Aerodynamic Braking Trajectories for Mars Orbit Attainment

THOMAS W. FINCH*
Douglas Aircraft Company, Inc., Santa Monica, Calif.

The problems associated with aerodynamic braking into a Martian orbit are examined from the standpoint of vehicle and trajectory capability. Mars entry corridors are presented for lifting vehicles. Trajectories are developed that minimize the propulsive orbit injection velocity increment. The magnitude of the propulsive velocity increment is examined for these trajectories as a function of orbit altitude, vehicle lift/drag (L/D) ratio and lift parameter, and entry velocity and peak load factor. Since the minimum propulsive velocity trajectories are found to be impractical because of extreme sensitivity and lack of control capability, a class of trajectories is proposed that minimizes these difficulties. Propulsive velocity increments are again examined as functions of orbit altitude, vehicle L/D ratio and lift parameter, and entry velocity and peak load factor. Since the second class of trajectories provides orbital plane rotation capability, the magnitude of the orbital plane rotation possible through aerodynamic maneuvering is examined as a function of the vehicle L/D ratio.

Introduction

RECENT manned Mars landing studies[1-3] have shown that the use of aerodynamic rather than propulsive braking to decelerate from hyperbolic approach velocity prior to Mars orbit attainment offers significant advantages. Reductions in the initial weight required in Earth orbit have been found to be as high as 20%. A subsidiary advantage accruing to the use of aerodynamic braking is that the aerodynamic maneuver capability of the vehicle may be employed during the braking operation to make required orbital plane rotations. Although the study reported here considers only the planet Mars, the feasibility of the technique may be readily shown for any planet for which direct entry is possible. The possible use of aerodynamic braking into an orbit on return to Earth rather than direct descent to the surface has also been suggested as a possible method of decreasing the demands on the spacecraft crew upon return from a lengthy interplanetary mission.

It is the purpose of this paper to investigate aerodynamic orbit attainment for the planet Mars. Several types of orbit attainment trajectories will be examined, and the required vehicle parameters will be established. Since total aerodynamic braking into a stable orbit is impossible, the propulsive velocity increment required to achieve circular orbit will be examined. The results presented provide sufficient information to fix the required vehicle L/D ratio on the basis of entry corridor, propulsive, and orbital plane rotation requirements.

Trajectory Requirements

The basic objective of the aerodynamic braking trajectories to be considered is the placing of a vehicle on an atmospheric exit trajectory, which permits transfer to the desired orbit with a minimum of additional energy expenditure. This must be accomplished while meeting several constraints during the atmospheric portion of the flight. The atmospheric trajectory must not subject either the vehicle or the crew to unduly severe aerodynamic loading or heating. However, the vehicle must penetrate the atmosphere to a depth sufficient to insure against premature atmospheric exit.

Presented as Preprint 64-478 at the 1st AIAA Annual Meeting, Washington, D. C., June 29–July 2, 1964; revision received November 5, 1964. Phases of work presented herein were accomplished by the Missile and Space Systems Division under programs supported by the George C. Marshall Space Flight Center of NASA.

* Aerodynamics Engineer, Missile and Space Systems Division. Member AIAA.

In view of the preceding requirements, the trajectory may be divided into four phases as seen in Fig. 1. In the first phase, the vehicle enters the atmosphere at hyperbolic velocity, employing either constant or variable lift to control the depth of penetration. Once the descent of the vehicle has been arrested, the second phase consists of a deceleration within the atmosphere. In general, modulation of the vehicle's lift vector is required during the deceleration phase to prevent premature exit or excessive atmospheric penetration. It is in this phase of the flight that orbital plane rotations may most effectively be accomplished by proper control of the lateral component of the lift vector. Once sufficient velocity has been dissipated, the third phase of the flight consists of atmospheric escape on a transfer orbit. In general, the transfer orbit will be elliptic with apocenter at or above the final orbit altitude. As the vehicle approaches the final orbit altitude, the fourth phase of the braking maneuver consists of a propulsive velocity addition to achieve the desired orbit. The requirement for a propulsive velocity increment is inescapable except in the unstable case of an orbit with pericenter within the sensible atmosphere. Trajectories designed to minimize the propulsive velocity increment will be discussed in a later section. Although this discussion has tacitly assumed the use of a lifting vehicle, it can be shown that, if corridor requirements can be met, aerodynamic braking into an orbit is also possible with a ballistic vehicle. However, the lack of trajectory control capability inherent with ballistic entry poses practical problems in achieving a given orbit. For this reason, the following discussion will be limited primarily to lifting entry.

