THE ART OF SPACECRAFT DESIGN:
A MULTIDISCIPLINARY CHALLENGE

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INTRODUCTION

It is an engineer's dream to have all aspects of analysis done in a relatively short time period so that many different configurations can be examined. Hence, the best suitable design product can be delivered on time. Although this may still be a dream, actual design turn-around time has become shorter due to the use of optimization techniques which have been introduced into the design process. It seems that what, how and when to use these optimization techniques may be the key factor for future aircraft engineering operations.

Another important aspect of this technique is that complex physical phenomena can be modeled by a simple mathematical equation. For example, it is known that interactions among aerodynamic, structure, control and thermal are strong in the hypersonic flow regime[1]. Often, each analysis may fail due to highly complex, nonlinear conditions. Engineers, however, wish to understand the coupling effect and relationships between these disciplines even in the preliminary design stage. Traditionally, this type of analysis takes a long time because all disciplines are depending on one anothers results. Therefore, a small change in one of the disciplines results may cause long delay in analysis since all the disciplines must be reanalyzed.

The new powerful multilevel methodology reduces this time-consuming analysis significantly while maintaining the coupling effects. This simultaneous analysis method stems from the implicit function theorem and system sensitivity derivatives of input variables.[2,3,4] Use of the Taylor's series expansion and finite differencing technique for sensitivity derivatives in each discipline makes this approach unique for screening dominant variables from nondominant variables.[5]

In this study, the current CFD* aerodynamic and sensitivity derivative/optimization techniques are applied for a simple cone-type forebody of a high-speed vehicle configuration to understand basic aerodynamic/structure interaction in a hypersonic flight condition.

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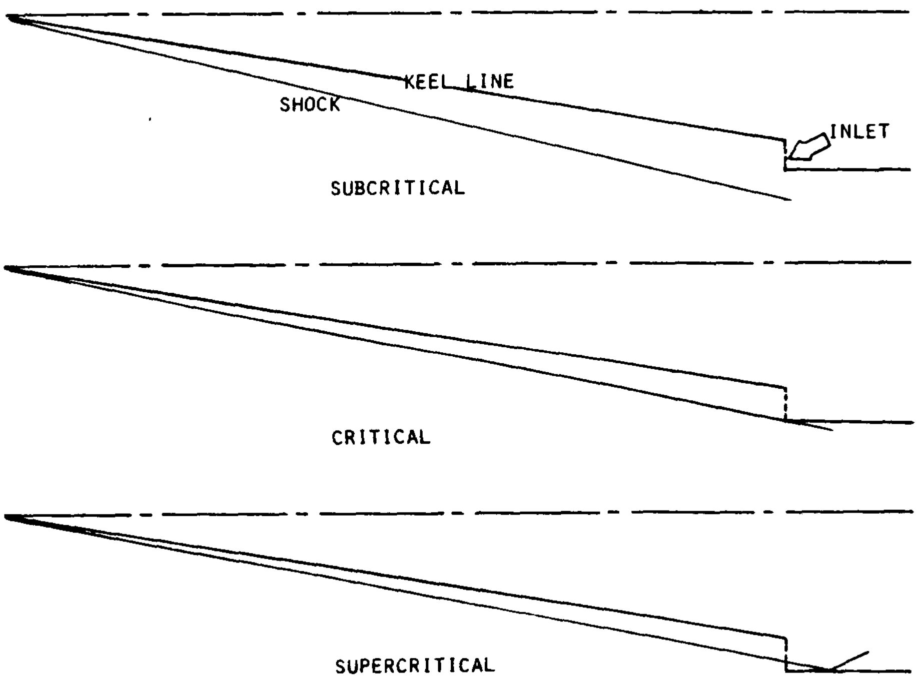
*Computational fluid dynamics (CFD).

PROBLEM IDENTIFICATION

The performance of hypersonic vehicles largely depends on shock strength and position at the engine's inlet. For example, a shock which is introduced at the nose of vehicle must be ingested by the inlet in order to avoid spillage of mass flow. Optimum performance can be expected when the shock impinges on the cowl's lip due to maximum mass flow and ram recovery. This condition, however, is marginally unstable in actual applications because small changes in angles of attack, yaw, boundary-layer separation (with or without thermal effects) and other changing conditions can induce the shock to move.

The main task of this study is to examine the effects of static aeroelasticity on the optimization of the forebody shape which is greatly dependent on the changes in the shock position.

