THE ROLE OF NASTRAN IN THE PRELIMINARY DESIGN CYCLE

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SUMMARY

This paper explains how NASTRAN can be utilized advantageously in the preliminary design cycle. The initial portion of the preliminary design process lends itself to programs that can produce multiple configurations or variations on a particular design with minimal cost or effort. The latter portion of the process encompasses refining the design and adding more detailed analyses (particularly for other disciplines). A method for quickly generating balanced spacecraft loading conditions for use in preliminary design and analysis also is explained.

The following additional sections are included:

1. Background
2. Symbols
3. Analytical Process
4. Aerodynamic Load Distributions
5. NASTRAN Applications
6. Conclusion
7. References

BACKGROUND

The preliminary design cycle seeks to obtain general as well as specific information rapidly and inexpensively, yet accurately. The preliminary design cycle (see fig. 1) for spacecraft or space systems usually involves evaluating multiple designs for a given configuration or evaluating several competing configurations. A process for the analysis and evaluation work has been established (ref. 1) and used (ref. 2) for several investigations. This process (fig. 1) starts with a solid representation of the design and evolves into a finite element representation for static and dynamic analysis. Various systems are available for performing the finite element analysis. Two such systems are IDEAS and NASTRAN. The process of preliminary design has, among other things, two objectives that can be opposing: (1) to provide an analytical representation that can be easily revised, and (2) to provide an analytical representation that can be refined as part of the design improvement after a configuration has been accepted. The IDEAS system readily lends itself to objective number (1), while NASTRAN is particularly useful for objective number (2).

Various researchers have suggested approaches (ref. 3 and 4) for optimizing a structural design. The optimization researchers usually start with a given configuration and loading condition. The preliminary design issues addressed in this paper allow consideration for a broader viewpoint. This broader viewpoint asks the following questions:

1. What is a good configuration?
2. What vehicle loads go with a particular configuration?

SYMBOLS

The following symbols are used in this paper:

ρ	air density (slugs/ft^3)
α	angle of attack (rad)
CAD	computer-aided design
q	dynamic pressure (lb/ft^2)
δ	gimbal angle (deg)
V_{gust}	gust velocity (ft/sec)
C_{N_α}	normal force coefficient slope (1/deg)
PL	payload
SRM	solid rocket motor
S_{ref}	surface reference area (ft^2)
T	thrust (lb)
$V_{vehicle}$	vehicle velocity (ft/sec)
V_{wind}	wind velocity (ft/sec)
X_{cg}	X coordinate of the center of gravity (in.)
X_{cp}	X coordinate of the center of pressure (in.)
X_{gimbal}	X coordinate of thrust vector application point (in.)

ANALYTICAL PROCESS

The process starts with a candidate design or configuration that needs to be evaluated. A computer-aided design (CAD) representation is created and serves as a basis for the finite element model. The basic finite element model can serve as the starting point for investigating alternate configurations. It usually takes at least one iteration through a segment (see fig. 2) of the process to get a reasonable estimate of the structural sizing and weights. The first pass-through also provides a good test of the model fineness. The analyst would like the finite element model to be fine enough to give believable stress and deflection predictions; however, it should be crude enough to keep computing costs and time at a low level.

The box entitled "Finite Element Model" (see fig. 2) could utilize any one of a number of different programs. The two most attractive systems for this project were IDEAS and NASTRAN. Table I gives a comparison between the two systems. In order to generate a good preliminary design, both programs (or other comparable ones) should be used: IDEAS (to compare configurations and to select one) and NASTRAN (to provide the starting point for detailed design and certain specialized analyses [e.g., flight control, flexible body loads, etc.]). This is shown in fig. 3.

Considerable effort has been spent in computing vehicle load conditions that are configuration dependent. Any preliminary design can only be as good as the vehicle loads being used. The issue of balanced load conditions is important because in the early stages (preliminary design) of a design meaningful loads are very difficult to obtain. Balanced load conditions on a vehicle allow an analyst to look at the computed stresses and deflections and not be concerned about how the results have been skewed by assumed boundary conditions or unbalanced loads. A balanced load condition is one where the sum of all forces and moments (aerodynamic, inertial, and thrust) acting on the vehicle are zero.