Entry Corridors

The successful execution of any entry maneuver requires that the vehicle enter the atmosphere within certain bound-

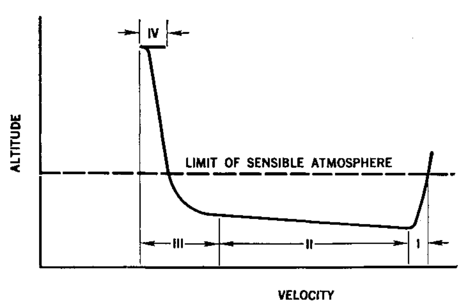

Fig. 1 Typical aerodynamic braking trajectory, altitude-velocity history.

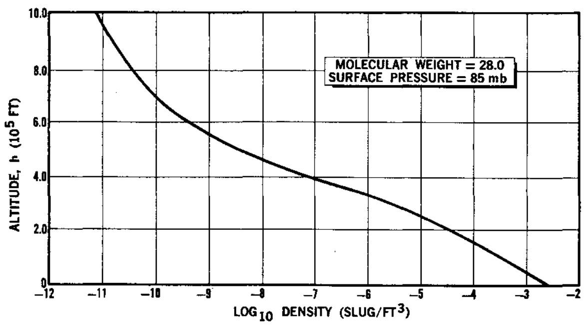

Fig. 2 Mean Mars model atmosphere, altitude-density profile.

aries commonly referred to as the entry corridor. For the purpose of this paper, we shall define the entry corridor in terms of a difference in flight path angle at entry. For entry trajectories terminating at the planetary surface, the boundaries of the entry corridor are established by the prevention of exit on one hand and the avoidance of excessive aerodynamic acceleration on the other. For the present case, other considerations may replace these. The vehicle must remain within the atmosphere only long enough to decelerate to elliptic orbit speeds and must not penetrate so deeply into the atmosphere that atmospheric escape becomes impossible. The definition of entry corridors for Mars based solely on these latter requirements was reported previously.[4] Examination of the definitions of the two sets of corridor boundaries, however, shows that the upper or overshoot boundaries are nearly identical, if the hyperbolic excess velocity at entry is appreciable. In addition, it has been determined, for a series of entry velocities and vehicles, that the undershoot limit for which atmospheric escape is impossible usually entails aerodynamic accelerations beyond the tolerance of a human crew. Hence, in practice, the corridor boundaries for aerodynamic orbit attainment are essentially identical to those for direct entry.

Entry corridor estimates for Mars are complicated by our relatively scant knowledge of the Martian atmosphere. Analysis of the effects of variations in Martian atmospheric parameters on entry corridors has been conducted.[2,3] However, the present paper will be limited to a discussion of the corridors for one model atmosphere. The mean model atmosphere and physical constants of Ref. 5 were chosen for this purpose. The variation of atmospheric density with altitude for this atmosphere is shown in Fig. 2.

The definition of the entry corridor is based on the assumption that no lift modulation occurs prior to pullout and that entry is initiated with the lift vector directed upward. Relaxation of these assumptions would produce increases in corridor magnitude at the expense of complex maneuvers during the most critical phase of entry and is therefore not considered here. The overshoot limit is defined by the trajectory that, when maximum negative lift is applied instantaneously at pullout, can just maintain zero rate of climb. The undershoot limit is defined by the trajectory that experiences the specified peak aerodynamic loading just prior to pullout.

