Analysis of In-Trail Following Dynamics of CDTI-Equipped Aircraft

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The Cockpit Display of Traffic Information (CDTI) system is being developed to enable pilots to observe the surrounding air traffic pattern. The CDTI application of directly allowing the pilots to maintain in-trail spacing (following) along terminal area approach paths is examined. First, the following dynamics governed by the choices of separation criteria are analyzed. Then the results of several cockpit simulator experiments of in-trail following tasks are used to assess the performance of the pilot/aircraft/CDTI system in acquiring and maintaining adequate spacing dynamics. Based on collected simulator data, a mathematical model of the longitudinal system dynamics is formulated. This model can be used to examine various dynamics phenomena and the stability of a string of aircraft along the approach path. Experimental results are also used to examine longitudinal spacing control effects on vertical and lateral path control.

Introduction

BOTH the use of more automation and more involvement of the pilot in the air traffic control (ATC) process are well understood to be future needs for providing greater terminal area capacity. A joint NASA-FAA research project is being conducted to explore uses of the cockpit display of traffic information (CDTI) to meet these needs.[1]

One application of particular interest is the use of the CDTI display by the pilot for nonvectored clearances relative to other traffic. Under this category are functions such as control into a traffic merge point and spacing along a route. In order to derive the control requirements for such functions, it is first necessary to understand the dynamics of merging and trailing aircraft.

Several questions arise associated with these CDTI-based terminal area traffic tactical control concepts. These include:

1) What are the basic dynamic phenomena associated with independently controlled aircraft in a string?

2) What conditions would produce instability in the string?

3) What information does each pilot need (from the CDTI and elsewhere) to merge his aircraft adequately into the string and then to maintain appropriate spacing (along with normal lateral and vertical guidance functions)?

4) What are the effects of measurement and display errors, wind shears, aircraft mixes, spacing constraints, and merge trajectories on the dynamics and control performance of the system?

5) What advantages does this concept have compared to ground-based control?

This study begins to address these questions from a systems point of view. In particular, only the first three questions are addressed in this paper.

Background

The flight system (i.e., the pilot/aircraft/CDTI combination interacting with other aircraft and ATC) is assumed to be entering the terminal area and proceeding along an established approach to landing. A sketch of such a scenario is depicted in Fig. 1.

The pilot views the horizontal positions of his (Own) aircraft and the surrounding (Other) aircraft on a cockpit display such as shown in the simplified sketch in Fig. 2. Here, Own's position is indicated by the chevron symbol one-third the distance up from the bottom and centered laterally. This is a heading-up display, and the route path and other display features move continuously with respect to the Own symbol. Other aircraft are indicated by triangles. Own and Other aircraft symbols are preceded by vectors proportional in length to the ground speeds. They may be curved proportional to bank angle, and they produce a prediction of where each aircraft will be at a future time. Figure 2 shows a trail of history dots behind the Other aircraft immediately leading Own. If these dots are dropped at regular time intervals, they give Own and a record of the lead's path and where it was T_D seconds earlier.

The CDTI display will have other information on it, including an indication of the desired spacing and alphanumeric data giving Own and Other aircraft altitudes, ground speeds, identities, etc. The CDTI display symbology can be based on results of multiple NASA human factors studies[2-4] concerning desired information content.

There has been considerable previous investigation of traffic flow and control problems of ground vehicles in strings.[5-7] Pipes' work[5] was an early attempt to utilize the methods of operations research. He derived a mathematical model for strings of automobiles (which was a basic model used by later researchers), and he studied dynamic behavior of a string of vehicles initially at rest or after a sudden stop of the leading vehicle. Haight[6] contributed a great deal to the understanding of traffic flow by assuming a stochastic environment and using queuing theory. However, his macroscopic approach was not suited for analyzing stability and control of individual vehicles.

Athans et al.[8,9] solved the optimal control problem of a string of vehicles via the well-known LQG (linear, quadratic, and Gaussian) method. They[9] applied these techniques to the problem of controlling aircraft under somewhat restrictive assumptions. The LQG approach is mathematically interesting and concise; however, it is not applicable to the CDTI application of controlling an aircraft system governed by nonlinear dynamics.

Based on the review of the above work and other pilot modeling efforts,[10-12] it was determined that a fresh start was needed to understand the dynamic phenomena and stability aspects of a string of decelerating, descending aircraft in a terminal area. This required analyses of different possible

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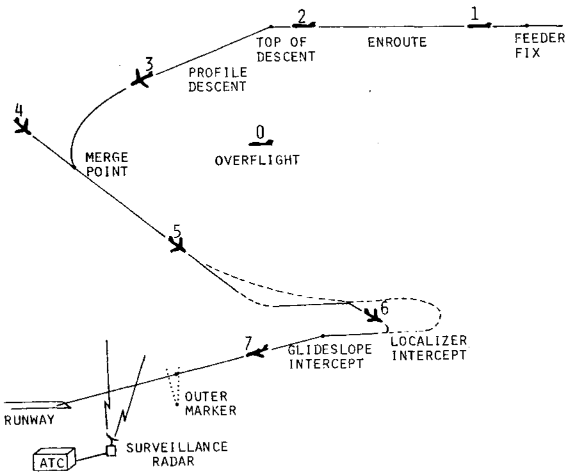

Fig. 1 Sketch of approaching aircraft in a terminal area scenario.

