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SUMMARY

A computer-simulation study was undertaken to investigate a maximum concealment guidance technique (called a pop-up maneuver), which military aircraft may use to capture a glide path from masked, low-altitude flight typical of terrain-following/terrain-avoidance flight enroute. The guidance system applied to this problem is the Fuel Conservative Guidance System. Previous studies using this system have concentrated on the saving of fuel in basically conventional land and ship-based operations. Because this system is based on energy-management concepts, it also has direct application to the pop-up approach which exploits aircraft performance. Although the algorithm was initially designed to reduce fuel consumption, the commanded deceleration is at its upper limit during the pop-up and, therefore, is a good approximation to a minimum-time solution. Using the model of a powered-lift aircraft, the results of the study demonstrated that guidance commands generated by the system are well within the capabilities of an automatic flight-control system. Results for several initial approach conditions are presented.

NOMENCLATURE

\dot{E}_n	normalized energy rate
g	gravitational constant
\dot{V}_a	rate of change of true airspeed
γ_a	aerodynamic flightpath angle

INTRODUCTION

A technique potentially useful for maximum concealment in military tactical operations consists of using low-altitude terrain-following/terrain-avoidance procedures to approach a landing site followed by a transition to a landing approach path. If the landing site is obscured from the aircraft by terrain, a pop-up maneuver is required to visually locate the runway, correct navigational errors, and to establish a minimum period of stable final descent prior to landing. This maneuver requires that the aircraft climb rapidly from its initial concealed altitude of 100

to 200 ft above ground level (AGL) to an altitude of about 500 ft AGL and then transition to a final-approach path. The requirement to reduce exposing the aircraft to visual or radar detection suggests that the pop-up maneuver must minimize flight time spent above the concealment altitude. If the pop-up maneuver is to be flown manually, an increased heavy workload is placed on the pilots, more so when the aircraft is flown on the backside of the power-required curve for powered-lift STOL operation.

An energy-management concept has been under development at NASA which has the potential to provide efficient pop-up maneuver guidance. The energy-management concept consists of a set of computer algorithms that plan flightpaths along three-dimensional, curved capture flightpaths, and prestored flightpaths using procedures which were designed to minimize fuel usage. The Fuel Conservative Guidance (FCG) system algorithms plan horizontal capture flightpaths to minimize the distance to a pilot-selected waypoint on a prestored reference flightpath. The vertical and speed profiles along the capture flightpath and the prestored flightpath are planned using simplified aero/propulsion performance models of the aircraft. These performance models are used also to optimize flight along the prestored flightpath. An important feature of the system which produces this fuel conservation is the detailed modeling of the airplane controls and their interaction to define the airplane's capabilities and limits. The FCG system uses this knowledge to optimally schedule these controls to follow the planned horizontal, vertical, and speed profiles. The system's capabilities to plan flight profiles and optimally provide configuration change and guidance commands for either manually or automatically flown approaches can be used in situations where fuel conservation is of secondary importance, as in the military scenario described above. These vertical and speed profiles are optimized such that the speed reduction and climb are closely coordinated to provide a time efficient pop-up maneuver. Previous flight tests have shown that guidance commands generated by the FCG system can be flown by an automatic system (ref. 1).

All of the previous studies using the FCG system have concentrated primarily on the saving of fuel in basically conventional land and ship-based operations (refs. 1-3). This study explores the use of the FCG system to provide guidance in situations which are more mission-critical and airplane-performance oriented than previous studies. Specifically, landing operations which feature a pop-up maneuver are investigated. These include entry approaches to a final descent to landing from any direction and heading relative to the runway. Computer generated data are presented to show that guidance and configuration-change commands can be generated to prompt the pilot through a difficult flight procedure or to provide those commands to a full-function autopilot.

SYSTEM DESCRIPTION

The basic objective of the FCG system is to plan a flyable flightpath from the current aircraft states through some specified intermediate states to desired terminal states. On command from the pilot, the system will then plan the flightpath in

real time and provide inputs either to an automatic control system or to an electronic display to enable the pilot to fly the aircraft along the planned path. Since a flightpath featuring a pop-up maneuver is described in this paper, the system description will concentrate on those aspects involved in it. A more complete and detailed system description is contained in reference 3.

The planned horizontal path consists of a fixed path, defined by a set of prestored waypoints and a capture path from the aircraft's initial position and course, to the position and course at the capture waypoint on the fixed path. The capture path is computed by the system to minimize the distance. It consists nominally of an initial turn, a straight segment, and a final turn. If capture is initiated when the aircraft is near the capture waypoint, a three-turn capture path may be generated.

The planning of a "flyable" flightpath implies compliance with certain constraints:

1. Operational constraints: maximum and minimum aerodynamic flightpath angles, maximum and minimum airspeed rates, maximum magnitude of normal acceleration, and maximum bank angle.
2. Geometric constraint: maximum magnitude of flightpath angle rate, changing from an initial to a final flightpath angle during the altitude change between two waypoints.
3. Aircraft and engine constraints: the result of limited capability of the aircraft and engines, including safety constraints. For example, a flightpath angle meeting the constraints in (1) and (2) may not be within the flight envelope of the aircraft for a particular flight condition.

