N87-11734

# OPTIMAL REDESIGN STUDY OF THE HARM WING

S. C. McIntosh, Jr.
McIntosh Structural Dynamics, Inc.
Palo Alto, California

M. E. Weynand
Texas Instruments Inc.
Lewisville, Texas

## PROJECT TASKS

The purpose of this project was to investigate the use of optimization techniques to improve the flutter margins of the HARM AGM-88A wing. The missile has four cruciform wings, located near mid-fuselage, that are actuated in pairs symmetrically and antisymmetrically to provide pitch, yaw, and roll control. The wings have a solid stainless steel forward section and a stainless steel crushed-honeycomb aft section. The wing restraint stiffness is dependent upon wing pitch amplitude and varies from a low value near neutral pitch attitude to a much higher value at off-neutral pitch attitudes, where aerodynamic loads lock out any free play in the control system. The most critical condition for flutter is the low-stiffness condition in which the wings are moved symmetrically. Although a tendency toward limit-cycle flutter is controlled in the current design by controller logic, wing redesign to improve this situation is attractive because it can be accomplished as a retrofit.

Project tasks are listed in figure 1. In view of the exploratory nature of the study, it was decided to apply the optimization to a wing-only model, validated by comparison with results obtained by Texas Instruments (TI). Any wing designs that looked promising were to be evaluated at TI with more complicated models, including body modes. The optimization work was performed by McIntosh Structural Dynamics, Inc. (MSD) under a contract from TI.

1. Develop simplified wing-only models and match TI frequencies and mode shapes for four root restraints--symmetric low and high stiffness, antisymmetric low and high stiffness.

2. Perform flutter analyses at $M = 0.8, 1.2, 1.5, 2.5$. Compare results with those computed by TI.

3. Optimize for improved flutter margins; concentrate on critical configuration (symmetric, low stiffness).

4. Assess optimized wing designs in cooperation with TI; perform additional analyses, optimizations, and assessments as time, funding permit.

5. Submit a Final Report.

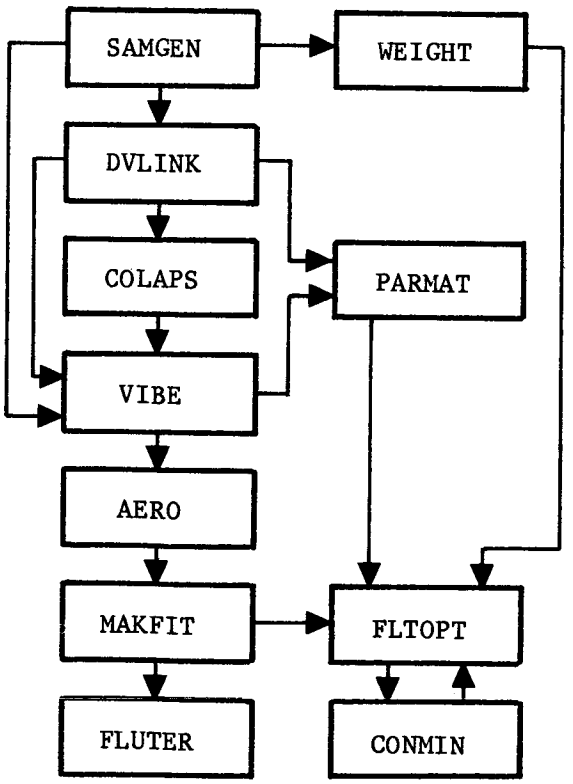
Figure 1

## FLOW DIAGRAM OF ANALYSIS AND OPTIMIZATION TASKS

The various computer codes used in this project and their functions are illustrated in figure 2. The tasks on the left side of the figure represent the traditional flutter-analysis cycle, with the exception of the design-variable linking capability in DVLINK. This code permits arbitrary combinations of design variables to be linked together, or slaved, so that a number of different optimization models can be created from a single output file of the finite-element code SAMGEN. DVLINK also includes a scaling capability, so that discrete finite-element models of any new design can be created without recourse to SAMGEN. Design variables for either bending or in-plane elements can be used.

