S, 27, 1, "S E C T" (1, B A, B T A B, M A S K, M A S K)
#D 14=0 S, 29, 1, "S E C T" (1, B A, B T A B, M A S K, M A S K)
#D 15=0 S, 30, 1, "S E C T" (1, B A, B T A B, M A S K, M A S K)
#D 16=0 S, 31, 1, "S E C T" (1, B A, B T A B, M A S K, M A S K)
#D 17=0 S, 41, 1, "S E C T" (1, B A, B T A B, M A S K, M A S K)
#D 18=0 S, 51, 1, "S E C T" (1, B A, B T A B, M A S K, M A S K)
#D 19=0 S, 61, 1, "S E C T" (1, B A, B T A B, M A S K, M A S K)
#D 110=0 S, 71, 1, "S E C T" (1, B A, B T A B, M A S K, M A S K)
#D 111=0 S, 81, 1, "S E C T" (1, B A, B T A B, M A S K, M A S K)
#D 112=0 S, 91, 1, "S E C T" (1, B A, B T A B, M A S K, M A S K)
#D 113=0 S, 101, 1, "S E C T" (1, B A, B T A B, M A S K, M A S K)
#D 114=0 S, 111, 1, "S E C T" (1, B A, B T A B, M A S K, M A S K)
#D 115=0 S, 121, 1, "S E C T" (1, B A, B T A B, M A S K, M A S K)
#D 116=0 S, 131, 1, "S E C T" (1, B A, B T A B, M A S K, M A S K)
#D 117=0 S, 141, 1, "S E C T" (1, B A, B T A B, M A S K, M A S K)
#D 118=0 S, 151, 1, "S E C T" (1, B A, B T A B, M A S K, M A S K)
#D 119=0 S, 161, 1, "S E C T" (1, B A, B T A B, M A S K, M A S K)
APPENDIX

1D120=DS,18,1,"SECT"(1,BA,BTAB,MASK,MASK)
1D121=DS,19,1,"SECT"(1,BA,BTAB,MASK,MASK)
1D122=DS,20,1,"SECT"(1,BA,BTAB,MASK,MASK)
1D123=DS,21,1,"SECT"(1,BA,BTAB,MASK,MASK)
1D124=DS,22,1,"SECT"(1,BA,BTAB,MASK,MASK)
1D125=DS,23,1,"SECT"(1,BA,BTAB,MASK,MASK)
1D126=DS,24,1,"SECT"(1,BA,BTAB,MASK,MASK)
1D127=DS,25,1,"SECT"(1,BA,BTAB,MASK,MASK)
*LABEL 1000
*JUMP U1
*SHOW
*XQT TAB
UPDATE=1
1DBV1=DS,1,"NNIV",1,1,0,DFH,DFH,0,0
1DBV2=DS,5,"NNIV",1,1,0,DFH,DFH,0
*JNZ,-1(1DBV2,1001)
1D11=RR
*JUMP 1007
*LABEL 1001
*JNZ,-1(1DBV2,1002)
1D12=RR
*JUMP 1007
*LABEL 1002
*JNZ,-1(1DBV2,1003)
1D13=RR
*JUMP 1007
*LABEL 1003
*JNZ,-1(1DBV2,1004)
1D14=RR
*JUMP 1007
*LABEL 1004
*JNZ,-1(1DBV2,1005)
1D15=RR
1D16=106
*JUMP 1007
*LABEL 1005
*JNZ,-1(1DBV2,1006)
1D16=RR
*JUMP 1007
*LABEL 1006
*JNZ,-1(1DBV2,1030)
1D17=RR
*JUMP 1007
*LABEL 1030
*JNZ,-1(1DBV2,1031)
1D18=RR
*JUMP 1007
*LABEL 1031
*JNZ,-1(1DBV2,1032)
1D19=RR
*JUMP 1007
*LABEL 1032
*JNZ,-1(1DBV2,1033)
1D10=RR
*JUMP 1007
*LABEL 1033
*JNZ,-1(1DBV2,1034)
1D11=RR
*JUMP 1007
*LABEL 1034
*JNZ,-1(1DBV2,1035)
1D12=RR
*JUMP 1007
*LABEL 1035
*JNZ,-1(1DBV2,1036)
1D13=RR
*JUMP 1007
*LABEL 1036
*JNZ,-1(1DBV2,1037)
1D14=RR
*JUMP 1007
*LABEL 1037
*JNZ,-1(1DBV2,1038)
1D15=RR
*JUMP 1007
*LABEL 1038
APPENDIX

*JNZ, -1(DVB2, 1039)
ID110*RR
*JUMP 1007
*LABEL 1039
*JNZ, -1(DVB2, 1040)
ID117*RR
*JUMP 1007
*LABEL 1040
*JNZ, -1(DVB2, 1041)
ID110*RR
*JUMP 1007
*LABEL 1041
*JNZ, -1(DVB2, 1042)
ID110*RR
*JUMP 1007
*LABEL 1042
*JNZ, -1(DVB2, 1043)
ID120*RR
*JUMP 1007
*LABEL 1043
*JNZ, -1(DVB2, 1044)
ID120*RR
*JUMP 1007
*LABEL 1044
*JNZ, -1(DVB2, 1045)
ID120*RR
*JUMP 1007
*LABEL 1045
*JNZ, -1(DVB2, 1046)
ID123*RR
*JUMP 1007
*LABEL 1046
*JNZ, -1(DVB2, 1047)
ID124*RR
*JUMP 1007
*LABEL 1047
*JNZ, -1(DVB2, 1048)
ID125*RR
*JUMP 1007
*LABEL 1048
*JNZ, -1(DVB2, 1049)
ID126*RR
*JUMP 1007
*LABEL 1049
*JNZ, -1(DVB2, 1050)
ID127*RR
*JUMP 1007
*LABEL 1050
*XQT EXIT
*LABEL 1007
*JNZ, -1(DVB1, 1008)
*DCALL(TueE BEAM)
*JUMP 1016
*LABEL 1008
*JNZ, -1(DVB1, 1009)
*DCALL(BOX BEAM)
*JUMP 1016
*LABEL 1009
*JNZ, -1(DVB1, 1010)
*DCALL(TEE BEAM)
*JUMP 1016
*LABEL 1010
*JNZ, -1(DVB1, 1011)
*DCALL(ANG BEAM)
*JUMP 1016
*LABEL 1011
*JNZ, -1(DVB1, 1012)
*DCALL(WFL BEAM)
*JUMP 1016
*LABEL 1012
*JNZ, -1(DVB1, 1013)
*DCALL(CHN BEAM)
*JUMP 1016
*LABEL 1013
*JNZ, -1(DVB1, 1014)
*DCALL(ZEE BEAM)
*JUMP 1016
*LABEL 1014
APPENDIX