Determining the aircraft constraints requires a fast-time solution of the aircraft's equations of motion. The algorithms used for this solution depend upon energy-rate methods and are described in references 1 and 3.

The basis of the energy-rate method is that the aircraft energy is defined as the sum of the kinetic and potential energies

$$E = mgh + \frac{1}{2} m\dot{V}_a^2 \quad (1)$$

After differentiation and appropriate substitutions related to aircraft flight, the normalized energy rate, \dot{E}_n , is derived as

$$\dot{E}_n = \sin \gamma_a + \frac{\dot{V}_a}{g} \quad (2)$$

For convenience, \dot{E}_n will be referred to simply as the energy rate and it represents the total capability of the aircraft to change altitude and speed. Thus the algebraic sum of commanded values of γ_a and \dot{V}_a/g must always be less than the maximum and greater than the minimum allowable energy rate. It also provides the means to apportion the available energy between altitude changes and speed changes. When a

change in altitude or speed is called for, the system will attempt to make the change at the maximum or minimum values of $\sin \gamma_a$ or \dot{V}_a/g . If the aircraft is on a performance limit and is only capable of an energy rate, \dot{E}_n^a , which is less than the desired value, the available \dot{E}_n is allocated according to

$$\frac{\dot{V}_a}{g} = \epsilon \dot{E}_n \quad (3)$$

$$\sin \gamma_a = (1 - \epsilon) \dot{E}_n \quad (4)$$

where ϵ is initially specified by the pilot. During the pop-up maneuver, the speed and altitude change in opposite directions, and it is desired to have these changes accomplished simultaneously in the shortest time possible. The algorithm for achieving this goal has the effect of a recomputation of ϵ such that either airspeed rate or flightpath angle is at its maximum or minimum value. Note that in this case ϵ is not restricted to $0 \leq \epsilon \leq 1$ as in the cases where speed and altitude changes are of the same sign.

After the desired flightpath angle and airspeed rate are determined for a flightpath segment, the next step is to determine whether the desired \dot{E}_n can be achieved at the current flight conditions, and if so, to determine the corresponding required control settings for flaps, angle of attack, and thrust. Sets of tabular data referred to as "energy-rate tables" have been generated for this purpose. These stored tables relate the total energy rate to the corresponding wing angle of attack, the thrust coefficient, the lift coefficient, and the flap setting. The thrust coefficient tables are stored for three different pressure ratios, and altitude is accounted for by linear interpolation on pressure ratio. Although most aspects of the FCG system are for a generic aircraft, the values in the energy-rate tables are for the specific aircraft for which the system is to be used. For this study, a powered-lift STOL transport aircraft is represented by data for NASA's Quiet Short-Haul Research Airplane (QSRA).

As the flightpath is planned, a command table is generated which includes the following information for each state-change location: index number of the next waypoint, time and distance to the final waypoint, flightpath angle, rate of change of airspeed, flap positions, roll angle, altitude, indicated airspeed, and lead distances for roll and flightpath angle (to compensate for finite rates). This information is used during flight to initialize integration for the next segment. For these tests, the commands are integrated to touchdown to provide presentation data.

THE POP-UP MANEUVER

An approach flightpath with a pop-up maneuver is illustrated in figure 1. The aircraft starts the approach at location A. The aircraft is assumed to be at an initial altitude of 100 to 200 ft altitude AGL and at near-cruise airspeed; i.e., a

terrain-following-type flightpath. The objective is to climb to capture a glidepath at approximately 1 min before touchdown. This procedure allows the pilot an opportunity to visually acquire the runway, correct navigation errors, and establish a stabilized approach to touchdown.

In order to reduce the probability of detection by opposing forces, a primary requirement is to minimize the time spent above the initial approach-entry altitude. The optimum method of performing this pop-up maneuver is to use the energy-management procedures described earlier to trade airspeed for altitude during the climb from point B to point C. By setting the operational constraints placed on airspeed rate and flightpath angle to their respective minimum and maximum allowable values, the FCG system can plan a flight segment so that deceleration to the final descent airspeed will coincide and will be synchronized with the climb from point B to point C, therefore both conditions are met simultaneously at point C.

For a powered-lift airplane like the QSRA, a configuration change from cruise mode to powered-lift mode will have to be made during the climb. Because this configuration change significantly alters the aircraft's speed reduction and climb capabilities and involves several control-system mode changes, it must be carefully done so as to accomplish the simultaneous speed reduction and climb. When the aircraft reaches point C, its state must have transitioned from a climb to a stabilized final descent to point D. For these tests, point D was defined as being at the touchdown point on the runway. Operationally, point D would be set at some altitude above the runway where a mode change would initiate automatic or display landing guidance. At this time, the pilot would correct the navigation errors and the descent flightpath. In case of large navigation errors, the pilot could disconnect immediately after beginning the descent to allow maximum time for corrections.

