AIRCRAFT CONFIGURATION OPTIMIZATION
INCLUDING
OPTIMIZED FLIGHT PROFILES

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FLIGHT OPTIMIZATION SYSTEM

The Flight Optimization System (FLOPS) is an aircraft configuration optimization program developed for use in conceptual design of new aircraft and in the assessment of the impact of advanced technology. Figure 1 shows the modular makeup of the program. It contains modules for preliminary weights estimation, preliminary aerodynamics, detailed mission performance, takeoff and landing, and execution control. An optimization module is used to drive the overall design and in defining optimized flight profiles in the mission performance. Propulsion data, usually received from engine manufacturers, are used in both the mission performance and the takeoff and landing analyses. Although executed as a single in-core program, the modules are stored separately so that the user may select the appropriate modules (e.g., fighter weights versus transport weights) or leave out modules that are not needed.
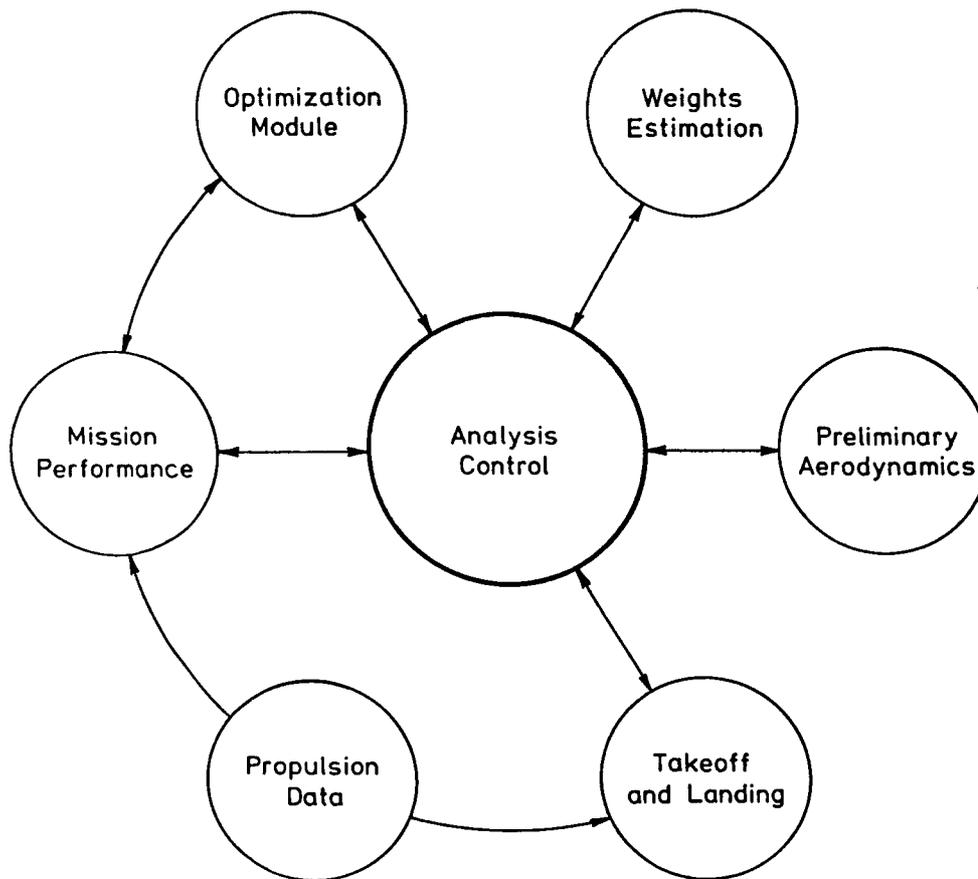
Figure 1

WEIGHT EQUATION DEVELOPMENT

The weight equations in the preliminary weights estimation modules were developed by curve fitting statistical data from existing aircraft using an optimization program. A form which made sense physically was selected for each equation and all constants (coefficients, exponents, factors, etc.) were optimized using nonlinear programming techniques. The objective was to minimize the sum of the squares of the percentage errors between the actual and predicted weights. A nonlinear programming technique is superior to traditional curve fitting techniques in that the form of the equation and the variables are arbitrary. Fighter weight equations were developed using a data base of 22 recent fighter and attack aircraft. The transport data base included aircraft from the T-39 Sabreliner to the Boeing 747. Figure 2 shows the correlation for the fighter fuselage weight equation.
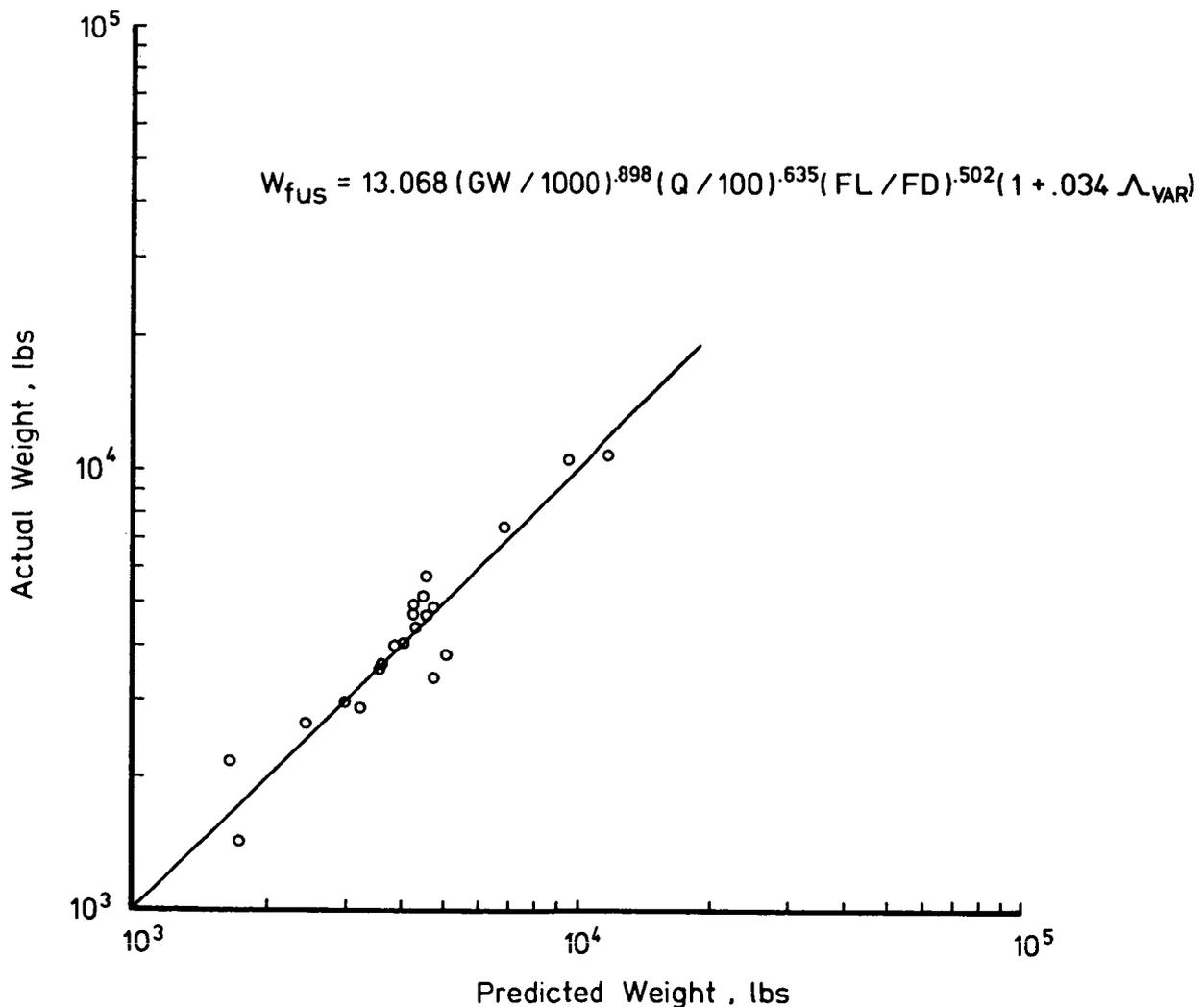
$$W_{fus} = 13.068\,(GW/1000)^{.898}\,(Q/100)^{.635}(FL/FD)^{.502}(1+.034\,\Lambda_{VAR})$$