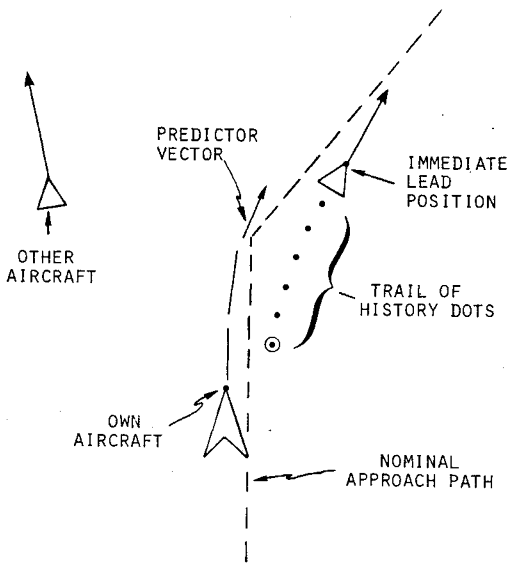

Fig. 2 Simplified sketch of CDTI display.

separation criteria and the development of new mathematical flight system models.

Longitudinal Separation Criteria

The separation criterion is the mathematical rule used as part of the CDTI display to indicate to the pilot what the desired separation should be between his and the Other leading aircraft. The criterion must establish a lower separation limit that is safe; yet, it must keep the aircraft close enough to provide for airspace and landing efficiency. The resulting implied acceleration commands must be within the normal limits of the aircraft. Finally, it should be possible to compute the criterion simply from available information and to display it to the pilot without ambiguity.

Two criteria which meet these qualifications for a single following aircraft are defined as follows.

Constant time predictor (CTP):

$$r_{\text{nom}} = r_T - r_o = T_p V_o \tag{1}$$

Constant time delay (CTD):

$$\begin{aligned} r_{\text{nom}} &= r_T(t) - r_T(t - T_D) \\ r_o(t) - r_T(t - T_D) &= 0 \end{aligned} \tag{2}$$

In Eqs. (1) and (2), r_{nom} is the desired longitudinal separation distance, r_T and r_o are the longitudinal ranges traveled from an initial feeder fix by the lead (or target) and Own aircraft, V_o is the ground speed of Own, and T_p and T_D are time constants.

Note that the Federal Aviation Regulations specify minimum separations in terms of distances rather than times. Thus, the time constants T_p and T_D must be chosen so that the minimum separation specifications at the slowest (landing) speeds are not violated.

The CTP separation criterion is indicated on the CDTI display by showing the predictor vector on Own aircraft (see Fig. 2) to be T_p times Own's ground speed in length. Proper spacing is achieved by controlling Own so that its predictor vector tip is on the lead aircraft symbol.

The CTD separation criterion consists of controlling Own to be where the lead aircraft was T_D seconds earlier. This position is indicated on the CDTI display by an enlarged history dot. Own is controlled so that its symbol is on top of this moving point.

The CTP and CTD separation criteria require more control changes on the part of the pilot than does following the current ATC vectoring instructions. The current ATC control maintains a nominal separation within reasonable bounds and insures that minimum separation distance is not violated. However, use of the CDTI with CTP or CTD criterion can potentially reduce the actual separations between aircraft to provide increased landing efficiency while reducing controller workload. Thus, there is a tradeoff between pilot workload and controller workload.

For the CTP criterion, the Laplace transform of the Own ground speed is

$$V_o(s) = \frac{1}{T_p s + 1} V_T(s) \tag{3}$$

Thus, the ideal speed of the Own aircraft is a lagged response with time constant T_p with respect to the lead. Similarly, for the CTD criterion, the ideal follower speed is

$$V_o(s) = e^{-T_D s} V_T(s) \tag{4}$$

This is simply a shift in time of the lead's ground speed, and each successive follower would ideally follow the same path in space as the lead. However, this is not true for the CTP criterion.

Figure 3 illustrates the theoretical ground speeds and separations which would result as a function of range-to-go for a string of nine aircraft (one lead and eight followers) using the CTP criterion with T_p of 60 s. The lead speed profile is a typical approach followed by a medium range twin-jet transport. Note that the lead deceleration causes successive slowdown of each following aircraft until the end where there is overcompensation causing increased landing speeds. The slowdown also produces generally decreased separation distances. Thus, apparent advantages of the CTD criterion are that 1) there is no inherent slowdown effect during deceleration portions of approach, and 2) there is no higher than nominal speed at the end of approach before landing.

This previous analysis is based on idealized dynamics. It does not account for delays and errors introduced by the pilot or the aircraft response to an acceleration command. The next step to extend these results was to include in the model 1) a control law representing pilot response to null out longitudinal separation and speed errors of the follower, and 2) simplified aircraft longitudinal acceleration response characteristics. A typical control law to null separation and speed errors would be

$$a_c = G_p \Delta r + G_v \Delta v \tag{5}$$

where G_p and G_v are control gains, a_c is the desired acceleration, and Δr and Δv are the errors. The response of the