RESULTS

Straight-in Approach

The first example of a pop-up approach is a straight-in flight to the runway with no lateral maneuvers required. The capability to plan such optimum capture paths is one of the primary features of the FCG system. In order to allow maximum planning flexibility, the fixed flightpath portion of the approach is defined by only two waypoints. Waypoint 1 is at 500 ft altitude on a 4.5° glide-slope angle and is aligned with the runway centerline. Waypoint 2 is located on the runway at the touchdown point. (These two waypoints correspond to points C and D of figure 1.) Airspeed for this segment is specified to be the normal 65 knots final approach descent airspeed for the QSRA. The airplane begins the approach at a altitude of 100 ft and an airspeed of 140 knots. A 10-knot headwind is assumed to be blowing.

The results of the FCG system's planned commands and the ensuing integration of those commands are shown in figure 2. The pop-up begins at about 14,000 ft from touchdown. The altitude increase is initiated with a flightpath angle of 2° .

Airspeed deceleration, limited to $-0.1 g$, starts at the same time. At 120 knots airspeed, the outboard flaps start extending and the throttles increase about 3%, thereby increasing the lift. The altitude rate increases as the flightpath angle is increased to 3° . After the outboard flaps are fully extended, the upper surface blowing (USB) flaps, which are located on the QSRA wing under the engine exhaust flow, extend with simultaneous throttle advancement. These USB-flap-throttle changes put the aircraft into the powered-lift mode. As the airplane nears waypoint 1 at the maximum specified altitude of 500 ft, the airspeed has decreased to 65 knots. The flightpath angle changes to transition from the climb to the final descent on the fixed flightpath defined by waypoints 1 and 2. The airplane descends at an aerodynamic flightpath angle of -4.5° at 65 knots airspeed, which is equivalent to a -6° inertial flightpath angle.

At the bottom of figure 2 are shown the maximum, actual, and minimum values of energy rate and thrust coefficient during the approach. The actual energy rate is near, but not at, the minimum until 10,000 ft from touchdown. This is consistent with the requirement to reserve 10% of total available energy rate for control in unexpected situations. The actual thrust coefficient is at the minimum for most of the ascent until the USB flaps extend and the throttles advance. This indicates that \dot{V}_a/g was limited at its minimum permissible value during this period. Since both of these terms in the energy rate equation (2) are at limits, the third term, $\sin \gamma$, is also fixed. At 10,000 ft, the outboard flaps began their commanded extension, thereby increasing the available lift forces on the airplane which, in turn, increased the available energy rate by lowering the minimum limit. This allowed either \dot{V}_a/g or $\sin \gamma$ or both to change. The FCG system changed both (see airspeed and flightpath angle) to retain the synchronized deceleration and climb. After the transition to the descending portion of the flightpath at about 6500 ft to touchdown, the actual energy rate remains well above the minimum, indicating that there is excess energy rate available to cope with disturbances.

The time required for this approach is illustrated in figure 3 where the altitude, airspeed, and flightpath angle are shown. The pop-up maneuver begins at 115 sec to touchdown and the climb takes about 55 sec. The elapsed time spent above 100 ft is 101 sec. Since the airspeed rate was at a minimum during the pop-up, a minimum time maneuver was performed. As required, the peak altitude occurs at about 1 min to touchdown. The airspeed changes at a rate of 1.5 ft/sec, then changes to about 3.2 ft/sec after the flap extension. With the exception of the first change at about $6^\circ/\text{sec}$, the flightpath angle changes at rates of 0.3 to $-1.6^\circ/\text{sec}$.

Turning Approach

An example of a turning entry to a pop-up approach is shown in figure 4. As discussed in a previous section, a horizontal capture path can be planned by the FCG system to capture a waypoint from any location and to minimize the capture path distance. This approach illustrates the horizontal path plan when the FCG system is engaged to capture a nearby waypoint. In this case, a horizontal approach path with a left turn, a straight segment, and a right turn is combined with a pop-up vertical

maneuver to capture the same waypoint as the straight-in approach described above. If the aircraft had been closer to the capture waypoint at engagement, a two- or three-turn approach with a pop-up would have been generated. If the aircraft were too close to the capture waypoint for a direct capture, a capture path with a turn greater than 360° would have been generated.

The radii of the first and second turns are computed to provide a maximum roll angle of 20° for a ground speed equal to the sum of the current airspeed of the airplane and the wind speed. In this case, the maximum roll angle is about -12° , figure 5, based on an initial airspeed of 140 knots and a 10-knot headwind parallel to the X-axis. During the early part of the first turn, at 17,000 ft to go until touchdown, the pop-up is started when the airspeed deceleration begins and the flightpath angle changes from 0 to 1.5° . The vertical-speed profile is similar to the straight-in approach, except that the airspeed must stabilize at 65 knots as specified for the capture waypoint before the final turn can begin so that the radius of the final turn can be minimized. The final turn ends at the capture waypoint. Therefore the speed decrease ends before the peak altitude is reached. To compensate for this loss of energy caused by changing airspeed (\dot{V}_a/g), the flightpath angle ($\sin \gamma$) is increased in accordance with the energy-rate equation. To allow this to happen and to compensate for the USB-flaps extension, the engine throttles must be advanced. When this occurs, the energy rate and thrust coefficient deviate temporarily from values near their minimums to near-maximums. Both return to values nearer minimum after the peak altitude is passed. The descent portion of this approach is similar to that for the straight-in approach.