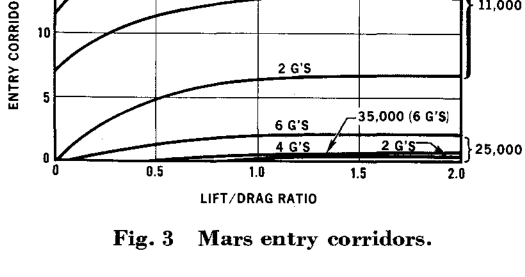

Fig. 3 Mars entry corridors.

Based on these definitions, entry corridors for Mars are presented in Fig. 3 for undershoot load factor limits of 2, 4, and 6 Earth g's as functions of vehicle L/D ratio for entry velocities of 11,000, 25,000, and 35,000 fps corresponding, respectively, to entry from a low-altitude orbit, from typical conjunction, and from opposition class transfer trajectories. The entry conditions represent values at an altitude of 800,000 ft. Comparison with similar data for Earth entry at hyperbolic speeds[2] shows that the requirements for successful entry are considerably less severe for Mars. This can be attributed to the combination of low planetary surface gravity and the resultant large scale height of the atmosphere. An L/D ratio of 0.5 is seen to be sufficient to provide a 6 g entry corridor over the velocity range of interest. In view of these factors, the availability of an entry corridor may not be the governing factor in selection of the L/D ratio for a Mars entry vehicle. Various maneuver requirements such as orbital plane rotation or landing site selection (in the case of direct entry) may well govern this choice.

Optimum Trajectories

Once the range of entry conditions permitting mission success has been established, possible trajectories for orbit attainment may be examined. It is apparent that an atmospheric braking trajectory that terminates in an orbit with pericenter outside of the planetary atmosphere cannot be achieved without some propulsive velocity addition. The problem of minimizing this propulsive velocity is of obvious interest. This problem may be equated to that of finding, for a given vehicle and entry conditions, the trajectory that yields an exit ellipse having an apocentric altitude equal to that of the final orbit and the minimum possible eccentricity (or maximum velocity at apocenter).

This problem has been examined using a two-dimensional atmospheric trajectory simulation that employs a calculus-of-variations procedure for trajectory optimization. A time history of a typical trajectory obtained in this analysis is shown in Fig. 4. The atmospheric trajectory is initiated at maximum positive lift. Soon after pullup, the lift is rapidly reduced to its maximum negative value. This value of negative lift is maintained through atmospheric exit. It can be shown that, if the requirement for a finite time derivative of the lift coefficient (inherent in the variational technique employed) is removed, the optimum lift program involves an instantaneous modulation from maximum positive to maximum negative lift. Since trajectory terminal conditions were found to be essentially independent of the choice between the two modulation techniques, instantaneous modula-

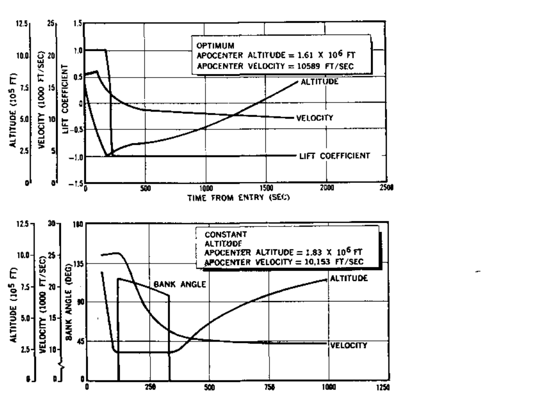

Fig. 4 Mars aerodynamic braking trajectories; L/D = 1.0, W/C_LS = 200 psf, $N_{T_{max}}$ = 4 g's.

tion was employed in the parametric analysis discussed as follows.