Figure 2

WING WEIGHT EQUATION DATA

The FLOPS program was developed for the evaluation and optimization of advanced aircraft concepts which usually have unconventional wings. Insufficient statistical data existed to accurately predict the effects on wing weight of composite aeroelastic tailoring, forward sweep, and strut bracing and the relationship between sweep angle and flutter and divergence weight penalties for very high aspect ratio wings. The Aeroelastic Tailoring and Structural Optimization program (ATSO, ref. 1) was used to generate a series of optimum wing designs to predict these effects. Trend data from these studies, some of which are shown in figure 3, were used with data from existing aircraft to generate a multi-term equation that accurately predicts weights for existing wings and provides reasonable trend data for unconventional wings.
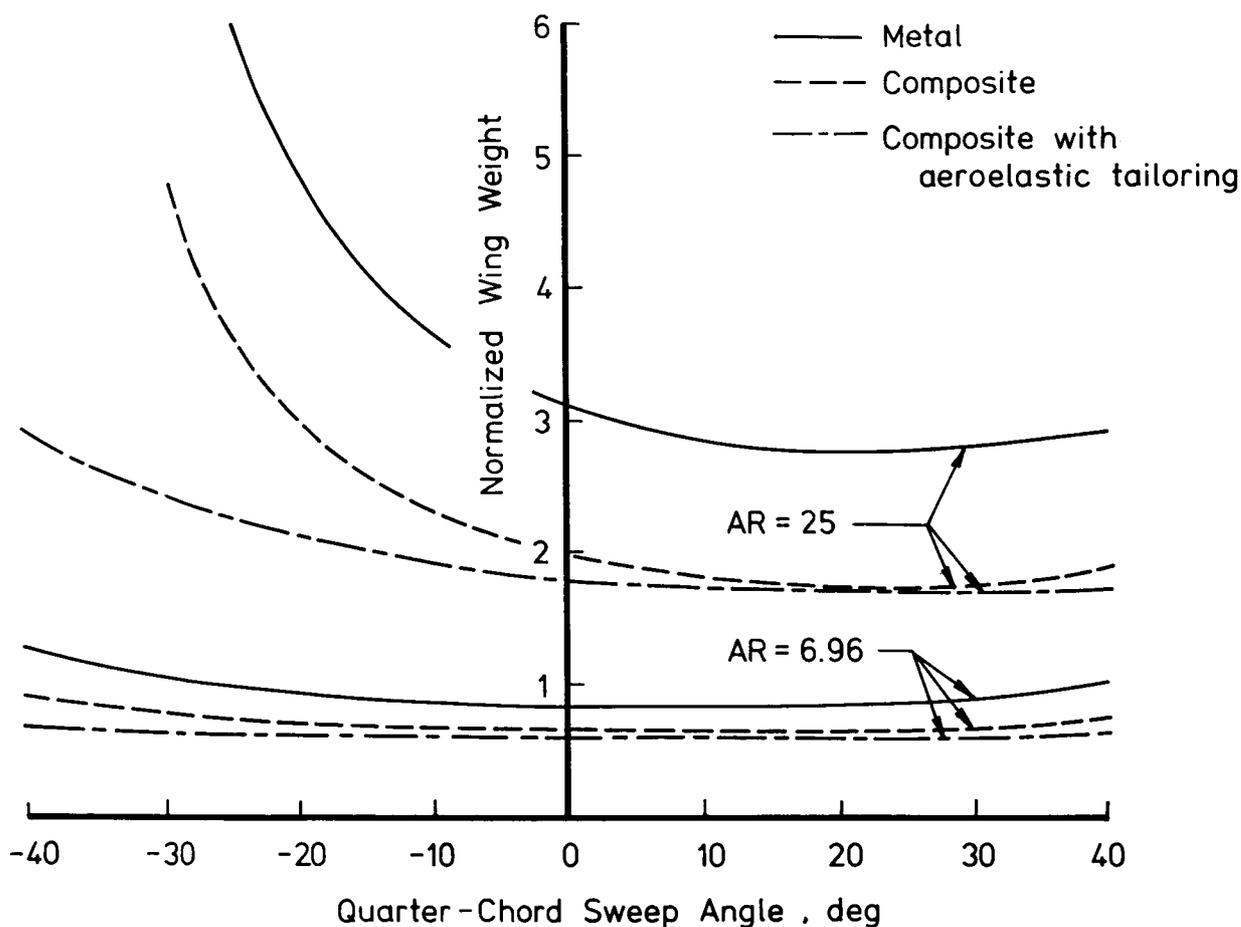

Figure 3

AERODYNAMICS MODULE

Preliminary aerodynamics data are generated using the Empirical Drag Estimation Technique (EDET, ref. 2). Modifications have been made to improve the accuracy of the calculations, such as implementation of the Sommer and Short T' Method for skin friction drag (ref. 3). In addition, modifications have been made to extend the range of the program to forward swept wings and higher aspect ratios, as indicated in figure 4, and to more accurately account for taper ratio. FLOPS also has the capability to use input aerodynamic data and scale it with changes in wing area and engine size. Typically, this option is used for supersonic cruise aircraft concepts, and EDET is used for subsonic aircraft.