An indication of the time required for this approach is given in figure 6. During the turning approach, the pop-up maneuver took longer than during the straight-in approach, spending 119 sec above 100 ft. This was due to the requirement for the airspeed to be at the final airspeed before beginning the final turn. The increase in time, therefore, is equal to the time required for the final turn, about 13 sec.

Alternate Initial Altitudes

The choice of a 100-ft initial altitude was somewhat arbitrary. Since a variety of initial altitudes could be desirable for entry to a pop-up maneuver, an examination of the primary effects of other initial altitudes is of interest. The altitude profiles for straight-in approaches with initial altitudes from 100 to 400 ft, in steps of 100 ft, are shown in figure 7. Another approach, at a constant 500 ft altitude to the descent point, is shown for comparison. The airspeed profile is also shown and is the same for all cases, indicating that for all initial conditions shown the airplane's deceleration capability is the limiting factor, not its climb capability. Since the speed change capability of the airplane is at a limit for all cases, the system computes the appropriate value of flightpath angle using equation (4) to accomplish the altitude change simultaneously with the airspeed reduction. Once these values are chosen, the outboard flaps are extended at the appropriate times. As shown in figure 7, the outboard and USB flaps are extended

sooner for higher initial altitudes. This is consistent with the need to extend the flaps as soon as allowable and necessary to sustain the required flightpath angle. The elapsed time spent above the initial approach altitude was 101 sec for the 100 ft approach, 88 sec for 200 ft, 76 sec for 300 ft, and 64 sec for 400 ft.

CONCLUSIONS

This study has demonstrated that guidance commands for the pop-up maneuver can be generated using energy-rate concepts. Data presented show that the QSRA aircraft as modeled in the aircraft-specific energy-rate tables could fly the flightpaths shown. Examples of horizontal, vertical, and speed profiles have shown the FCG system's ability to minimize pop-up flight time and carefully coordinate the airplane's controls for this performance-oriented flight-guidance requirement. Data presented indicates that a flight profile can be planned for a range of initial altitudes, even if the airspeed-change control parameters are operating at their limits.

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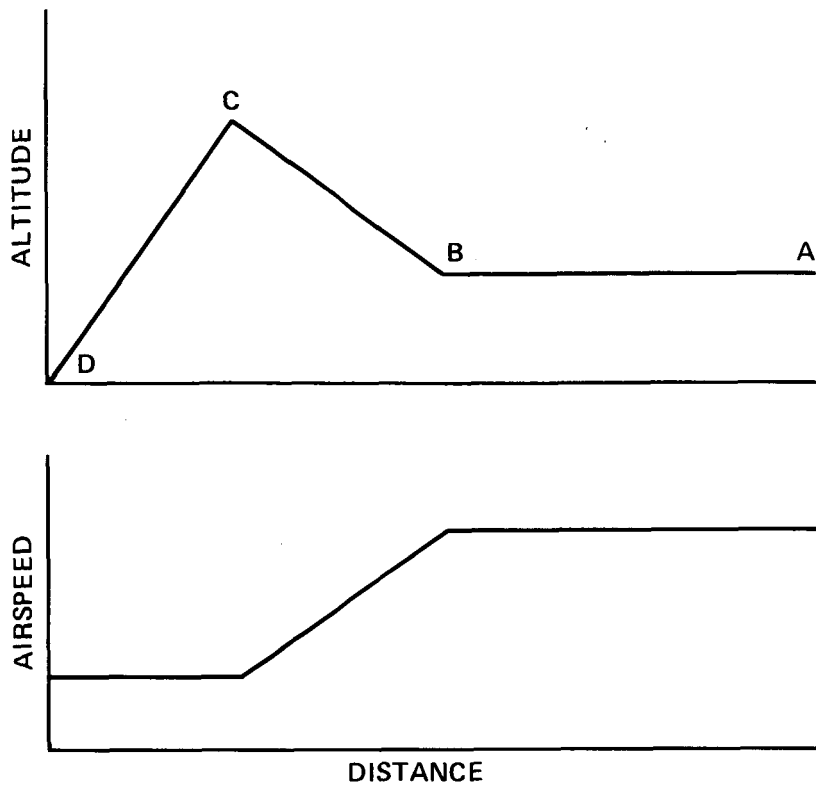


Figure 1.- Pop-up maneuver vertical-speed profile.