In order to obtain some indication of the magnitude of the propulsive velocity requirements as functions of orbit altitude, vehicle parameters, and entry conditions, a study has been conducted using the lift modulation scheme indicated previously. To reduce the number of parameters involved, it was assumed that a circular orbit was required and that transfer to the final orbit took place at the apocenter of the exit ellipse. Figure 5 shows, for these conditions, the variation of the propulsive velocity increment with orbit altitude for a vehicle having an L/D ratio of 1.0 and a lift parameter of 200 psf, entering at a velocity of 25,000 fps with an entry flight path angle yielding a peak load factor of 4 g's. The velocity increment is seen to vary nearly linearly from 147 fps at an orbit altitude of 10^6 ft to 700 fps at 4×10^6 ft. The variation of the propulsive velocity increment with vehicle L/D ratio and lift parameter are shown in Fig. 6 again for an entry velocity of 25,000 fps and a maximum load factor of 4 g's. The variation with both L/D ratio and lift parameter is seen to be so small as to be almost negligible. The effects of entry velocity and maximum load factor on the propulsive velocity increment were determined to be less than ± 0.5 fps for entry velocities between 17,500 and 40,000 fps and load factors between 2 and 10 g's.

As is often the case with trajectories that are optimum in one respect, the class of trajectories discussed previously suffers from some serious drawbacks. As has been noted, these trajectories utilize maximum negative lift during the deceleration phase, thus leaving no margin for trajectory control or corrective maneuvers. The correction of this difficulty by using less than maximum negative lift during deceleration is possible, but another drawback still exists. The flight path during the deceleration is so close to the negative lift equilibrium glide path that any disturbance causes a violently unstable maneuver resulting in either a premature atmospheric exit or excessive penetration. The rapidity of this divergence is such that it is doubtful whether a real guidance and control system would be capable of handling the situation. For example, a variation in the time of lift reversal of $\pm 10^{-4}$ sec yields, at one extreme, a trajectory that never leaves the atmosphere and, at the other extreme, a trajectory that leaves the atmosphere with greater than parabolic velocity. This extreme sensitivity is sufficient cause to explore other schemes of trajectory control that, while requiring slightly greater propulsive velocity increments to achieve orbit, do not place unreasonable demands on the vehicle's guidance and control systems.

Constant Altitude Trajectories

The obvious remedy for some of the difficulties encountered with the trajectories described previously is to perform the deceleration maneuver at a lower altitude, thus maintaining a greater degree of trajectory control capability.

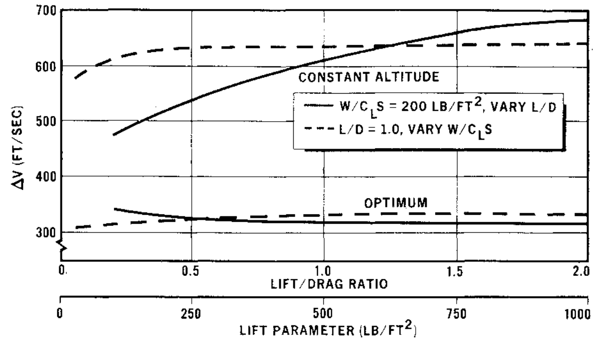

Fig. 6 Variation of orbital velocity increment with L/D ratio and lift parameter; $N_{T\max} = 4$ g's, $V_e = 25{,}000$ fps, orbit altitude $= 1.83 \times 10^6$ ft.

One simple trajectory control scheme meeting these requirements is described in the following. Again, the vehicle reaches pullout without lift modulation. After pullout, deceleration is continued at approximately constant altitude, maintained by lift modulation. At an appropriate velocity, the lift vector is directed upward, and the vehicle leaves the atmosphere. A time history of such a trajectory is shown in Fig. 4. In this case, the vehicle angle of attack was held constant throughout the trajectory, and lift modulation was achieved by variation of the bank angle. A comparison of this trajectory with the optimum trajectory reveals that after the initial pullout the dynamic pressure is about an order of magnitude higher for the constant altitude trajectory. This higher dynamic pressure is sufficient to provide adequate control capability for any necessary corrective maneuvers.