Program PARMAT makes use of the system's natural modes from VIBE and the discrete mass and stiffness matrices from DVLINK associated with each design variable to create the corresponding generalized mass and stiffness matrices. Program WEIGHT makes use of the input data for SAMGEN to compute weight coefficients for each design variable to be used in determining the objective function (weight). All this information is passed to the optimization executive routine FLTOPT, which is coupled to the general-purpose optimization code CONMIN (ref. 1). The development of the original versions of the analysis codes is described in refs. 2 and 3.

All of the MSD computations were performed on a DEC VAX 11/780 minicomputer.




| Program | Purpose |
|---|---|
| SAMGEN | Generate finite-element model, discrete derivative matrices |
| DVLINK | Generate linked, scaled finite-element model |
| COLAPS | Collapse mass, stiffness matrices |
| VIBE | Compute natural modes, frequencies |
| AERO | Compute generalized aerodynamic forces--doublet lattice (subsonic), Mach box (supersonic) |
| MAKFIT | Compute polynomial fits of generalized aerodynamic forces in Mach number, reduced frequency |
| FLUTER | Perform flutter analyses |
| WEIGHT | Compute weight coefficients for objective function |
| PARMAT | Compute generalized derivative matrices |
| FLTOPT | Control optimization; evaluate constraints and constraint gradients |
| CONMIN | Optimization driver (feasible directions) |

Figure 2

## WING FINITE-ELEMENT MODEL

The wing node-point layout and original design-variable numbering are illustrated in figure 3. The node-point layout on the wing and the element thicknesses were identical with those used at TI. The solid forward section was represented by solid triangular bending elements and the sandwich aft section by sandwich triangular bending elements. The TI wing model incorporated quadrilateral elements and sandwich elements with shear flexibility, which the MSD sandwich elements did not have. The MSD wing model was therefore somewhat stiffer than the TI model, and this resulted in MSD-computed natural frequencies that were greater than those computed at TI, particularly for the higher mode numbers. Mode shapes and frequencies for the lower mode numbers (say, the first three) were in very good agreement, however, for both cantilever and free-free test cases.