*JNZ,-1(DVB1,1015)
*DCALL(GIVN BEAM)
*JUMP 1016
*LABEL 1016
*JNZ,-1(DVB1,1020)
*DCALL(DS Y BEAM)
*JUMP 1016
*LABEL 1020
*XOT EXIT
*LABEL 1016
ISEC1="SECT"
ISEC2=FREE()
IDVB1=FREE()
IDVB2=FREE()
*RETURN

ENDBA2
$-----------------------------------------------
$ *(TUBE BEAM) ENDTUB$ SET TUBE SECTION PROPERTIES
BA TUBE "SECT","DI1","DI2"
*RETURN
*
ENDTUB

$-----------------------------------------------
$ *(BOX BEAM) ENDBOB$ SET BOX SECTION PROPERTIES
BA BOX "SECT","DI1","DI2","DI3","DI4"
*RETURN
*
ENDBOB

$-----------------------------------------------
$ *(TEE BEAM) ENDTEB$ SET TEE SECTION PROPERTIES
BA TEE "SECT","DI1","DI2","DI3","DI4"
*RETURN
*
ENDTEB

$-----------------------------------------------
$ *(ANG BEAM) ENDANB$ SET ANG SECTION PROPERTIES
BA ANG "SECT","DI1","DI2","DI3","DI4"
*RETURN
*
ENDANB

$-----------------------------------------------
$ *(WFL BEAM) ENDWFB$ SET WFL SECTION PROPERTIES
BA WFL "SECT","DI1","DI2","DI3","DI4","DI5","DI6"
*RETURN
*
ENDWFB

$-----------------------------------------------
$ *(CHN BEAM) ENDCBH$ SET CHN SECTION PROPERTIES
BA CHN "SECT","DI1","DI2","DI3","DI4","DI5","DI6"
*RETURN
*
ENDCHB

$-----------------------------------------------
$ *(ZEE BEAM) ENDZEB$ SET ZEE SECTION PROPERTIES
BA ZEE "SECT","DI1","DI2","DI3","DI4","DI5","DI6"
*RETURN
*
ENDZEB

$-----------------------------------------------
$ *(GIVN BEAM) ENDGVP$ SET GIVN SECTION PROPERTIES
BA
GIVN "SECT","DI17","DI18","DI19","DI10","DI11","DI12","DI13","DI14","DI15","DI16"
*RETURN
* ENDSV8
$ $----------------------------------------------$ $ *(DSY Beam) ENDSY
BA DSY "SECT","DI17","DI18","DI19","DI10","DI11","DI12","DI13","DI17","DI19","DI20","DI21","DI22","DI23","DI24","DI25","DI16","DI15"
*RETURN
* $ $----------------------------------------------$ $ *(EFIL JCUB) ENDEDU
*XGT DCU
*JZ(DE21,8010)
DISABLE 1 E21 EFIL MASK MASK
CHANGE 1 EE21 EEIL 1 "IIIV",E21 EFIL 1 2
*LABEL 8010
*JZ(DE23,8011)
DISABLE 1 E23 EFIL MASK MASK
CHANGE 1 EE23 EEIL 3 "IIIV",E23 EFIL 3 2
*LABEL 8011
*JZ(DE31,8012)
DISABLE 1 E31 EFIL MASK MASK
CHANGE 1 EE31 EEIL 6 "IIIV",E31 EFIL 6 3
*LABEL 8012
*JZ(DE32,8013)
DISABLE 1 E32 EFIL MASK MASK
CHANGE 1 EE32 EEIL 7 "IIIV",E32 EFIL 7 3
*LABEL 8013
*JZ(DE33,8014)
DISABLE 1 E33 EFIL MASK MASK
CHANGE 1 EE33 EEIL 8 "IIIV",E33 EFIL 8 3
*LABEL 8014
*JZ(DE41,8015)
DISABLE 1 E41 EFIL MASK MASK
CHANGE 1 EE41 EEIL 9 "IIIV",E41 EFIL 9 4
*LABEL 8015
*JZ(DE42,8016)
DISABLE 1 E42 EFIL MASK MASK
CHANGE 1 EE42 EEIL 10 "IIIV",E42 EFIL 10 4
*LABEL 8016
*JZ(DE43,8017)
DISABLE 1 E43 EFIL MASK MASK
CHANGE 1 EE43 EEIL 11 "IIIV",E43 EFIL 11 4
*LABEL 8017
*JZ(DE44,8018)
DISABLE 1 E44 EFIL MASK MASK
CHANGE 1 EE44 EEIL 12 "IIIV",E44 EFIL 12 4
*LABEL 8018
*RETURN
* $ $----------------------------------------------$ $ *(DCU EFIL) ENDEDE
*XGT DCU
*JZ(DE21,8000)
CHANGE 1 EE21 EFIL 2,EE21 EEIL 1 "IIIV"
*LABEL 8000
*JZ(DE23,8001)
CHANGE 1 EE23 EFIL 3 2,EE23 EEIL 3 "IIIV"
*LABEL 8001
*JZ(DE31,8002)
CHANGE 1 EE31 EFIL 6 3,EE31 EEIL 6 "IIIV"
*LABEL 8002
*JZ(DE32,8003)
CHANGE 1 EE32 EFIL 7 3,EE32 EEIL 7 "IIIV"
*LABEL 8003
*JZ(DE33,8004)
CHANGE 1 EE33 EFIL 8 3,EE33 EEIL 8 "IIIV"
*LABEL 8004
*JZ(DE41,8005)
APPENDIX