Table I. Comparison of IDEAS and NASTRAN

FINITE ELEMENT MODEL	
IDEAS	**NASTRAN**
Advantages	Advantages
• Quick turnaround • Complete solutions • Low cost • Static and dynamic results • Color graphics • Database capability	• Easy to interface with other programs/disciplines • Wide usage in U.S. • Highly portable • Sophisticated solutions available
Disadvantages	Disadvantages
• Limited capability to interface with other programs/disciplines • Limited usage in U.S. • Available on limited platforms • Specialty (e.g., buckling, etc.) solutions not available	• Not easy to generate multiple configurations • No built-in color graphics • No convenient database features • "Not so quick" turnaround • Not particularly low cost

AERODYNAMIC LOAD DISTRIBUTIONS

An auxiliary program was set up to provide flexible and rapid inputs to the finite element model for in-flight aerodynamic load distributions on launch vehicles. This method is particularly useful for evaluating the sensitivity of aerodynamic loads due to uncertainties. These uncertainties may be in trajectory parameters, such as: dynamic pressure (q), angle of attack (α), or vehicle center of gravity location (X_{cg}).

Aerodynamic forces normal to the vehicle longitudinal axis cause local loads and bending moments on the vehicle structure. They also require the rocket engines to be deflected (gimbaled) to balance the aerodynamically induced overturning moment on the vehicle. As shown in fig. 4, the loads analysis uses inputs that define certain basic aerodynamic, vehicle, and trajectory parameters.

Aerodynamic inputs consist of the normal aerodynamic force characteristics (transverse to the vehicle longitudinal axis). The aerodynamic normal forces and moments depend on the size and shape of the vehicle elements, and the trajectory parameters including: flight Mach number, angle of attack (α), and dynamic pressure (q). The vehicle size and shape determine the magnitude and shape of the normal force and the location of the airload center of pressure. The normal force is typically represented by distributed normal force coefficient slope, C_{N_α}, along the vehicle. C_{N_α} distributions are obtained empirically or from test data available for similar configurations. Empirical methods (ref. 5) were used for estimating the C_{N_α} variations along vehicle components of various shapes and for a wide range of flight Mach numbers.

The magnitude of α is typically obtained from dynamic trajectory simulations with superimposed wind shear and gusts. If trajectory simulations are not available, an approximate value for α can be estimated by superimposing the wind and gust speeds (ref. 6) on the vehicle speed.

$$\alpha = \mathrm{Tan}^{-1}\left(\frac{V_{wind} + V_{gust}}{V_{vehicle}}\right), \mathrm{rad} \qquad (1)$$

With the trajectory parameters of q and α, and with the C_{N_α} distribution defined along the vehicle, the auxiliary program is used (fig. 5). The method computes the distributed normal forces, net pressures, and the summed forces and moments about the vehicle's center of gravity. Using this method, a vehicle segment of incremental length is subjected to an aerodynamic normal force where the magnitude depends on C_{N_α}, q, and α.

$$\Delta\text{Normal Force} = q\, S_{ref}\, C_{N_\alpha}\, \alpha, \text{ lb/in.} \tag{2}$$

where:

$C_{N\alpha}$ = distributed normal force coefficient slope, 1/(in.-rad)

q = dynamic pressure, $1/2\ \rho\ (V_{vehicle})^2$ (lb/ft^2)

S_{ref} = reference area (ft^2)

α = angle of attack (rad)

ρ = atmospheric density (slugs/ft^2)

The above equations are used to compute the normal load distribution along the vehicle. It is then integrated within the auxiliary program to compute the load and moment summations about the center of gravity. The presence of additional elements, such as solid rocket motors (SRMs), can be accounted for by adding their point-load contributions to the total forces and moments.