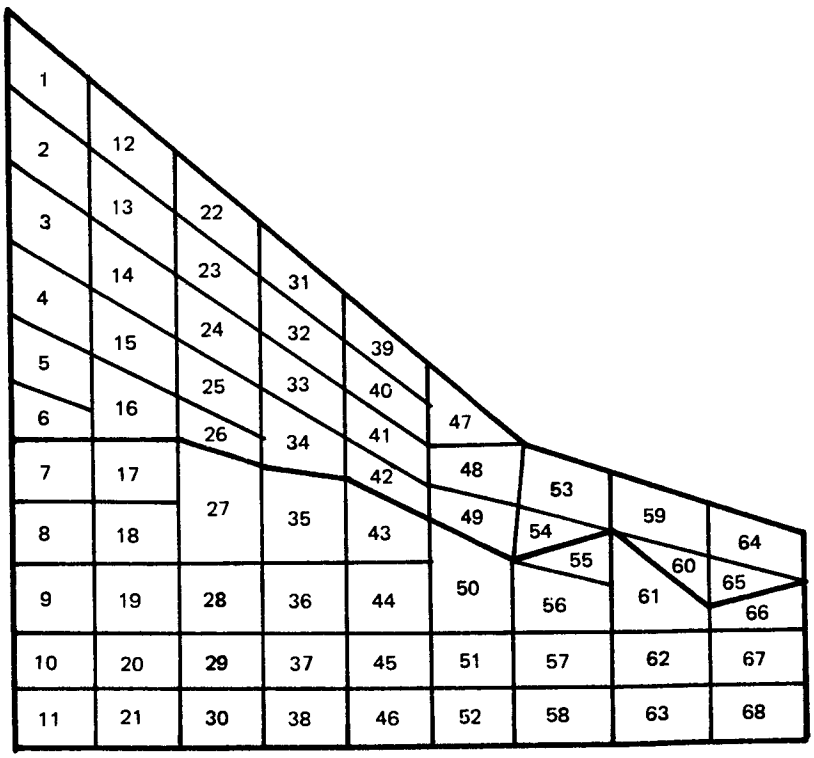



Figure 3

## FREQUENCY COMPARISONS

The wing model to be optimized had linear springs at the root to represent restraint stiffnesses in the pitch (control) and flap (transverse) directions. Four separate configurations had been analyzed by TI--low and high stiffness values for both symmetric and antisymmetric control motions. These four configurations were also analyzed by MSD. Nominal equivalent linear spring rates supplied by TI were used initially for the root restraints and were then varied to provide the best possible match with TI-computed frequencies, where these were available. The results of this matching effort are given in figure 4. For the two low-stiffness configurations, the first two frequencies were matched virtually exactly, with relatively minor variations from the nominal stiffness values. For the one high-stiffness configuration for which TI-computed frequencies were available, it was not possible to match the frequencies very well. In this case, the simple two-spring model was not adequate to represent the root restraint given by the actual hardware. A more representative simplified model was not developed for this configuration, since the two low-stiffness configurations were more critical for flutter.

| | SYMMETRIC | | | | ANTISYMMETRIC | | | |
|---|---|---|---|---|---|---|---|---|
| | $K_\theta$ | $K_f$ | $f_1$ | $f_2$ | $K_\theta$ | $K_f$ | $f_1$ | $f_2$ |
| | Low Stiffness | | | | Low Stiffness | | | |
| TI | 209.0 | 7,880 | 42.78 | 96.00 | 3,279 | 8,640 | 78.29 | 150.8 |
| MSD | 294.6 | 6,458 | 41.53 | 96.72 | 1,679 | 18,550 | 77.84 | 150.9 |
| | High Stiffness | | | | High Stiffness | | | |
| TI | 1,016 | 16,000 | 80.5 | 128 | 2,962 | 28,410 | - | - |
| MSD | 1,930 | 16,000 | 78.8 | 156 | 2,962 | 28,410 | 87.5 | 183 |

$K_\theta$ = pitch stiffness, in-lb/deg
$K_f$ = flap stiffness, in-lb/deg
$f_1$ = first mode frequency, Hz
$f_2$ = second mode frequency, Hz

Figure 4

## ENFORCEMENT OF FLUTTER-SPEED CONSTRAINT

Flutter analyses of the isolated wing with the four root-restraint conditions discussed previously confirmed that the symmetric low-stiffness condition was the critical one, with the flutter margin in the low supersonic Mach number range most in need of improvement. Redesign to improve the flutter speed at Mach 1.5 was therefore selected as the principal goal. Improvement in the flutter speed was sought by posing the usual optimization problem with weight as the objective function, but with an initial flutter-related constraint that was violated. The flutter constraint was imposed by requiring that the damping parameter g be less than or equal to a critical value of 0.03 (in other words, flutter was defined for 3% structural damping). The altitude, Mach number, and airspeed were fixed. Figure 5 illustrates this concept. An initially infeasible point on the critical flutter branch in V-g space was to be driven to $g = 0.03$ or less along a constant-V line. The optimization algorithm was thus confronted with two tasks--first, to bring the flutter constraint function $g = 0.03$ to an acceptable value, and second, to reduce the wing weight, if possible, without violating this constraint.

During constraint evaluation, the value of the reduced frequency was varied to keep the airspeed associated with the critical root equal to the desired airspeed. Generalized coordinates defined by the natural modes of the initial design were retained throughout the optimization.