FOREBODY/INLET AND SHOCK PATTERN

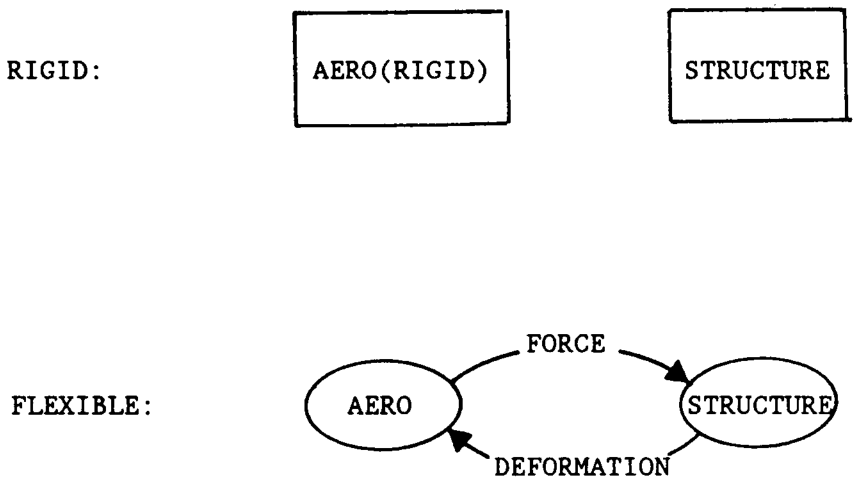


OBJECTIVES

Objectives of this study are two-fold: (1) finding the design parameters of a hypersonic forebody configuration which gives the maximum mass flow rate over the drag ratio at a specified inlet station and (2) examining the effect of the forebody static aeroelasticity.

The first level is the aerodynamic analysis for a rigid forebody. Sensitivity derivatives of the rigid body will be analyzed in this level. The second level is a structure analysis in terms of elastic boundary condition application. A vibration analysis is performed based on the predetermined FEM* and structural condition. Several mode shapes will be extracted from this level.

In the actual hypersonic flight regime, these two disciplines are uniquely coupled, and their interaction has a significant effect on the shock location. A new method to solve this type of coupled problems based on the implicit function theorem will be used to compute global sensitivity derivatives and these derivatives will be passed to an optimizer.



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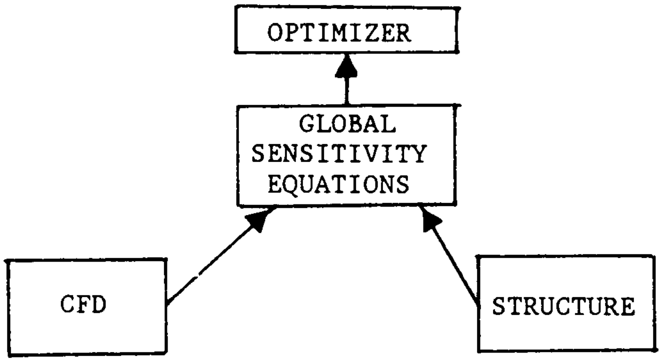
*Finite-element method (FEM).

APPROACHES

A new approach to analyze interaction between the design disciplines (aero, structure and dynamics) simultaneously and optimize required design parameters is introduced based on the implicit function theorem. The use of Taylor's series expansion and finite differencing technique for computing local sensitivity derivatives in each discipline make this approach unique since all discipline analyses can be performed concurrently.

The definition of objective function, in general, is a difficult task mainly due to unknown mathematical functions. Use of CFD analysis bypasses this time-consuming mathematical function identification by evaluating a series of digital points. Using these point distributions, one can create a simple mathematical model based on linear or quadratic function.



ADVANTAGES OF NUMERICAL SENSITIVITY DERIVATIVE/ OPTIMIZATION METHOD

- NO MATHEMATICAL FUNCTION DEFINITION IS REQUIRED
- CFD AND STRUCTURE ANALYSES ARE DONE INDEPENDENTLY
- SCREENING OF DESIGN OR LOCAL PARAMETERS IS EASY
- COUPLING EFFECT BETWEEN DISCIPLINES IS INCORPORATED

FORMULATION OF THE PROBLEM

A simple problem is assumed in this study. Since a basic configuration already exists, the sensitivity derivative and optimization technique is used to indicate the most feasible direction in which to find the optimum forebody shape. In order to set the correct direction in optimizing the objective function, a small perturbation technique based on the Taylor's series expansion method is used[5]. Therefore, the sensitivity derivatives are also evaluated at the initially known condition of the objective function.

Optimization of the ratio of mass flow rate ($\dot{m}_a$) and drag at a given station by changing design parameters X_i can be expressed as

$$\dot{m}_a/D = f\,(X_i) \tag{1}$$

where $\dot{m}_a/D$, or μ, is the mass flow rate-drag ratio at a given station, and X_i is the independent design variable.

By the use of Taylor's series expansion, Eqn. (1) is rewritten as

$$\dot{m}_a/D = (\dot{m}_a/D)_0 + \frac{\partial f}{\partial X_i} \triangle X_i \tag{2}$$

where $(\dot{m}_a/D)_0$ is the known initial condition.