o EDET – Empirical Drag Estimation Technique

o Modifications :

    ● Forward Swept Wings

    ● Sommer and Short T' Method

    ● Efficiency Variation with Aspect Ratio and Taper Ratio

o All or Part of Aerodynamics Data May Be Input and Scaled

Figure 4

TAKEOFF AND LANDING ANALYSIS

FLOPS has the capability to perform detailed takeoff and landing analyses, as shown in figure 5, including evaluation of constraints on approach speed, missed approach climb gradient, second segment climb gradient, landing field length, and takeoff field length (or balanced field length for multi-engine aircraft) including ground effects. FLOPS also has a series of handbook-type formulas which predict these quantities. These formulas have been correlated against the detailed analyses and are normally used during optimization with the detailed analysis used for a point design evaluation.
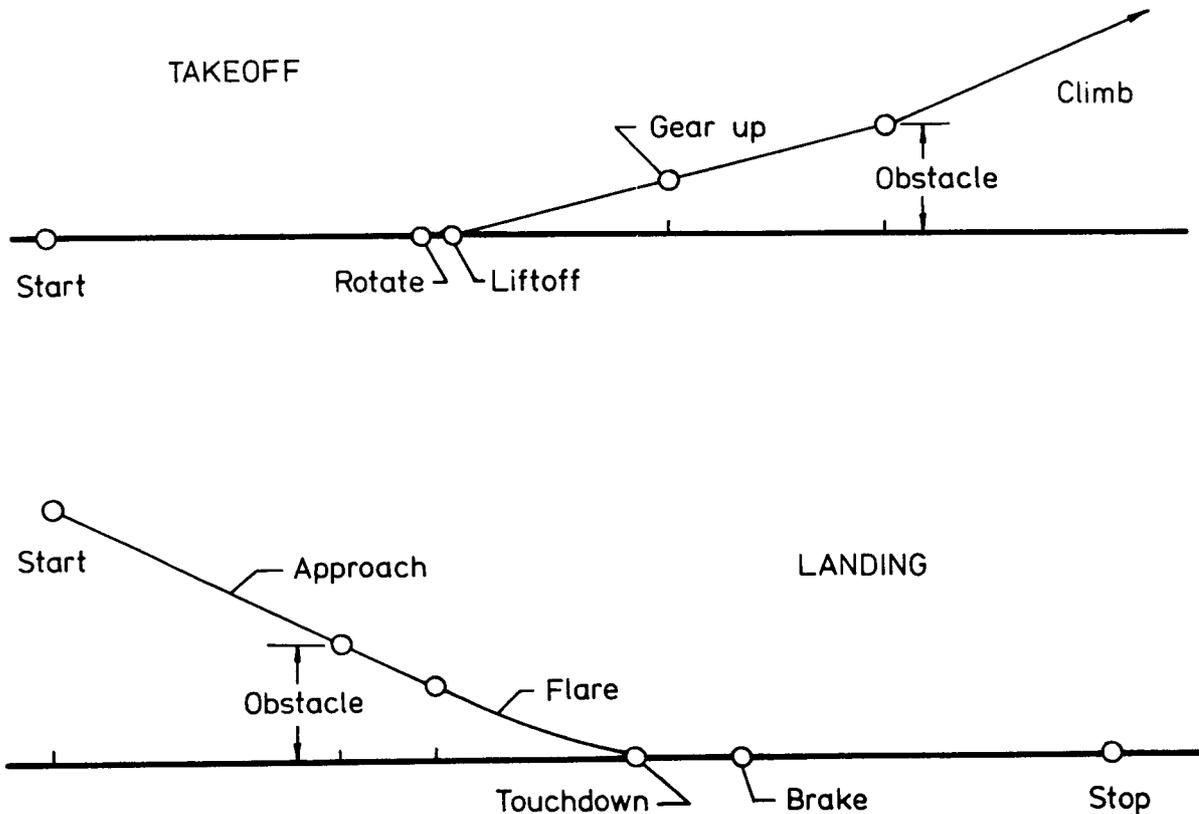

Figure 5

MAIN MISSION ANALYSIS

Mission performance is calculated for all segments using a step integration technique to provide precise values for fuel burned, elapsed time, distance covered, and changes in speed and altitude. The primary mission can be composed of any reasonable combination of climbs, cruises, refuelings, payload releases, accelerations, turns, holds, and descents. A typical military attack mission is shown in figure 6. Speed and altitude continuity may be maintained or ignored at the analyst's option.
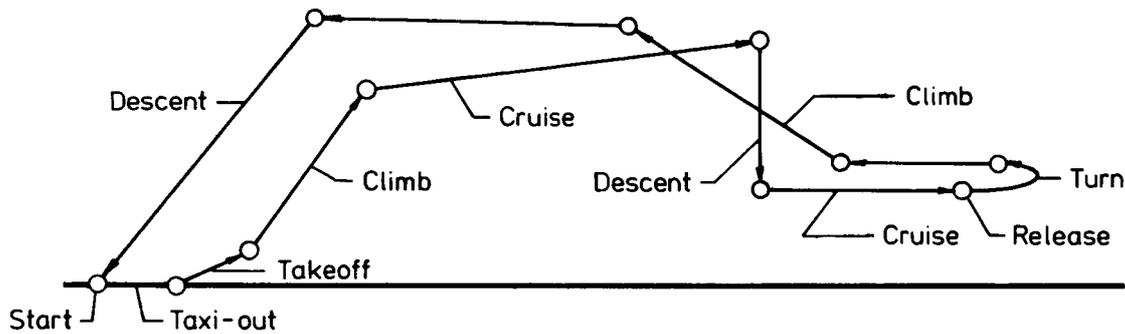
Figure 6