Static balance calculations are included in the program to determine the amount of engine gimbal angle (δ) required to overcome (or balance) the aerodynamic moment. This is computed from the moment balance between the aerodynamic forces and the engine thrust, as shown below.

$$T\sin(\delta)(X_{gimbal} - X_{cg}) = \Sigma(C_{N_\alpha})q\alpha S_{ref}(X_{cg} - X_{cp}) \tag{3}$$

The above equation is then solved for the gimbal angle, δ.

$$\delta = \sin^{-1}\left(\frac{\Sigma(C_{N_\alpha})q\alpha S_{ref}(X_{cg} - X_{cp})}{T(X_{gimbal} - X_{cg})}\right), \text{deg} \tag{4}$$

where:

$\Sigma(C_{N_\alpha})$ = integrated normal force coefficient slope on vehicle (rad)

q = dynamic pressure (lb/ft^2)

S_{ref} = reference area (ft^2)

T = engine thrust (lb)

X_{cg} = center of gravity station (in.)

X_{cp} = center of pressure station (in.)

X_{gimbal} = engine gimbal station (in.)

α = angle of attack (rad)

δ = engine gimbal angle for balancing the aero forces (deg)

For the case when additional engines exist, as in the case of SRMs, the above static moment balance is altered to include such engines. With the SRM and Core subscripts used for the appropriate elements, the moment balance expression becomes:

$$(T_{Core} + T_{SRM})\mathrm{Sin}(\delta)(X_{gimbal} - X_{cg}) = q\alpha S_{ref}\left\{C_{N_{\alpha Core}}(X_{cg} - X_{cpCore}) + C_{N_{\alpha SRM}}(X_{cg} - X_{cpSRM}\right\} \tag{5}$$

where $C_{N_{\alpha Core}}$ corresponds to the core stage element and is equivalent to $\Sigma(C_{N_\alpha})$ in the previous moment balance equation.

Then:

$$\delta = \mathrm{Sin}^{-1}\left(\frac{q\alpha S_{ref}\left\{C_{N_{\alpha Core}}(X_{cg} - X_{cpCore}) + C_{N_{\alpha SRM}}(X_{cg} - X_{cpSRM})\right\}}{T_{Core}(X_{gimbal} - X_{cg}) + T_{SRM}(X_{gimbal} - X_{cg})}\right), \mathrm{deg} \tag{6}$$

With the gimbal angle defined, the axial and tangential thrust values are calculated. These thrust components are then used to compute the axial and tangential accelerations (normal to the vehicle longitudinal axis), which are input into the finite element model.

$$\text{axial acceleration} = \frac{\text{total axial thrust}}{\text{vehicle weight}} \tag{7}$$

$$\text{tangential acceleration} = \frac{\text{total tangential thrust} + \Sigma(\text{normal force})}{\text{vehicle weight}} \tag{8}$$

Key load parameters can be changed easily in the program to see their influence on loads and engine control deflections. A change in dynamic pressure, (q), angle of attack (α), or vehicle center of gravity (X_{cg}) will readily show the sensitivity of aerodynamic loads to such changes.

NASTRAN APPLICATIONS

The Background section of this paper discussed using two different finite element programs for structural analysis. Why not just use one model/program for the entire preliminary design cycle? The two systems, IDEAS and NASTRAN, have different advantages and disadvantages (see table I).

The finite element solver that is internal to IDEAS is a valuable tool, especially when rapid results based on model variations are desired; however, for certain applications, a NASTRAN finite element representation is much more useful. Figure 6 shows some of the static and dynamic applications that can be supported by the NASTRAN model.

The IDEAS finite element model can be used in its full mass and stiffness representation to compute the first few system mode shapes and natural frequencies of the accepted configuration. This information can be used as a check on the mode shapes and frequencies that are later computed using a reduced dynamic model (e.g., flexible body loads model) generated with NASTRAN.

CONCLUSION

The early portion of the preliminary design cycle makes the use of the finite element code in IDEAS attractive because a vehicle analysis can be quickly redone after sizing changes are made. This paper describes a procedure for preliminary design and shows how NASTRAN can be used as a vital tool in that process. Additionally, a method for setting up balanced vehicle load conditions, as an integral part of that procedure, has been explained in detail. The challenge in the preliminary design cycle is to create a large amount of meaningful information rapidly and inexpensively, to use the preliminary design analytical representation to interact with many disciplines, and to support the evolution of a detailed design.