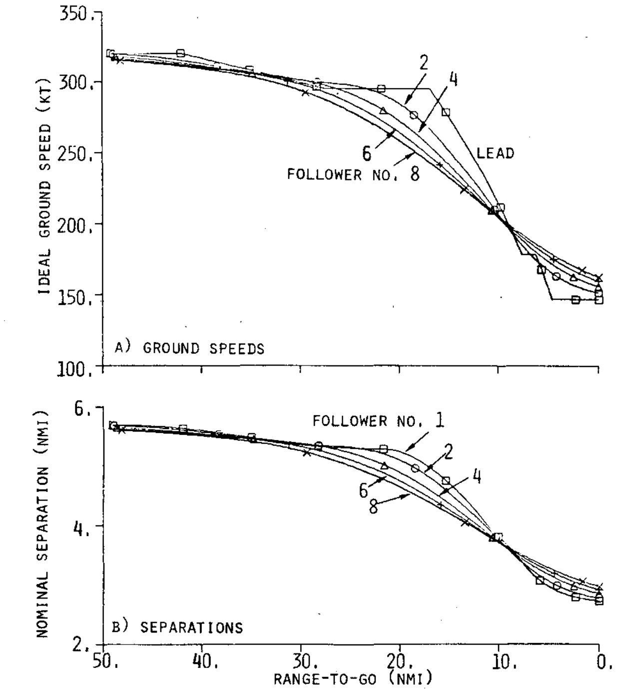

Fig. 3 Ideal speeds and separations for nine-aircraft string with $T_p = 60$ s.

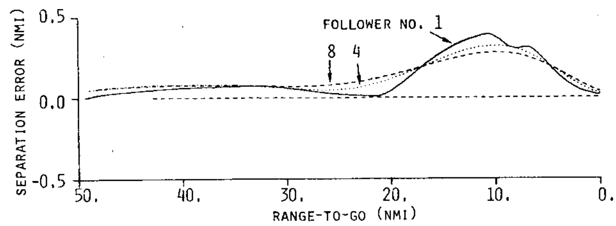

Fig. 4 Separation errors from nine-aircraft string (CTP).

aircraft to longitudinal acceleration commands can be modeled as a first-order lag with time constant τ_a.

For the CTP criterion, if V_M and V_L are the modeled values of Own and lead speeds, then, from Eq. (3),

$$\Delta v(s) = V_M(s) - \frac{1}{T_p s + 1} V_L(s) \tag{6}$$

The separation error is, from Eq. (1),

$$\begin{aligned} \Delta r(s) &= r_{\text{nom}}(s) - r_{\text{act}}(s) \\ &= T_p V_M(s) - [r_L(s) - r_M(s)] \end{aligned} \tag{7}$$

where r_{act} represents the actual separation, and r_L and $_M$ are the ranges traveled by lead and Own, respectively. Similarly, for the CTD criterion,

$$\Delta v(s) = V_M(s) - e^{-T_D s} V_L(s) \tag{8}$$

$$\Delta r(s) = r_M(s) - e^{-T_D s} r_L(s) \tag{9}$$

Equations 6-9 were simulated along with the aircraft acceleration characteristics to determine the effects of these additional terms on speed, separation, and separation error. Typically, they caused a small positive separation error (i.e., the follower is too close) as shown in Fig. 4 for the CTP criterion. This plot is based on using the same lead as Fig. 3,

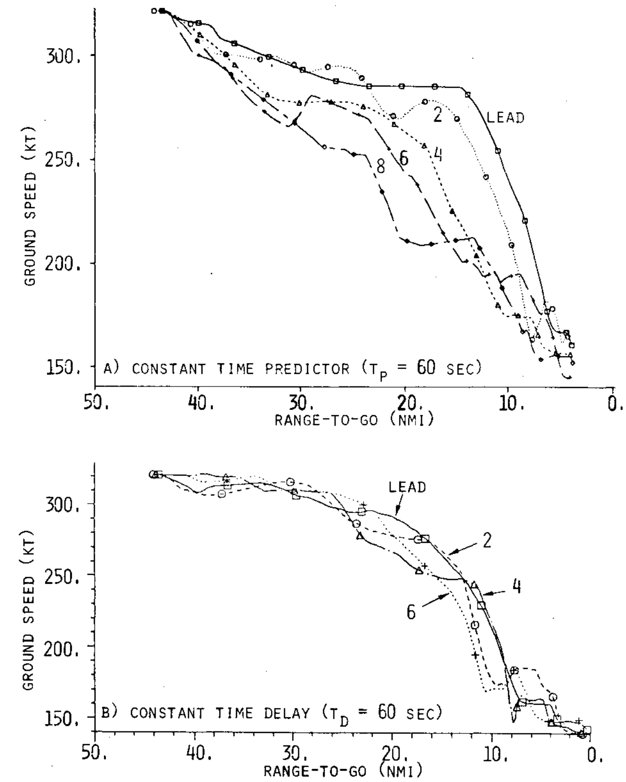

Fig. 5 Ground speed vs range from daisy-chain experiments.

G_p and G_v of $-2/\text{h}\cdot\text{s}$ and $-0.00833/\text{h}$, time constant τ_a of 4 s, and eight following aircraft. The gains G_p and G_v have values chosen to give the model response characteristics similar to what might be expected from a typical pilot. These are later tuned to match simulator results.

The CTD criterion results were characterized by smaller separation errors and leveling-off speeds at successively lower values with overshoot oscillations. Also, to keep the overshoot oscillation acceptably small, the speed error gain G_v had to be increased to $-0.2/\text{h}$.