CHANGE 1 E41 EFIL 9,EE41 EEIL 9 "IIV"
*LABEL 8005
*JZ(DE42>8006)
CHANGE 1 E42 EFIL 10,EE42 EEIL 10 "IIV"
*LABEL 8006
*JZ(DE43>8007)
CHANGE 1 E43 EFIL 11,EE43 EEIL 11 "IIV"
*LABEL 8007
*JZ(DE44>8008)
CHANGE 1 E44 EFIL 12,EE44 EEIL 12 "IIV"
*LABEL 8008
*RETURN

ENDDEL

$--------------------------------------------------------------- 16$
$$(STRS DERV)$$
$$CALCULATE STRESS DERIVATIVES
IIE1=NLST$LOOP OVER LOAD SETS
*LABEL 2102
*JLZ=-1(II1,2103)
INIE1=NLST-IE1$LOAD SET NUMBER
IIEV=NDV
IIS=0
IISS=0
*LABEL 2100
*JLZ=-1(IIEV,2101)$LOOP OVER DESIGN VARIABLES
IIIV=NDV-IIEV
DVPS=JS,1,"IIIV",II1,DESV,CNMN,MASK,MASK
*DCALL(EFIL DCU)
*DELV=DVPS
*AQ=1,0/DELV
IBQ=-1,*AQ
INCA=LCAS$ LOOP OVER LOAD CASES
*LABEL 3000
*JLZ=-1(INCA,3001)
*XQT AUS
INCAS=LCAS-NCA
IN1=IIV*LCAS-LCAS+NCAS
DEFINE U1=PREV DISP "NIE1" 1 "NCAS","NCAS"
DEFINE U2=DU1V CAPV "NIE1" 1 "N11","N11"
*JGI(IS,3025)
U DELU "NIE1" 1 $SUM(U1, "DELV" U2)
IIS=IIS+1
*JUMP 3026
*LABEL 3026
DEFINE TEMP=U DELU "NIE1" 1
DU=$SUM(U1, "DELV" U2)
UDEL TMP=UNIONTEMP,DU
*XQT DCU
CHANGE 1 UDEL TMP 1,0 DELU "NIE1" 1
*LABEL 3026
*JUMP 3000
*LABEL 3001
INAM1="U"
INAM2="DELU"
INAM3="NIE1"
INAM4="MASK"
*DCALL(CALC STRS)
IIS=0
I1SS=ISS+1
*DCALL(DCU EFIL)
*JUMP 2100
*LABEL 2101
IIIV=FREE()
IIEV=FREE()
IIIV=FREE()
INCA=FREE()
IN1=FREE()
IIIV=FREE()
INCA=FREE()
INAM1=FREE()
INAM2=FREE()
INAM3=FREE()
INAM4=FREE()
*XQT AUS
OUTLIB=1
*JZ(DE21>2104)

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APPENDIX

IE=NE21
INAM5=IE21
*DCALL(OSIG EIJ)
*LABEL 2104
*JZ(DE23,2105)
IE=DE23
INAM5=IE23
*DCALL(OSIG EIJ)
*LABEL 2105
*JZ(DE31,2106)
IE=DE31
INAM5=IE31
*DCALL(OSIG EIJ)
*LABEL 2106
*JZ(DE32,2107)
IE=DE32
INAM5=IE32
*DCALL(OSIG EIJ)
*LABEL 2108
*JZ(DE41,2109)
IE=DE41
INAM5=IE41
*DCALL(OSIG EIJ)
*LABEL 2109
*JZ(DE42,2110)
IE=DE42
INAM5=IE42
*DCALL(OSIG EIJ)
*LABEL 2110
*JZ(DE43,2111)
IE=DE43
INAM5=IE43
*DCALL(OSIG EIJ)
*LABEL 2111
*JZ(DE44,2112)
IE=DE44
INAM5=IE44
*DCALL(OSIG EIJ)
*LABEL 2112
JUMP 2102
*LABEL 2103
NIE1=FREE()
NIE2=FREE()
NIE3=FREE()
INAM5=FREE()
*RETURN

ENDSTD

$---------------------------------------------------------------------$
$*(CALC STRS) ENDCCS$
$$ ** CALCULATES STRESSES OF DESIGN VARIABLES IN**$
$$ ** ES FORMAT TO BE USED IN STRESS DERIVATIVE**$
$$ ** AND CONSTRAINT CALCULATIONS.$$
$$**$$
**OUTL= "Oolib"**$
**U= "NAM1" "NAM2" "NAM3" "NAM4"**$
PNUDE= 2
NDDES= 0
*JZ(NE21,2500)
IE=NE21
INAM5=IE21
*DCALL(STRS GRP)
*LABEL 2500
*JZ(DE23,2501)
IE=DE23
INAM5=IE23
*DCALL(STRS GRP)
*LABEL 2501
*JZ(DE31,2502)
IE=DE31
INAM5=IE31
APPENDIX

*DCALL (STRS GRP)
*LABEL 2502
*JZ(DE32, 2503)
  IE=DE32
  INAM5=IE32
*DCALL (STRS GRP)
*LABEL 2503
*JZ(DE33, 2504)
  IE=DE33
  INAM5=IE33
*DCALL (STRS GRP)
*LABEL 2504
*JZ(DE41, 2505)
  IE=DE41
  INAM5=IE41
*DCALL (STRS GRP)
*LABEL 2505
*JZ(DE42, 2506)
  IE=DE42
  INAM5=IE42
*DCALL (STRS GRP)
*LABEL 2506
*JZ(DE43, 2507)
  IE=DE43
  INAM5=IE43
*DCALL (STRS GRP)
*LABEL 2507
*JZ(DE44, 2508)
  IE=DE44
  INAM5=IE44
*DCALL (STRS GRP)
*LABEL 2508
*DCALL (CAL STRS)
  IE=FREE()
  INAM5=FREE()
*RETURN
*
ENDCCS