The later stages of the preliminary design can be effectively handled by NASTRAN because of its ability to:

1. Handle many thousands of degree problems relatively cheaply
2. Run on many different platforms
3. Easily interface with other programs/data sources

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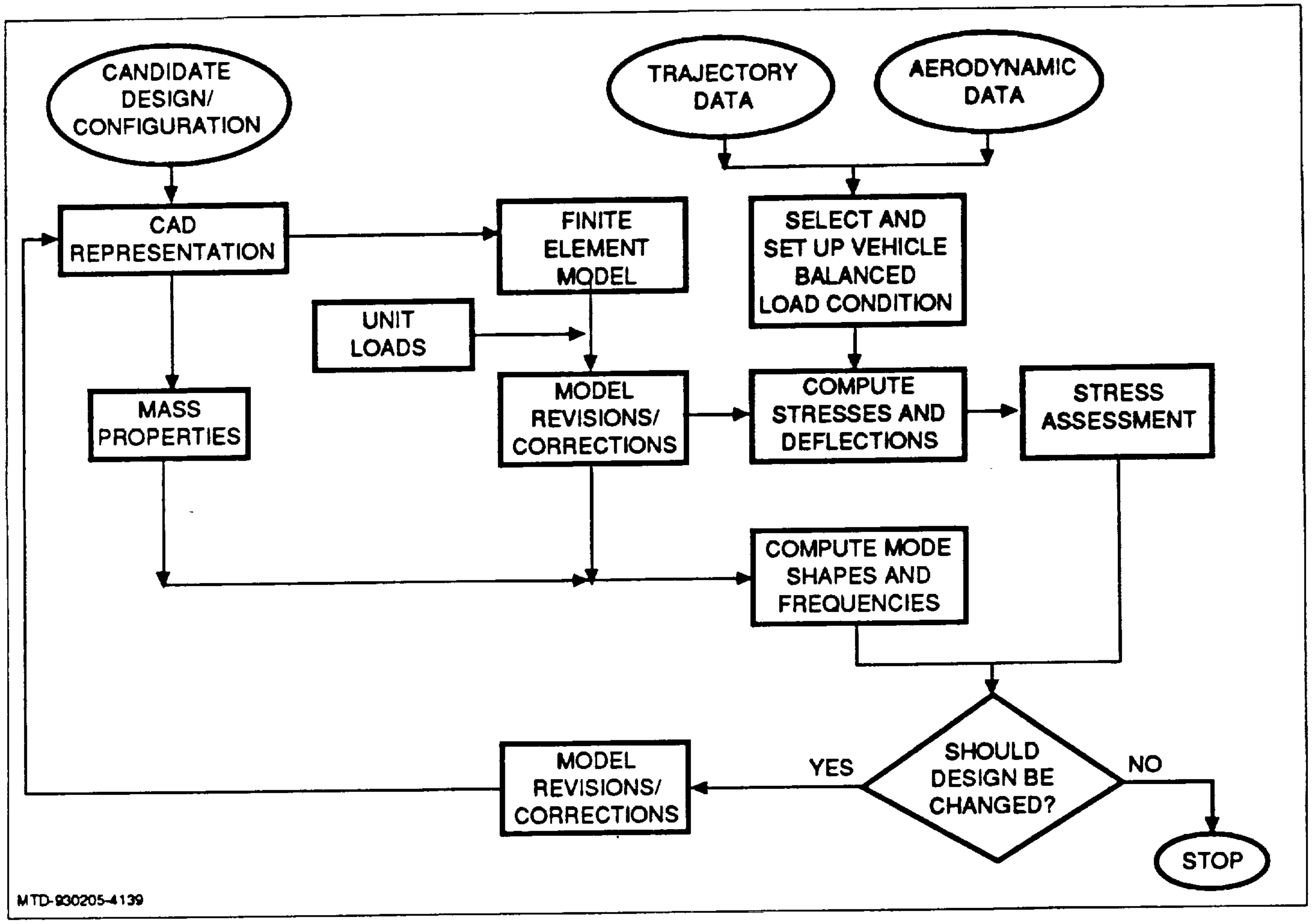

