Engineering Notes

Some Applications of Performance Optimization Techniques to Aircraft

S. K. LANDGRAF*
McDonnell Aircraft Corporation, St. Louis, Mo.

TODAY'S high-performance aircraft have flight envelopes encompassing large ranges of speed and altitude. Large changes in potential and kinetic energy therefore occur when these aircraft are operated to the extremes of their envelopes. For today's aircraft, this is usually only for brief periods, but tomorrow's aircraft will be designed to operate at high-altitude and high-speed conditions (high-energy) during the major part of their design mission, and the speeds and altitudes attained will be an order of magnitude greater than we know today. This will make it imperative that the transition to the high-energy level (acceleration and climb) be made in the most efficient manner.

For an interceptor-type aircraft, the best flight path will be a minimum-time path to the target, constrained, however, by inherent aircraft limitations such as stagnation temperature, load factor capability, or quantity of fuel available. On the other hand, for aircraft designed for long ranges with cruise condition specified to occur at high altitudes and Mach numbers, a minimum-fuel flight path to this cruise condition will be desired. The increasing importance of performing this portion of the mission efficiently is illustrated in Fig. 1. Even when the flight path to the cruise condition has been specified as minimum-fuel, the percentage of the total fuel that is required for the acceleration and climb increases steadily with the energy level of the cruise condition and eventually becomes the major portion. These data are derived from several high-performance aircraft studied at McDonnell Aircraft Corporation (M.A.C.) in recent months, and results from the recent NASA supersonic transport (SST) feasibility studies check these results very well.

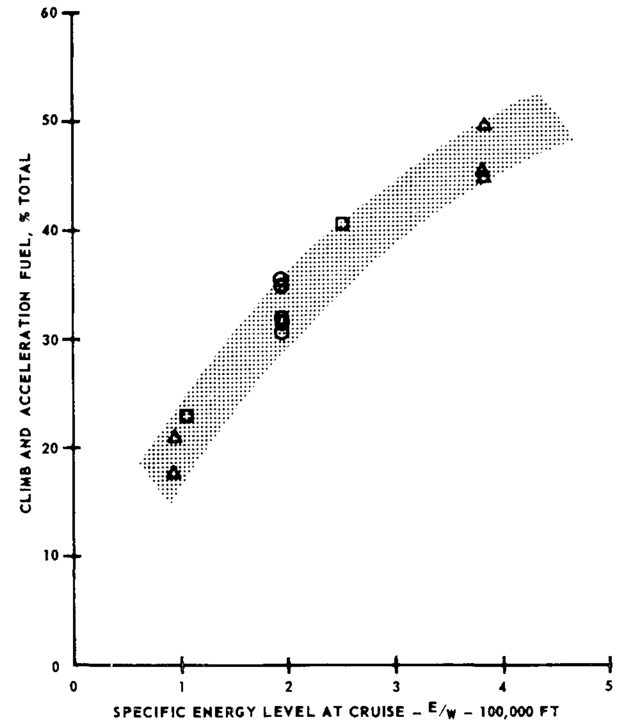

Fig. 1 Fuel used in climb and acceleration to cruise condition.

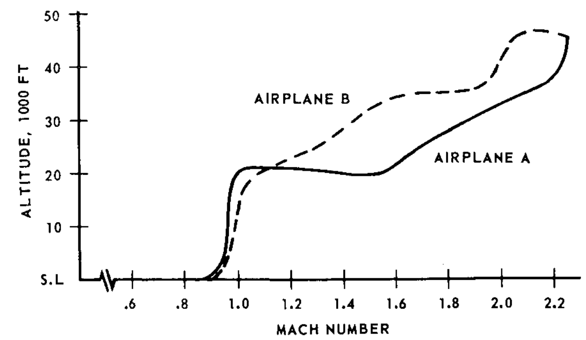

Fig. 2 Optimum climb: acceleration paths.