*CAL (STRS)
ENDCALL

*JZ(NE21, 2500)
  IE=NE21
  INAM5=NE21
*DCALL (STRS CALC)
*LABEL 2500
*JZ(DE23, 2501)
  IE=DE23
  INAM5=DE23
*UCALL (STRS CALC)
*LABEL 2501
*JZ(DE31, 2502)
  IE=DE31
  INAM5=DE31
*DCALL (STRS CALC)
*LABEL 2502
*JZ(DE32, 2503)
  IE=DE32
  INAM5=DE32
*UCALL (STRS CALC)
*LABEL 2503
*JZ(DE33, 2504)
  IE=DE33
  INAM5=DE33
*UCALL (STRS CALC)
*LABEL 2504
*JZ(DE41, 2505)
  IE=DE41
  INAM5=DE41
*DCALL (STRS CALC)
*LABEL 2505
*JZ(DE42, 2506)
  IE=DE42
  INAM5=DE42
*DCALL (STRS CALC)
*LABEL 2506
*JZ(DE43, 2507)
  IE=DE43

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APPENDIX

INAM5='E43
@DCALL(STRS CALC)
@LABEL 2507
@JZ(IE43,2508)
IE='E44
INAM5='E44
@DCALL(STRS CALC)
@LABEL 2508
IE='FREE()
INAM5='FREE()
*RETURN
*
ENDCALL
$
$------------------------------------------------------------$
$ (STRS CALC)   ENDS
INAMJ=IE
@LABEL 2500
@JZ=1(INAMJ,2501)
IV=IE-NAMJ
@DCALL(STRS BLD)
@JUMP 2500
@LABEL 2501
INAMJ=IE
@LABEL 2500
@JZ=-1(INAMJ,2601)
IV=IE-NAMJ
@DCALL(INCHG NAME)
@JUMP 2600
@LABEL 2601
INAMJ='FREE()
IV='FREE()
*RETURN
*
ENDS
$
$------------------------------------------------------------$
$ (STRS BLD)   STRS8
@JLZ(IN11,5000)
@XQT AUS
INLIB='OLIB'
OUTLIB='OLIB'
$ISS
$IN11
$10LIB
$INAM5
$INIE1
$1ISS
$IV
DEFINE ENEW='OLIB' ES 'NAM5' 'NIE1' 'IV'
$ENEW='UNION(ETMP)
@JZ(155,2202)
'DEFINE EOLD='OLIB' EST 'NAM5' 'NIE1' 'IV'
$EOLD='UNION(ESSL)
EST 'NAM5' 'NIE1' 'IV' = UNION(EOLD,ENEW)
@XQT DCU
CHANGE 'OLIB' EST 'NAM5' 'NIE1' 'IV'
,EST 'NAM5' 'NIE1' 'IV'
$ TUC 'OLIB'
$PRINT 'OLIB' EST 'NAM5' 'NIE1' 'IV'
@JUMP 3001
@LABEL 2202
EST 'NAM5' 'NIE1' 'IV' = UNION(ENEW)
@XQT DCU
$ TUC 'OLIB'
$PRINT 'OLIB' EST 'NAM5' 'NIE1' 'IV'
@LABEL 3001
@LABEL 5000
*RETURN
*
STRS8
$------------------------------------------------------------$
$ (STRS GRP)   ENDRP
INAMJ=IE
@LABEL 1000
@JZ=-1(INAMJ,1001)
IV=IE-NAMJ
"NAM5" "IV"

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APPENDIX

*JUMP 1000
*LABEL 1001
*RETURN

ENDGRP

*CHNG NAME)
NII
*JLI(NII,5000)
III
III
*JLI(IIIV,3000)
JUMP 5000
*LABEL 3000
*QXT DCU
CHANGE "QLIB" EST "NAM5" "NIE1" "IV",ES "NAM5" "NIE1" "IV"
*LABEL 5000
*RETURN

ECHG

*DSIG EIJ)
ENDSG

SUBPROGRAM USED TO CALCULATE STRESS DERIVATIVES
USING PRASAD'S METHOD

IIIE2=IE
*LABEL 2200
*JL2=1(IIIE2,2201)$LDP OVER GROUPS
INN1=1
IIIV=1E2-IE$GRUP NUMBER
IIIV=NDV
*LABEL 2100
*JL2=1(IIIV,2101)$LDP OVER DESIGN VARIABLES
IIIV=NDV-IIIV
IDVP=DS1,"IV",1(1,DESV,CNNN,MA$K,MA$K)
IDELV=DRDV
IAQ=1,JDELV
IBG=1,*AQ
INCA=LCASA LOOP OVER LOAD CASES
*LABEL 3000
*QXT AUS
*JL2=1(NCA,3001)
INCAS=LCASA-NCAS 
INII=IIIV*LCASA=LCASA+NCAS
*XQ$ AUS
DEFINE STRP=1 ES "NAM5" "NIE1" "IV" "NCAS","NCAS"
DEFINE STRN="QLIB" ES "NAM5" "NIE1" "IV" "NII","NII"
BAIL=SUM("AQ" STRN,"BQ" STRP)
**QXT DCU
$ TOC 1
**PRINT 1 B81 MASK MASK MASK
**QXT AUS
*JL2=1(INN1,2202)
INN1=NN1+1
DEFINE DS$=DSIG "NAM5" "NIE1" "IV"
$DSG=UNION(DS$)
$DSG=UNION(DSG,B81)
DTPM "NAM5" "NIE1" "IV"=UNION(DSG,B81)
*XQ$ DCU
CHANGE 1 DTPM "NAM5" "NIE1" "IV",DSIG "NAM5" "NIE1" "IV"
$ TOC 1
**PRINT 1 DSIG "NAM5" "NIE1" "IV"
**QXT AUS
*JUMP 3000
*LABEL 2202
INN1=NN1+3
DSIG "NAM5" "NIE1" "IV"=UNION(B81)
**QXT DCU
$ TOC 1
**PRINT 1 DSIG "NAM5" "NIE1" "IV"
**QXT AUS
*JUMP 3000
*LABEL 3001
*JUMP 2100
*LABEL 2101
*JUMP 2200
*LABEL 2001