RESERVE MISSION ANALYSIS

The reserves may be specified as a percentage of the total fuel or as the fuel required to fly an alternate mission or as a combination of the two. A typical reserve mission is shown in figure 7 consisting of fuel for a missed approach, flight to an alternate airport, and a specified hold. Each type of segment for the main and reserve missions is specified independently and the segments are linked together to fly the mission.
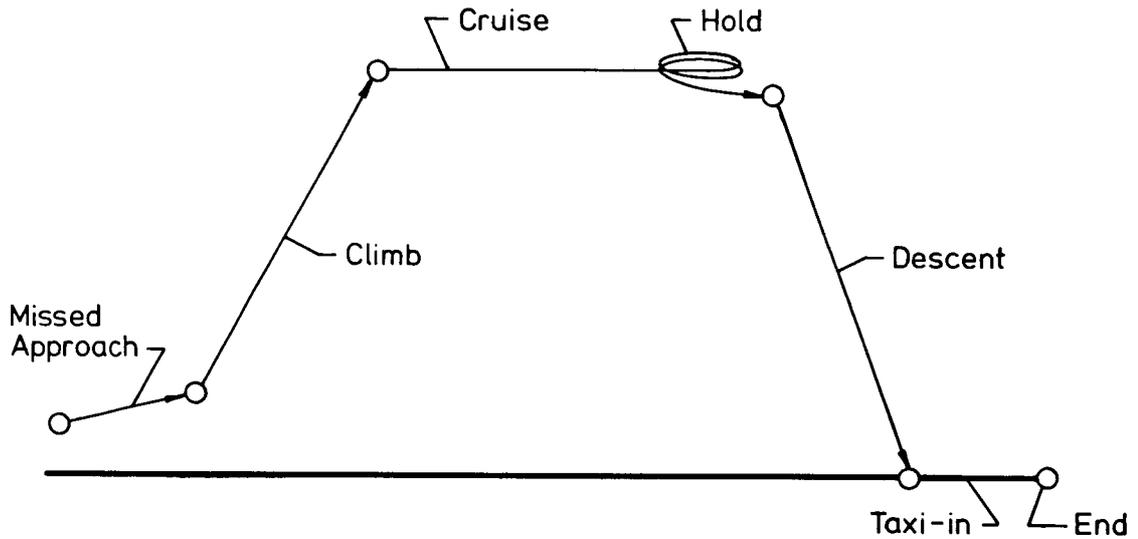
Figure 7

CLIMB PROFILE OPTIMIZATION

The climb profiles may be specified by the user or they may be optimized by the program. For optimization, the climb is divided into a series of energy steps, and the combination of speed and altitude that maximizes the objective is determined for each energy level. The objective may be minimum time to climb, minimum fuel to climb, minimum time to distance (interceptor mission), or minimum fuel to distance (the most economical). Figure 8 shows a minimum fuel to climb profile superimposed on a contour plot of the objective function used for this case.
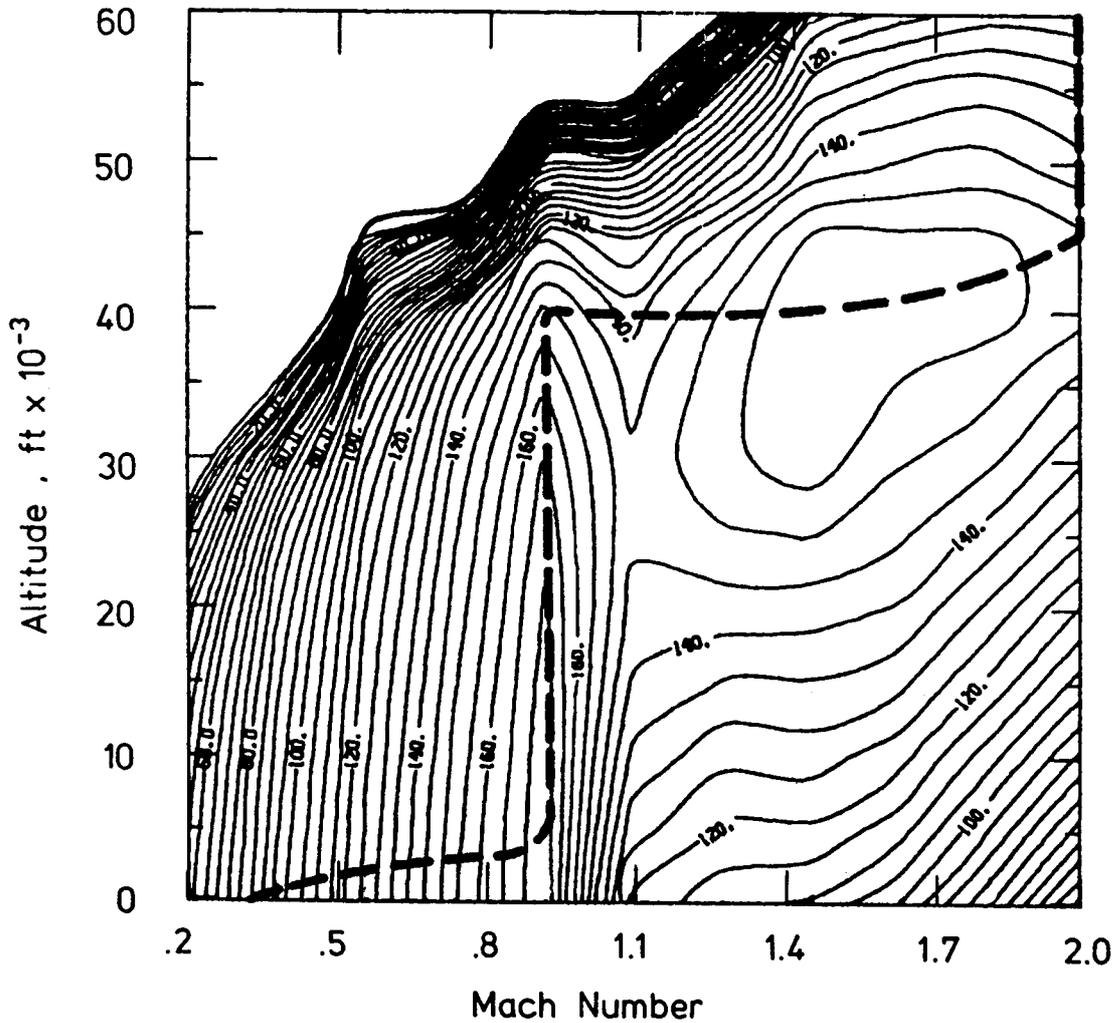