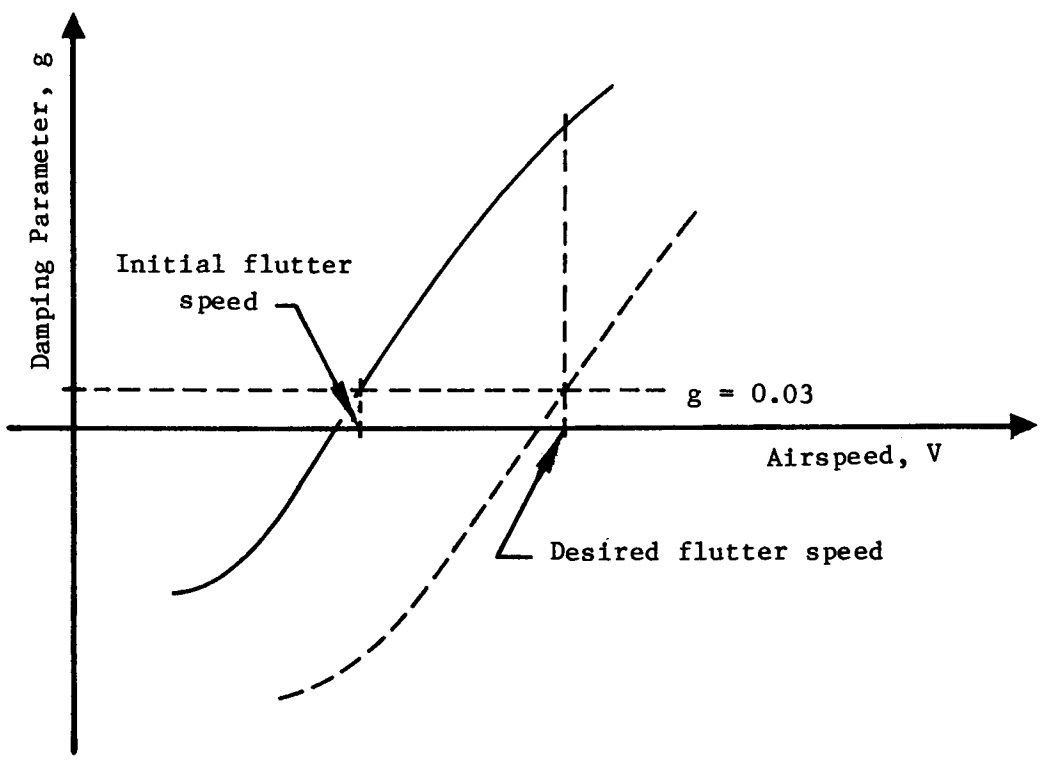


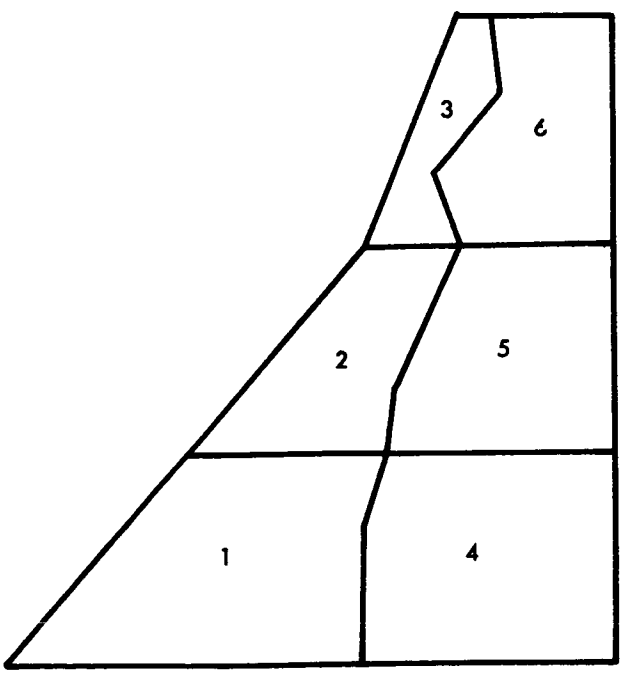

Figure 5

## OPTIMIZATION MODEL NO. 1

In all of the optimization models, the design variables were scale factors on the initial element thicknesses. Hence, the initial values of the design variables were always 1.0. In addition to the primary flutter constraint, upper and lower bounds were also imposed on the design variables.

The first optimization model had six design variables, three in the solid section and three in the sandwich section. An improvement of 300 fps was sought in the flutter speed, with the Mach number and altitude fixed, respectively, at 1.5 and 22,000 ft. Upper and lower bounds of 3.0 and 0.5, respectively, were imposed on the design variables. Convergence was obtained in 14 iterations, and it was found that almost two lb had to be added to achieve the desired increase in flutter speed. Only one design variable--T(1)--was not at an upper or lower bound. Most of the weight increase came from the 30% or so increase in thickness called for by T(1), which governed the inboard leading-edge portion of the wing. These results are illustrated in figure 6.