Longitudinal Following Model

The first in-trail following experiment was run using a CDTI display in the NASA Langley TCV (737) cockpit simulator. The nominal approach path followed by the lead aircraft was along a profile descent leading to Denver Stapleton Runway 35R. Altitude was controlled by a pilot-assisted (inertial) flight-path angle hold mode. In the first part of the experiment, the CTP criterion was used with T_p of 60 s. During the first of nine runs made, the pilot followed a nominal vertical approach path. During each successive run, the pilot manually followed the profile of the aircraft immediately in front of him. In this way, a nine-aircraft string, or "daisy-chain," was simulated.

For the second part of the experiment, the separation criterion was changed to CTD with T_D set at 60 s. Here, the lead was followed by six runs to form a seven-aircraft string.

Figure 5 shows the resulting ground speeds vs range-to-land for the daisy-chain experiments. These results show the full effect of the nonlinear, stochastic response of the pilot in 1) estimating the longitudinal separation error from the CDTI display, 2) deciding whether to apply control to reduce the error or continue monitoring, and 3) applying acceleration control through throttle or spoilers. It is clear from these experimental data that there is more of a slowdown effect when the CTP criterion is used. However, in comparing Fig. 5a to Fig. 3a, it is seen that there are additional slowdown effects caused by piloting. This is also true to a lesser extent for the CTD criterion. However, we can also see that there is

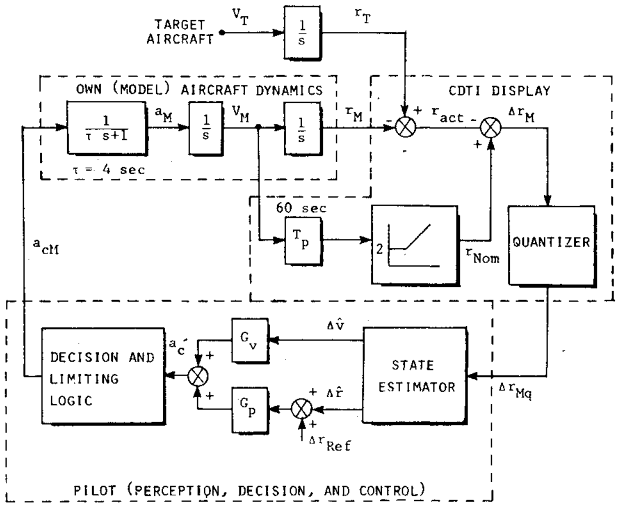

Fig. 6 First level block diagram of in-trail following flight system model for CTP criterion.

no adverse speed response characteristics which we would label as instability. More detail is found in Ref. 13.

It was desirable to capture the essence of this in-trail following behavior in model form so that 1) the piloting aspects which cause the imperfect following performance could be identified, 2) an understanding of the sensitivity of following performance to variations in various system parameters could begin, and 3) in-trail following could be simulated in fast-time without using a cockpit simulator. This modeling was begun based on the in-trail following results of the daisy-chain experiments, where lateral and vertical control effects and initial capture or merging requirements were minimal.

Figure 6 is a first-level block diagram of the longitudinal pilot/aircraft/CDTI system model for the CTP criterion. It is based on extending the analytical following equations given earlier and observing individual following performance characteristics in the experimental data. These observations include:

1) The pilot primarily used separation error as presented in the display to govern his control actions. It was assumed that he estimated rate information from the error rather than from alphanumeric speed differences.

2) The CDTI display had an effective quantization of 0.2 n.mi. when Own speed was above 200 knots and 0.1 n.mi. below 200 knots by the pilot's choice of map scale.

3) The aircraft acceleration/deceleration was limited between -1.25 knots/s and $+1.0$ knots/s for normal throttle activity. Spoilers provided deceleration of -1.6 knots/s when the aircraft was below 200 knots.

4) For a period during the beginning of each run, each pilot would limit his deceleration to a value less (in magnitude) than -1.25 knots/s.

5) The pilot would not decelerate to a speed much less than the lead speed, and never below the 130 knots landing speed.

6) The pilot would move the throttle in discrete steps after allowing separation errors to build up.

7) The pilot would not consistently hold small separation errors. There seemed to be a drift in separation error that varied from time to time in both magnitude and direction. This could be due to either lack of attention, competing piloting tasks, or lack of familiarity with the CDTI and the associated control task.

The above characteristics were imbedded in the longitudinal model in the form of the quantizer block, the decision and limiting logic block, the state estimator, and the time-varying separation error term Δr_{ref} ("wander factor") shown in Fig. 6. The model is changed in the CDTI display block if the user wishes to go from CTP to CTD criterion.