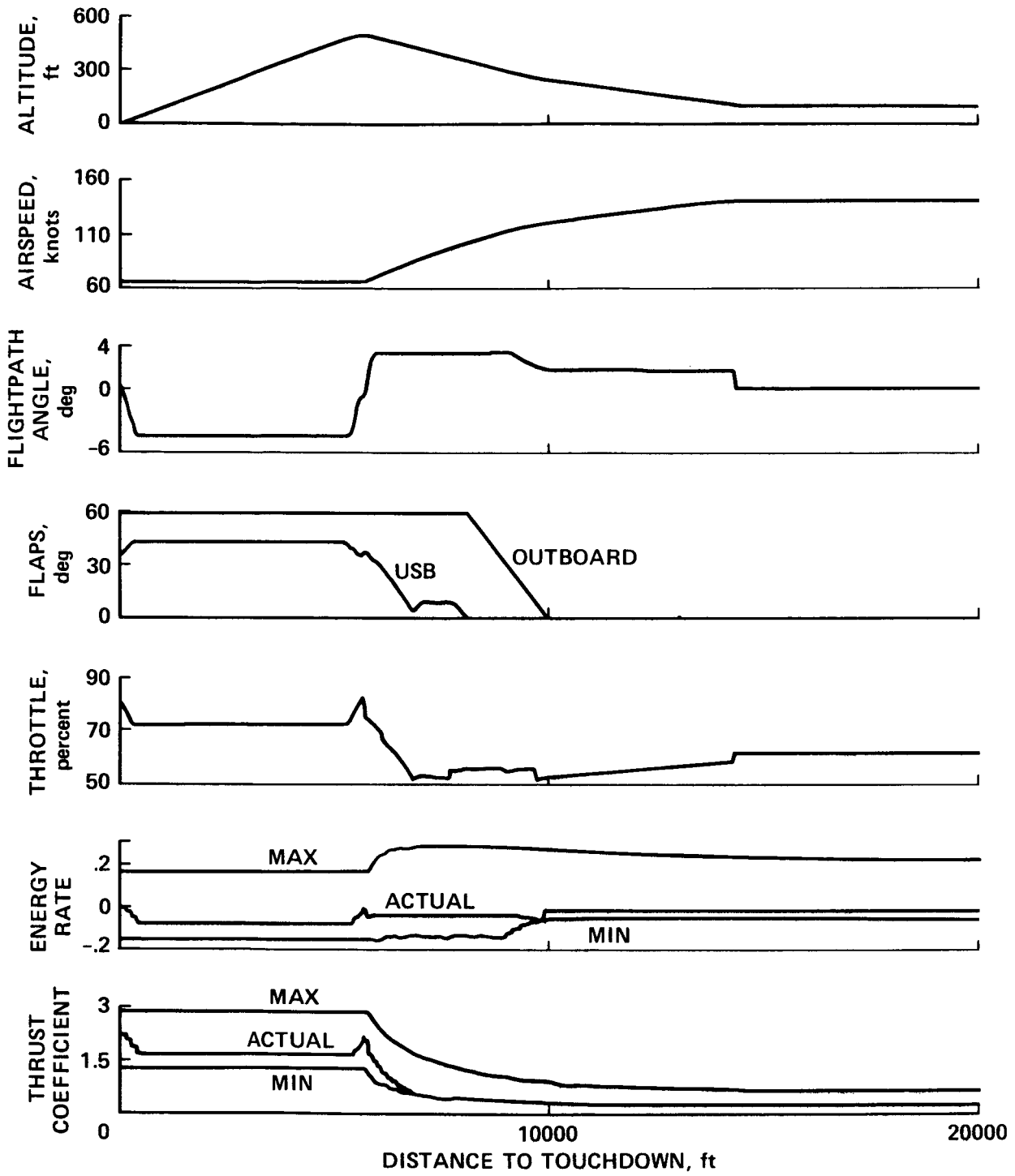


Figure 2.- Straight-in pop-up approach.