TASKS

OBJECTIVE: maximize $\dot{m}_a/D$

CONSTRAINT: volume = volume required

VARIABLES: X_i

PROCEDURE: evaluate $\partial f/\partial X_i$

CFD ROLE IN OPTIMIZATION

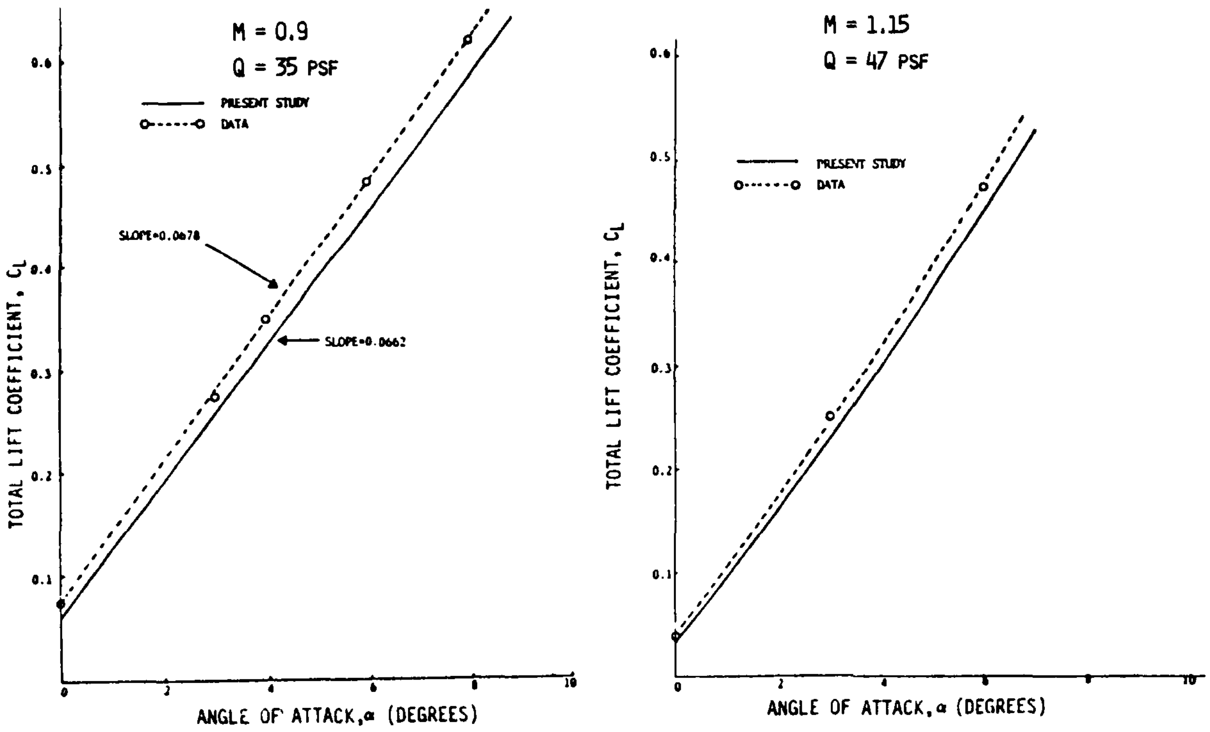
One of the objectives of this study is to show how CFD and products of CFD are used in an optimization technique.[2,5] The purpose of CFD analysis is to compute the aerodynamic flow and forces for a given object shape. Therefore, the input shape geometry is the most important factor that determines flow characteristics.[6,7,8]

CFD methods are the main tool to analyze and generate the aerodynamic sensitivity derivatives. Normally, CFD analysis is performed for at least three different points for a given variable. For example, to compute $\partial L/\partial \alpha$ as an element of the local sensitivity derivatives matrix, L must be evaluated at three different α's. By using three points, the nonlinear effect due to α change can be easily integrated into the optimization process.

If the nonlinear effect is very strong, more than three points can be used. Also, if L is evaluated for wide range of α once the same curve can be used for the optimization without reconstructing $\partial L/\partial \alpha$ curve.

