COMPOSITE SIZING AND PLY ORIENTATION FOR STIFFNESS REQUIREMENTS USING A LARGE FINITE ELEMENT STRUCTURAL MODEL

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SUMMARY

A NASTRAN bulk dataset preprocessor was developed to facilitate the integration of filamentary composite laminate properties into composite structural resizing for stiffness requirements. The NASCOMP system generates delta stiffness and delta mass matrices for input to the flutter derivative program. The flutter baseline analysis, derivative calculations, and stiffness and mass matrix updates are controlled by engineer defined processes under an operating system called CBUS. A multi-layered design variable grid system permits high fidelity resizing without excessive computer cost.

The NASCOMP system uses ply layup drawings for basic input. The aeroelastic resizing for stiffness capability was used during an actual design exercise.

INTRODUCTION

Design of efficient structures is a classic problem for high performance and fuel efficient aircraft. This is highlighted by the continuing search for more efficient materials to be used in the design process. Current aircraft designs are focusing on composites.

Aircraft designs require structural sizings which satisfy aeroelastic requirements within the airplane flight envelope. The more successful designs achieve this with lowest possible structural weight.

It is not uncommon to separate the structure sizing process into two phases: (1) sizing for strength, fatigue, and buckling, and (2) sizing for flutter, deflection constraints, tailoring for loads alleviation, and aircraft flexible stability derivatives requirements. The latter are grouped together as design for stiffness, and the structural sizing increment over the strength sized structure is known as the stiffness weight increment. While tailoring the structure characteristics to reduce loads is not the same as satisfying flutter requirements, the methodology and approach are the same. However, stiffness weight increment loses some of its meaning.

Current aircraft designs incorporate aircraft structural arrangements for fuselage, wing, canards, vertical and horizontal surfaces, which often preclude adequate structural representation by the more traditional EI/GJ based models used in dynamic analyses. Consequently, dynamic analyses require more complex structural modeling details which were once reserved only for stress analyses.

One major problem with the finite element approach is the timely availability of a strength sized design early in the design process. First, the fabrication of the finite element model is a labor intensive process. Second, the sizing of the finite element model requires first rigid loads and then flexible loads. This procedure

produces at least two sizings. If the sizing is not automated, then the strength sized model may not be available for stiffness design.

The issue of generating a finite element model which is strength sized is being addressed by Lockheed in an Independent Research and Development Project called Preliminary Aeroelastic Design of Structures or PADS. PADS generates the Finite Element Model (FEM), the loads, strength sizings, stiffness sizing, and performs all related analyses.

The PADS strength sizing capability, however, relies heavily on existing computer programs which size cover panels for buckling, fatigue, and stress. These programs are for metallic structures. Currently, there is no comparable automated panel sizing capability for composites.

Recently, the design process changed and fell somewhere between the PADS environment where the FEM is not available and the configuration is changing, and the production design environment where the strength-sized model is available and the configuration is frozen. In this new environment, strength-sized models were made available while the configuration was changing.

Vehicle level structural sizing for aeroelastic requirements is contingent on either using the same mathematical structural model for the stress, loads, and flutter, or translating/interpreting/migrating structural sizing properties between different models. If the decision is made to use one structural model, which because of model size limitations must be more a stiffness model and less a stress model, the issue then is how to manage and use a large FEM (15,000 to 30,000 degrees of freedom) for designing to stiffness requirements.

Four major issues involved in conditioning a large composite finite element model for use in stiffness design are (1) the translation of high level engineering composite specifications into equivalent smeared element property values, (2) the automatic generation of the NASTRAN bulk data deck based on the high level inputs by the engineer, (3) the efficient computation of delta stiffness matrices due to changes in design variables as specified by the engineer, (4) the generation of delta weight data associated with the change in design variable.

A major development thrust was made in translating high level engineering data inputs into processes which generate delta weight and stiffness matrices. The approach uses existing programs, such as NASTRAN, and builds necessary pre and postprocessors to generate the bulk data and prepare the weight and stiffness data for use in the structural resizing. The process involved more than 20 separate programs. The functional description and the criteria for designing some of these pre- and postprocessors are described in the following paragraphs.

BUILDING ON EXISTING CAPABILITY

PADS demonstrated in References 1, 2, and 3 the feasibility of integrating diverse programs into engineering defined processes under the control of macros to size finite elements for static and dynamic gust loads, taxi loads, strength, buckling, flutter, and deflection constraints.

There are two key elements in PADS. The first element is the operating system called CBUS (Continuous Batch User System). CBUS permits the user to define

engineering processes using existing computer programs. CBUS then integrates
different computer programs without the need to change original functions or original
user access methods. Figure 1 shows CBUS as a tree from which computer programs are
hung and organized under a shell. The processes are defined in a macro-like shell,
which permits nesting, branching, sub-and-super process definitions. Within CBUS is a
powerful ALTER capability for real-time modification of macros which contain process
definitions as well as data blocks.

The second element of PADS is the integration of static and dynamic loads,
stress, structure modeling, weight, flutter, and computer programming disciplines in
real-time working environment. While significant levels of automation and integration
of engineering processes were accomplished under PADS, demonstration of individual
discipline control within an integrated working environment was more significant.

The PADS technical capabilities which transferred directly to the current project
were the generation of grid transformations between any paired coordinate systems, the
generation of the delta-k matrices which relate changes in structural stiffness due to
changes in design variables, the specification of user macros for flutter analyses, and
data management functions. CBUS gives the engineer the capability to define complex
processes in terms of modular subprocesses. Basic subprocess macros are the building
blocks to form other macro functions. As the macros are developed, a collection of
engineering processes become available to use at an expert-system-like level. Macros
define standard but flexible solution procedures.

CBUS macros relieve the engineer from remembering and performing countless
details required when executing computer programs one at a time. Relieved of the
repetitive tedium, the engineer focuses his energy and expertise on the definition of
processes, the management of the design flow, and, most importantly, the
interpretation of the computer studies for timely inputs into the design process.
Figure 2 shows the typical user on top of a pyramid constructed from user defined
macros which are executed through CBUS to access computer programs and databases
installed on a typical computer facility. The final cornerstone, however, is the
willingness of members on the team to learn the system and to develop their own macros
and tailor them to satisfy current requirements. The smaller footprint on top of the
pyramid gives the engineer more time to work out the problem physics and requires less
time to master the mechanics of getting analyses out of the computer.

MAPPING PHYSICAL TO MODEL PARAMETERS

In a top-down approach, the engineer modifies the structural model
characteristics by specifying the changes to the structural physical parameters.
Going from composite skin layup drawings to FEM material property values should
require only the layup definitions and not modeling judgments to match FEM areas with
ply area definitions.

Likewise, the data generated using the structural model must give the direction
to move the design in terms of the structural physical parameters rather than model
variables.

The goal then was to develop a preprocessor where the inputs consist of
structural physical parameters and the output is the FEM model parameters, such as
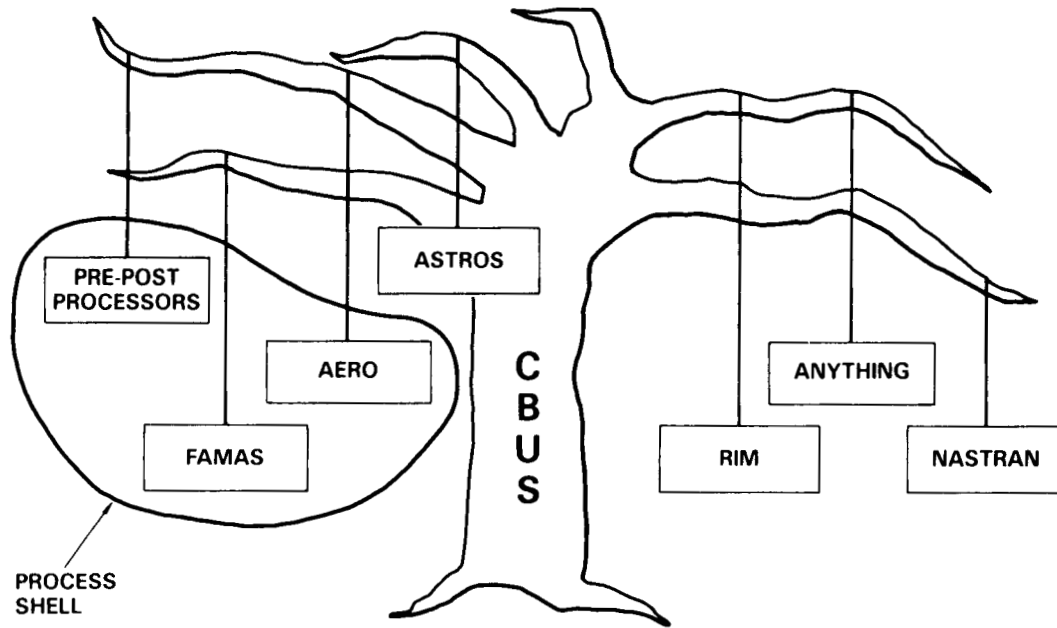anisotropic values for NASTRAN *QUAD and *TRIA elements.
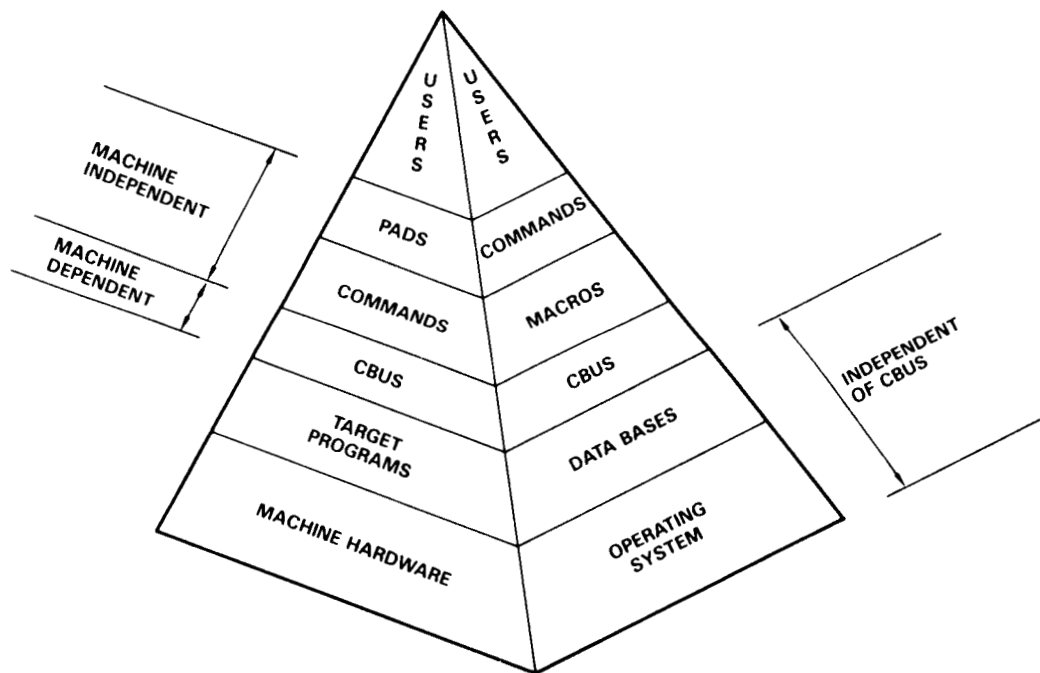
Figure 1. CBUS as an Integrating System