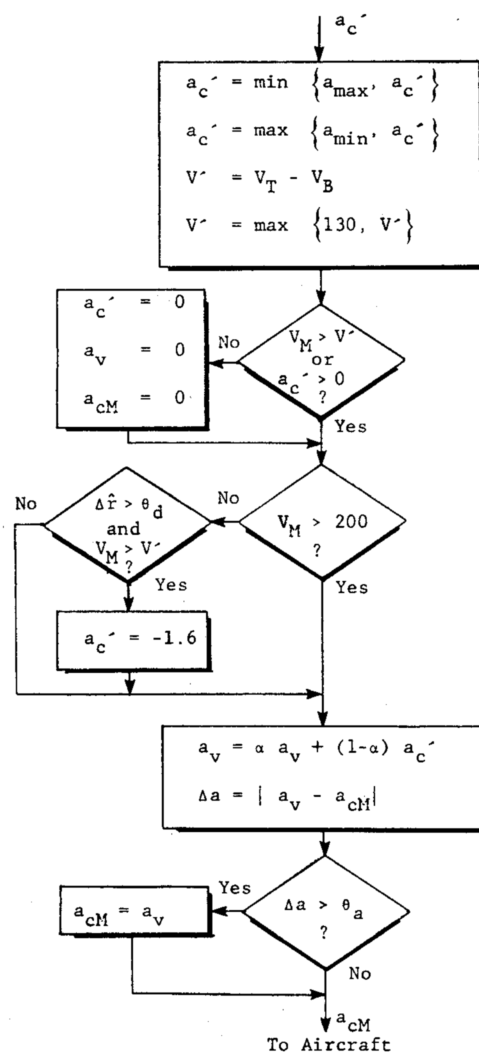

Fig. 7 Pilot decision and limiting logic for longitudinal acceleration command generation.

The state estimator block is a simple α-β filter which proved adequate. The decision and limiting logic is shown in further detail in Fig. 7. In this logic, $a_{\max}$ and $a_{\min}$ are maximum and minimum acceleration limits. V_B is the bias term on limiting ground speed to the current target value. Below 200 knots, the Θ_d term is used to determine if spoiler deceleration of -1.6 knots is to be used. Finally, the α and Θ_a terms are an inverse time constant and a threshold value used to create discrete throttle changes (see Refs. 14 and 15 for more detail).

The models are driven by the recorded ground speed V_T of the lead aircraft. The initial values of the Own speed V_M and range r_M are set from each experiment run, and thereafter, the model state variables are governed by V_T. Parameters in Figs. 6 and 7 are adjusted so that the rms differences between the model speed V_M of Own aircraft and recorded Own speed are small (less than 8 knots). In this way the model could be made to match the actual pilot performance for individual runs.

Figure 8 is an example comparison of recorded and modeled variables using the CTD criterion. Figure 8a depicts the recorded target and Own ground speed and the modeled Own ground speed. Figure 8b shows the actual and modeled separations r_{act} plus the nominal separation r_{nom}. Figure 8c presents the resulting separation errors (Δr and Δr_M), and it includes the variable reference bias Δr_{ref} used for this run. As can be seen, the model separation error has the same trends as the actual recorded data.

The modeling process was used to create eight following models to match each run of the CTP daisy-chain and six

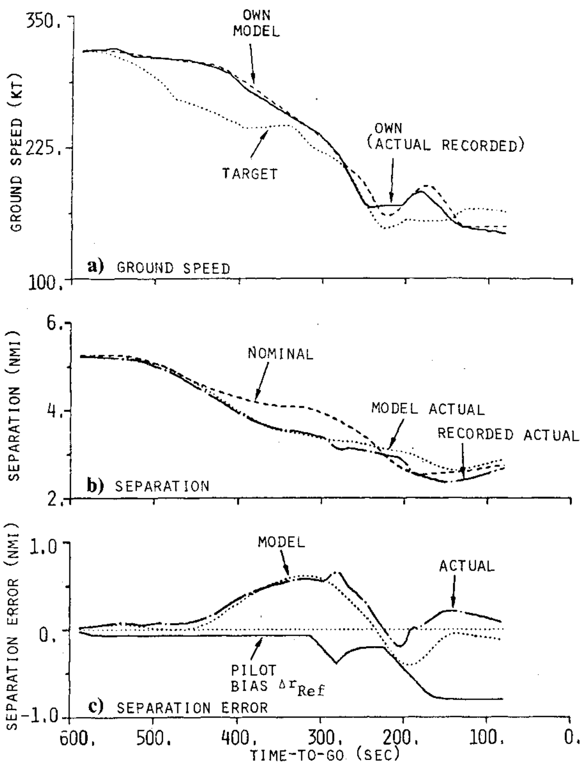

Fig. 8 Comparison of actual and model derived variables for CTD criterion.

following models to match the CTD runs. These models were then used to form purely analytical models (not driven by recorded data) of two strings of aircraft—one using CTP and the other using CTD. The lead aircraft profile used in these string models closely matched the paths followed during the experiments. As was expected, the resulting string models had the same slowdown behavior and following performance characteristics as were seen in the experimental data.

Parameters were then varied one at a time in the string models to assess their effect on the following performance. For the CTP criterion, the slowdown effects seen in Fig. 5a were primarily caused by the presence of the Δr_{ref} separation bias term in the model which represented individual pilot inattention to control of separation error. Removing the acceleration averaging and threshold (α and Θ_a in Fig. 7) used to create discrete throttle change behavior caused some of the modeled followers to have too high a landing speed (a secondary effect). Thus, it can be said that for this criterion, the general decrease in approach speeds of successive aircraft is produced primarily by lack of close separation control on the part of the pilot (i.e., he tends to hang back) in addition to the inherent slowdown characteristic of the CTP criterion.