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APPENDIX

II2=FREE()  
IIV=FREE()  
III=FREE()  
IIIE=FREE()  
INCA=FREE()  
IN1=FREE()  
INCA=FREE()  
*RETURN  
  ENDOSG  
$  
$------------------------------------------------------------  17  
$  
*(*ELS METH)  
ENDNM  
$%  
$% CALCULATES DERIVATIVES OF VIB. OR BUCK. MODES  
$% AND/OR LOADS ANALYTICALLY.  
*OCALL(BOND CONO)  
IJDF=DS,2,1,11,JDF1,BTAB,1,6  
INMD=MODE  
IT1=EQAL(NAM9,MDE1)  
IT2=EQAL(NAM9,MDE2)  
*XQT AUS  
INNDV=NNDV  
*LABEL 4109  
*JLZ=-1(NNDV,4108)  
II=IDV=NNDV  
TABLE(NJ=1,NI="MODE")=DIAG "NAM9" 1 "IDV"  
1=1;J=110.  
*JUMP 4109  
*LABEL 4100  
*LABEL 2010  
*JLZ=-1(NNDV,2000)$LOOP ON MODES  
INM=MODE-NNMD  
IN1=NM  
INMD=DS,1,"NM",11,MODE,NUM,MASK,MASK  
II=SKIP=MOT-MODN  
I=BASE=MODN-1  
$ FIND EIGENVALUE  
*XQT AUS  
DEFINE L=PREV "NAM7" 1 1  
TABLE(NJ=1,NI=11)=LAM1 AUS 1 1  
TRANSGS=SOURCE,L,BASE="IDV",ILIM=1,SKIP="ISK"  
*XQT U1  
LAMM=DS,1,1,11,LAM1,AUS,1,1  
LAMMM=S*LAMM  
*XQT AUS  
DEFINE PP=PREV "NAM7" 1 1  
MODN="MODN"  
PHI=UNION(1.0 PP)  
*XQT DCU  
PRINT 1 PHI  
*XQT AUS  
*JZ(TI1<100)  
LDE=DIAG 0=UNION("LAMM"
DMP)  
DEFINE LDEM=LDE=DIAG  
ASP SPAR=SUM(KP,=-1.0 LDEM)  
*LABEL 4100  
*JZ(TI2<101)  
LAMMM=S*LAMM  
LDE=DIAG 0=SUM("LAMM" KGP,"LAMM" KGP)  
ASP SPAR=SUM(KP,0.0 LDEM)  
*LABEL 4101  
PONE=UNION("LAMM" PHI)  
INNDV=NNDV  
*LABEL 2006  
*JLZ=-1(NNDV,2001)$LOOP OVER DESIGN VARIABLES  
II=IDV=NNDV  
IJDF=DS,2,1,11,JDF1,BTAB,1,6  
INDF=JDF1,JDF  
*JZ(TI1<2003)  
DEFINE DM=OMD=DIAG 0 "IDV"  
*LABEL 2003  
*JZ(TI2<2004)  
DEFINE DM=OKG SPAR "NDF" "IDV"  
*LABEL 2004  
DEFINE OK=OKD=SPAR "NDF" "IDV"  
PTWO=PROD(DM,PONE)  
PTRI=PRODI(KP,PHI)  
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APPENDIX

PFOR=XTYD(PHI, PTR1)
PFIV=XTYD(PHI, PTWQ)
*JZ(TTI, 4500)
PSIX=SUM(PFOR, -1, PFIV)
*LABEL 4500
*JZ(TT2, 4501)
PSIX=SUM(1, PFOR, 1, PFIV)
*LABEL 4501
EDER DIAG "MODN" "IDV" = UNION(1,0, PSIX)
EDEDG=DS;i, j, 1(1,EDER, DIAG,"MODN","IDV")
TABLE=NJ, N="MODE");; DV, VAL "NAM9" 1 "IDV"
OPERATION=SUM
I="MODN"; J=1 "EDDG"
$SEV=UNION("EDDG" PHI)
*JZ(TTI, 4102)
PATE=PROD(1, PSEE)
*LABEL 4102
*JZ(TT2, 4103)
PATE=PROD(-1, KGP, PSEE)
*LABEL 4103
PHIN=SUM(PATE, -1, PTR1)
*JZ(TT1, 4600)
P LOAD "IDV" = SUM(PHIN, PTWQ)
*LABEL 4600
*JZ(TT2, 4601)
P LOAD "IDV" = SUM(PHIN, -1, PTWQ)
*LABEL 4601
INIDV=IDV
DEFINE P1=P LOAD "IDV"
*JNZ,-1(NIDV, 2005)
TMP1=UNION(1,0, P1)
*JUMP 2007
*LABEL 2005
SUM1=UNION(TMP1, P1)
TMP1=UNION(1,0, SUM1)
*LABEL 2007
*JZ(TTI, 4110)
*XRT AUS
*LABEL 4110
*JUMP 2006
*LABEL 2001
APPL FORC 3, 1=UNION(1.0, TMP1)
*JGZ,-1(NM1, 2013)
*LABEL 2013
IJOF=DS;i, j, 1(1, IJOFL, BTAB, 1, 8)
DEFINE XXL=PREV "NAM8" 1 1 "MODN", MODN
I=MNX XXL
IZ1=GS;i, j, 1(1, Z* AUS, MASK, MASK)
IZ4=Z1/"IJOF"+1
TABLE=N1, N=1, IZZ4
J=I, "ZZ"*4
IZ3=IFIX(IZ4)
INJNT=DS;i, j, 1(1, ZZ5, AUS, MASK, MASK)
IZ3=GS;i, j, 1(1, IJOFL, BTAB, 1, 8)
INJN1=INJNT-1
IRR=IJOFL*INJN1
ITDEG=Z1-RRR
INDEG=IFIX(TITDEG)
IJOF=DS;i, 1("NDEG"; I1, IN, EX, MASK, MASK)
#CALL (BGN0, COND)
ZERO "NDEG"; "INJNT"
*XRT RSI
RESET K=ASP
*XRT SSL
RESET K=ASP
RESET SET=3
INMIV=NNDV
*LABEL 2009
*JZ(-1(NNNDV, 2008)
IIDV=NNDV=NNNDV
*XRT AUS
DEFINE VDER=STAT DISP 3; 1 "IDV", "IDV"
DEFINE F=APPL FORC 3; 1 "IDV"; "IDV"
F=UNION(F)
VDER=UNION(VDER)
*JZ(TTI, 4105)
APPENDIX