C_L VS ANGLES OF ATTACK OF STATICALLY DEFORMED WING FOR

TRANSONIC AND SUPERSONIC FLOW CONDITIONS

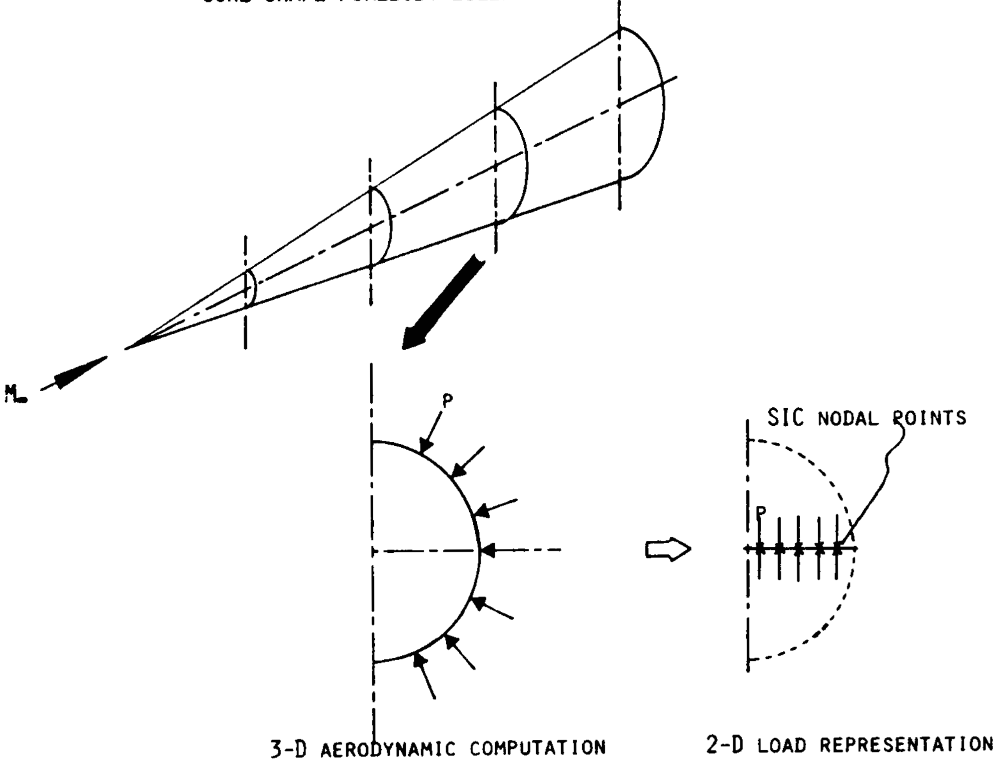


EULER-MARCHING CODE

The current NAA Euler marching code (EMTAC-MZ)[9] solves a set of Euler equations for a complex 3-D configuration across the Mach number range. In the code, a finite volume, multizone implementation of high accuracy total variation diminishing (TVD) formulation (based on Roe's scheme) is used. This code has been applied for numerous configurations including shuttle orbiter with external tank and solid rocket boosters, and the F-14 fighter. It has proved to be accurate as well as robust.

Aerodynamic pressure forces are computed on the 3-D body surface which is contoured in the perpendicular plane to the longitudinal direction as shown in figure below. The pressure forces are summed in the mean plane where structural influence coefficients (SIC) are defined. This process is repeated for each station where SIC's are present.

CONE SHAPE FOREBODY EULER-MARCHING MODEL



SIC VS MODAL APPROACH

While it is possible to conduct static and dynamic aeroelastic analyses starting either with direct SIC's or with modal data, the modal approach has some advantages in providing a measure of physical insight into the aeroelastic phenomena. Also, there is a very serious disadvantage to the SIC approach: the SIC approach tends to produce surface ripples which are not present in the modal approach. This type of ripple could produce unwanted shocks or the code may blow up if it is severe enough. In order to avoid this problem, the modal approach was taken for this study. The modal approach can reduce the size of the sensitivity derivatives matrix significantly due to utilization of generalized coordinates.

ADVANTAGES OF MODAL APPROACH

- The deformed shape is smooth and does not have any abrupt geometry slope changes (good for aerodynamic analysis)
- No need for extra smoothing operation of body geometry
- The system is considered a summation of known shapes (modal data); thus, variables can be reduced significantly by generalization
- Each mode shape has a physical meaning and is easy to identify, ie., 1st bending, 1st torsion, etc

ISSUES OF GRID TRANSFORMATION

- CFD - FEM grid transformation

  through interpolation techniques
- CFD - generalized coordinates transformation

  through MODE shapes
- FEM - generalized coordinate transformation

  through CFD-generalized coordinate transformation

SENSITIVITY DERIVATIVES

The two disciplines in this study are aerodynamics and structure. Aerodynamic discipline computes generalized lift and drag. Also, $\dot{m}_a/D$ is computed at a specified location. Structure discipline computes SIC with FEM model and mode shapes from vibrational analysis. Thus, the following is the sensitivity derivative matrix

$$\begin{array}{c|ccc|}
 & L_i & \mu & M_j \\
L_i & 1 & 0 & -\frac{\partial f(L)}{\partial M} \\
\mu & 0 & 1 & -\frac{\partial f(\mu)}{\partial M} \\
M_j & -\frac{\partial f(M)}{\partial L} & -\cancelto{0}{\frac{\partial f(M)}{\partial \mu}} & 1
\end{array}
\left\{\begin{array}{c} \frac{\partial L}{\partial X} \\ \frac{\partial \mu}{\partial X} \\ \frac{\partial M}{\partial X} \end{array}\right\}
=
\left\{\begin{array}{c} \frac{\partial f(L)}{\partial X} \\ \frac{\partial f(\mu)}{\partial X} \\ \frac{\partial f(M)}{\partial X} \end{array}\right\}$$

where $\mu = \dot{m}_a/D$, $f(L)$, $f(\mu)$ and $f(M)$ are functions of aerodynamic force, mass flow rate and mode shape respectively. Also,