Figure 1. Preliminary Design and Analysis Cycle

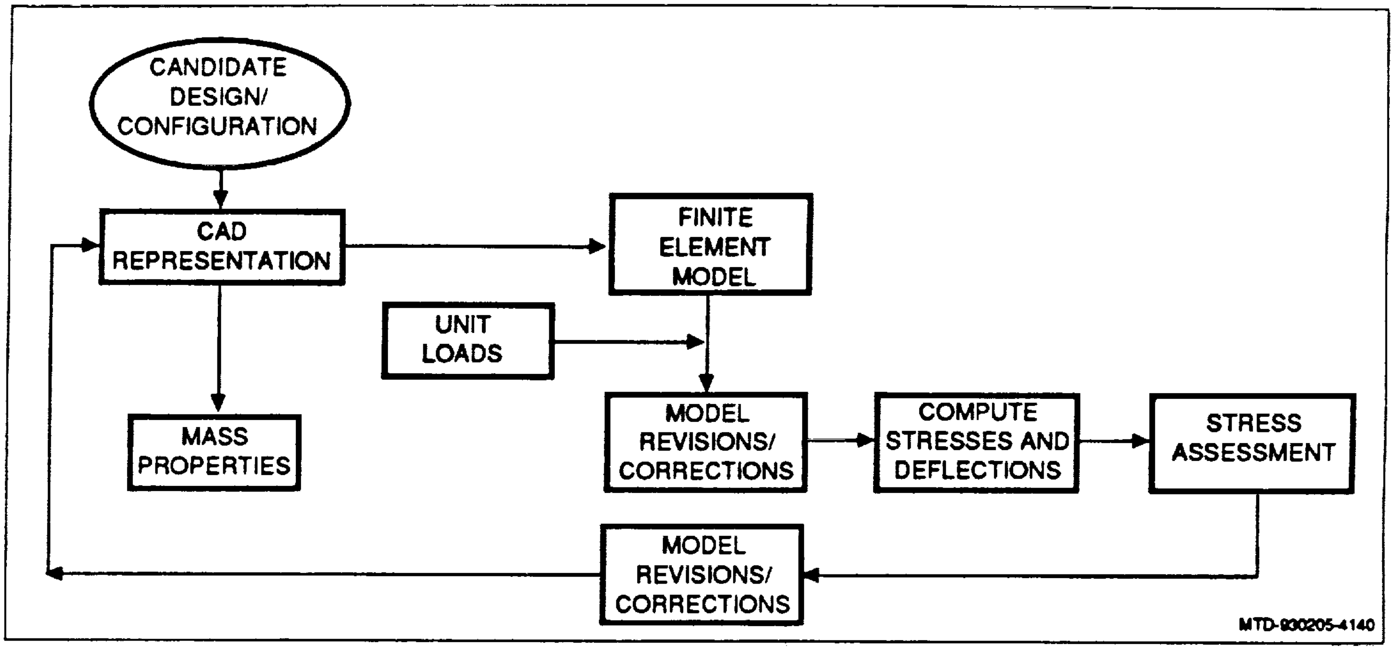

Figure 2. Units Loads are Used to Assess the Initial Design