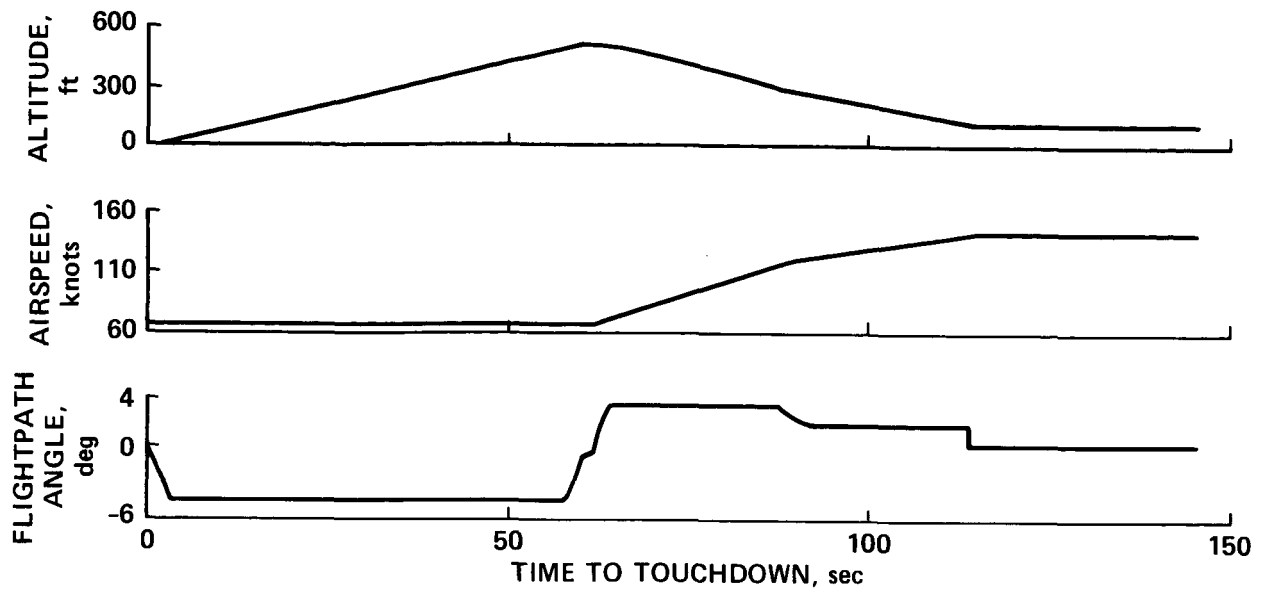


Figure 3.- Time for straight-in pop-up approach.

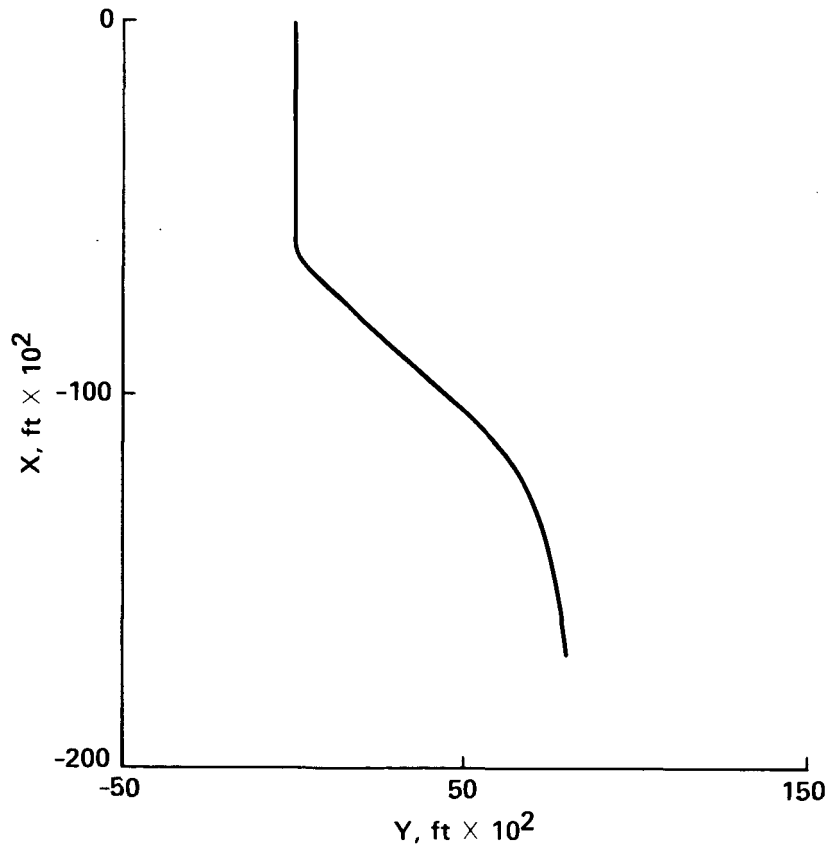


Figure 4.- Turning approach horizontal profile.