$\partial f(L_i)/\partial M_j$ - change in aerodynamic force due to change in mode shape

$\partial f(\mu)/\partial M_j$ - change in mass flow rate due to change in mode shape

$\partial f(M_j)/\partial L_i$ - change in mode shape due to change in aerodynamic force

$\partial L_i/\partial X_k$, $\partial \mu/\partial X_k$ and $\partial M_j/\partial X_k$ - global sensitivity derivatives with respect to the design parameter X_k

$\partial f(L_i)/\partial X_k$, $\partial f(\mu)/\partial X_k$ and $\partial f(M_j)/\partial X_k$ - change in aerodynamic force, mass flow rate, mode shape due to design parameter change

i is generalized force index
j is mode shape index
k is design parameter index

ISSUES OF GENERATING SENSITIVITY DERIVATIVES

The terms $\partial f(L)/\partial M$, $\partial f(\mu)/\partial M$, $\partial f(L)/\partial X$ and $\partial f(\mu)/\partial X$ are easy to compute since CFD operation requires geometry input and M and X relate this input geometry directly. The $\partial f(M)/\partial L$ and $\partial f(M)/\partial X$ computations, on the other hand, are not easy due to introduction of the generalized coordinate which requires special treatment. This special treatment is shown below.

COMPUTATION OF $\partial f(M)/\partial L$

$$\text{Given } \{p_G\} = [M]^T\{p_D\} \text{ and } \{\delta_D\} = [M]\,\{\delta_G\}$$

where p is load, δ is deflection, [M] is mode shape matrix, subscript G is generalized, and D is SIC nodal coordinate systems. The potential energy, U, is

$$U = (1/2)\{\delta_D\}^T\{p_D\} = (1/2)\{\delta_G\}^T\{p_G\}$$

Since $\{\delta_D\}=[sic]\{p_D\}$, the above equation will take the following form:

$$\begin{aligned} U &= (1/2)\{\delta_D\}^T\,\{p_D\} \\ &= (1/2)\{\delta_D\}^T[sic]^{-1}\{\delta_D\} \\ &= (1/2)\{\delta_G\}^T[M]^T[sic]^{-1}[M]\{\delta_G\} \\ &= (1/2)\{\delta_G\}^T\{p_G\} \end{aligned}$$

Therefore, $\{\delta_G\} = [\ [M]^T[sic]^{-1}[M]\ ]^{-1}\ \{p_G\} \equiv [B]\{p_G\}$ and the specific relationship matrix [B] is the sensitivity.

COMPUTATION OF $\partial f(M)/\partial X$

Based on the sensitivity matrix [B], $\partial f(M)/\partial X$ is computed as;

$$\begin{tikzcd}
 & FEM^+ \arrow[r] & {[sic]^+} \arrow[r] & {[B]^+} \arrow[r] & \{\delta_G\}^+ = [B]^+\ \{p_G\}_0 \\
FEM_0 \arrow[ur, "+\Delta X"] \arrow[dr, "-\Delta X"'] & & & & \\
 & FEM^- \arrow[r] & {[sic]^-} \arrow[r] & {[B]^-} \arrow[r] & \{\delta_G\}^- = [B]^-\ \{p_G\}_0
\end{tikzcd}$$

where 0 is the fixed condition, ΔX is the perturbation. From this process, $\partial f(M)/\partial X = (\{\delta_G\}^+ - \{\delta_G\}^-)/(2\Delta X)$ is computed.

CONFIGURATION CRITERIA

A simple cone type forebody hypersonic configuration has been selected. Flow condition is selected as M_∞=16, α=0.0 and the dynamic pressure, Q, of 1500 psf. Also, this study is a simulation of a wind tunnel model so that the aft section of the vehicle is fixed in space. Consequently, no free-free mode shapes are introduced. The three mode shapes used here are all structural mode shapes.