Various methods of flight path optimization have been developed, and all of them have their individual merits and drawbacks. It is not intended to discuss or compare these methods here, but rather to present some of the results obtained using the IBM 7094 flight path optimization program developed by M.A.C. under Air Force contract. It is based on the "method of steepest descent" and is in current use in missile, spacecraft, and aircraft design. It is proving especially useful in at least two applications to manned aircraft: first, in comparing the true maximum performance capability of various configurations in the preliminary design stages; second, two aircraft designed for the same task but differing in configuration should not be required to fly the same flight plan if a true comparison is desired; rather each should be flown on its own optimum path. Figure 2 shows the optimum (minimum-time) flight paths of two fighter aircraft differing only in powerplant when intercepting the same target. A fuel quantity constraint forced airplane B, whose engine had higher fuel flows, to a higher altitude than airplane A.

The other general area in which the program is being used is in the development of optimum operational procedures for aircraft already in service in situations not covered in the flight manuals, such as defining the flight path for minimum

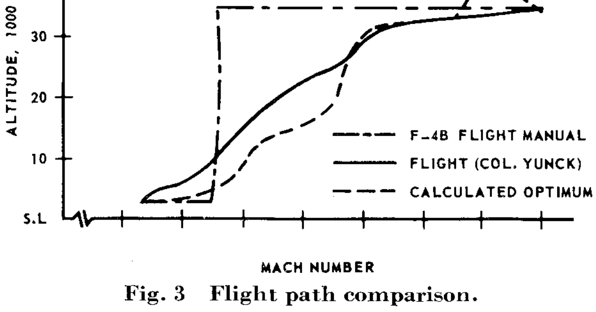

Fig. 3 Flight path comparison.

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* Section Manager, Aerodynamics. Member AIAA.

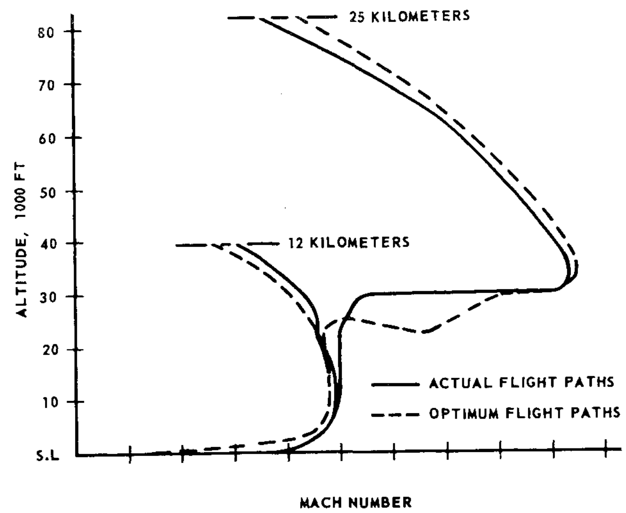

Fig. 4 Comparison of actual and calculated optimum flight paths for two F-4B time-to-climb record flights.

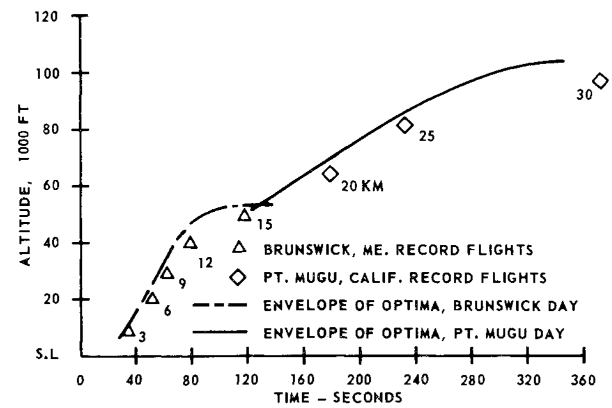

Fig. 5 Actual and calculated time to climb.

time to intercept moving targets or programing optimum turns to acquire targets during which target aspect and missile capability must be taken into account as well as airplane performance. That these calculated optimum paths are substantiated in practice is shown in Fig. 3, which compares an F-4B minimum-time path, flown by Marine Col. Yunck, with the calculated optimum. Both the predicted path and the one actually flown were about 23% better than the corresponding profile prescribed by the flight manual.