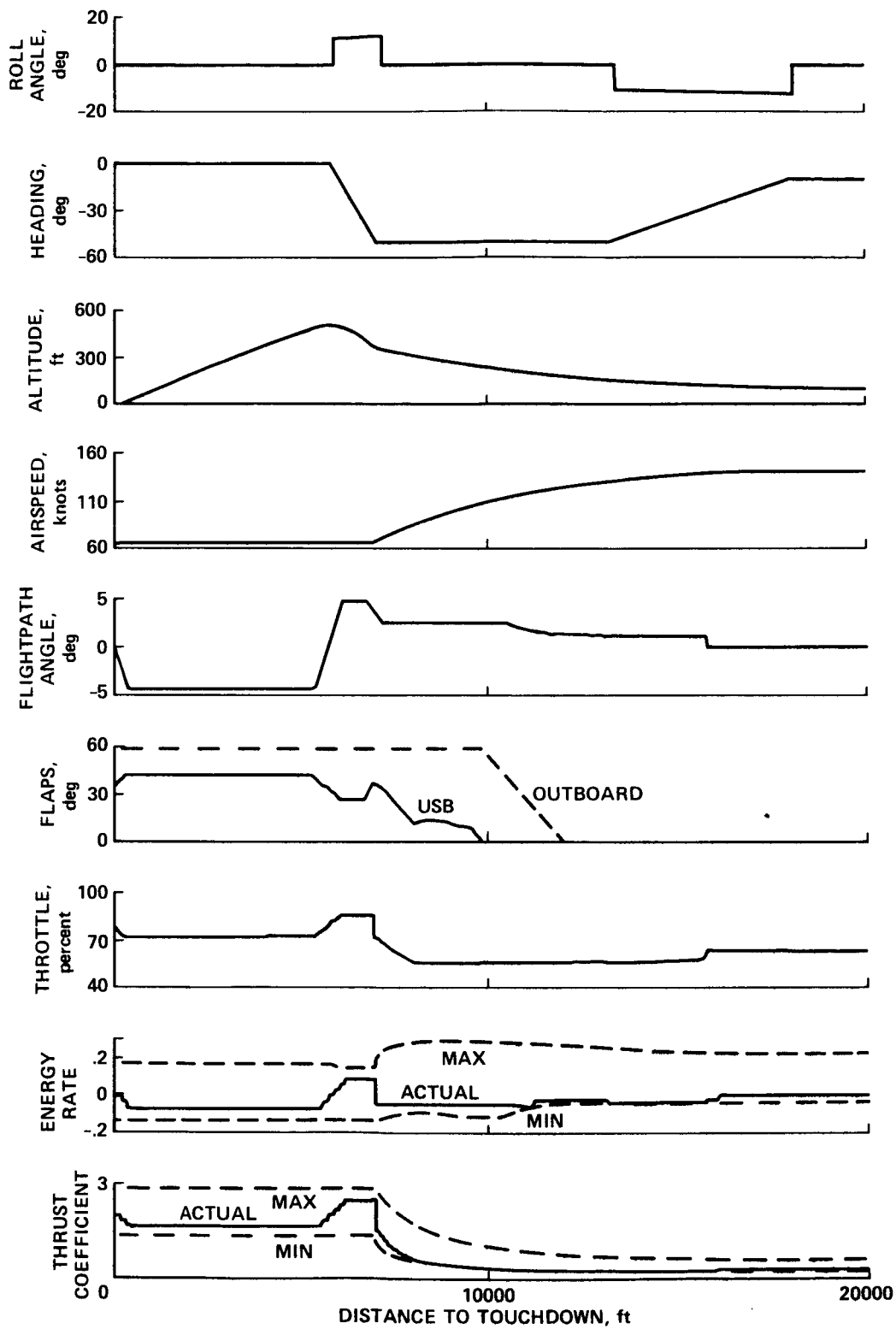


Figure 5.- Turning pop-up approach.