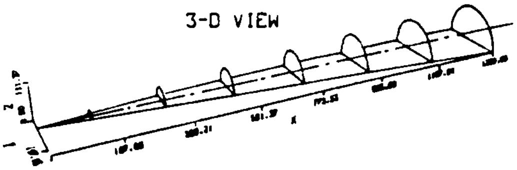
FLOW CONDITION

$M_\infty = 16.0$

$\alpha = 0.0$

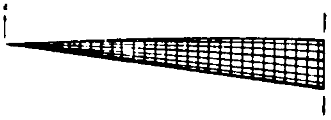
$Q = 1,500$ psf

HYPERSONIC VEHICLE FOREBODY CONFIGURATION



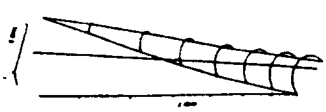
3-D VIEW

AERODYNAMIC MODEL

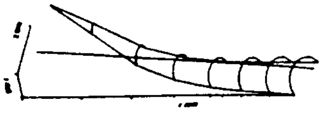


FEM MODEL

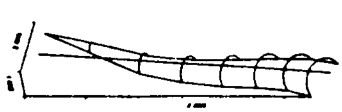
VIBRATIONAL ANALYSIS AND MODE SHAPES



1ST BENDING 0.76 HZ



2ND BENDING 2.3 HZ



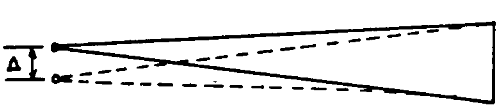
3RD BENDING 3.5 HZ

DESIGN PARAMETER SELECTIONS

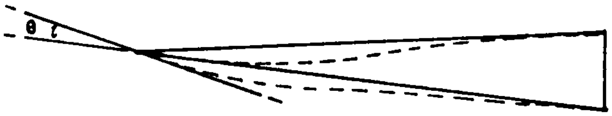
A total of four design parameters are selected from previous experiences. They are length, vertical nose position, keel line shape, and fuselage radius. A volume constraint (equality type) is also included.

SELECTED DESIGN PARAMETERS

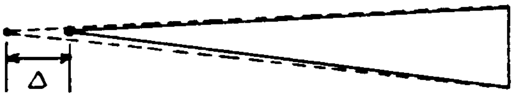
KEEL LINE TRANSLATION (nose point moves vertically)



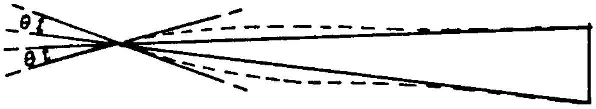
KEEL LINE ROTATION (nose point rotate)