TONE=PR0D(UEMP,VDER)
DEFINE DM=MD0V DIAG O "IDV"
*LABEL 4105
*JZ(TT2+106)
TONE=PR0D(KGP,VDER)
DEFINE DM=UKG SPAR "NDF" "IDV"
*LABEL 4106
TND=XTY0(PHI=+TONE)
TTR1=PK0D(DM,PHI)
TFORD=XTY0(PHI=O.3 TTR1)
*JZ(TT1+108)
CEE=SUM(-1, TTW0-1, TFORD)
*LABEL 4108
*JZ(TT2+109)
CEE=SUM(TTW0, TFORD)
*LABEL 4109
*XOT U1
ICCE=DS(1,111,CEE,MASK,MAK,S,MASSK)
*XOT AUS
TFIV=UNIon("CEE", PHU)
DM0D "NAME" "MODN" "IDV"=SUM(VDER,TFIV)
GGG=PRAV(ASP,DM0D "NAME" "MODN" "IDV")
GRG=SUM(XNW=-1, GGG)
*XOT AUS
*JUMP 2009
*LABEL 2008
INNM=NM
*JNZ=-I(INNM,2010)
*JUMP 2010
*LABEL 2000
INM=FREE()
INM=FREE()
INNM=FREE()
IJ0D=FREE()
ILDP=FREE()
I1DP=FREE()
I2DP=FREE()
I3DP=FREE()
I4DP=FREE()
I5DP=FREE()
I6DP=FREE()
INNDV=FREE()
INNDV=FREE()
INNDV=FREE()
INNDV=FREE()
INNDV=FREE()
INNDV=FREE()
INNDV=FREE()
*RETURN
* ENNDNM

$----------------------------------------
* (BOND COND) ENDBCO
*XOT TAB
CON=1
ZERO 1,2,3,4,5,65,1,2
ZERO 1,2,4,5,6515,16
*RETURN
* ENDBCO

$---------------------------------------- 18
$ *
* (NELS MET2) ENDL2
$$ $$ CALCULATE DERIVATIVES OF $$ $$ $Buckling or vibration loads analytically.$
*CALL (BOND COND)
IJDF=DS(2,5,1,I,JDF1,STAB,1,8)
INNM=MODE
*XOT AUS
INN0V=MODE
*LABEL 4111
*JLP=-I(INNDV,4110)
IDV=NOIV-N0IV
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APPENDIX

TABLE(NJ=1,N1="MODE");DVAL "NAM9" 1 "IDV"  
  I=1;J=1;0.  
  *JUMP 4111  
  *LABEL 4110  
  ITTI=EQUAL(NAM9,MDE1)  
  ITTZ=EQUAL(NAM9,MDE2)  
  *LABEL 2801  
  *JLZ=-1(NAM9,2800)  
  SKIP ON MODES  
  INM=MODE-NNHD  
  INML1=NM  
  MODN=DS,1,"NM",11,MODE,NUM,MASK,MASK  
  ISKPN=MODE-NNHD  
  IBSE=MODN-1  
  $  
  FIND EIGENVALUE  
  *XQT AUS  
  DEFINE L=PREV "NAM7" 1 1  
  TABLE(NJ=1,NJ=1);LAM1 AUS 1 1  
  TRANS(SOURCE=L,SBASE="IBSE",ILIM=1,SSKIP="ISKN")  
  *XQT U1  
  LAMN=LAMM+0.1,1(1,LAM1,AUS,1,1)  
  LAMN=LAMM+0.5  
  *XQT AUS  
  DEFINE PP=PREV "NAM8" 1 1 "MODN","MODN"  
  PHI=UNION(1.0 PP)  
  *JZ(ITT1,4000)  
  LDEM DIAG 0 0=UNION("LAMM","DEMP")  
  ASP SPAR=SUM(KP,-1. LDEM)  
  *LABEL 4000  
  *JZ(ITT2,4001)  
  LDEM DIAG 0 0=SUM("LAMM","KGP","LAMN","KGP")  
  ASP SPAR=SUM(KP,LDEM)  
  *LABEL 4001  
  PONE=UNION("LAMM","PHI")  
  INDV=NNDV  
  *LABEL 2806  
  *JLZ=-1(INDV,2801)  
  IIDV=NNDV-INDV  
  JDF=DS,2,1,1(1,JDF,GTAB,1,8)  
  INDV=JDF-JDF  
  *JZ(ITT1,2803)  
  DEFINE DM=MODV DIAG 0 "IDV"  
  *LABEL 2803  
  *JZ(ITT2,2804)  
  DEFINE DM=DKG SPAR "NDF" "IDV"  
  *LABEL 2804  
  DEFINE DK=DOKV SPAR "NDF" "IDV"  
  PTWO=PRIJ(DM,PONE)  
  PFI=PRIJ(DK,PHI)  
  PFD=XYD(PHI,PFI)  
  PFIV=XYD(PHI,PTWO)  
  *JZ(ITT1,4400)  
  PSIX=SUM(PFIV,-1. PFIV)  
  *LABEL 4400  
  *JZ(ITT2,4401)  
  PSIX=SUM(PFIV,PFIV)  
  *LABEL 4401  
  EDER DIAG "MODN","IDV"=UNION(1.0 PSIX)  
  IEDG=DS,1,1,1(1,EDER,DIAG="MODN","IDV")  
  TABLE(NJ=1,NI="MODE");DVAL "NAM9" 1 "IDV"  
  UPKATION=SUM  
  I="MODN";J=1;1;"EDDG"  
  *JUMP 2806  
  *LABEL 2807  
  INM=FREE()  
  INM1=FREE()  
  INDV=FREE()  
  MODN=FREE()  
  IBSE=FREE()  
  ILAMM=FREE()  
  IIDV=FREE()  
  INDV=FREE()  
  ITTI=FREE()  
  ITTZ=FREE()  
  IN5=FREE()  
  *JUMP 2801  
  *LABEL 2800  
  *LABEL 2807  
  *RETURN  
  ENDNLZ
This runstream has been deleted.