Figure 2. CBUS/PADS System Architecture

The end product is a change in structural stiffness for a change in a design variable, which is defined in terms of the structure physical parameters. While the formulation of delta stiffnesses is just a special application of mapping of physical parameters to model parameters, the mechanization details are critical relative to defining computer resource requirements.

So far, the mapping of physical parameters to model parameters has focused on the sizing specification. There are geometric mappings from the physical to the model which are used to optimize a design. The general category of shape optimization has been limited to t/c variations.

The formulation of the FEM property values directly from structural physical parameters is necessary not only for the baseline structure but also for perturbations of the baseline configuration.

In summary, the mapping of physical parameters to FEM model parameters must

- Use as input the ply layup drawings

- Map ply level changes directly into the FEM.

- Map ply level changes directly into the FEM for definition of delta stiffness and mass matrices.

- Accommodate FEM models in excess of 20,000 degrees of freedom.

- Map t/c changes to the FEM geometry.

- Accommodate automation.

- Accommodate the integration of strength sizing in the future.

AEROELASTIC STRUCTURAL SIZING OVERVIEW

Structural sizing for aeroelastic requirements involves a number of disciplines; namely, flutter, dynamic and static loads, stress, and stability and control. One way to move the design to best satisfy each discipline requirement is to generate structural sizing derivatives relative to the goals of each discipline. Even when the weighting of one discipline goal against the other for purposes of reaching a best design is known, the overall process in the academic sense is extremely complex. The issue becomes manageable, however, in practical designs when the engineer recognizes the loosely coupled interactions between one or more of these disciplines.

The need to generate strength-related derivatives are eliminated by allowing the internal loads within the structure to remain fixed while the individual structural elements are sized for those loads. Once the new sizing has been generated, new flexible loads are computed and new internal loads are then derived. Structural sizing which is compatible with internal loads converges within three loads/strength sizing cycles. Once the structure has been sized for flexible loads, the impact of the structural design on flutter margins and control effectiveness is established. Aeroelastic tailoring to reduce the loads can also be evaluated at this time.

Structural resizing for flutter is the extension of the baseline flutter analysis and the associated sensitivity studies. During the baseline flutter analyses, there are investigations into what kind of parameter variations will affect flutter margins. The more common are Mach number, fuel condition, and aerodynamic factors. Flutter margin sensitivities to actuator stiffness, control surface aerodynamics, and lifting surface gross stiffness variations produce data for identifying the existence of any major flutter margin role players.

Figure 3 summarizes the analysis parameter variations performed under baseline configuration flutter analyses and under aeroelastic optimization.

Strong interrelationships between baseline flutter analyses and the sizing of the structural components to achieve flutter margin goals is evident in Figure 4. The figure names specific outputs from the baseline flutter analyses which are critical to the optimization process.

The traditional velocity-frequency-damping, Figure 5, (VFG plots) are the mainstay of flutter analyses. The airplane aeroelastic deflections, Figure 6, computed where eigenvalue damping is equal to zero graphically describe the dominant motions for the flutter mode.

At the flutter point, energy input to the structure from the aerodynamics is balanced by the energy dissipation from structural damping and the aerodynamic damping on a per cycle basis. The energy distribution is plotted on the flutter vector plot planform. The energy distribution vector is summed over different segments of the airplane. Figure 7 shows a typical bar plot and clearly illustrates the horizontal

BASELINE CONFIGURATION FLUTTER ANALYSES

- STRESS FINITE ELEMENT MODEL

- ANALYSIS PARAMETER VARIATIONS
  - MACH NUMBER
  - FUEL - ZERO TO MAXIMUM TAKEOFF
  - CONTROL SURFACE ACTUATOR STIFFNESS
  - LIFTING SURFACE STIFFNESS
  - HORIZONTAL STABILIZER t/c
  - TAIL BOOM STIFFNESS
  - ENGINE SUPPORT STIFFNESS
  - CONTROL SURFACE AERODYNAMICS
    DERIVATIVES

- MODIFICATION OF UNSTEADY AERODYNAMICS
  - WINDTUNNEL DATA
  - CFD COMPUTER RUNS
    -- QUADPAN AND TEAM CODE

AEROELASTIC OPTIMIZATION

- STRESS FINITE ELEMENT MODEL

- COMPOSITE STRUCTURE RESIZING
  - COVERS - THICKNESS IN EACH PLY
    DIRECTION
  - SPAR THICKNESS
  - RIB THICKNESS
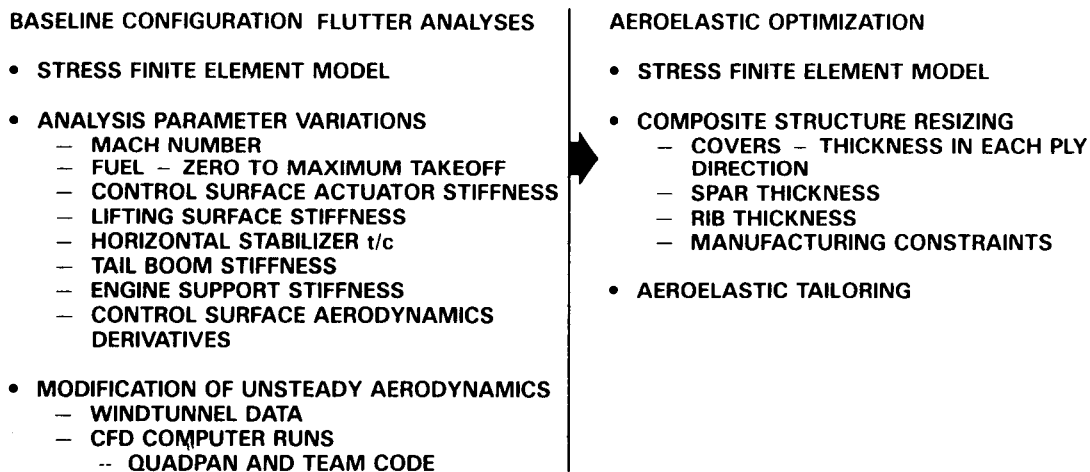 - MANUFACTURING CONSTRAINTS

- AEROELASTIC TAILORING

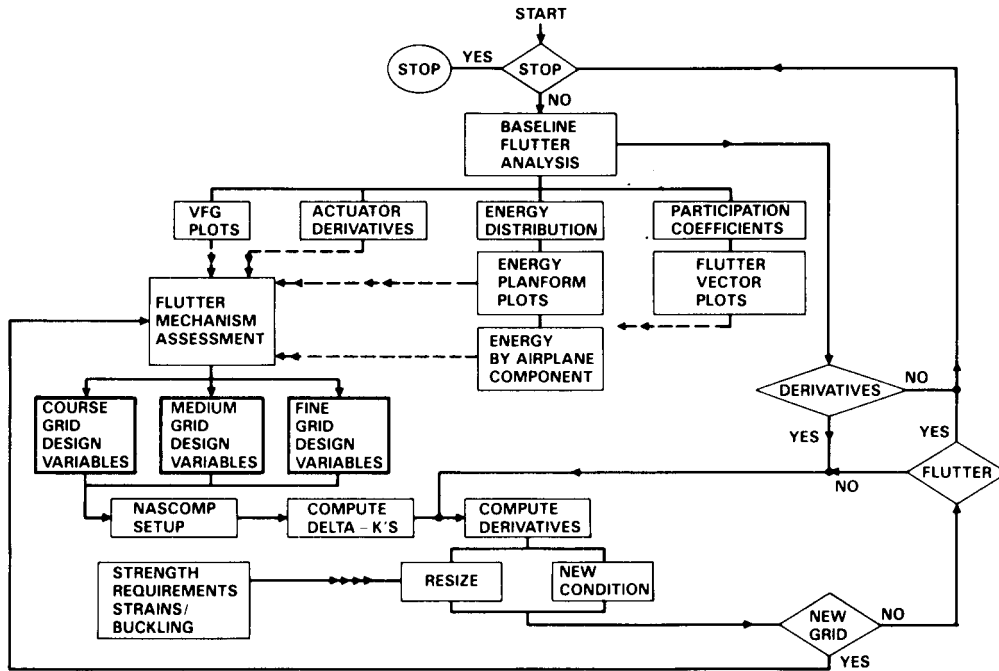Figure 3. Flutter Analysis and Resizing for Flutter