A complete flutter analysis of the final design with the original generalized coordinates (nine in all) confirmed that the first-mode branch was still the critical flutter branch. It was therefore not necessary to select other points in V-g space to be constrained; this was the case for all the optimization problems considered.




OPTIMIZATION RESULTS
Optimization Model No. 1 - 6 DV's

| | |
|---|---|
| Initial Weight: | 8.707 lb |
| Initial Flutter Speed, M = 1.5: | 1540 fps |
| Final Weight: | 10.57 lb |
| Final Flutter Speed, M = 1.5: | 1842 fps |

Optimal Design:

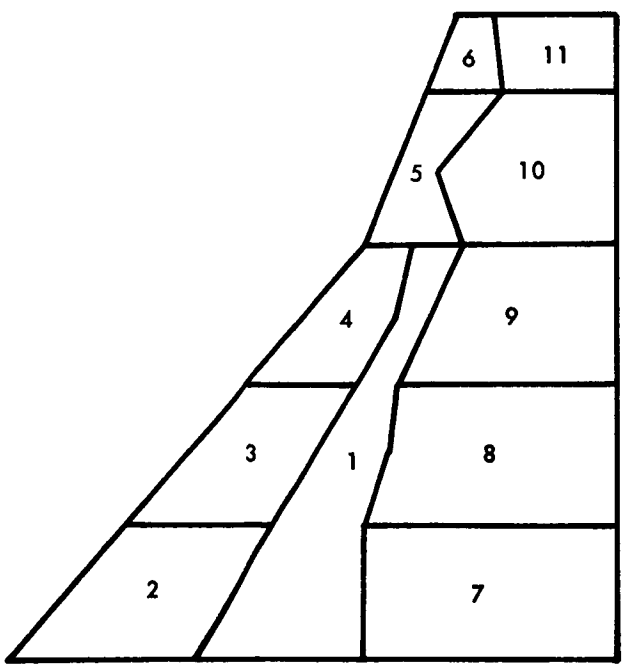
| I | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| T(I) | 1.308 | 0.5 | 0.5 | 0.5 | 3.0 | 3.0 |

Figure 6

## OPTIMIZATION MODEL NO. 2

For the next optimization model, 11 design variables were chosen, as illustrated in figure 7. To allow in a very approximate manner for strength considerations, design variable no. 1 was selected to govern a spanwise portion of the solid section just forward of the juncture between the solid and sandwich sections. Stress analyses at TI has indicated that stresses were highest in this area for the design loading conditions for strength. A more restrictive lower bound, 0.9, was selected for this design variable, and the same 300-fps increase in flutter speed was sought. Convergence was again obtained after 14 iterations, with the desired flutter speed obtained and a weight reduction of over two lb. All design variables except T(6) were at their lower bounds, and T(6) was almost at its upper bound. These results suggest very strongly that much lighter construction--perhaps sandwich--could be used for most of the leading-edge wing portions as well, with a strong spar to carry wing loads into the root. The increase for T(6), which is at the tip, can be interpreted as calling primarily for mass balance, since the increased stiffness there will have little effect.

With such a drastic change in the design, it could be anticipated that the use of fixed modes would result in some inaccuracies. To test this, the optimal design was re-analyzed for flutter with normal modes. The flutter speed calculated for this model was an astonishing 2442 fps--some 600 fps more than the desired flutter speed and 900 fps more than the flutter speed of the initial design. This of course illustrates even more strongly the value of the redesign. In other cases, it is likely that the improvement would not be as great as estimated with fixed modes, and in general it must be expected that the modes would have to be updated and the optimization repeated in order to obtain satisfactory accuracy.