For the CTD criterion, the following performance results were sensitive to variations in most of the model parameters. Removal or variation in the Δr_{ref} history, the initial deceleration limit (a_{min}), the acceleration averaging and threshold (α, Θ_a), or the filtering parameters each caused substantial oscillations in the modeled following behavior. It was further seen that the model results were affected to a large degree by the control law response to separation error rate $\Delta\hat{v}$. These large sensitivities could be removed by replacing the derivative of $\Delta\hat{r}$ (that is, $\Delta\dot{\hat{r}}$) in the control law by $V_T(t - T_D) - V_M$. This points out that, for good control with the CTD criterion, the pilot would get his rate information by directly observing the relative speed between his CDTI symbol (Own) and that of the target (i.e., the history dot) T_D seconds earlier. This would be in place of estimating this rate from $\Delta\hat{r}$. This would increase his mental workload, however. Probably for this reason, most of the pilots slightly preferred the CTP criterion.

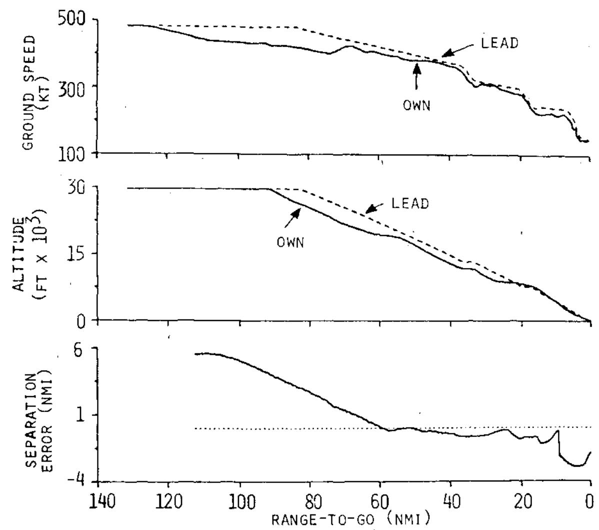

Fig. 9 Sample data from profile descent experiment.

Longitudinal Capture

A second experiment was run using the NASA Ames B-747 cockpit simulator as a single follower. This pilot used the CDTI to follow a single lead along a profile descent from cruise into Denver Stapleton Runway 26L. The nominal separation for the experiment was to maintain approximately 100 s between the lead and Own aircraft by using a combination CTD and CTP criterion. This criterion was expressed mathematically as

$$r_T(t - N\Delta) - r_M(t) = T_p V_M \tag{10}$$

where $N\Delta$ was 8 sample periods, each 4.2 s long, and T_p was a 66.4 s time constant. For this experiment, a matrix of five airline pilots flying Own, five variations in the lead aircraft profile, and five different initial separation errors of up to ± 40 s were used. Also, in this experiment, each pilot had to control his vertical profile in such a way as to pass through two altitude windows at waypoints along the profile descent. Normally, a pilot would go to idle throttle at the top of descent and thereafter use elevator and speed brake for vertical and speed control. Here, however, the pilot had to depart from his nominal speed profile to accomplish the longitudinal capture and tracking.

After passing the second waypoint at about 20 n.mi. to go, the pilot began lowering flaps, and he reverted to nominal speed control for landing the aircraft. It was found that the landing workload during final approach was too great for him to continue the in-trail spacing task.

Figure 9 shows data from this experiment with the trailing aircraft being initially 40 s (5.6 n.mi.) ahead of the nominal 100-s separation. Own aircraft pilot throttles back while in cruise, and then he keeps a lower speed than the lead after descent begins so that the positive (too close) separation error is removed when range-to-go of 65 n.mi. is reached. For the case when Own is too far back, the pilot remains longer in cruise at speed V_{cruise} before throttling back to descend. He continues to use throttle while descending to close the separation error. In this experiment, the pilots were quite proficient in reducing initial separation errors.

To extend the longitudinal model to include this capture phase required augmenting the control law [Eq. (5)] by using five control regions defined in Fig. 10. When Own is within ± 0.5 n.mi. and ± 10 knots of the desired separation, it is in region 5, and the regular control law [Eq. (5)] is used. Otherwise, the following accelerations are commanded:

Region 1:

$$a_c' = 0, \qquad \text{if} \quad V_M(t) \geq V_{cruise}$$

$$a_c' = [G_p \Delta\hat{r} + G_v \Delta\hat{v}]_{0.1}^{0.5} \qquad \text{if} \quad V_M(t) < V_{cruise}$$

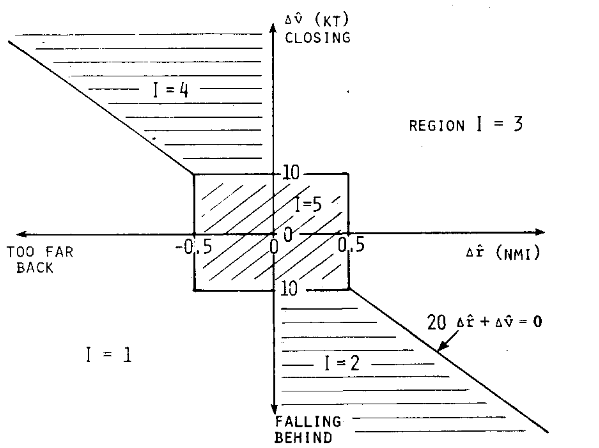

Fig. 10 Definition of various control regions for longitudinal capture.

Region 2:

$$a_c = 0.35 \text{ knots/s}$$

Region 3:

$$a_c' = [G_p(V_M - V_{\text{ref}})]^{0.2}_{-1.0}$$

$$V_{\text{ref}} = V_{\text{cruise}} - 40, \quad \text{if in cruise}$$

$$a_c' = [G_p \Delta\hat{r} + G_v \Delta\hat{v}]^{0.2}_{-1.0} \quad \text{if not in cruise}$$

Region 4:

$$a_c = -0.35 \text{ knots/s}$$

Results of simulating this capture control strategy confirmed its validity; it produced longitudinal dynamics similar to those observed in the experiments.