This runstream has been deleted.
APPENDIX

*DCALL(PRINT OSIG)
*LABEL 3111
*JZ(DED44,3112)
  IIE=DE44
  INAM5=DE44
*DCALL(PRINT OSIG)
*LABEL 3112
  IIE1=FREE()
  INIE1=FREE()
  IN1=FREE()
  INAM5=FREE()
*RETURN
  ENDPS
*
$---------------------------------------------$
$*(PRINT OSIG)  ENDPS$
  IIE2=IE
*LABEL 3113
*JLZ=-1(IE,3114)$ LOOP OVER GROUP NUMBER
  IIV=IE2=IE$GROUP NUMBER
  IIE1=NLST$ LOOP OVER LOAD SETS
*LABEL 3102
*JLZ=-1(IE1,3103)$LOAD SET NUMBER
  INIE1=NLST-IE1
  PRINT 1 OSIG "NAM5" "NIE1" "IV"
  JUMP 3102
*LABEL 3103
*JUMP 3113
*LABEL 3114
*RETURN
  ENDPS
$
$---------------------------------------------$
$*(PRINT OSIG)  ENDPS$
  IIE2=IE
*LABEL 3120
*JLZ=-1(NI1,3121)$ LOOP OVER DESIGN VARIABLES
  IIV=NDV=N1%DESIGN VARIABLE NUMBER
  INMD=MODE
*LABEL 3122
  ITT1=EQUAL(NAM9,MDE1)
  ITT2=EQUAL(NAM9,MDE2)
*JZ(ITT1,3125)
  IN1=VBD
  JZ=2(N1,3123)
*LABEL 3125
*JZ(ITT2,3126)
  IN1=UCD
  JZ=2(N1,3123)
*LABEL 3126
*JLZ=-1(NMD,3123)$ LOOP OVER MODES
  INM=MODE-NMD
  IMOD%DS,NM,M1,MODE,NUM,MASK,MASK$MODE NUMBER
  PRINT 1 OADD "NAM9" "MODN" "IV"
  JUMP 3126
*LABEL 3123
  ITT1=EQUAL(NAM9,MDE1)
  ITT2=EQUAL(NAM9,MDE2)
*JZ(ITT1,3127)
  IN1=VBD
  JZ=2(N1,3120)
*LABEL 3127
*JZ(ITT2,3128)
  IN1=UCD
  JZ=2(N1,3120)
*LABEL 3128
  PRINT 1 OADD "NAM9" 1 "IV"
  JUMP 3120
*LABEL 3120
  IN1=FREE()
  IV=FREE()
  ITT1=FREE()
  ITT2=FREE()
  IN1=FREE()
  IN1=FREE()
APPENDIX

IN#FREE()
IN#ODN=FREE()
*RETURN
  ENDPMO
$
$--------------------------------------------------------------- 21
$
*OCALL(DRV GRD4)
*XQ EXIT
REFERENCES


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<tr>
<th>Processor name</th>
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<td>TAB</td>
<td>Creates data sets containing tables of joint locations, section properties, material constants, and so forth</td>
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<tr>
<td>ELD</td>
<td>Defines the finite-element connections in model</td>
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<tr>
<td>E</td>
<td>Generates sets of information for each element, including connected joint numbers, geometrical data, material, and section property data</td>
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<td>EKS</td>
<td>Adds the stiffness and stress matrices for each element to the set of information produced by the E processor</td>
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<tr>
<td>SEQ</td>
<td>Determines joint sequences, i.e., equation numbering sequences to be used in sparse matrix solution methods</td>
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<tr>
<td>TOPO</td>
<td>Analyzes element interconnections and topology and creates data sets used to assemble and factor the system mass and stiffness matrices</td>
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<td>K</td>
<td>Assembles the unconstrained system stiffness matrix in a sparse matrix format</td>
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<tr>
<td>M</td>
<td>Assembles the unconstrained system mass matrix in a sparse matrix format</td>
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<tr>
<td>KG</td>
<td>Assembles the unconstrained system initial-stress (geometric stiffness) matrix in a sparse matrix format</td>
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<td>INV</td>
<td>Factors the assembled system matrices</td>
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<tr>
<td>RSI</td>
<td>Similar to INV</td>
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<tr>
<td>DRSI</td>
<td>Similar to RSI; factors double precision SPAR format matrices</td>
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<tr>
<td>EQNF</td>
<td>Computes equivalent joint loading associated with thermal, dislocational, and pressure loading</td>
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<tr>
<td>SSOL</td>
<td>Computes displacements and reactions due to applied loading at the joints</td>
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<td>Similar to TOPO</td>
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<td>LSK</td>
<td>Forms partial or complete system stiffness (K) and damping (D) matrices in a sparse matrix form called LS-format</td>
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<td>LSU,RMK</td>
<td>Translates arbitrary source K and M data into LS- or SPAR-format and transforms SPAR- and LS-format matrices</td>
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<td>GSF</td>
<td>Generates element stresses and internal loads</td>
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<td>Prints the information generated by the GSF processor</td>
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<td>Analyzes element interior state, given joint displacements, and initial strains, if present; creates and stores stresses and internal load data</td>
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<tr>
<td>EIG</td>
<td>Solves linear vibration and bifurcation buckling eigenproblems</td>
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<td>E4</td>
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<tr>
<td>SYN</td>
<td>Produces mass and stiffness matrices for systems comprised of interconnected substructures</td>
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<tr>
<td>STRP</td>
<td>Computes eigenvalues and eigenvectors of substructured systems</td>
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<tr>
<td>SSBT</td>
<td>Back-transforms synthesized system results into individual substructure terms used in conjunction with SYN and STRP</td>
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<tr>
<td>AUS</td>
<td>Performs matrix arithmetic functions and is used in construction, editing, and modification of data sets</td>
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<tr>
<td>DCU</td>
<td>Performs data management functions including display of table of contents, data transfer between libraries, changing data set names, printing data sets, and transferring data between libraries and sequential files</td>
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<tr>
<td>VPRT</td>
<td>Performs editing and printing of data sets which are in the form of vectors on the data libraries</td>
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<tr>
<td>PLTA, PLTB, PXY</td>
<td>Produce graphic displays of finite-element models and computed results such as vibration and buckling modes, stresses, and response histories</td>
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<tr>
<td>PR</td>
<td>Generates reports of dynamic response analysis</td>
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<td>DR</td>
<td>Computes linear transient modal response and back-transforms to determine any required system response details and maximum-minimum and time-of-occurrence data</td>
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<td>U1</td>
<td>Creates, edits, and manipulates runstreams and permits direct table input</td>
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<td>Produces tabular multipage reports, using formats, headings, and footnotes prescribed by the user at execution time</td>
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<td>Enables vector arithmetic functions</td>
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<td>FSM</td>
<td>Creates SPAR-format matrices for compressible fluid elements</td>
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<td>Prints SPAR-format matrices and factored system matrices produced by RSI or DRSI</td>
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<td>Utility processor which operates on element state information</td>
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<td>Prints contents of the element state</td>
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<td>E32, E42</td>
<td>Triangular and quadrilateral uncoupled (bending only) plate elements, respectively</td>
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<td>E33, E43</td>
<td>Triangular and quadrilateral coupled (membrane and bending) plate elements, respectively</td>
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<td>Shear panel element</td>
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## TABLE 3.- NODAL COORDINATES FOR SWEPT WING