The variation of the propulsive velocity increment with orbit altitude is shown in Fig. 5. Comparison of the optimum and constant altitude trajectories reveals that the penalty paid for added control capability varies from 500 fps at an altitude of 10^6 ft to only 90 fps at an altitude of 3.5×10^6 ft. However, the total propulsive velocity required is still less than 5% of that required for complete propulsive braking. Figure 6 shows the variation of the propulsive velocity increment with vehicle L/D ratio and lift parameter for an entry velocity of 25,000 fps and a peak load factor of 4 g's. A greater effect of vehicle parameters is seen than for the optimum trajectories, but the propulsive velocity requirement remains relatively small. The effects of entry velocity and maximum load factor on the propulsive velocity increment are shown in Fig. 7 for a vehicle L/D ratio of 1.0 and a lift parameter of 200 psf. The propulsive velocity required is seen to increase with decreasing entry velocity and increasing load facor. In contrast to the optimum trajectories, the constant altitude trajectories evidence relatively low sensitivity to variations in maneuver time. This is demonstrated in Fig. 8 where the variation in apocenter altitude with the velocity at which maximum positive lift is commanded is shown for the vehicle and entry conditions of Fig. 5.

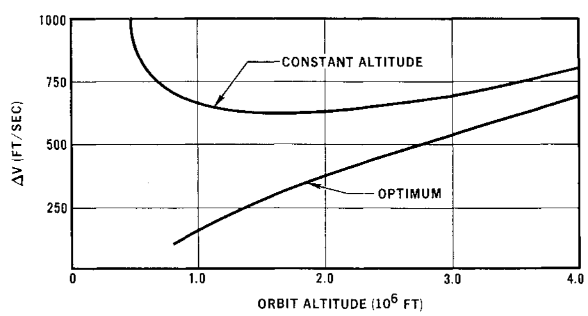

Fig. 5 Variation of orbital velocity increment with orbit altitude; $L/D = 1.0$, $W/C_LS = 200$ psf, $N_{T\max} = 4$ g's, $V_e = 25{,}000$ fps.

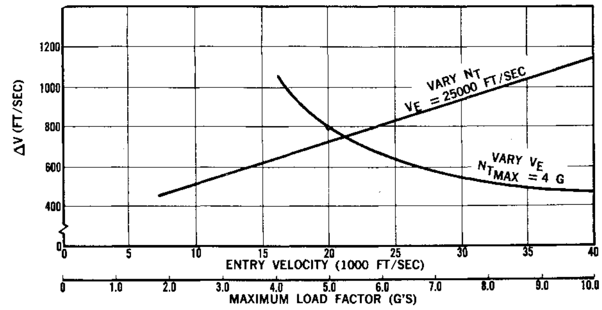

Fig. 7 Variation of orbital velocity increment with entry velocity and peak load factor; $L/D = 1.0$, $W/C_LS = 200$ psf, orbit altitude $= 1.83 \times 10^6$ ft.

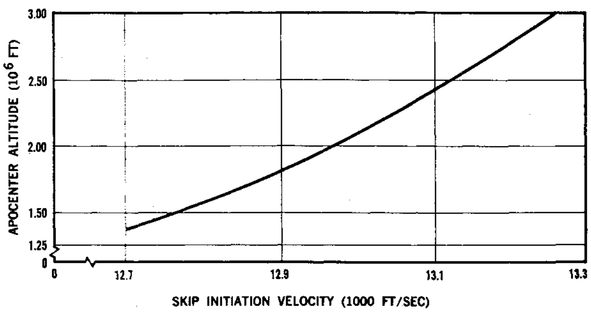

Fig. 8 Variation of apocenter altitude with skip initiation velocity; $L/D = 1.0$, $W/C_LS = 200$ psf, $N_{T_{max}} = 4$ g's, $V_e = 25{,}000$ fps.