Figure 8

MINIMUM TIME TO CLIMB PROFILE

A minimum time to climb profile is shown on figure 9 superimposed on contours of its objective function, specific excess power. The program tracks the maximum rate of climb until it reaches the specified cruise conditions. These plots were for a small, high thrust-weight ratio fighter. A variety of constraints, such as obeying FAA rules or not diving through Mach 1, may be placed on the climb segment. In addition, a suboptimization may be performed on engine power setting for minimum fuel options. This is normally used for engines with afterburners.
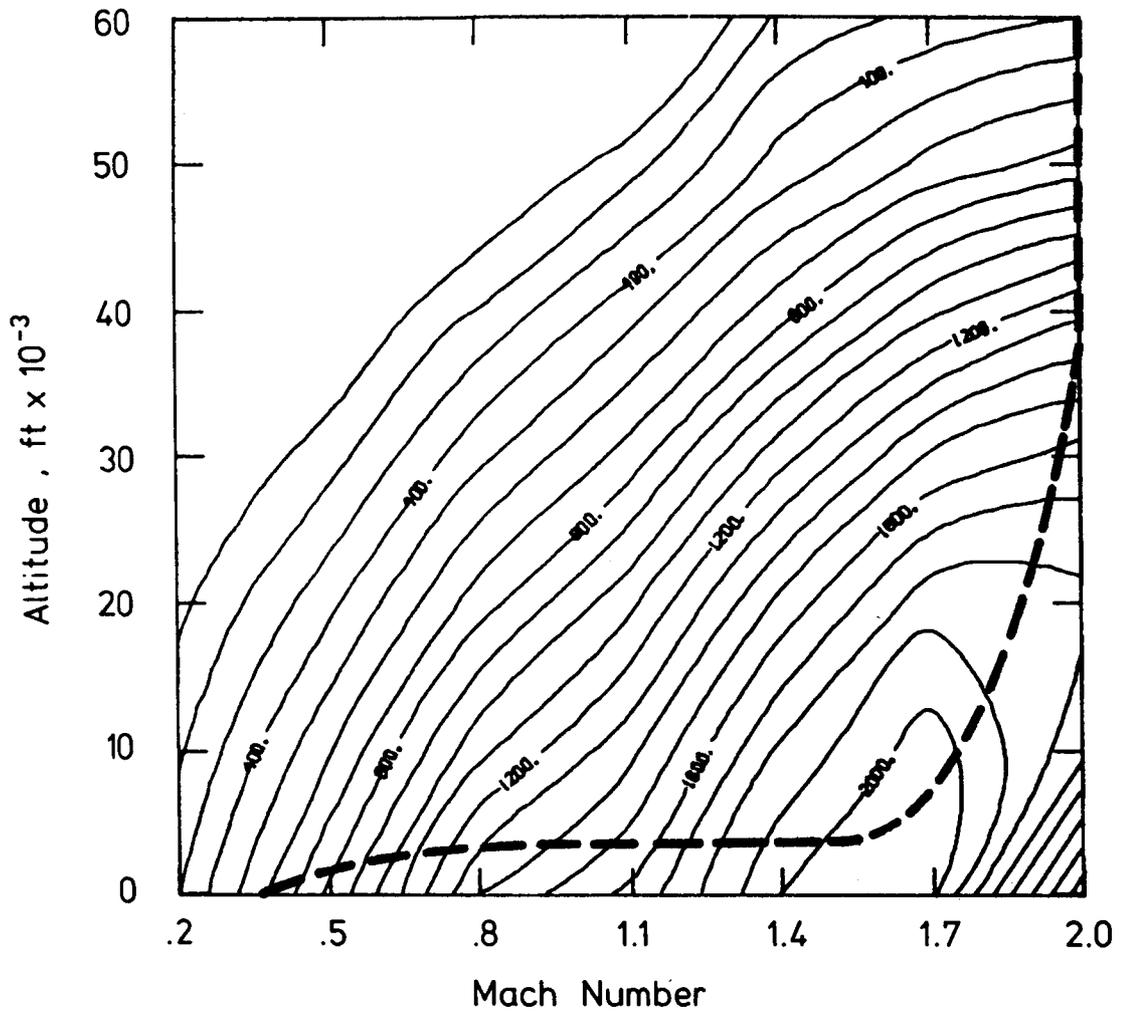

Figure 9

IMPACT OF CRUISE OBJECTIVE

There are ten options for specifying each cruise segment: optimum altitude, optimum Mach number, or both for either maximum specific range or minimum fuel flow (endurance segment); fixed Mach number and altitude; fixed altitude and constant lift coefficient; and maximum Mach number for either fixed altitude or optimum altitude. In addition, a suboptimization may be performed on feathering engines. This is particularly useful in endurance missions. Figure 10 shows the differences in altitude and speed for a very long range turboprop transport flown to achieve maximum range and maximum endurance.
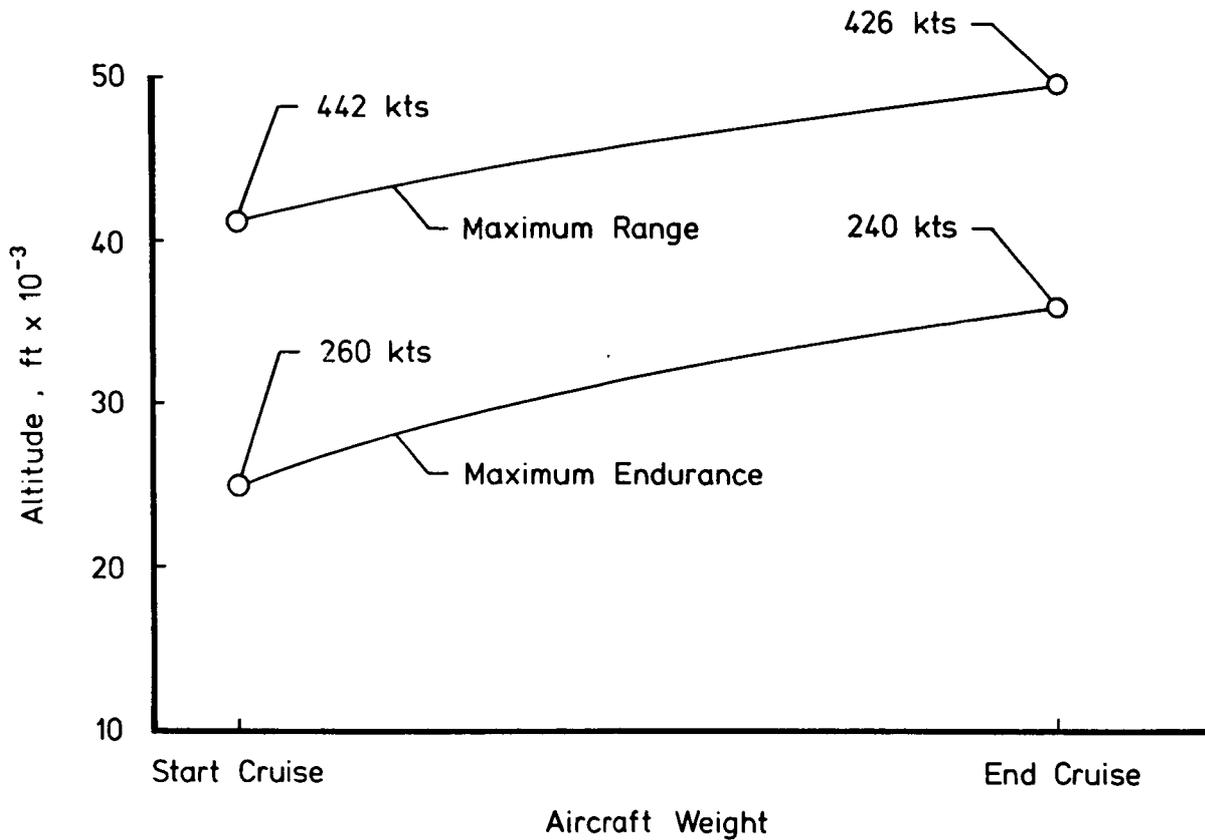