Figure 4.   Baseline Flutter/Resizing Functional Flow Chart

Figure 5A.   Frequency Versus Airplane
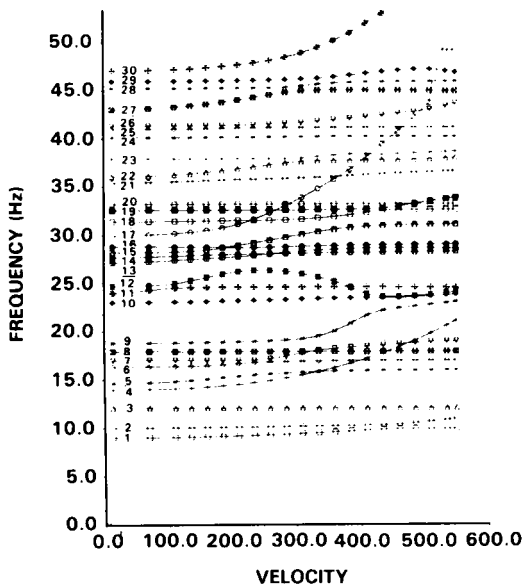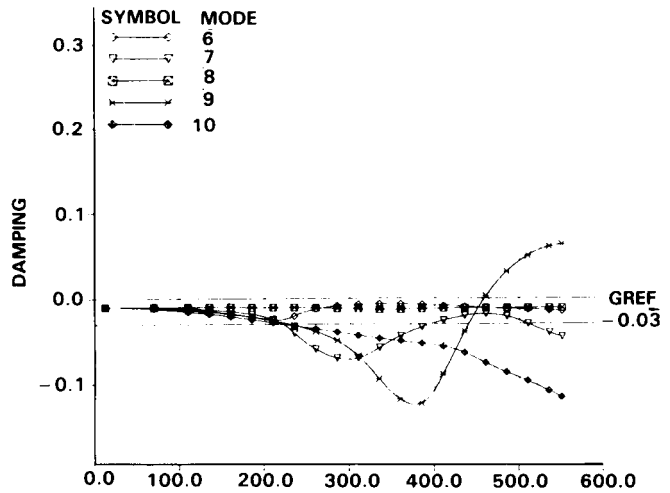Velocity (Typical)

Figure 5B.   Damping Versus Airplane
Velocity (Typical)

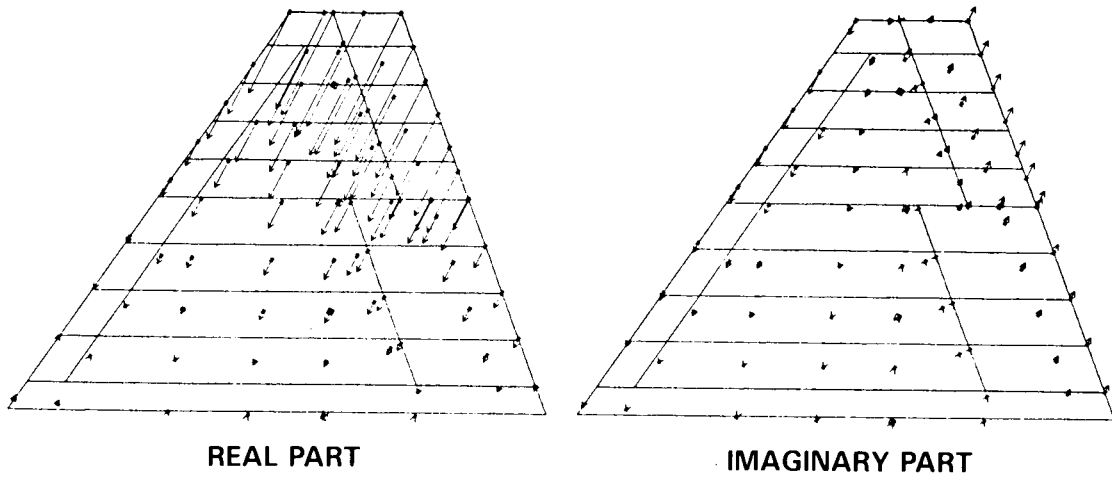REAL PART   IMAGINARY PART

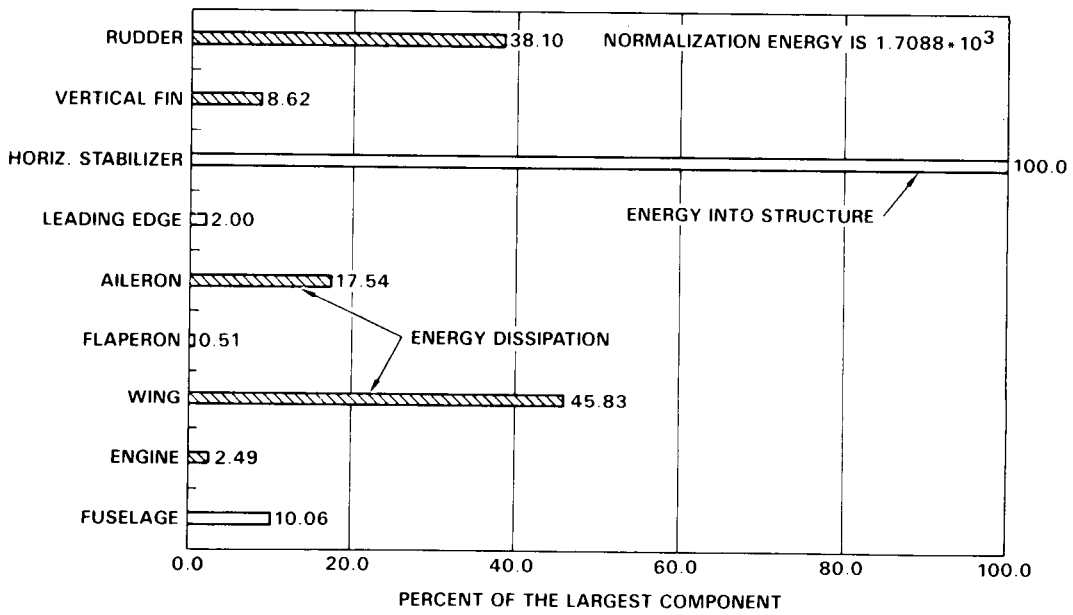Figure 6. Airplane Deflection at Flutter Point

Figure 7. Airplane Component Aerodynamic Energy Distributions

stabilizer surface pumping energy into the structure and the rudder and wing removing energy from the structure.

The final source of information which may aid in establishing the flutter mechanism is the actuator flutter velocity bar plots. Figure 8 shows the stabilizer actuator as the more effective in increasing the flutter speed.

Similar plots are available for increasing the damping at the top of hump modes.

Flutter derivatives are especially helpful in establishing the flutter mechanism of deficient flutter modes. In Figure 4, this point in the aeroelastic resizing path is labelled "flutter mechanism assessment." The process is now ready to consider the definition of design variables to compute flutter derivatives.

Generally, a first definition of design variables will cover the complete airplane. The coarse grid variables are only in terms of total thickness increases and not ply level thicknesses. The medium grid design variables cover the complete surface which has been targeted for resizing. The medium grid includes ply level thickness and ply orientations. The medium design variables isolate that part of the structure which will be further subdivided to form fine grid design variables. The identification of three levels of grids for design variables is a trade-off of computer costs against resizing fidelity. Typically, the fine grid design variables cover 40 percent of the surface to be resized. The ratio of finite elements to design variables is three or less.