OPTIMIZATION RESULTS
Optimization Model No. 2 - 11 DV's

| | |
|---|---|
| Initial Weight: | 8.707 lb |
| Initial Flutter Speed, M = 1.5: | 1540 fps |
| Final Weight: | 6.430 lb |
| Final Flutter Speed, M = 1.5: | 1842 fps |

Optimal Design:

| I | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| T(I) | 0.9 | 0.5 | 0.5 | 0.5 | 0.5 | 2.796 |

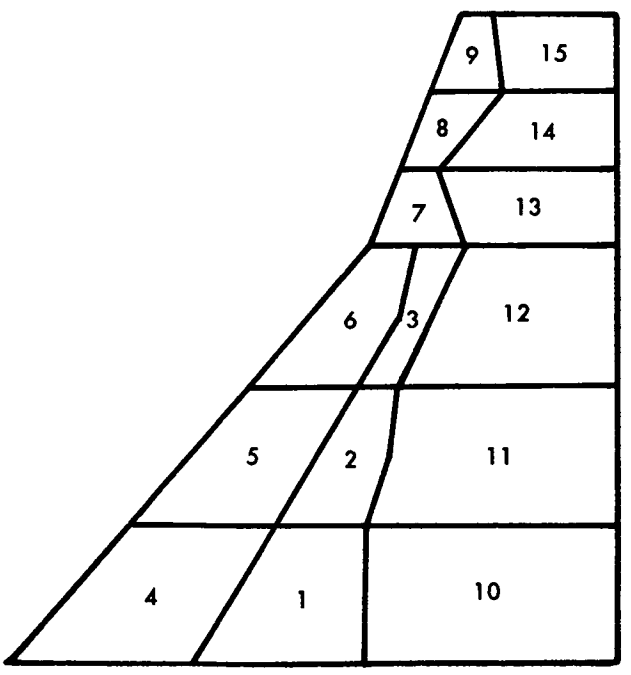
| I | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|
| T(I) | 0.5 | 0.5 | 0.5 | 0.5 | 3.0 |

Flutter speed, M = 1.5, optimal design with normal modes - 2442 fps!

Figure 7

## OPTIMIZATION MODEL NO. 3

This model resembled model no. 2, but more chordwise divisions were chosen, and the number of design variables was increased to 15. The optimal design was obtained in 13 iterations and is almost the same as that found for the 11-DV case, as can be seen in figure 8.




OPTIMIZATION RESULTS
Optimization Model No. 3 - 15 DV's

Initial Weight: 8.707 lb
Initial Flutter Speed, M = 1.5: 1540 fps

Final Weight: 6.466 lb
Final Flutter Speed, M = 1.5: 1842 fps

Optimal Design:

| I | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| T(I) | 0.9 | 0.9 | 0.9 | 0.5 | 0.5 | 0.5 |

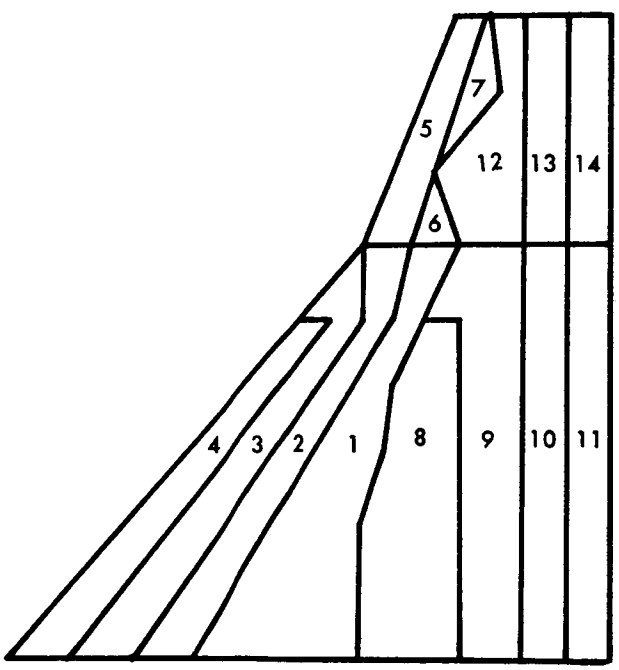
| I | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|
| T(I) | 0.5 | 0.5 | 2.754 | 0.5 | 0.5 | 0.5 |

| I | 13 | 14 | 15 |
|---|---|---|---|
| T(I) | 0.5 | 0.8260 | 3.0 |

Figure 8

## OPTIMIZATION MODEL NO. 4

For this model, additional spanwise cuts were selected in order to see if more design flexibility in the chordwise direction would produce different results. However, the optimal design for this 14-DV case was not substantially different from the two previous optimal designs; see figure 9 for details.