During these profile descent experiments, the pilots were instructed to focus on controlling speed to achieve the desired longitudinal spacing. This often caused the actual speed to be in error from the profile descent speed specifications for passing through the waypoint altitude windows. This points out that there can be a conflict in objectives between longitudinal spacing control and nominal speed control along the approach profile.

Combined Longitudinal/Vertical Control

Another CDTI following task was run using the NASA Ames multicab facility where three cockpits with 727 dynamics were used simultaneously to study following performance on approach into San Jose airport. The CDTI display in each cockpit showed the location of Own and two other aircraft. The three pilots flew their simulators three consecutive times to build up a nine-aircraft string. The third pilot's path was recorded and replayed as the lead aircraft for the fourth pilot, and similarly, the sixth pilot's path was recorded for the seventh pilot. Three sets of three airline pilots participated in this effort. Both CTP and CTD criteria were tested with 90-s time constants. Initial separation errors of ±30 s were present. Also, first the pilots had to merge onto the nominal approach path from alternating sides with about 6 n.mi. initial lateral position error and 30-deg heading error. The nominal approach was straight in along a 3-deg glideslope. The pilots' objectives were to capture and maintain the indicated nominal longitudinal separation as well as to capture and maintain normal descent along the glideslope to landing. Throttle and elevator were both used for longitudinal and vertical control. These simulators did not have spoilers or flaps as did the previously mentioned B-737 and B-747 simulators.

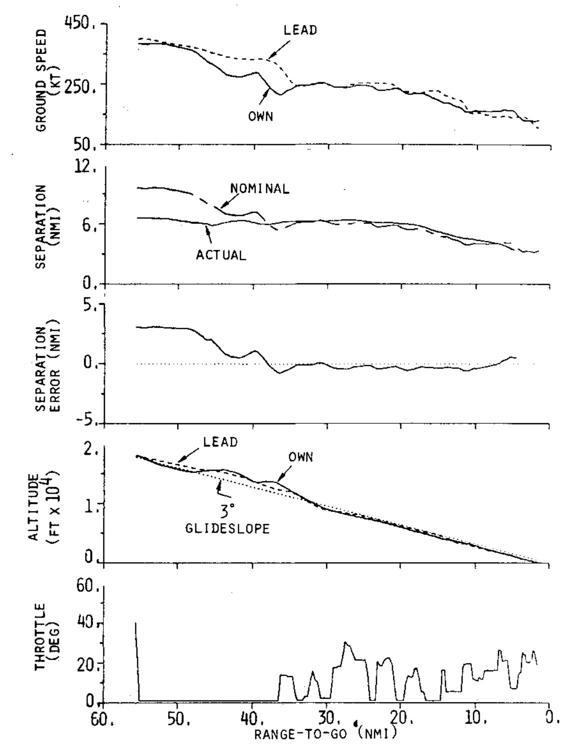

Fig. 11 Example of combined longitudinal/vertical control from multicab experiment with CTP criterion.

Figure 11 presents data recorded for one particular pilot using the CTP criterion. He begins with an initial 3.3 n.mi. (30 s) spacing error. (He is too close.) The pilot begins by cutting his throttle to idle. There is insufficient deceleration to increase his separation, so he next pitches up above the glideslope to decrease his speed and to null the spacing error. He then pitches down to get back on the glideslope. This causes the spacing error to grow again so he again pitches up to slow down. At a range of 35 n.mi. to go, he decides to capture the glideslope and, thereafter, he uses throttle control to maintain a small spacing error. This sequence of controls was common during the 48 individual following runs made.

In these runs, it was observed that pilots would initially try to null separation error and maintain glideslope with only elevator control. The throttle would be held on idle. Then at about 30 n.mi. to go they would capture and thereafter maintain glideslope with pitch control while attempting to control spacing with their throttle. This points out that the pilots were not familiar with using continuous throttle control in general, and they would learn this after discovering that speed and flight-path angle could not both be controlled with the elevator. Figure 11 also indicates erratic pitch and throttle control which would produce an uncomfortable ride. It is apparent that additional flight-path or thrust guidance via automatic or flight director means is necessary for this configuration. Further training would also be necessary to realize proficient dual control in the longitudinal and vertical directions.

By using the throttle and spoiler for longitudinal control and the elevator for flight-path (vertical) control, the longitudinal and vertical dimensions can be treated separately. After a point, normal flap settings would be required, and the pilot would have to revert to nominal speed control to land the aircraft.