After the set of design variables are defined, the next task is to generate delta K's and delta M's through the NASCOMP process. Once the delta matrices are available,
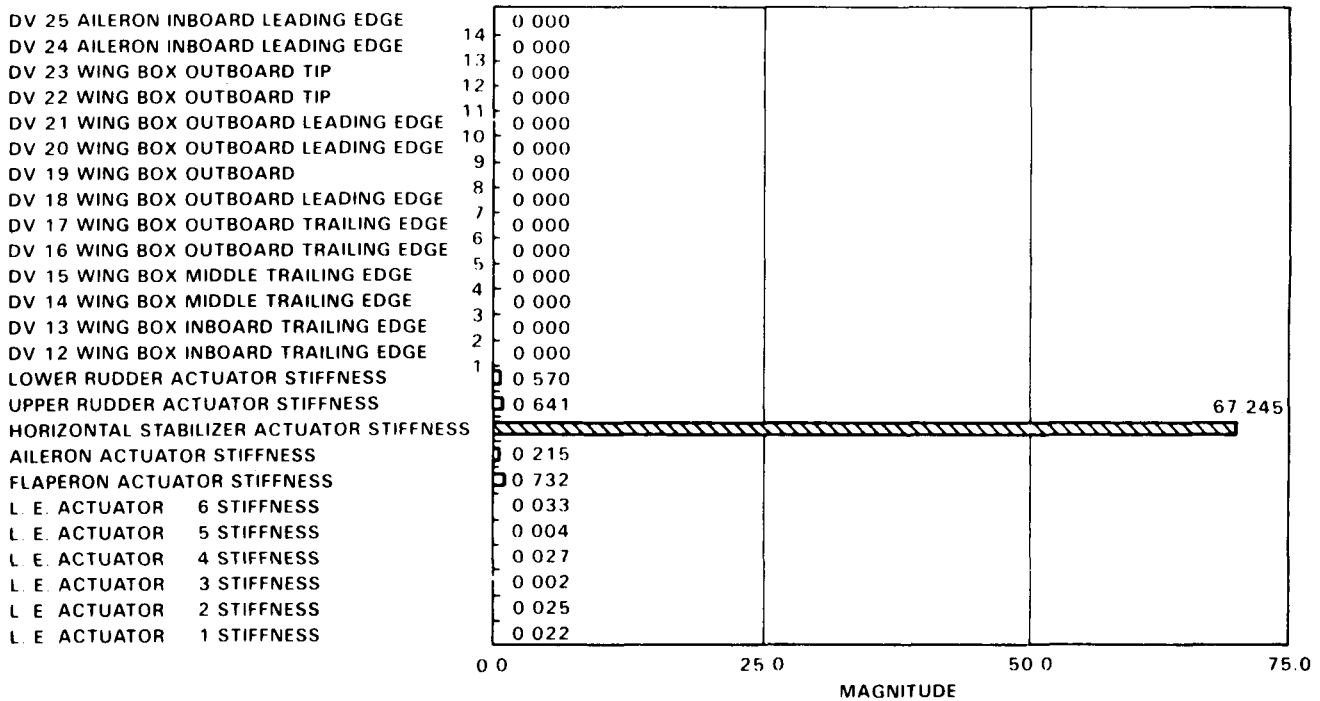
DV 25 AILERON INBOARD LEADING EDGE	0 000		
DV 24 AILERON INBOARD LEADING EDGE	0 000		
DV 23 WING BOX OUTBOARD TIP	0 000		
DV 22 WING BOX OUTBOARD TIP	0 000		
DV 21 WING BOX OUTBOARD LEADING EDGE	0 000		
DV 20 WING BOX OUTBOARD LEADING EDGE	0 000		
DV 19 WING BOX OUTBOARD	0 000		
DV 18 WING BOX OUTBOARD LEADING EDGE	0 000		
DV 17 WING BOX OUTBOARD TRAILING EDGE	0 000		
DV 16 WING BOX OUTBOARD TRAILING EDGE	0 000		
DV 15 WING BOX MIDDLE TRAILING EDGE	0 000		
DV 14 WING BOX MIDDLE TRAILING EDGE	0 000		
DV 13 WING BOX INBOARD TRAILING EDGE	0 000		
DV 12 WING BOX INBOARD TRAILING EDGE	0 000		
LOWER RUDDER ACTUATOR STIFFNESS	0 570		
UPPER RUDDER ACTUATOR STIFFNESS	0 641		67 245
HORIZONTAL STABILIZER ACTUATOR STIFFNESS			
AILERON ACTUATOR STIFFNESS	0 215		
FLAPERON ACTUATOR STIFFNESS	0 732		
L E ACTUATOR 6 STIFFNESS	0 033		
L E ACTUATOR 5 STIFFNESS	0 004		
L E ACTUATOR 4 STIFFNESS	0 027		
L E ACTUATOR 3 STIFFNESS	0 002		
L E ACTUATOR 2 STIFFNESS	0 025		
L E ACTUATOR 1 STIFFNESS	0 022		

0 0   25 0   50 0   75.0

MAGNITUDE

Figure 8. Flutter Speed Derivatives

the flutter velocity or top of the hump damping derivatives are computed for flutter deficient modes. Then either new grids are defined or structural resizing is performed.

NASCOMP PREPROCESSOR SYSTEM

NASCOMP is a collection of preprocessing programs designed to facilitate the integration of filamentary composite laminate properties into a NASTRAN finite element model (FEM). It is also used extensively to prepare the FEM for the generation of incremented stiffness matrices based on ply-level design variables. An incremented stiffness matrix, $[K + \Delta K]$, is a matrix that differs from a basic matrix, $[K]$, in that it is computed for a structural design in which one design variable is modified by a small amount. As a result, the derivative of $[K]$ with respect to the design variable can be approximated by a finite difference quotient.

The excessive time required for the generation of a new NASTRAN bulk data deck for each composite structure design iteration is a hindrance to the flutter optimization process. A preprocessor designed to make the desired modifications, with minimal, user-friendly instructions, greatly facilitates the optimization process as well as eliminating any error-prone hand editing of the bulk data.

The NASCOMP Preprocessor System consists of eight independent FORTRAN programs, each with a specific function, plus COMAIN, an existing program created by the Composite Development Center.

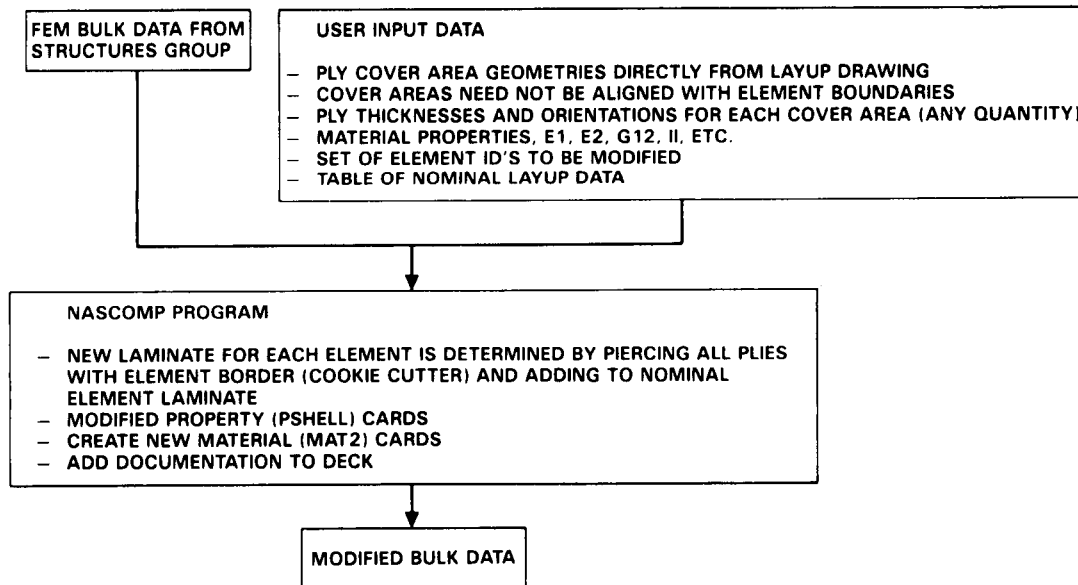Figure 9 summarizes the input and process definition of NASCOMP.

Figure 9. NASCOMP Input and Process Definition

PARTIT - This program simply reads the user input file and separates it into the datablocks required by the other programs. Each datablock is written to a temporary dataset which is passed along to the proper program. All user input is entered through PARTIT.

ELMSRT - This program scans the bulk data deck, extracts all necessary data pertaining to a selected set of elements, and outputs it to a single file. The inputs to the program include the types of elements to scan for and the ID ranges. The output is a table containing, for each element scanned, the element ID, the element type (CQUAD4, CTRIA3, etc.), the grid IDs and coordinates making up the element, and the property card (PSHELL, PROD, etc.) ID. By having all the necessary data in a single, concise file, multiple scans of the bulk data are avoided.

INTSCT - Also known as the "cookie-cutter," this program finds the intersections between ply cover areas and the elements contained in the table formed in ELMSRT. The inputs are the cover area definitions; i.e., the coordinates of the vertices, and the ply thicknesses and orientations. Figure 10 illustrates typical ply layups over the FEM grid points. The number of cover areas and the number of plies are unlimited. Any number of plies, with any orientation, can be applied to a given area. When computing the intersection, the three cases which must be considered are (1) the element lies completely inside the area; (2) the element is fully outside the area; and (3) the element is partially inside the area. If the element is completely inside the area, the full ply thickness is applied to the element. If the element is fully outside the area, then, obviously, nothing is applied to the element. If the element
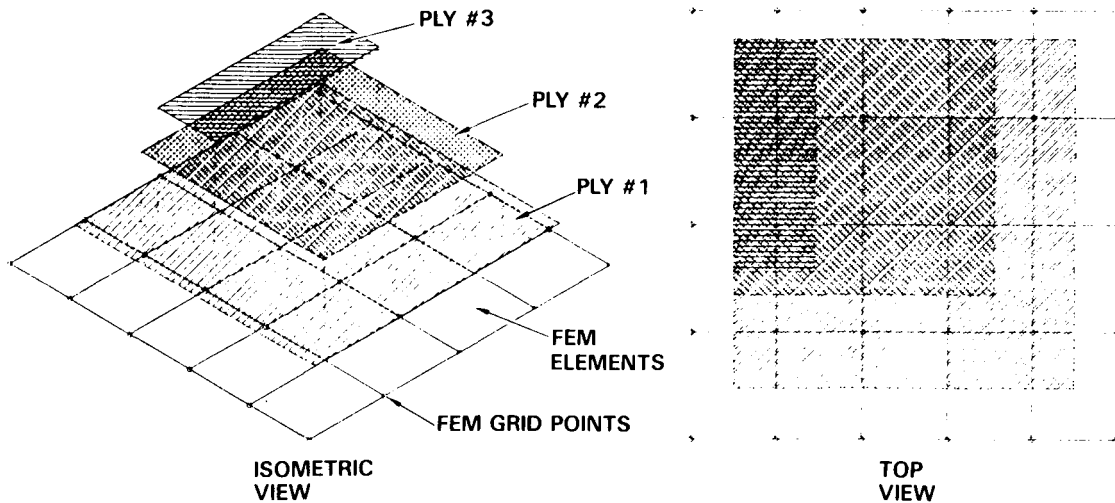

Figure 10. Ply Layups Over FEM Grid Points

is partially inside the area then a portion of the ply thickness (proportional to the ratio of intersected area to the element area) is applied to the element. The output file is a table which contains, for each element, all of the applied ply thicknesses and orientations. Elements which have no intersections with any of the areas are not listed.