OPTIMIZATION RESULTS
Optimization Model No. 4 - 14 DV's

Initial Weight: 8.707 lb
Initial Flutter Speed, M = 1.5: 1540 fps

Final Weight: 6.755 lb
Final Flutter Speed, M = 1.5: 1842 fps

Optimal Design:

| I | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| T(I) | 0.9 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |

| I | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|
| T(I) | 3.0 | 0.5 | 0.5 | 0.5 | 0.5 | 0.8066 |

| I | 13 | 14 |
|---|---|---|
| T(I) | 3.0 | 3.0 |

Figure 9

## COMPARISON OF NATURAL FREQUENCIES

The optimal wing-only design from optimization model no. 2 was modelled at TI and incorporated in a model of the complete missile which includes wings, tail fins, missile body, and shafts, actuators, and linkage. Figure 10 presents comparisons of the isolated-wing natural frequencies, the optimized complete-model natural frequencies, and those for the baseline complete model. Frequencies computed at TI for the wing model are in excellent agreement with those computed at MSD. When this wing model was coupled with the rest of the missile, only the first wing bending mode was affected. The interaction of the optimized wing with the internal structure and the missile body has resulted in a much lower frequency.

| Mode Description | Frequency (HZ) | | | |
|---|---|---|---|---|
| | Optimized Wing Model | | Complete Model | |
| | MSD | TI | Optimized | Baseline |
| Damper (pitch) | - | - | 9.0 | 8.7 |
| Actuator (pitch) | 40.3 | 39.6 | 40.5 | 42.4 |
| First Body Bending | - | - | 45.8 | 45.5 |
| First Wing Bending | 92.9 | 89.1 | 73.6 | 96.3 |
| Second Body Bending | - | - | 141 | 141 |
| Second Wing Bending | 175 | 170 | 171 | 204 |

Figure 10

## FLUTTER BOUNDARY OF COMPLETE MODEL

The optimized complete model was then analyzed for flutter at TI, at Mach numbers of 1.2, 1.5, and 2.0. These flutter points are compared with the flutter boundary of the baseline model in figure 11. Although the improvement in the flutter boundary at Mach 1.5 is not as great as is indicated by the wing-only analysis, it is nevertheless very significant. This improvement carried over to Mach 2.0, but there was virtually no change in the flutter boundary at Mach 1.2. This indicates that a somewhat different flutter mechanism was involved at Mach 1.2, and an additional flutter constraint at that Mach number would have to be included to obtain improvement there.