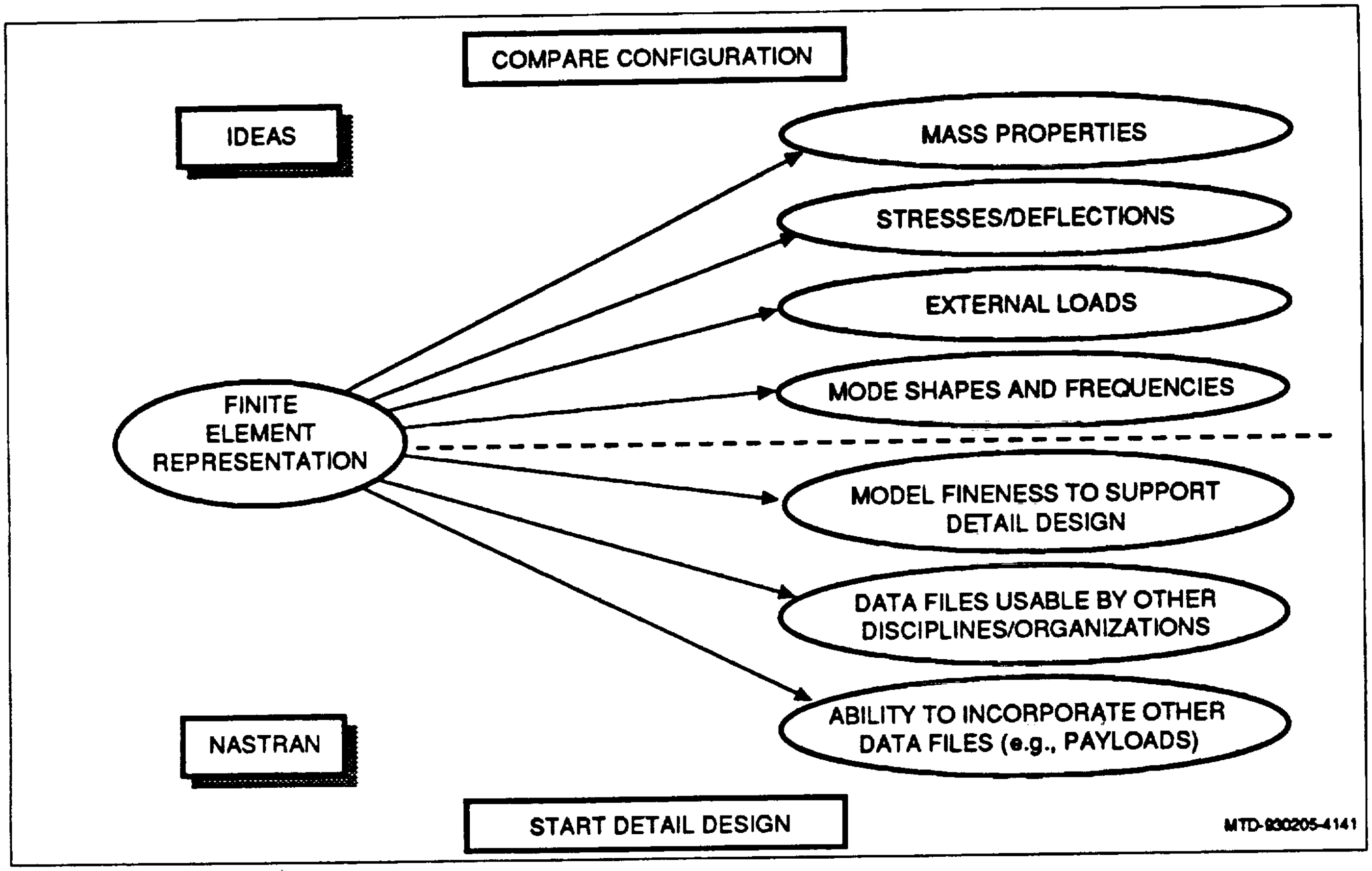

Figure 3. NASTRAN and IDEAS are Used for Different Purposes

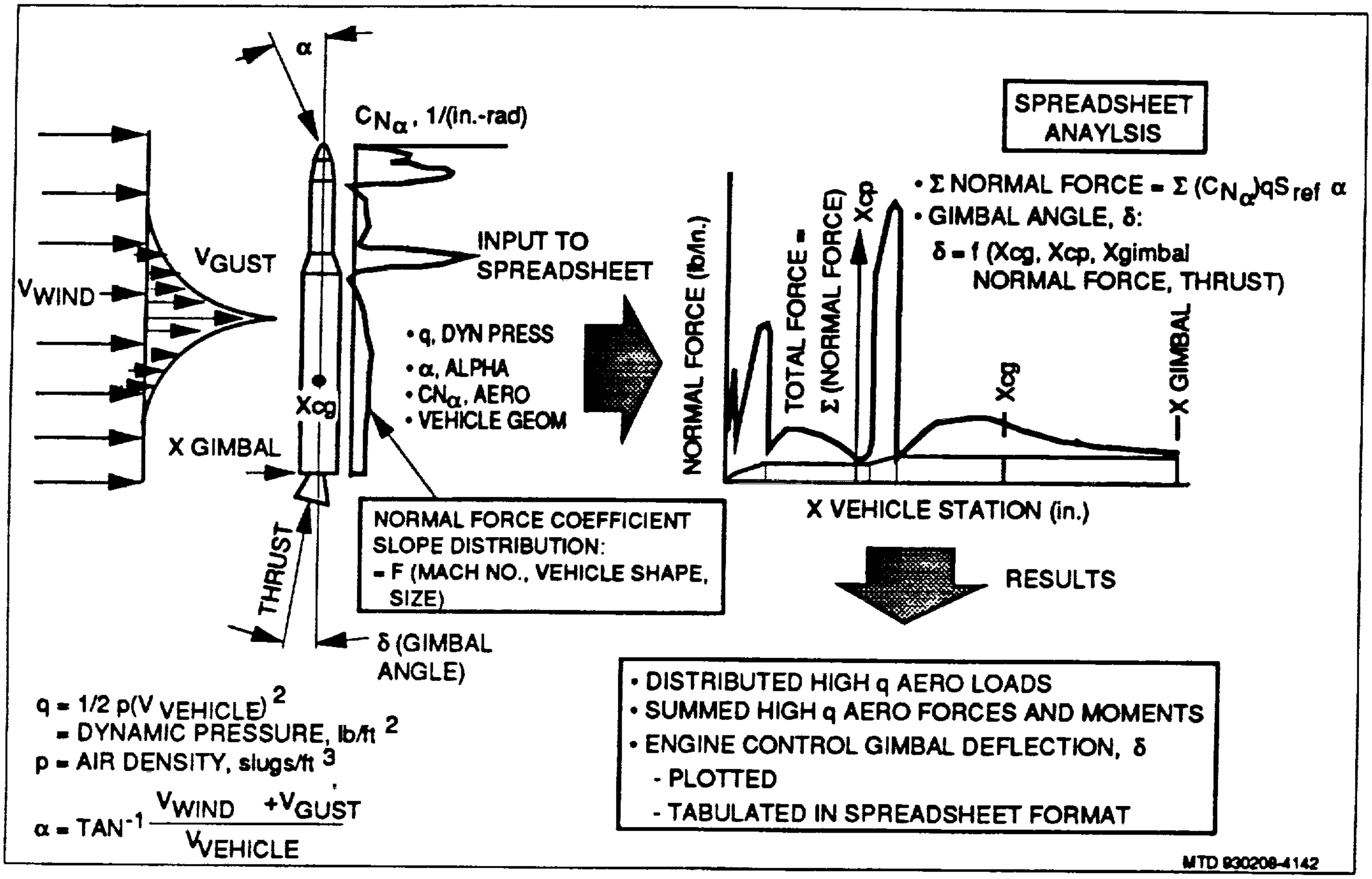