BASBLK - This program takes the element ply table from INTSCT and, for each element listed in the table, adds the layup data corresponding to the nominal sizing found in the FEM. This nominal sizing data is usually obtained from the Structures Group. To compute the new element stiffness properties, the entire laminate, including both baseline data and increments, must be reconstructed. The output format is the same as the input.

COLECT - The file which is output in BASBLK, in general, contains many ply thickness/orientation entries for each element. COLECT combines all thicknesses with equal orientation angles for every element in the input table. These combined plies, or layers, are then redistributed according to a rudimentary stacking sequence specified by the user. Since several elements (e.g., adjacent) may consist of identical laminates, a filtering process is performed to separate the unique laminates. The output is a series of complete laminates, each of which is unique, and a table which relates the element IDs to these laminates.

COMPRE - This program prepares the laminate data for input to COMAIN.

COMAIN - This program, developed by the Composite Development Center, uses classical lamination theory to compute the laminate stiffness matrices for membrane, bending, and membrane-bending coupling loading conditions for thin, laminated, anisotropic plates of unit width. These matrices are usually referred to as the A, D, and B matrices respectively. They are defined below.

$$
\left\{
\begin{array}{c}
Nx \\
Ny \\
Nxy \\
\hline
Mx \\
My \\
Mxy
\end{array}
\right\}
=
\left[
\begin{array}{ccc|ccc}
a11 & a12 & a13 & b11 & b12 & b13 \\
a21 & a22 & a23 & b21 & b22 & b33 \\
a31 & a32 & a33 & b31 & b32 & b33 \\
\hline
b11 & b12 & b13 & d11 & d12 & d13 \\
b21 & b22 & b23 & d21 & d22 & d33 \\
b31 & b32 & b33 & d31 & d32 & d33
\end{array}
\right]
\left\{
\begin{array}{c}
\epsilon x \\
\epsilon x \\
\gamma xy \\
\hline
\kappa x \\
\kappa y \\
\kappa xy
\end{array}
\right\}
$$

where:

Nx (ϵx)   = normal force (strain) along laminate x-direction;

Ny (ϵy)   = normal force (strain) along laminate y-direction;

Nxy (γxy) = in-plane shear force (strain);

Mz (κx)   = bending moment (curvature) along axis normal to laminate x-z plane;

My (κy)   = bending moment (curvature) along axis normal to laminate y-z plane;

Mxy (κxy) = twisting moment (curvature) along laminate x or y axis.

or

$$\begin{Bmatrix} N \\ \overline{} \\ M \end{Bmatrix} - \begin{bmatrix} A & | & B \\ \hline B & | & D \end{bmatrix} \begin{Bmatrix} \epsilon \\ \overline{} \\ \kappa \end{Bmatrix}$$

COMPOS - The A, B, and D matrices, as well as the laminate thickness is extracted from the COMAIN output and passed along to the next step.

BDDWRT - This program modifies the bulk data to reflect the new elemental laminates. The element shell property (PSHELL) cards are modified or optionally replaced with new ones. The laminate thickness as well as the new material card IDs are entered on the PSHELL card. The A, B, and D matrices are normalized to the laminate thickness, T, to form the material moduli:

$$G_{membrane} - [A] / T$$

$$G_{bending} - [D] / (T^3/12) - [D] / I$$

$$G_{coupling} - [B] / T^2$$

The user can specify which of the moduli will be utilized for the elements; e.g., membrane only, membrane and bending, etc. All new material property (MAT2) cards are created, one or more for each laminate. The non-modulus entries on the MAT2 cards, such as density, thermal expansion coefficients, etc., are specified by the user. The new bulk data is written out including an echo of all user input data.

EDITING LARGER NASTRAN BULK DATA SETS

BULKEDIT is a general-purpose utility program designed to make changes to an existing bulk data deck. It has a wide range of capabilities including the ability to

- Replace one or more fields on selected ranges of cards with new data

- On selected ranges of cards, extract a numerical value from a certain field, modify it, and return it to the field

- Comment the cards out

- Add cards

The program performs these functions, in a fraction of the time, with minimal user input and eliminates the errors introduced by hand editing. The process is instantly repeatable; if an updated model is obtained, the changes/additions can be incorporated in seconds. BULKEDIT input/output is shown in Figure 11.

Example: A sensitivity study may require the rotation of the material property orientation axis (direction of 0-degree plies) on a range of 1000 skin elements by 10 degrees, the input cards are
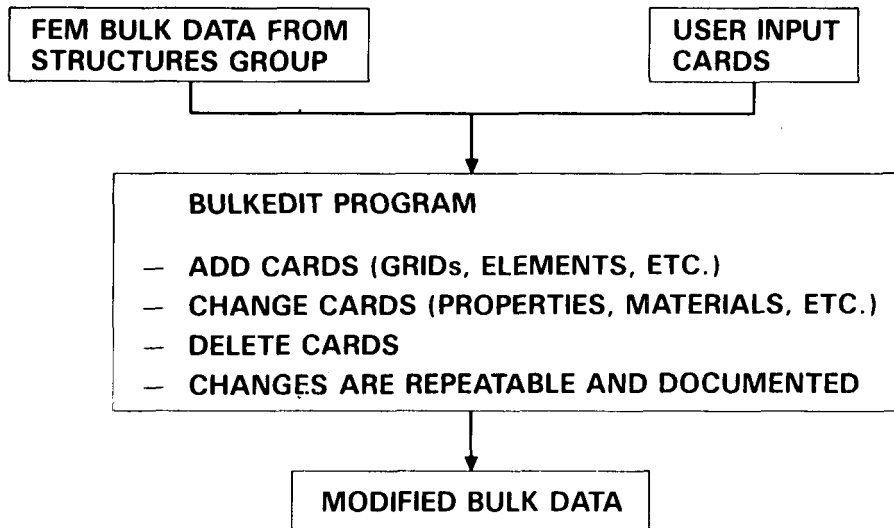
```
FEM BULK DATA FROM                          USER INPUT
STRUCTURES GROUP                            CARDS
```

BULKEDIT PROGRAM

— ADD CARDS (GRIDs, ELEMENTS, ETC.)
— CHANGE CARDS (PROPERTIES, MATERIALS, ETC.)
— DELETE CARDS
— CHANGES ARE REPEATABLE AND DOCUMENTED

MODIFIED BULK DATA

Figure 11. BULKEDIT Program

```
CQUAD4    +                                              10.0
60001   60500
61001   61500
END
```

Field 8 (columns 57-64) on the CQUAD4 card contain the axis specification. Program BULKEDIT will add 10.0 to the quantity in field 8 on all CQUAD4 cards found with element numbers in the ranges from 60001 through 60500 and 61001 through 61500. The "+" operator in field 2 (column 9) can optionally be a "*" to multiply by 10.0 or a "#" to replace with 10.0.

Additional cases requiring different rotation angles could be completed with the change of one card.

DELTA MASS MATRICES

Delta mass matrices, corresponding to a small change in the structural model, for each design variable are required to compute the flutter speed derivatives. Program DVMASS was written to generate these matrices. A convenient output table from NASTRAN lists, among other things, the areas, A, of all plate/web elements and the lengths, L, of all rod/bar elements. This table, combined with a design variable specification table, are input to DVMASS. For each design variable, DVMASS computes the delta mass of each designated element ($\Delta m = \rho A \Delta t$ for shells and webs and $\Delta m = \rho L \Delta A$ for rods and bars) and the geometry of the element centroid. The program outputs are one delta

417

mass matrix per design variable and a single matrix containing the centroid geometry of all elements involved. The geometry matrix is used to generate the transformation matrices needed to produce the delta mass matrices in terms of the structural degrees-of-freedom.

The design variable specification table shown below defines the input to the program.

```
$   DV    ELEM ID       INCR.  DENS  PART  MIN   DELK  DELW
$   #     RANGE(S)      THK           #     THK   MAT#  MAT#
$
$      0 DEGREE PLIES, VERTICAL FIN SECTION IA
    1   60001 60009   .005   .060  40.00 .006  3801  2801
+       60101 60109
$   + 45 DEGREE PLIES, VERTICAL FIN SECTION IB
    2   60010 60019   .007   .100  40.00 .006  3802  2802
+       60110 60119
$     90 DEGREE PLIES, VERTICAL FIN SECTION IB
    2   60010 60019   .007   .100  40.00 .006  3803  2803
+       60110 60119
$
etc.
```

Besides being convenient for documentation, the table contains all input necessary to generate the delta mass and stiffness matrices.
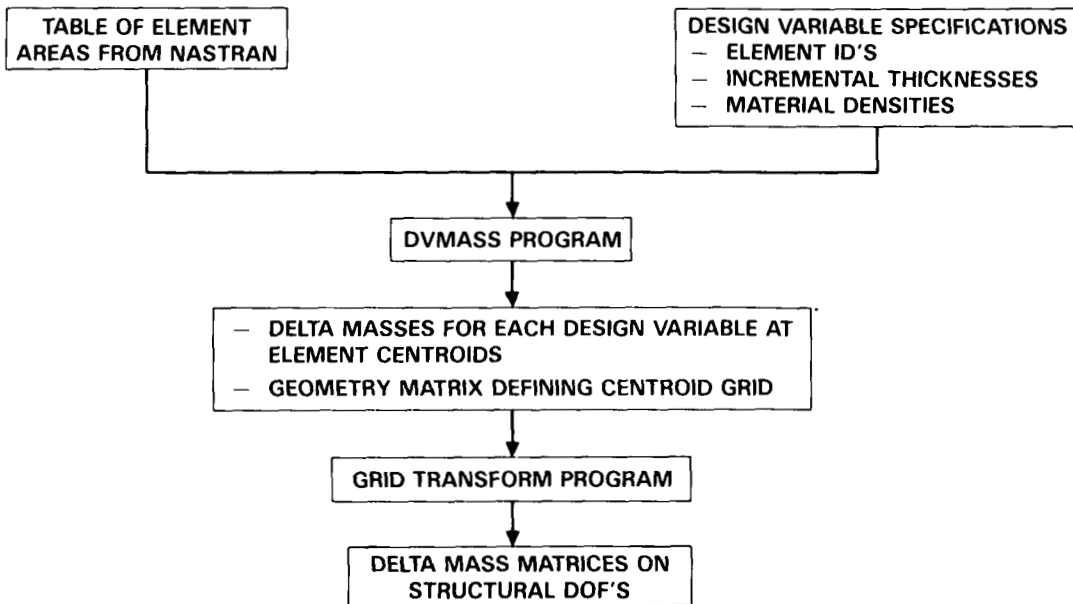
The DVMASS program flow is shown in Figure 12.