FUSELAGE LENGTH



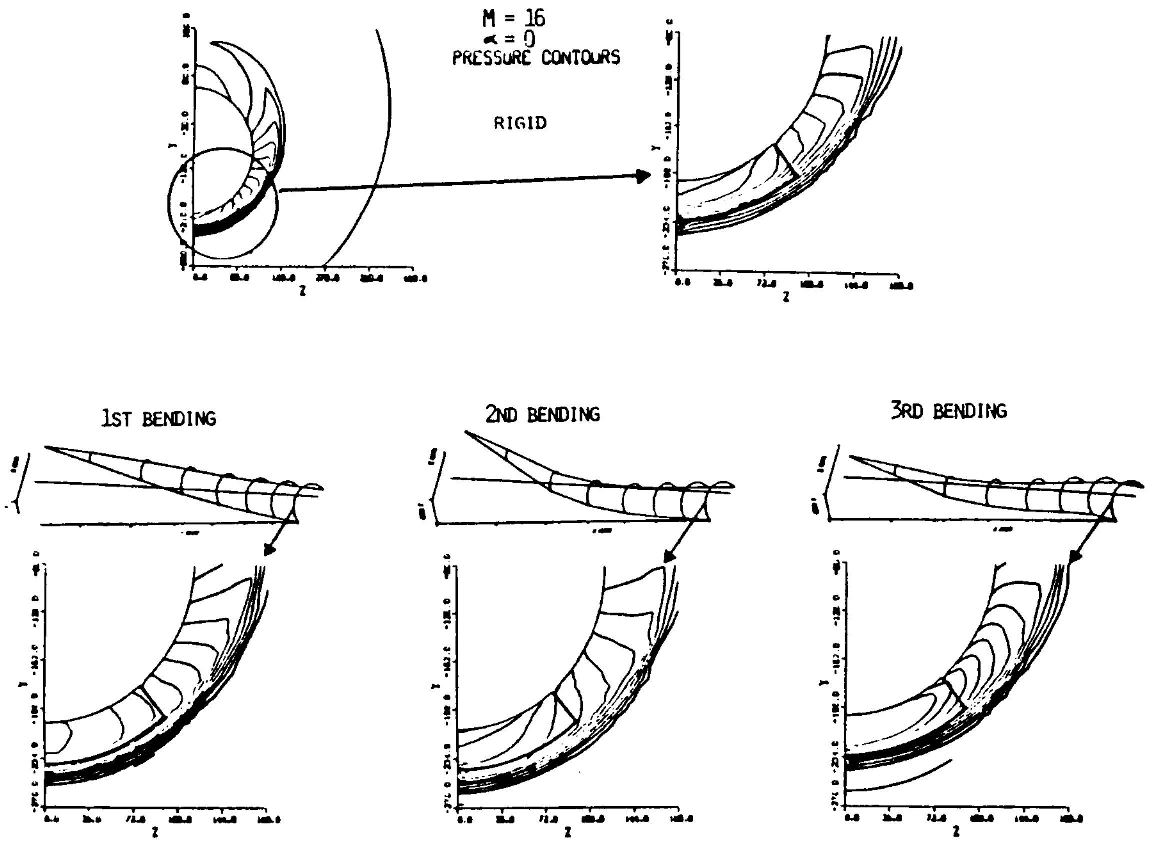
FUSELAGE RADIUS



EFFECT OF THE MODAL SHAPE ON AERODYNAMICS

The three mode shapes computed by the structural analysis were analyzed by the Euler marching code. The results are shown in the figure below. They were then used to calculate the local sensitivities which were fed into the global sensitivity equations. The first and second bending modes produced a decrease in $\dot{m}_a/D$, while mode three showed a considerable increase.

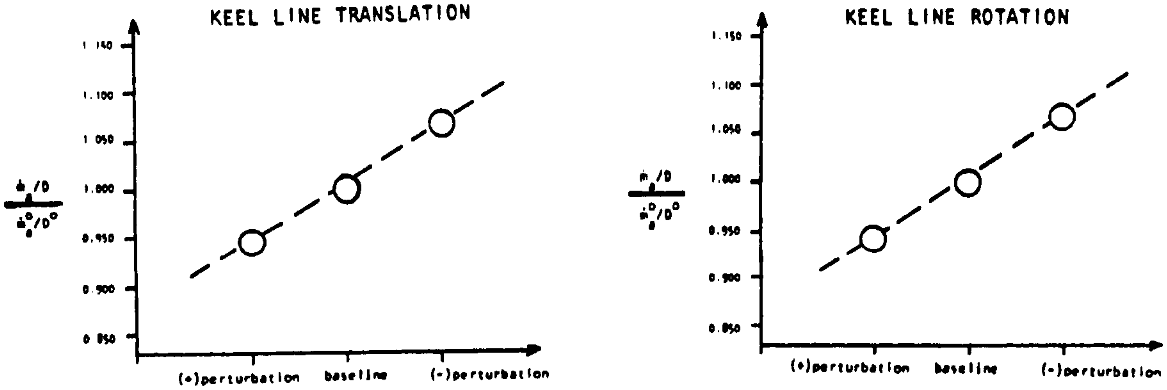
HYPERSONIC FLOW CHANGES DUE TO ELASTIC EFFECT



AERODYNAMIC SENSITIVITIES TO DESIGN PARAMETERS

The aerodynamic sensitivities were obtained using computational fluid dynamics (CFD). A baseline analysis was computed. Then, analysis was performed for a positive and a negative perturbation of each design parameter. The results for the two design parameters which effect the translation and rotation of the keel line are presented in the figure below. These parameters affect the objective function, but they have no effect on the volume constraint.

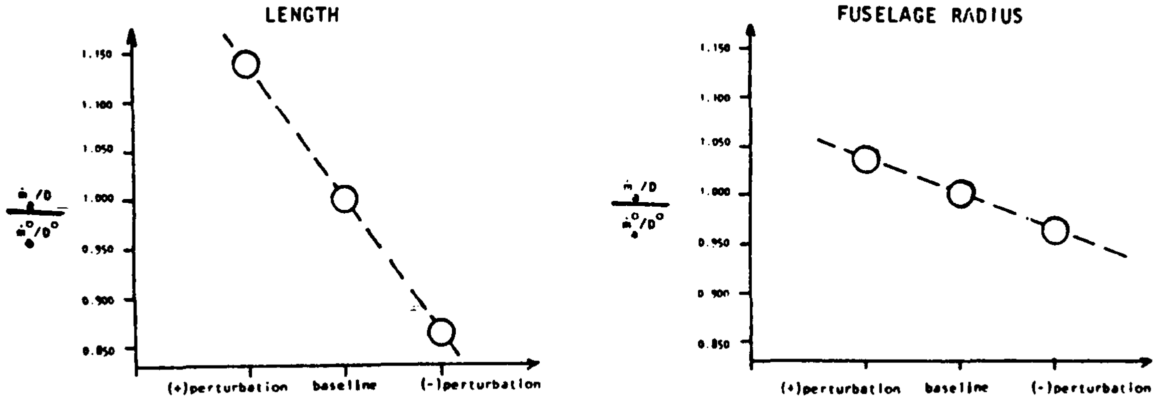
SENSITIVITY OF OBJECTIVE FUNCTION TO KEEL LINE SHAPE



AERODYNAMIC SENSITIVITIES (CONCLUDED)

The length and radius of the fuselage directly affect the volume constraint. The results for these two parameters are shown in the figure below. During the optimization process, there will be a trade-off between these two variables inorder to maintain the same volume.