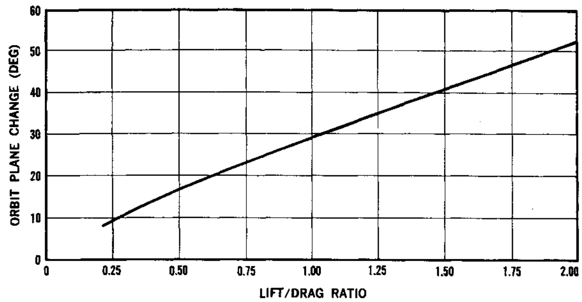

Fig. 9 Variation of orbit plane rotation with L/D ratio; $W/C_LS = 200$ psf, $N_{T_{max}} = 4$ g's, $V_e = 25{,}000$ fps.

Referring to Fig. 5, the deceleration at the time of skip initiation is seen to be approximately 30 ft/sec². Combining this value with the data of Fig. 8 shows that an error of 0.1 sec in the time at which positive lift is commanded yields a difference of approximately 8000 ft in orbit altitude as compared with an effectively infinite difference in the case of the optimum trajectory. An additional feature of the alternate trajectories is that, if lift modulation is accomplished by variation of the bank angle, an appreciable rotation of the orbit plane may be accomplished during the braking maneuver. The orbit plane rotation capability is shown in Fig. 9 as a function of L/D ratio for vehicles having a lift parameter of 200 psf. For the assumed entry velocity of 25,000 fps and peak load factor of 4 g's, the orbit plane rotation capability is seen to vary from 9.5° at an L/D ratio of 0.2 to 52° at an L/D ratio of 2.0. These data represent the orbit plane rotation achieved using bank angle histories similar to that of Fig. 4. Varying amounts of orbit plane rotation up to these maximums may be achieved by alternating between positive and negative bank angles or by combined angle of attack and bank angle modulation during the constant altitude flight.

Conclusions

The problems associated with aerodynamic braking into a Martian orbit have been examined from the standpoint of vehicle and trajectory requirements. Mars entry corridors for direct descent and orbit attainment were found to be considerably less restrictive than in the case of Earth entry. An L/D ratio of 0.5 or greater permits 6 g entry at most velocities of interest.

Since aerodynamic braking to an orbit with pericenter outside of the planetary atmosphere is impossible, some propulsive velocity addition is required to achieve a stable orbit. Trajectories have been obtained which minimize this propulsive velocity increment. The propulsive velocity increment was found to increase with orbit altitude but to be nearly independent of vehicle L/D ratio, lift parameter, entry velocity, and maximum load factor. These trajectories were found to be sensitive to maneuver time to the extent of being impractical for real system.

Trajectories were then developed which provided better trajectory control and a lesser degree of sensitivity to maneuver time. The propulsive velocity requirements for these trajectories were found to be somewhat greater than the minimums established previously and showed greater variations with vehicle characteristics and entry conditions. However, all trajectories examined yielded propulsive velocity requirements that were a small fraction of the requirements for direct propulsive braking. Orbit plane rotation capability for these latter trajectories was investigated as a function of vehicle L/D ratio and was found to vary from 9.5° for an L/D ratio of 0.2 to 52° for an L/D ratio of 2.0. The combination of entry corridor, propulsive, and orbit plane rotation requirements are then sufficient to fix the L/D ratio required for aerodynamic attainment of a particular orbit with given initial conditions.

References

[1] Lowe, R. E. and Gervais, R. L., "Manned entry missions to Mars and Venus," Douglas Aircraft Co. Paper 1223 (1961).

[2] Finch, T. W., "Manned Mars exploration in the unfavorable (1975–1985) time period, Final study report. Volume VI, Entry analysis," Douglas Aircraft Co. Rept. SM-45580 (1964).

[3] "Study of subsystems required for a Mars mission module, Volume 4, Aerobraking," North American Aviation, Inc., Rept. SID-61-1-4 (1963).

[4] Warga, J. and Hailey, W. C., "The determination of extreme entry angles into a planetary atmosphere," AIAA Preprint 63-152 (1963).

[5] Evans, D. C. and Wasko, P. E., "Model atmospheres for the planet Mars," Douglas Aircraft Co. Rept. SM-44552 (1963).