Figure 10

DESCENT PROFILE

The descent segment may be flown along a specified profile, at a constant lift coefficient, or at the maximum lift-drag ratio. An optimized profile is shown in figure 11 superimposed on a contour plot of an objective function based on lift-drag ratio.
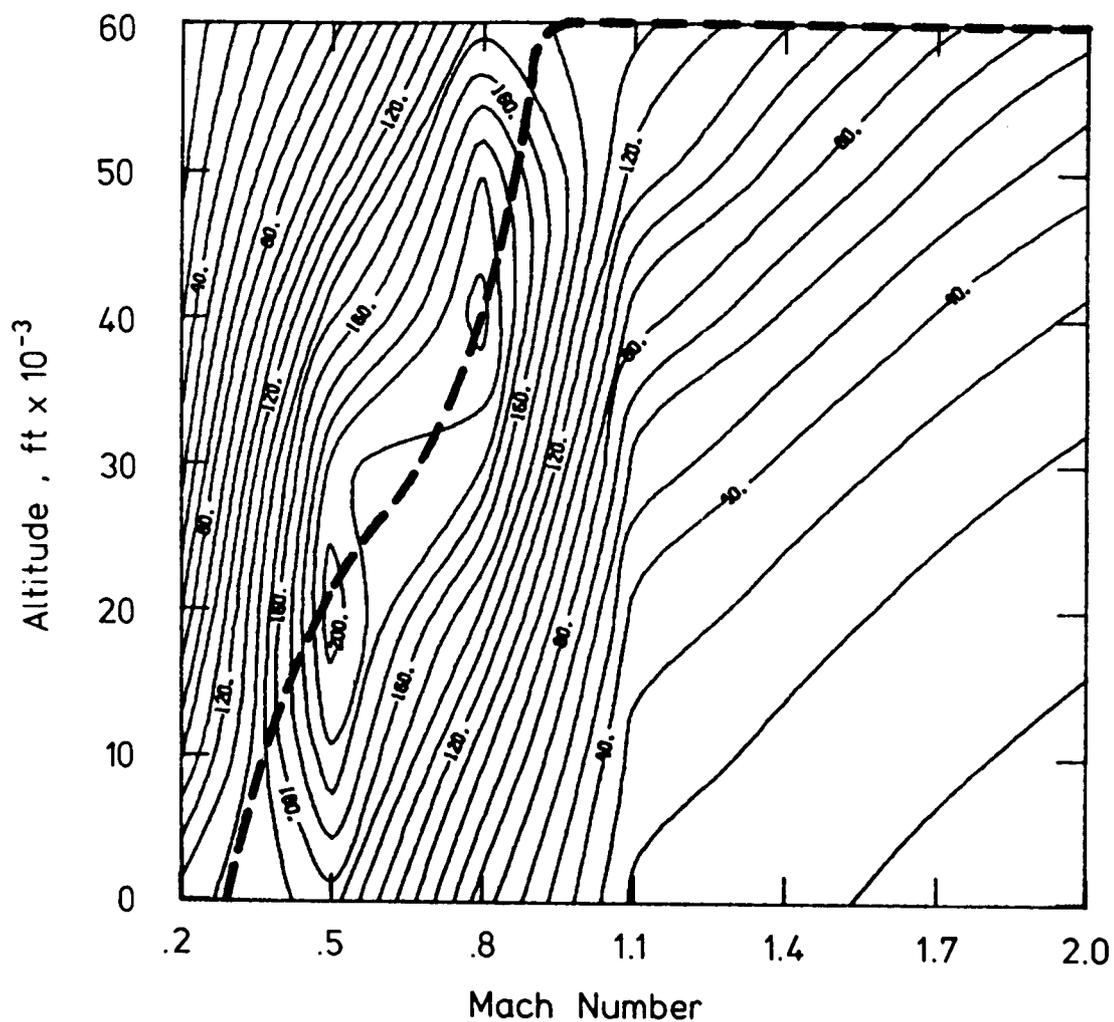

Figure 11

DESIGN VARIABLES AND CONSTRAINTS

The nine available design variables for parametric variation or optimization as well as the six available constraints are shown in figure 12. Usually the altitude and Mach number are determined during flight profile optimization and are not used as design variables. Also, there are two modes of operation of the program. If the gross weight is specified (or an active design variable), the range (or endurance time) is calculated and should be a constraint in an optimization. A more effective way to use the program is to fix the range and iterate to find the gross weight. In this way the range constraint is always satisfied and the gross weight is a fall out, not a variable, leaving only six active design variables and five constraints for a normal problem.

DESIGN VARIABLES

o Wing Area
o Wing Aspect Ratio
o Wing Thickness – Chord Ratio
o Wing Taper Ratio
o Wing Sweep Angle
o Thrust (Engine Size)
o Gross Weight
o Maximum Altitude
o Maximum Mach Number

CONSTRAINTS

o Range
o Takeoff Field Length
o Landing Field Length
o Approach Speed
o Second Segment
    Climb Gradient
o Missed Approach
    Climb Gradient