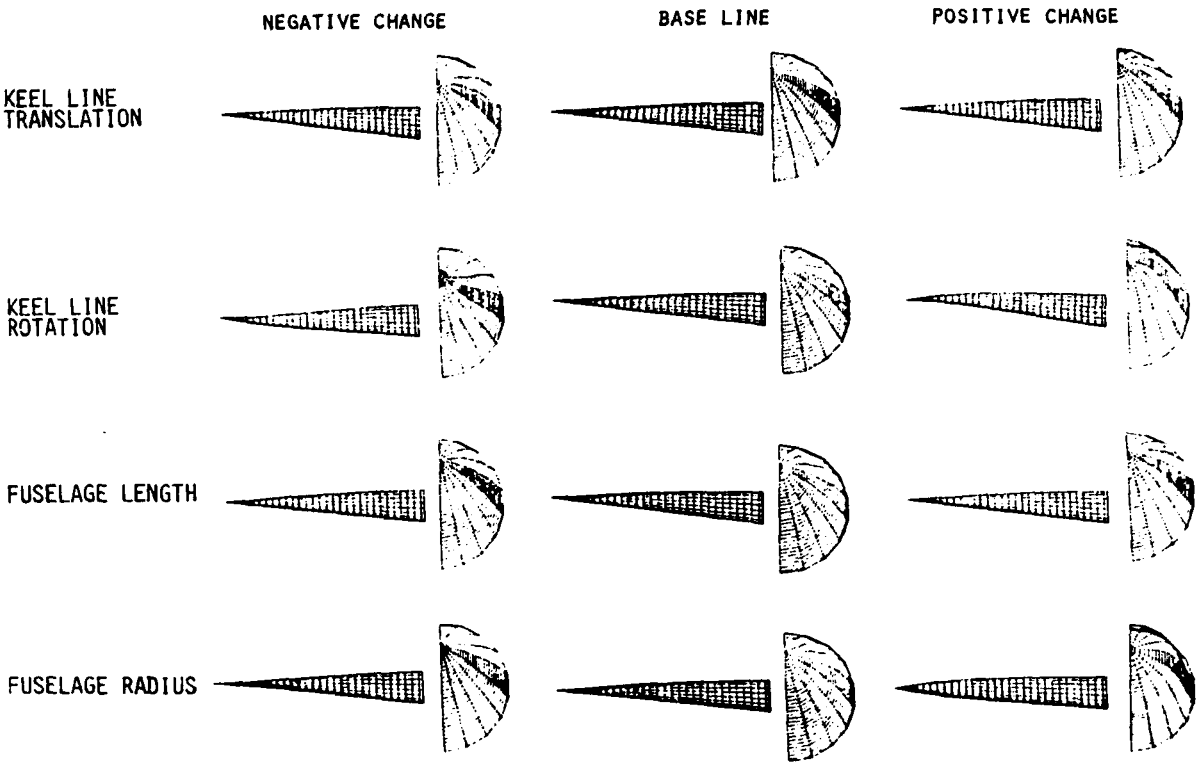
SENSITIVITY OF OBJECTIVE FUNCTION
TO THE LENGTH AND RADIUS OF THE FUSELAGE



STRUCTURAL ANALYSIS

Structural sensitivity derivatives are generated by using Rockwell, NAA's rapid structural optimization program (RSOP)[10] which includes FEM generation, structural analysis and optimization, thermal analysis and automatic data/grid transformation. The trend study of the RSOP analysis for the selected design parameters shows that the fuselage radius is the dominant parameter. The results of the RSOP analysis of the forebody shapes due to parameter change are shown below.

DESIGN PARAMETERS TREND FOR STRUCTURAL ANALYSIS



OPTIMIZATION RESULTS

Optimization was performed for a rigid (aerodynamics only) and a flexible (aerodynamics and structures) forebody. The results for each are presented in the figure below. The results were computed using ADS[11] with ISTRAT-0 (no strategy, go directly to optimizer), IOPT-4 (Method of Feasible Directions), and IONED-7 (find the minimum of an constrained function by first finding bounds and then using polynomial interpolation). A volume equality constraint was employed. The results shown are a first pass through the optimizer. At this point the process would continue by first analyzing the present shape, this shape then becomes the new baseline. Next, the local sensitivity analysis is performed about the new baseline and they are fed into the global sensitivity equations. The new global sensitivities are then used by the optimizer to produce a new optimized shape. This process is repeated until a converged shape is obtained.

FIRST PASS OPTIMIZATION RESULTS

Rigid	Flexible
Change in design parameters	
- increased length (31.36 in.)	- decreased length (0.55 in.)
- decrease in fuselage radius	- increase in fuselage radius
- nose tip moved downward	- nose tip moved downward
- negative keel line rotation	- negative keel line rotation
Objective function value (normalized)	
OBJECTIVE - 1.08345	OBJECTIVE - 1.05871

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