Vertical control can be modeled as changing the flight-path angle to drive altitude and altitude rate errors to zero. The pilots are quite familiar with maintaining glideslope accurately. However, it seemed that they could use assistance in determining what correct throttle position to use for proficient longitudinal capture and spacing. A throttle

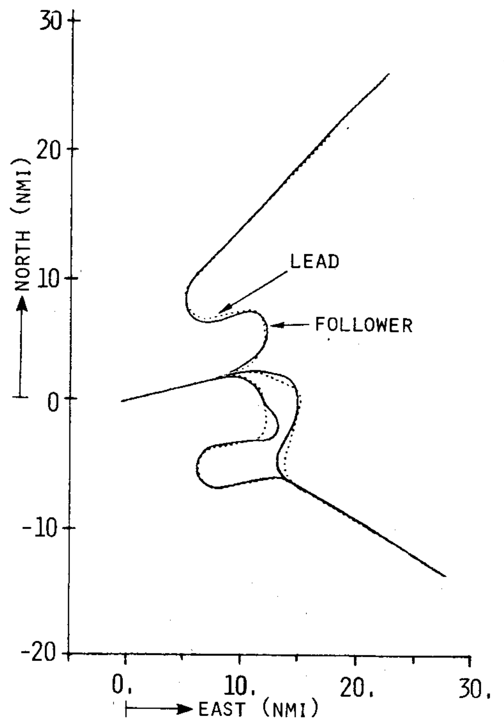

Fig. 12 Examples of lateral control using the CDTI to follow an ATC vectored lead.

director based on separation error seems to be a logical solution.

It was also observed in these experiments that some pilots had difficulty capturing the lead history dot with the CTD criterion when their lead aircraft approached the nominal path from the opposite side. Again, further training would be helpful to enable the pilot to project where the history dot would intercept the nominal path in relationship to his Own interception point. The CDTI display graphics could be expanded to assist in this merging task.

Lateral Control

A fourth CDTI following experiment was run with the NASA Langley DC-8 simulation cab. The objective of this experiment was to evaluate whether a CDTI-equipped aircraft could be successfully steered to follow and space behind another aircraft which was being vectored by ATC. Eight unique curved approaches representative of the vectoring techniques currently used in the Denver Stapleton terminal area were flown and recorded in the simulator as target aircraft. The test pilots then flew behind these profiles by maintaining 80-s spacing with both CTP and CTD separation criteria.

Figure 12 shows three of the vectored paths used in the experiment and Own's paths in following them. When the lead path is curved like this, it gives the follower another dimension for control. He can either use path stretching (turning a wider corner than the lead) to increase separation or corner cutting to decrease separation. It is noted, however, that in this particular study, the following pilots were instructed to follow the leading horizontal path as closely as possible. It was not suggested that they use lateral control as a means of longitudinal spacing regulation.

In these experiments, it was seen that the CDTI provided adequate information to the following pilots so that they could follow the approach path of another aircraft without ATC assistance. In general, the pilots could control separation more accurately using the CTD criterion. However, their lateral tracking had less deviation off of the lead path using the CTP criterion.

Pilot comments on both these and the multicab experiments indicate a desire for more automation or more CDTI throttle guidance (i.e., a throttle director) to reduce their workload and to improve their tracking accuracy. Also, it was seen that practice with a given system would be helpful for both reducing workload and increasing accuracy.

For purely following a curved horizontal path, the lateral control and heading can be analyzed and modeled separately from the longitudinal and vertical dimensions. If lateral control is used regularly as a means of longitudinal separation adjustment, then it must be coupled into the longitudinal model. This remains as a future study.

Recommendations

There are several more items that should be investigated regarding the in-trail following task. These include the effects of mixed types of aircraft, winds, some aircraft not being CDTI-equipped, and the CDTI sensor and display errors. The presence of wind shear, variable aircraft speed envelopes, flap schedules, and landing speed constraints all pose additional factors which must be accounted for in choosing the separation criterion.

Beyond this, the dynamic phenomena associated with merging several aircraft into a common string requires further experimental study. The dynamic aspects of pilot/air traffic controller interaction for terminal area merging and spacing using CDTI concepts need to be experimentally examined. Also, the tradeoff between pilot workload using the CDTI and controller workload with today's in-trail separation methods needs to be assessed. This includes the evaluation of fuel usage and potential landing rate between the current ATC control methods and the CDTI-based methods studied here.

Conclusions

This paper presents an outline of experimental and analytical work conducted to begin to evaluate use of the cockpit display of traffic information (CDTI) by the pilot for merging and in-trail following applications. Full details of this study can be found in Refs. 14 and 15. From the study, the following conclusions can be made.

1) Forming strings of following aircraft on decelerating approach paths to touchdown does not cause unstable longitudinal oscillations. However, successive pilots in the string tend to go slower than their immediate leaders.

2) The constant time predictor (CTP) separation criterion has an inherent slowdown effect not present in the constant time delay (CTD) criterion. Thus, the CTP criterion tends to be less suitable. However, further study is required before finalizing this choice.

3) Pilots are very adept at removing initial separation errors (either too close or too far back) using CDTI spacing information. This separation control task can be in opposition to normal speed control requirements along an approach profile, however.

4) By beginning on the glideslope, pilots tend to begin to use their elevator for both in-trail spacing and flight-path (vertical) control while leaving the throttle on idle. Later they switch to throttle control for in-trail spacing. There is a need for either throttle director assistance as part of the CDTI information format or more pilot practice in using the throttle for spacing control.

5) The CDTI provides adequate information to allow accurate horizontal following of an ATC-vectored lead aircraft. With a lead curved path, the CDTI also allows the follower to use lateral path stretching and corner cutting to regulate his longitudinal separation.

6) A longitudinal following model was developed from the experimental data which, by tuning of model parameters, could duplicate the characteristics of the pilot/aircraft/CDTI system for in-trail spacing. This model is useful to determine the source of spacing error, stability of aircraft strings, and fast-time terminal area simulations.

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