Figure 4. An Example of High Dynamic Pressure Region Vehicle Loads

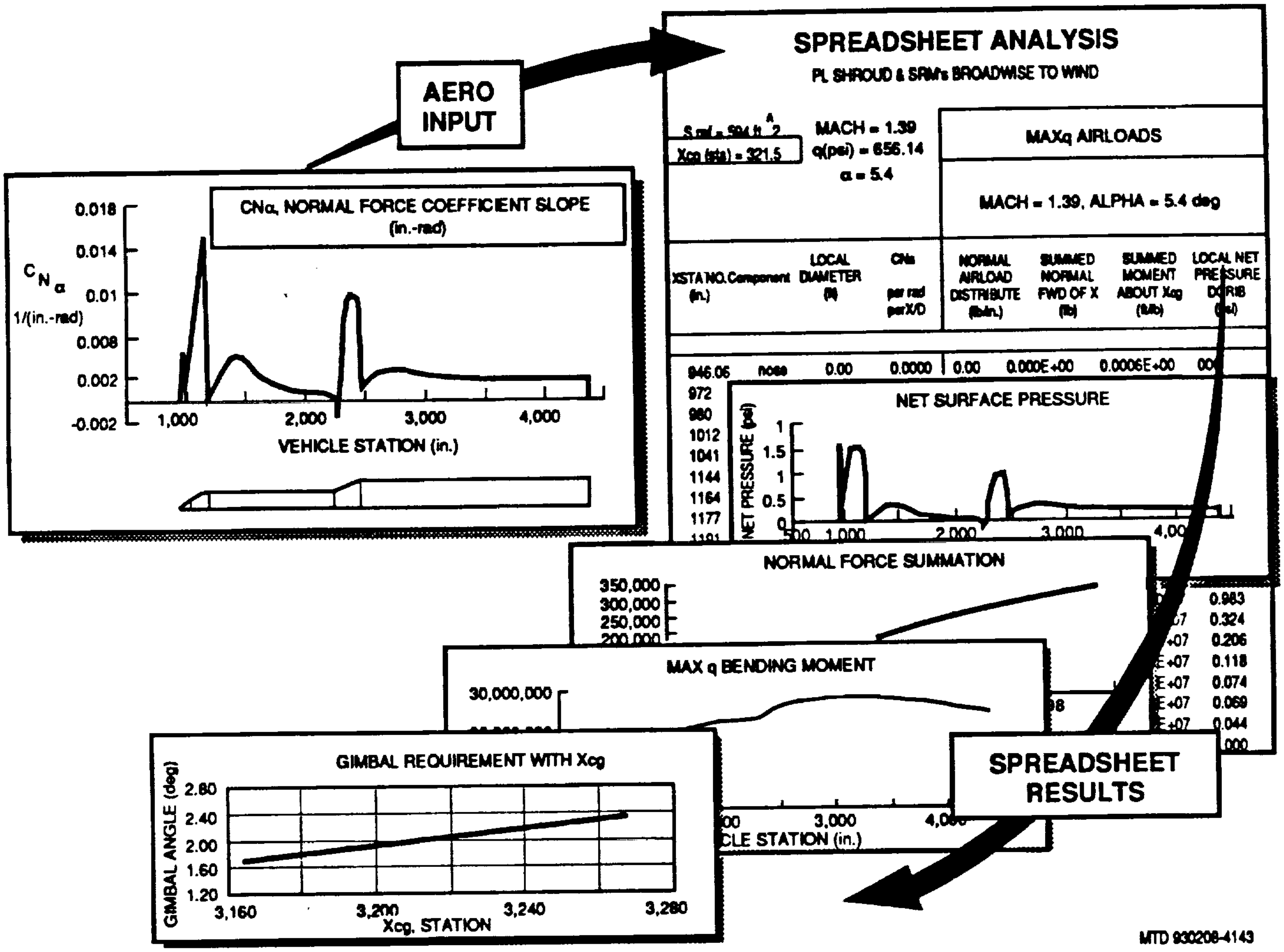

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Figure 