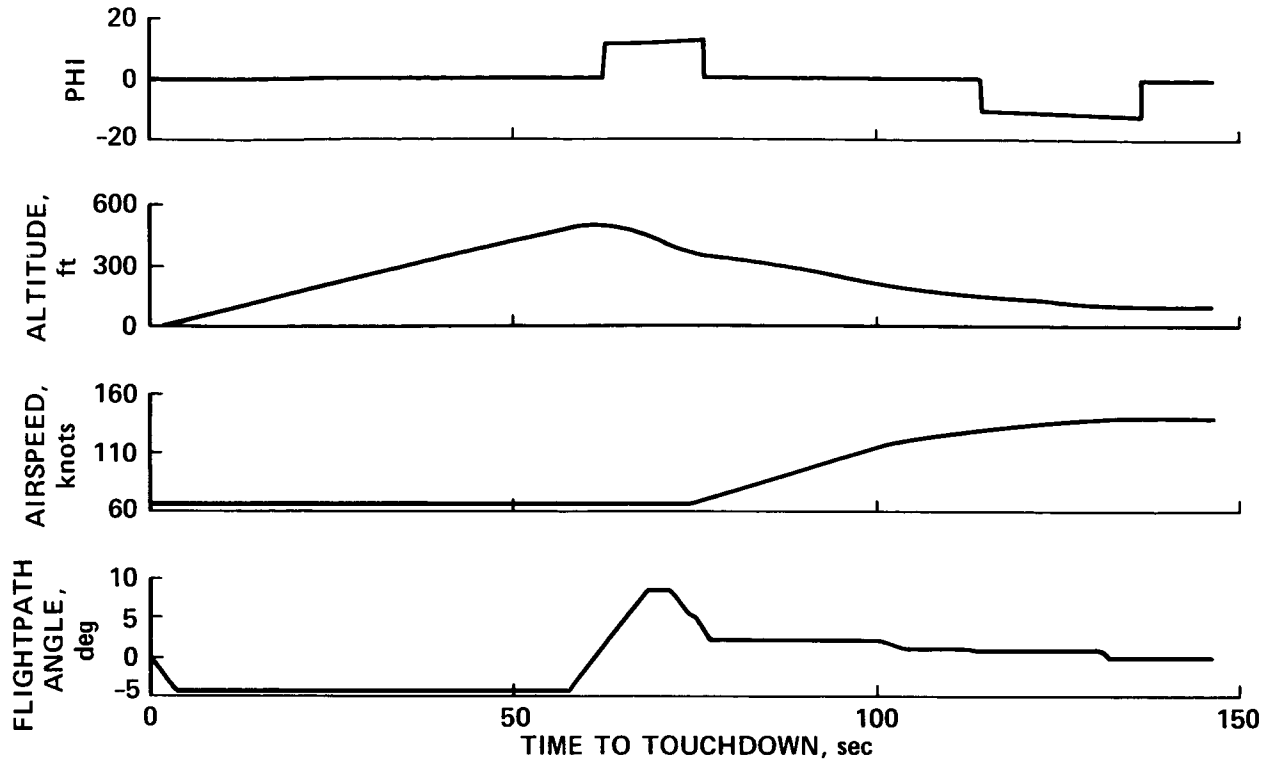


Figure 6.- Time for turning pop-up approach.

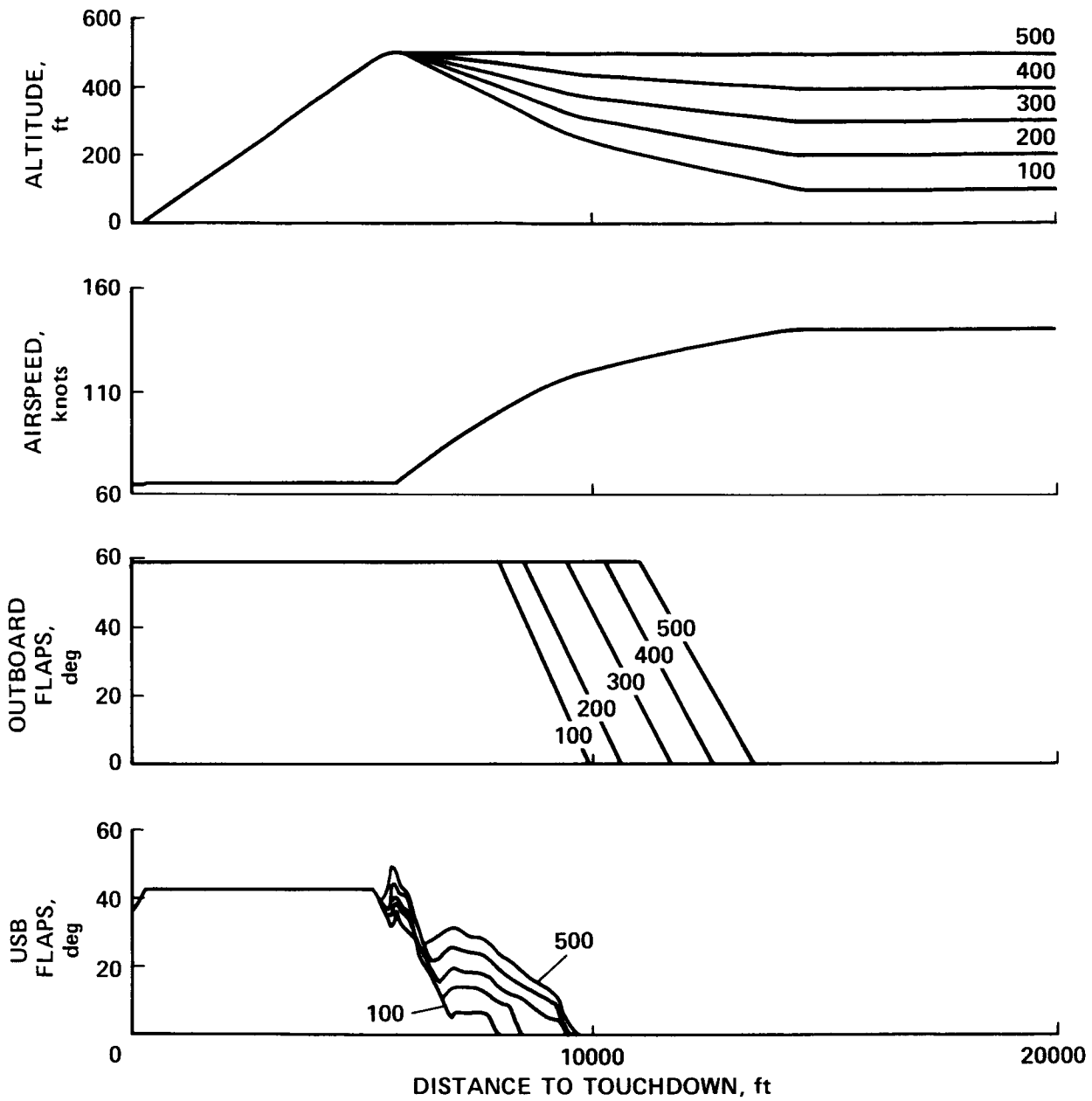


Figure 7.- Straight-in pop-up approaches with alternate initial altitudes.

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