Another situation in which optimum operational procedures are required is in planning for record flights such as the F-4B time-to-climb records in the Spring of 1962. The flights to the lower altitudes (3–15 km) were made at Brunswick, Maine, and to the higher altitudes (20–30 km) at Point Mugu, Calif., in order to take advantage of atmospheric conditions existing in each location.

At the time that the records were achieved, the M.A.C. flight path optimization program was not in existence, and flight programing guidance was obtained by means of a simpler performance program on a "cut-and-try" basis to search out the optimum path. This process consumed considerable computing time. Recently, the optimization program now available was used to compute minimum-time paths to various altitudes. Several of these paths shown in Fig. 4 are compared to the actual record flights to 12 and 25 km and show that the flights were flown in a near-optimum manner. Envelopes of the computed minimum times to altitude for both Brunswick and Point Mugu days are given in Fig. 5. Work is continuing at M.A.C. to improve this program by shortening the required computing time and expanding its capability and versatility.

An Evaluation of the Far Field Overpressure Integral

RAYMOND M. HICKS* AND JOEL P. MENDOZA*
NASA Ames Research Center, Moffett Field, Calif.

Nomenclature

$A(t)$ = cross-sectional area of vehicle, ft²
$B(t)$ = equivalent cross-sectional area due to lift, ft²
c = coefficient of $(t_N - t_{N-1})$
$F(\tau)$ = effective area-distribution function given by Eq. (2)
K = reflection factor
l = length of vehicle, ft
M = Mach number
n = number points used to subdivide the axis of the vehicle for numerical integration, see Eq. (3)
p = reference pressure, psf
τ_0 = value of τ giving the maximum positive value of $\int_0^\tau F(\tau)d\tau$
t = distance along longitudinal axis from nose of vehicle, ft
y = vertical distance of vehicle from point where overpressure is measured, ft
β = $(M^2 - 1)^{1/2}$
γ = ratio of specific heats
Δp = sonic boom overpressure, psf
τ = dummy variable of integration or upper limit of integration
$(\ )'$ = first derivative
$(\ )''$ = second derivative

Introduction

THE maximum sonic boom overpressure in the far field for a smooth, slender configuration in supersonic flight is given by (these equations are given in their dimensionless form in Ref. 1)

$$\frac{(\Delta p/p)_{\max}(y/l)^{3/4}}{\beta^{1/4}K} = \frac{2^{1/4}\gamma}{l^{3/4}(\gamma+1)^{1/2}}\left(\int_0^{\tau_0} F(\tau)d\tau\right)^{1/2} \quad (1)$$

where

$$F(\tau) = \frac{1}{2\pi}\int_0^\tau A''(t)(\tau - t)^{-1/2}dt + \frac{\beta}{4\pi}\int_0^\tau B''(t)(\tau - t)^{-1/2}dt \quad (2)$$

For most practical configurations the cross-sectional area distribution $A(t)$ and the cross-sectional area equivalent to lift $B(t)$ are defined only at a finite number of points along the axis of the vehicle. This means that, to evaluate the two integrals in Eq. (2), it is necessary to use a curve-fitting technique to obtain an equation for $A(t)$ and $B(t)$. The method of Ref. 1 combines $A(t)$ and $B(t)$ into one equation by fitting the curve $A(t) + B(t)$ with a series of parabolic arcs. This fitted curve is then differentiated twice, and Eq. (2) is evaluated. The purpose of the present paper is to derive equations that avoid the necessity of calculating derivatives of the approximating functions to $A(t)$ and $B(t)$. An equation that does not involve derivatives has been derived in Ref. 2, using a different mathematical approach from that used herein.

Table 1 Comparison of the maximum sonic boom overpressure parameter calculated by Eq. (3) with the exact solution

Configuration 1		Configuration 2	
Exact	Eq. (3)	Exact	Eq. (3)
0.0371	0.0371	0.0687	0.0686

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* Research Scientist, Aeronautics Division.