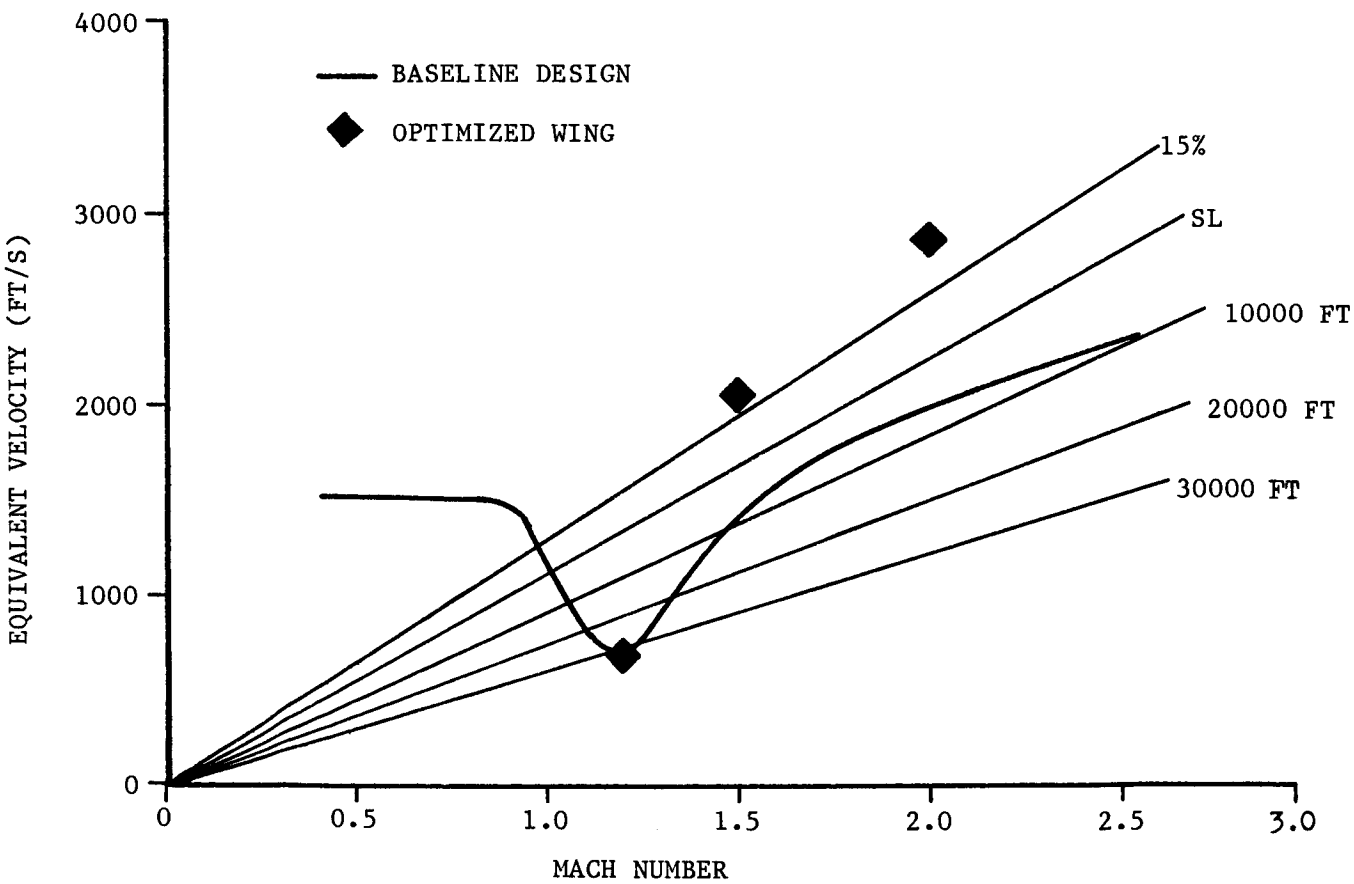



Figure 11

## CONCLUDING REMARKS

Although the results obtained here cannot be translated directly to a new design, they do indicate strongly how a redesign could proceed, with both reduced weight and substantially improved flutter margins. It is also worth noting that sensitivity studies from the initial design would not necessarily suggest modifications such as were finally determined by optimization. For example, the weight histories in all of the cases studied above showed an initial increase in weight, sometimes of three lb or more, just to satisfy the constraint before any weight reduction was attempted. Optimization can thus be viewed as an organized and effective way of arriving at an often counterintuitive result.

## REFERENCES


1. Vanderplaats, G. N.: CONMIN--A Fortran Program for Constrained Function Minimization. User's Manual. NASA TM X-62282, Aug. 1973; Addendum, May 1978.

2. Gwin, L. B. and S. C. McIntosh, Jr.: A Method of Minimum-Weight Synthesis for Flutter Requirements, Part I--Analytical Investigation, Part II--Program Documentation. AFFDL-TR-72-22, Pts. I and II, June 1972.

3. Gwin, L. B. and S. C. McIntosh, Jr.: Large Scale Flutter Optimization of Lifting Surfaces, Part I--Analytical Investigation, Part II--Program Documentation. AFFDL-TR-73-91, Pts. I and II, Jan. 1974.