5. The Aerodynamic Influence is Displayed Different Ways

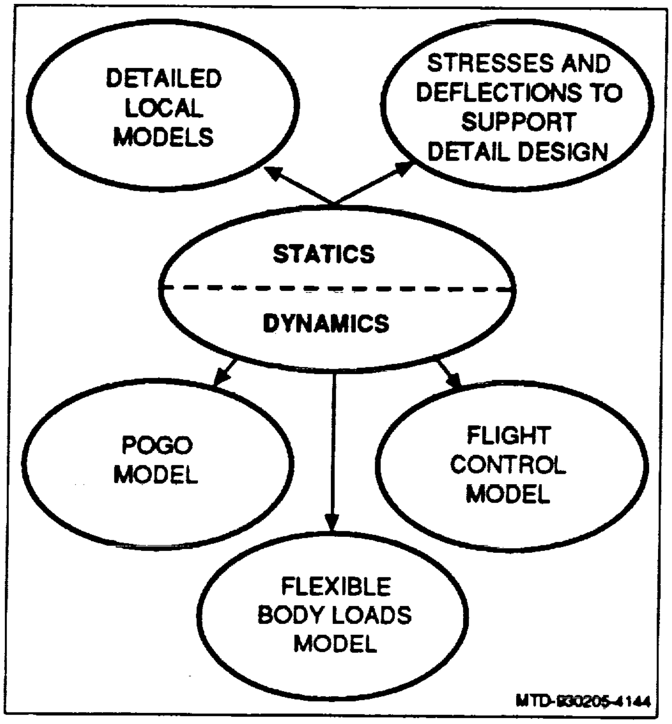

Figure 6. Applications of a NASTRAN Representation