Figure 12. Delta Mass Generation

418

DELTA STIFFNESS MATRICES

The computation of the delta stiffness matrices, ΔK_i, requires the submittal of a NASTRAN job for each design variable. In addition, for each design variable, the bulk data must be altered to reflect a small increment to the structural sizing. When a large number of design variables (80-100) are in use, the data management aspect of the process is quite unwieldy. Using CBUS, a macro was developed to allow the complete ΔK generation process to be executed automatically. Referring to Figure 13, the bulk data from the current resizing step is the only input to the macro. The macro contains all of the data required to run both NASCOMP and BULKEDIT for each design variable. NASCOMP is executed when ply-level ΔK's are to be computed and BULKEDIT is executed for other design variables, e.g., metal spar thickness. After the bulk data has been modified, the macro generates first the NASTRAN executive and case control decks then the Job Control Language (JCL) and finally submits the NASTRAN job for execution. All subsequent design variables are processed similarly. The spawned NASTRAN jobs will run independently of the "mother" process, considerably reducing the turnaround time.

The method in which the ΔK matrices are computed by NASTRAN was tailored to reduce the run time (=cost). The delta stiffness is first computed on a superelement basis and then reduced using the existing Guyan transformation matrix. For small increments, this technique produced results that agreed very well with the results obtained by updating the Guyan transformation matrix.
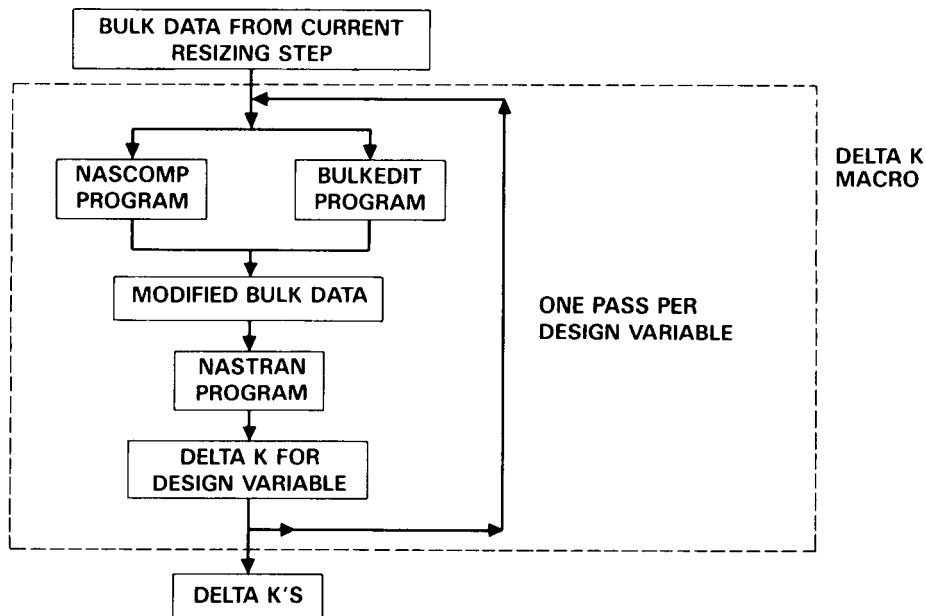

Figure 13. Delta Stiffness Generation

FLUTTER SPEED DERIVATIVES

The delta stiffness matrices, ΔK, and the corresponding delta mass matrices, ΔM, one for each design variable, are used to compute the flutter derivatives (Figure 14). At the present time, there is the capability to compute derivatives for two types of modes, at the flutter crossing and at the top of the hump mode. The derivatives at the flutter crossing, the point where the mode in neutrally stable are

$\dfrac{\delta V}{\delta m_i}$ = The derivative of the flutter crossing speed with respect to the design variable i. [KEAS/lb]

$\dfrac{\delta f}{\delta m_i}$ = The derivative of the flutter crossing frequency with respect to the design variable i. [Hz/lb]

The derivatives at the top of the hump mode, the point of minimum damping, are

$\dfrac{\delta V}{\delta m_i}$ = The derivative of the top of the hump speed with respect to the design variable i. [KEAS/lb]

$\dfrac{\delta g}{\delta m_i}$ = The derivative of the damping value at the top of the hump with respect to the design variable i. [percent damping/lb]

Computing the flutter derivatives has traditionally been a two step process: perform a flutter analysis to get the frequency and damping versus speed data (VFG plots); then manually select the critical modes and compute the derivatives.
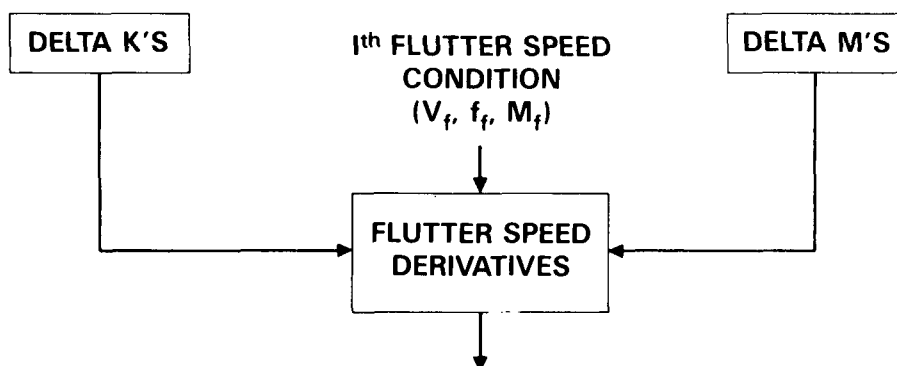

Figure 14. Flutter Speed Derivatives

Recently, a program has been developed that will process the flutter output and select the critical modes based on user-specified parameters. Speed range, frequency range, minimum damping, and which, if any, modes to exclude (if known a priori) are among the inputs. The program selects all modes which satisfy these criteria. This program was integrated into the flutter analysis stream using CBUS, and it is now possible to do the flutter analysis and get the derivatives with one job submittal.

STRUCTURAL RESIZING PROGRAM

The Structural Resizing Program computes the sizing increment based on either a specified weight increment or flutter speed increment. The effectiveness of each of the derivatives is assumed to diminish linearly as weight is added to the structure; i.e., they are fully effective for zero added weight and are completely ineffective at some predetermined weight increment, DWO. Figure 15 illustrates the declining effectiveness concept. The program computes the sizing increment, DWI, based on the most efficient use of the derivatives. If a weight increment is specified, the resulting weight distribution gives the largest velocity increment. If a velocity increment is specified, the resulting weight increment is minimum. The process is illustrated in Figure 16.

Manufacturing constraints dictate whether the resulting laminates are acceptable - laminate thickness must correspond to an integral number of finite-thickness laminate. In addition, laminate symmetry and balance must be considered.
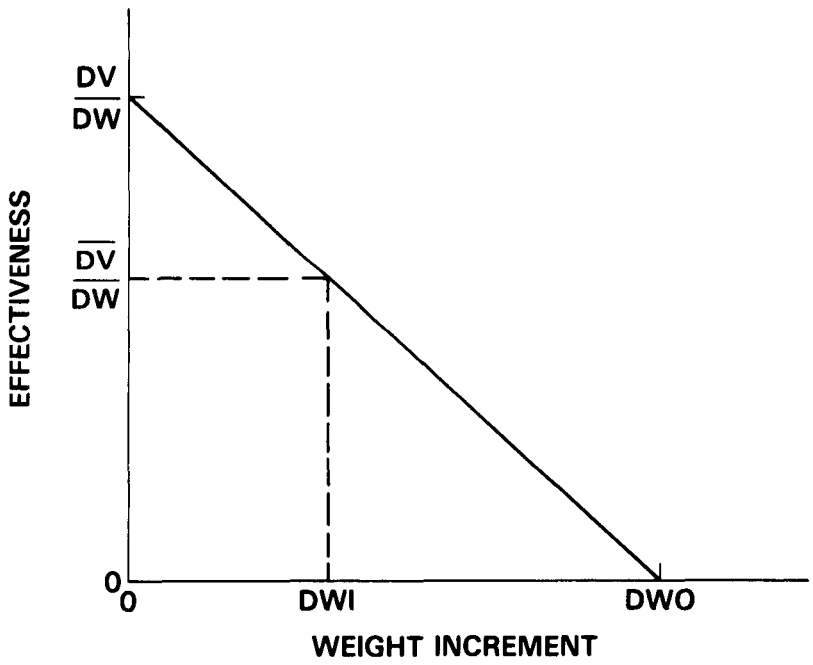