Figure 12

PARAMETRIC VARIATION

A matrix of point designs may be created by parametrically varying one or more design variables. If two variables are used, contour plots such as the one shown in figure 13 can be obtained. Contours of supersonic cruise range are plotted for variations in wing loading (which can be used instead of wing area) and thrust-weight ratio (instead of thrust). Using this option, sensitivities to the design variables can be determined.
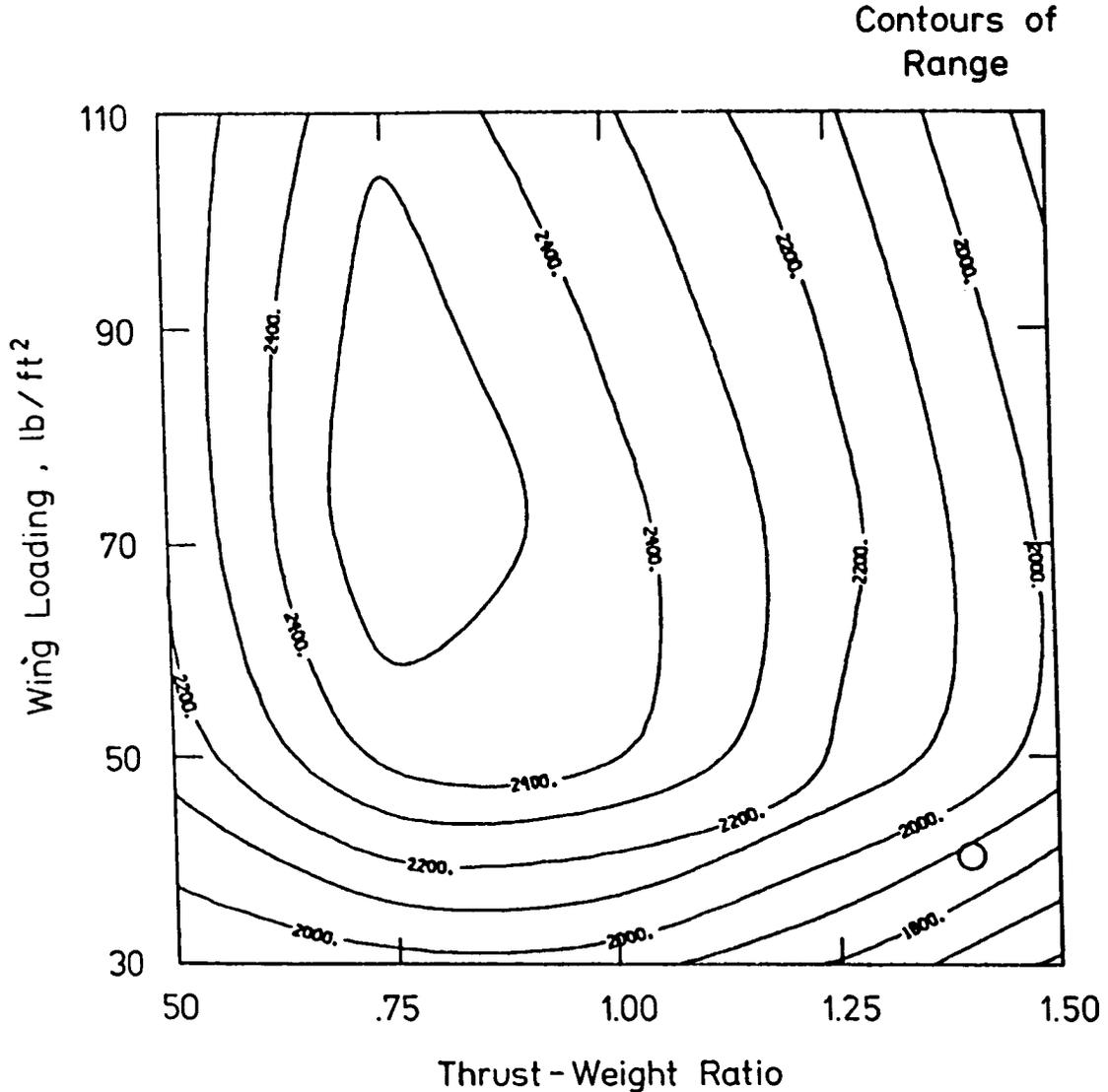
**Contours of
Range**

Figure 13

OPTIMIZATION

   As shown in figure 14, the objective function for the configuration optimization is a function of gross weight, total fuel, and range. This provides the capability to minimize the gross weight or fuel for a specified range or to maximize the range for a given gross weight. Figure 14 also indicates some of the optimization techniques used. Programs containing simplex and feasible directions algorithms were also used for optimization. The results, however, were inferior to those obtained using the DFP and BFGS algorithms.

o   Objective = $F_1 \cdot$ Weight + $F_2 \cdot$ Fuel + $F_3 \cdot$ Range

o   Davidon - Fletcher - Powell (DFP) or

   Broyden - Fletcher - Goldfarb - Shano (BFGS) Algorithm

o   Quadratic Extended Interior Penalty Function

o   One - Dimensional Search Uses Quadratic
   Interpolation to a Minimum

Figure 14

Figure 15 shows the path taken by the program for the unconstrained optimization of range on a fixed gross weight supersonic cruise fighter. The starting point thrust-weight ratio was 1.4 for high maneuverability, and the wing loading was 40 psf for a low approach speed. The figure shows that if both of these constraints are relaxed, the range may be increased by over 35 percent. All contour plots shown in this presentation were made using the FLOPS contour plot options.
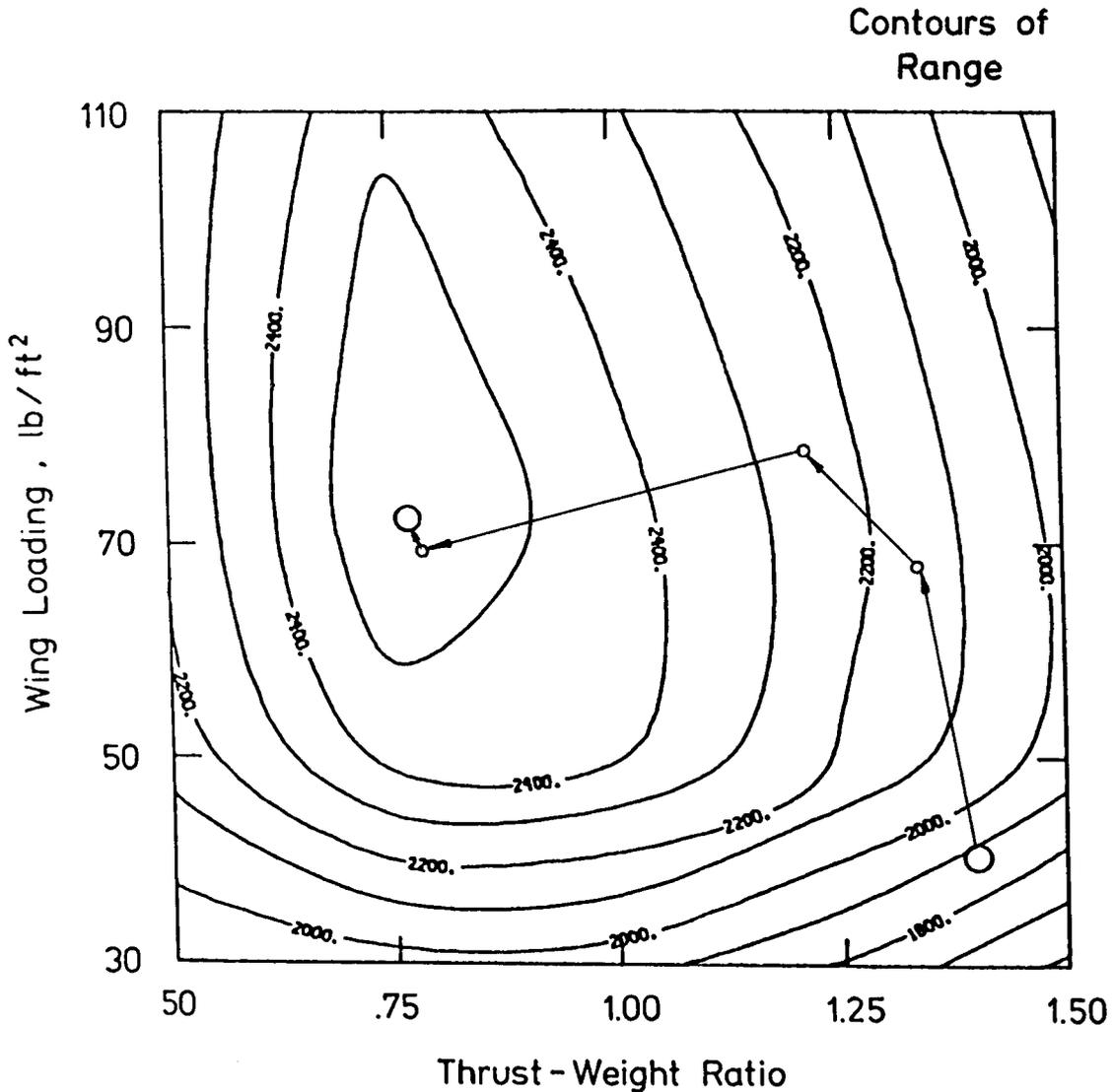