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### TABLE 5. - LOAD DATA FOR SWEPT WING

\[ f_x = 0 \text{ and } f_y = 0 \]

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<th>Node</th>
<th>( f_z' ) lb</th>
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TABLE 6.- SUMMARY OF SENSITIVITY ANALYSIS FOR SWEPT WING

(88 nodes; 194 elements; 2 load conditions; 32 design variables; 164 degrees of freedom)

(a) Convergence for displacement derivatives

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<th>Error,(^a) percent for -</th>
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\(^a\)Relative to analytical method.

(b) Solution time for displacement derivatives

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<tr>
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</table>
TABLE 7.- SUMMARY OF SENSITIVITY ANALYSIS FOR BOX BEAM

28 nodes; 77 elements; 1 load condition; 9 independent
design variables; 10 dependent design variables;
122 degrees of freedom

(a) Solution time comparison

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(b) Typical values of derivatives

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TABLE 8.— NODAL COORDINATES FOR STIFFENED CYLINDER
TABLE 9.- SUMMARY OF SENSITIVITY ANALYSIS FOR STIFFENED CYLINDER WITH A CUTOUT

80 nodes; 190 elements; 1 load condition; 3 independent design variables; 5 dependent design variables; 352 degrees of freedom

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TABLE 11.- THERMAL LOADING ON RADIOMETER ANTENNA

[Values are given relative to 80°F reference temperature]

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TABLE 12.—SUMMARY OF ANTENNA REFLECTOR SENSITIVITY ANALYSIS

[109 nodes; 420 elements; 1 load condition; 3 design variables]

(a) Solution time comparison

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<th>Method</th>
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<tr>
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<td>Displacement</td>
<td>Stress</td>
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<td>Finite difference</td>
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(b) Comparison of derivatives of center deflection

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<th>Independent variable, cross-sectional area</th>
<th>Value of derivative of center deflection</th>
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<td>Upper surface</td>
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<tr>
<td>Diagonals</td>
<td>$-8.3 \times 10^{-5}$</td>
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<tr>
<td>Lower surface</td>
<td>$-1.8 \times 10^{-4}$</td>
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</table>
**Figure 1.** The EAL system terminology and configuration.

(a) System configuration.

(b) Sample input file.

(c) Sample runstream data set.
(a) Finite-element model of cantilevered channel-section beam.

(b) Section A-A showing cross-sectional geometry and structural variables.

Figure 2.- Cantilevered channel-section beam used to illustrate analytical derivative method.
Figure 3.- Geometry and node numbering for swept wing. All dimensions are in inches.
Figure 4.- Element numbering for swept wing.
Figure 5.- Overall geometry and nodal numbering for box beam.
Figure 6. - Elements for box beam.
Figure 7. - Overall geometry and nodal numbering for stiffened cylinder with cutout.
(a) Overall model.

Figure 8.- Finite-element model of radiometer-antenna reflector.
(b) Upper surface.

Figure 8.- Continued.
(c) Lower surface.

Figure 8.- Concluded.
Figure 9.- Flowchart for system of runstreams to calculate structural-sensitivity derivatives with semianalytical method. Numbers indicate appropriate sections of runstreams in appendix.
Figure 10. - Flowchart of section of runstream system which calculates derivatives of stiffness, mass, and geometric stiffness matrices. Numbers indicate appropriate sections of runstreams in appendix.
Loop over independent design variables \( V_k \)

Form pseudo load vector:
\[
\{F\}_k = \frac{\partial f}{\partial V_k} \{u\} + \frac{\partial f}{\partial V_k} \{V_k - V_k^0\}
\]

Form matrix of pseudo load vectors
\[
\left[ F \right] = \left[ F_1, F_2, \ldots, F_{N_IDV} \right]
\]

Calculate \( \frac{\partial u}{\partial V} \)

Test if stress derivatives are desired

Yes

Loop over independent design variables \( V_k \)

Calculate
\[
\{u\}_{V_k}^n = \{u\}^0 + \frac{\partial u}{\partial V_k} \{V_k - V_k^0\}
\]
\[
\{\sigma\}_{V_k}^n = \left[ \sigma \right]_{V_k}^n \{u\}_{V_k}^n - \left[ G \right] (T - T_0)
\]

Calculate
\[
\frac{\partial \{\sigma\}}{\partial V_k} = \frac{\{\sigma\}_{V_k}^n - \{\sigma\}^0}{V_k - V_k^0}
\]

Increment \( k \)

No

Figure 11.— Flowchart of section of runstream system which details calculation of displacement and stress derivatives. Numbers indicate appropriate sections of runstreams in appendix.
Figure 12. - Flowchart of section of runstream for calculation of derivatives of vibration and of buckling eigenvectors and eigenvalues. Numbers indicate appropriate sections of runstreams in appendix.
This paper describes the implementation of static and dynamic structural-sensitivity derivative calculations in a general purpose, finite-element computer program denoted the Engineering Analysis Language (EAL) System. Derivatives are calculated with respect to structural parameters, specifically, member sectional properties including thicknesses, cross-sectional areas, and moments of inertia. Derivatives are obtained for displacements, stresses, vibration frequencies and mode shapes, and buckling loads and mode shapes. Three methods for calculating derivatives are implemented (analytical, semianalytical, and finite differences), and comparisons of computer time and accuracy are made. Results are presented for four examples: a swept wing, a box beam, a stiffened cylinder with a cutout, and a space radiometer-antenna truss.