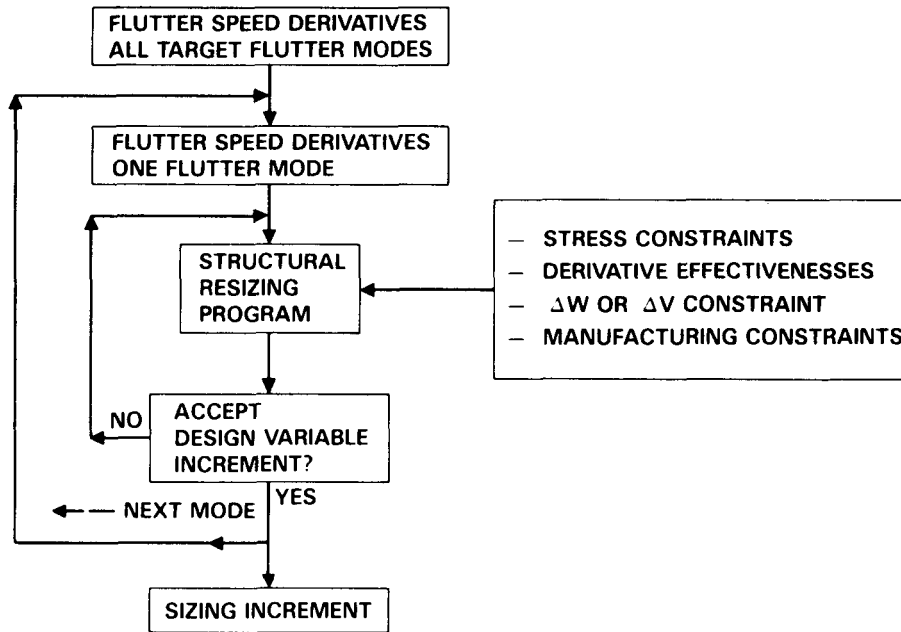Figure 15. Derivative Effectiveness Model

Figure 16. Structural Resizing Program

UPDATED MASS AND STIFFNESS MATRICES

After the resize increment has been determined using the resizing program, the new stiffness and mass matrices are generated. The resize program outputs the incremental thicknesses to be applied to each design variable. These increments are then input to the stiffness update macro (see Figure 17). The macro generates all of the necessary control cards for the BULKEDIT program and the NASCOMP programs. Similar to the Delta K generation process, the update macro modifies the bulk data as required and spawns a single batch job. The bulk data is saved for use in generating a new set of ΔKs. The first step of the job is the execution of NASTRAN to compute the updated stiffness matrix. The second step is a FAMAS program that will generate the updated mass matrix. The mass matrix is computed by adding an incremental mass matrix to the nominal mass matrix. The incremental mass matrix is calculated using multiples of the delta mass matrices (Δm's) based on the resizing increment.

EXAMPLES AND RESULTS

Dual Rudder Vertical Stabilizer

The initial design of the dual rudder vertical stabilizer was strength sized for loads. The design, however, was deficient in flutter margin requirements by more than 100 KEAS. The structural resizing for stiffness goal was to hold the weight constant, keep the strain margins at or below the initial design levels and raise the flutter
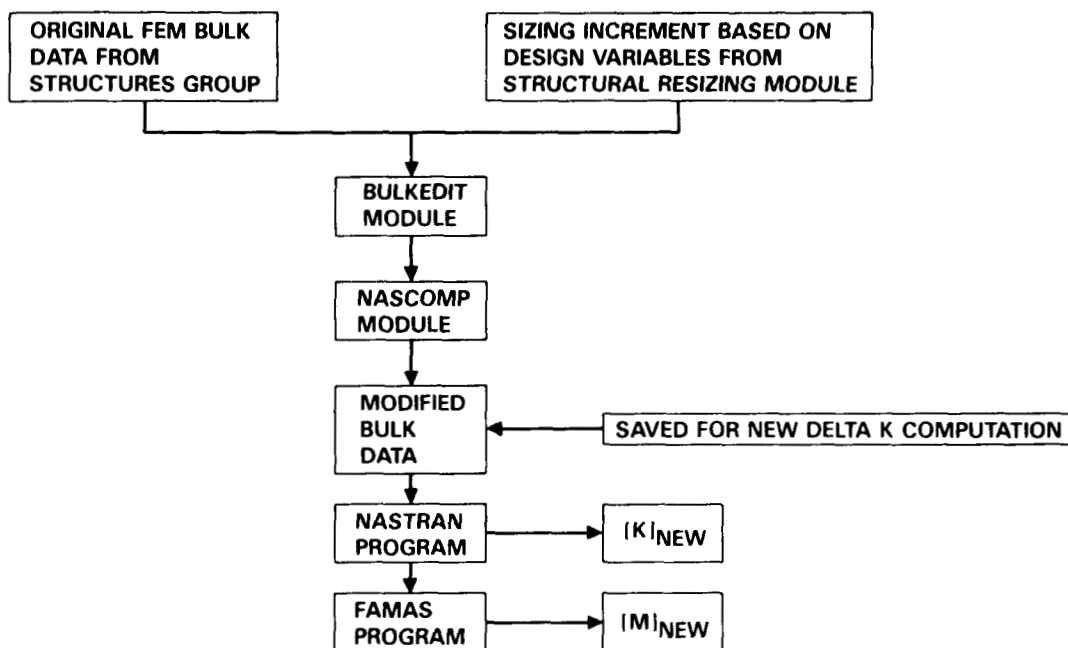
```
┌─────────────────────┐          ┌───────────────────────────┐
│ ORIGINAL FEM BULK   │          │ SIZING INCREMENT BASED ON │
│ DATA FROM           │          │ DESIGN VARIABLES FROM     │
│ STRUCTURES GROUP    │          │ STRUCTURAL RESIZING MODULE│
└─────────────────────┘          └───────────────────────────┘
          │                                  │
          └──────────────┬───────────────────┘
                         ▼
                 ┌──────────────┐
                 │  BULKEDIT    │
                 │  MODULE      │
                 └──────────────┘
                         │
                         ▼
                 ┌──────────────┐
                 │  NASCOMP     │
                 │  MODULE      │
                 └──────────────┘
                         │
                         ▼
                 ┌──────────────┐      ┌──────────────────────────────────┐
                 │  MODIFIED    │◄─────│ SAVED FOR NEW DELTA K COMPUTATION │
                 │  BULK        │      └──────────────────────────────────┘
                 │  DATA        │
                 └──────────────┘
                         │
                         ▼
                 ┌──────────────┐      ┌──────────┐
                 │  NASTRAN     │─────▶│ [K]NEW   │
                 │  PROGRAM     │      └──────────┘
                 └──────────────┘
                 ┌──────────────┐      ┌──────────┐
                 │  FAMAS       │─────▶│ [M]NEW   │
                 │  PROGRAM     │      └──────────┘
                 └──────────────┘
```

Figure 17. Mass and Stiffness Matrices Update

speed by 100 KEAS. This was a cantilevered case and the computer time was not a
significant factor.

The derivatives for the baseline case indicated that the structure needed to be
stiffened at the leading edges and the upper 1/3 of the fin structure. The move
vector,which satisfied minimum and maximum thickness requirements,redistributed the
material from the mid-center section out to the leading edge support structure. After
three resizings, the flutter margin deficiency was removed; the critical strain values
were reduced by 20 percent; the weight addition was zero.

Horizontal Stabilizer

This was the initial attempt at sizing a composite structure which was not
cantilevered. While the design variables were relatively large, structural resizing
produced an interesting result.

This case required the addition of material to the structure to satisfy the
flutter requirements. However, with ply orientations of the material as design
variables, the weight increase could be substantially reduced. The optimum ply
orientation, Figure 18, for the tailored structure was an offset of the bending axes
relative to the torsion axes. A check of the buckling requirements indicated that the
tailored ply orientation was better. Figure 19 shows a weight savings of 70 pounds at
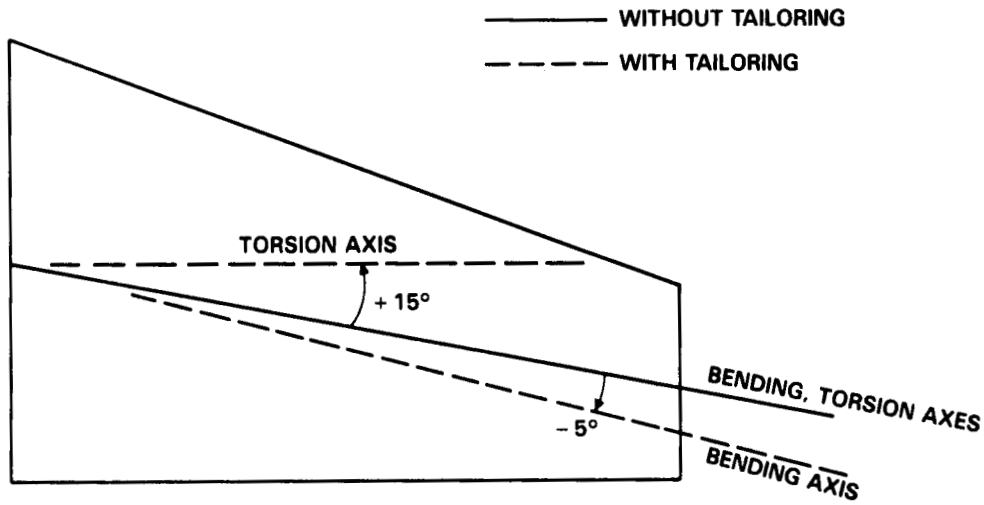the actuator design point.