Figure 15

WEIGHT VARIATION WITH OBJECTIVE FUNCTION

  Figure 16 shows the variation of operating weight empty (OWE), gross weight, and mission fuel with aspect ratio for a series of optimum designs. Wing sweep, thickness-chord ratio, and wing area were also active design variables. Delta weights shown are from values for the minimum gross weight design at an aspect ratio of 9.3. The minimum OWE design at an aspect ratio of less than six saves about 12,000 pounds in OWE but uses over 40,000 pounds more fuel. The minimum fuel design at an aspect ratio of about 17 saves nearly 20,000 pounds of fuel but has an OWE penalty of nearly 100,000 pounds which is off the scale in the figure.
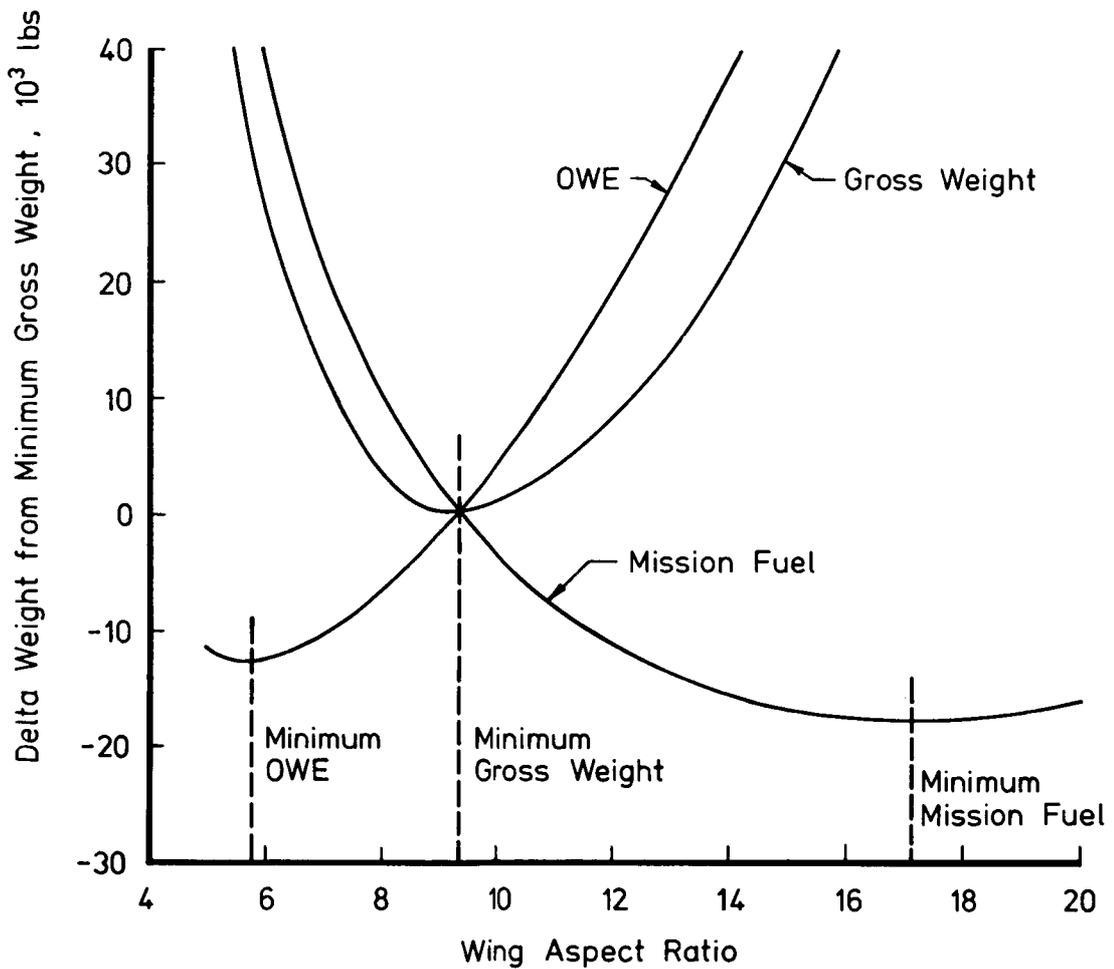

Figure 16

PROBLEM AREAS

There are several problem areas, as shown in figure 17, which can make convergence to an optimum design more difficult. The degree of design variable interdependence necessitates the use of at least an approximate second order algorithm. For example, in order to increase the thickness-chord ratio, it is usually necessary to increase the wing sweep or decrease the Mach number. Design variable scaling, when dealing with variables several orders of magnitude apart, is as important as the optimization algorithm. The initial value to the two-thirds power seems to work well as a scaling factor. In a program with multiple nested iterations, analytical convergence is crucial to accurate gradients and smooth convergence of the optimization process. In addition, the objective function is not always well defined.

In conclusion, optimization techniques and programs exist which can be used routinely to help solve engineering problems. They should be used not necessarily to define the optimum piece of hardware to be built, but as essential tools in the design process.

o   Design Variable Interdependence

o   Design Variable Scaling   [VALUE$^{2/3}$]

o   Analytical Convergence

o   What is the Objective ?

Figure 17

REFERENCES

1. McCullers, L. A.; and Lynch, R. W.: Dynamic Characteristics of Advanced Filamentary Composite Structures, Volume II - Aeroelastic Synthesis Procedure Development. AFFDL-TR-73-111, 1974.

2. Feagin, Richard C.; and Morrison, William D., Jr.: Delta Method, An Empirical Drag Buildup Technique. NASA CR-15171, 1978.

3. Sommer, Simon C.; and Short, Barbara J.: Free-Flight Measurements of Turbulent-Boundary-Layer Skin Friction in the Presence of Severe Aerodynamic Heating at Mach Numbers From 2.8 to 7.0. NACA TN-3391, 1955.