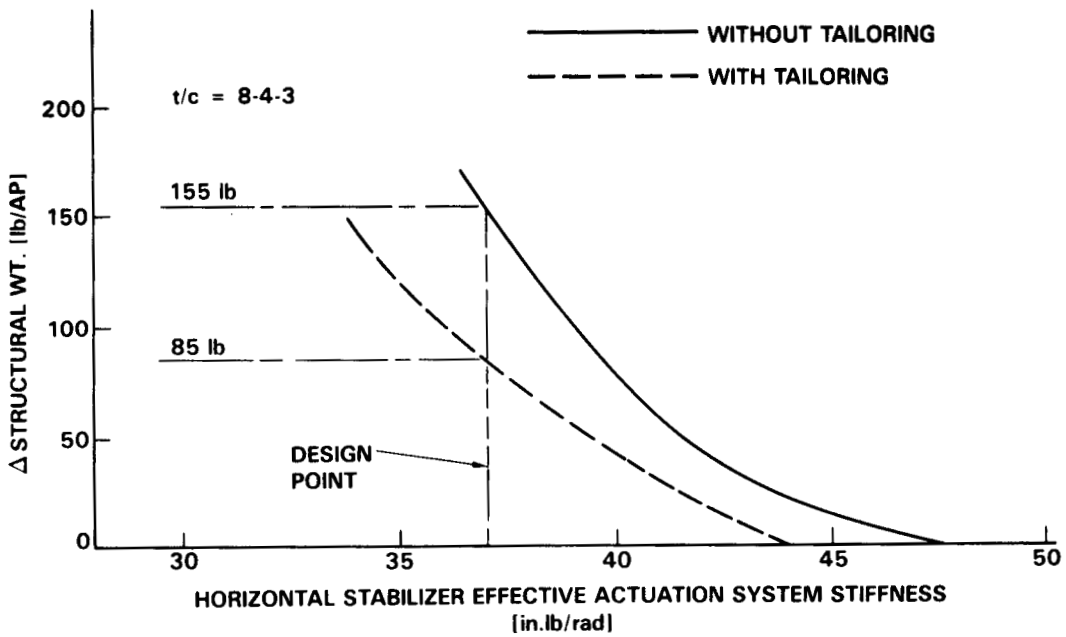**Figure 18.** Optimization of Horizontal Stabilizer Ply Direction For Improved Flutter Characteristics

Figure 19. Horizontal Stabilizer Effective Actuation System Stiffness

Whole Airplane - Coarse-Medium-Fine Grid Example

The airplane design showed flutter deficiencies primarily at one subsonic and one supersonic speed. Both symmetric and antisymmetric boundary conditions were involved. There was principally one critical weight condition. First, design variables were constructed using total thicknesses for the wing, vertical and horizontal stabilizers. The flutter derivatives clearly demonstrated that wing design variables were not important to increasing the flutter speed of any of the deficient flutter modes. The medium design variable grid was defined for the control surface which the coarse grid design variable derivatives showed to be the prime candidate for resolving the flutter deficiency.

Results from the medium grid model further narrowed the candidate structure for resizing to 40 percent of the original control surface. A fine grid design variable derivatives were computed. Figure 20 shows sections of the control surface where the flutter derivatives were significantly higher than the surrounding structure.   The figure shows flutter derivatives for ±45 plies. The structure was resized with a goal of increasing flutter speed margin by 40 KEAS. This goal was achieved with a weight increment of less than 2 pounds per surface.

FINAL OBSERVATIONS AND RECOMMENDATIONS

The full impact of the overall capability is difficult to assess in a meaningful way. Table 1 lists the steps used in the structural resizing for stiffness along with the computer setup times for each step. The major bottleneck is the significant
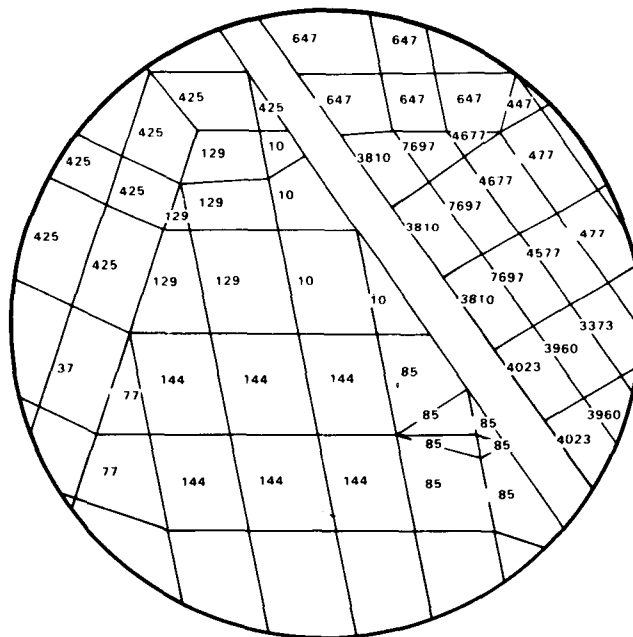

Figure 20. Normalized Flutter Velocity Derivatives (KEAS/LB) for ± Plys

TABLE 1. DESIGN TO STIFFNESS TABLE SUMMARY

GENERAL MODEL STATISTICS

NASTRAN Gset DOF ⟶ 24000   DESIGN VARIABLES ⟶ 80 TO 100
        Aset DOF ⟶   400
VIBRATION   DOF ⟶   370
FLUTTER   DOF ⟶   50

STEP	TASK	SOFTWARE	CONDITIONS	OUTPUTS	SETUP TIMES	CPU TIMES
1	FLUTTER BASELINE	FLUTTER MACRO CONTROLLED BY 30 FREE FORMATTED INPUTS- TITLES VEL RANGE MACH, FUEL, DERIVATIVES	4 MACH NUMBERS 5 FUEL CONDITIONS SYM AND ANTISYM	VFG, VECTOR PLOTS, ENERGY PLOTS, 80 FLUTTER DERIVATIVES	4 MINUTES FOR SETUP PER RUN	80 CPU MINUTES (IBM 3081) PER RUN
2	SENSITIVITY STUDIES	FLUTTER MACRO SAME AS STEP 1	SAME AS STEP 1	ACTUATOR STIFFNESS, AERO-DYNAMIC FACTOR, CONTROL SURF H.M., A.C. SHIFT, CANTILEVERED ANALYSIS, MODE TRACKING	6 MINUTES FOR SETUP PER RUN	10 TO 50 CPU MINUTES DEPENDS ON THE TASK PER RUN
3	DESIGN VARIABLE DEFINITIONS	SIMPLE BATCH PROGRAMS FOR PLOTTING FEM GRID, ELEMENTS PREPARATION OF INPUT DATA FOR NASCOMP, DELTA MASS, ETC. PROGRAMS CADAM	COARSE WHOLE AIRPLANE GRID MEDIUM SURFACE GRID FINE SURFACE GRID 80 TO 100 DESIGN VARIABLES FOR EACH GRID		2 PERSON DAYS PER GRID	LESS THAN 20 MINUTES TOTAL

TABLE 1. DESIGN TO STIFFNESS TABLE SUMMARY (Continued)

STEP	TASK	SOFTWARE	CONDITIONS	OUTPUTS	SETUP TIMES	CPU TIMES
4	DELTA MASS MATRICES	DVMASS BATCH PROGRAM	DATA FROM STEP 3	OUTPUTS 80 TO 100 DELTA MASS MATRICES	30 MINUTES SETUP	LESS THAN 5 MINUTES TOTAL
5	DELTA STIFFNESS MATRICES	DELTAK MACRO (UNDER CBUS) IS A MOTHER JOB WHICH GENERATES 80 TO 100 NASTRAN JOBS	DATA FROM STEP 3	OUTPUTS 80 TO 100 DELTA STIFFNESS MATRICES	60 MINUTES SETUP	400 TO 500 CPU MINUTES TOTAL
6	FLUTTER DERIVATIVES	FLUTTER MACRO	SAME AS STEP 1 OPTION-COMPUTED WHEN FLUTTER POINTS OR TOP OF HUMP MODES APPEAR	FLUTTER VELOCITY DERIVATIVES MODAL DAMPING DERIVATIVES	PART OF STEP 1 OR 3 MINUTES	12 MINUTES FOR FIRST FLUTTER FLUTTER MODE/HUMP THEN 3 MINUTES FOR EACH ADDITIONAL
7	RESIZE STRUCTURE	BATCH/INTER-ACTIVE PROGRAMS	OPTIONS TO SET: DERIVATIVE EFFECTIVENESS FACTORS, ACTIVE/ INACTIVE DESIGN VARIABLES, MULTIPLE CONDI-TIONS, WEIGHT ON/OFF, VELOCITY/ OR WEIGHT TARGET INCREMENTS	DESIGN VARIABLES INCREMENTS	30 MINUTES	LESS THAN 2 MINUTES
8	UPDATE STIFFNESS MATRIX MASS MATRIX	UPDATE MACRO SIMILAR TO DELTAK MACRO EXCEPT SUBMITS ONE NASTRAN JOB	USES OUTPUT FROM STEP 7	UPDATED STIFFNESS MATRIX UPDATED MASS MATRIX	30 MINUTES	30 MINUTES

computer resource requirements. For example, in step 5, the process setup time for the engineer is 60 minutes while the compute time for 100 NASTRAN jobs is more than 6 CPU hours. Even more leverage of CPU to setup time is possible when submitting standard flutter analyses where four minutes of setup time results in using 80 CPU minutes of computer resources.

The benefits of running analysis and optimization processes under CBUS are repeatability, low engineering setup hours, user defined levels of automation, flexibility, user defined process definition, and more visibility of the design process.

The benefits of using one FEM for stress, loads, and flutter are common basis for specifying requirements, the maintenance of one structural model, and improved analysis integrity between disciplines.

While the FEM model may not meet the full requirements for detailed stress analysis, and while the FEM may be too detailed for stiffness analyses and design requirements, the authors conclude that the benefits far outpace the limitations and that strength sizing and loads generation should be integrated to provide interdisciplinary aeroelastic design capability at a complete vehicle level.

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