Preview Control Pilot Model for Near-Earth Maneuvering Helicopter Flight

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A preview control model of the human pilot maneuvering a helicopter in near-Earth flight is developed. The model is simple in form and extends a description of pursuit tracking behavior in which preview is used to compensate for inherent time delays in the pilot/vehicle system. Data from manned simulation and flight test are used to support the modeling approach. Although attention is focused primarily on lateral-directional flight tasks, an example of vertical flight path preview control is also included.

Introduction

IT has long been known that the ability of the human being to look ahead, or preview, is inherent and of crucial important in many manual control tasks. Here, preview control is defined as control activity in which the desired future vehicle path is previewed by the pilot and used to generate present control inputs to the vehicle. Helicopter flight at low (near-Earth) altitudes is obviously one task in which preview is important. Since current and future military helicopter combat operations involve flight at extremely low altitudes to increase survivability,[1] preview control models of the pilot may be of considerable use in pilot/vehicle analyses of these tasks. Indeed, as will be seen, the inclusion of preview behavior may well be indispensable in obtaining an accurate description of pilot control activity in near-Earth maneuvering flight. A number of the preview control models of the human operator that have been proposed and discussed in the literature, e.g., Refs. 2-6, will now be briefly reviewed.

Sheridan[2] discusses three models of human preview control. The first involves extended convolution, in which the human's control output is considered as the sum of two integrals, one describing the familiar convolution of a weighting function (impulse response) with system error over past time and a second integral describing the convolution of a weighting function with system input over future time. Sheridan's second model is one in which the human's control output is expressed as an integral over future time of the error between system input and predicted system output, suitably weighted. The predicted system output is obtained by human use of a fast-time internal model of the vehicle dynamics. This internal model is hypothesized to be used in rapid repetitive fashion to produce estimates of future vehicle output, given present vehicle states and control inputs. The reader may recognize this second preview model as equivalent to a "Zeibolz" controller.[7] The fast-time circuit, as described by Sheridan, can be employed in two ways to generate predictions, based either on the assumption that control action is unchanged during the prediction span or on the assumption that the closed-loop response of the man/machine system is equivalent to that of a simple servomechanism. In the latter case, the human's internal model would also contain a model of his own dynamics. In the final model proposed by Sheridan, the human control output is that producing a system output that minimizes a specified combination of trajectory error and control effort.

Reid and Drewell[3] measured human describing functions in single-axis tasks in which varying amounts of preview were available to the human operator. Although the tasks used preview, a compensatory control structure was assumed for purposes of measurement. Their data showed that dramatic improvement in tracking performance was possible with preview but that this performance improvement abated with preview times in excess of about 0.4 s.

Tomizuka and Whitney[4] modeled the manual preview control problem in discrete-time fashion, where additional state variables were introduced as values of the system input defined at discrete values of future time. The problem was formulated as an optimal manual control problem similar to that in Ref. 8. In a set of accompanying experiments, the authors of Ref. 4 corroborated Reid and Drewell's results by showing that the critical preview time needed for the human pilot to accomplish almost all possible performance improvement lies between 0.3 and 0.7 s.

Elements of preview control have also been discussed by Allen and McRuer[5] and by Hess[6] as logical extensions of models of pursuit control. A common theme appearing in Refs. 5 and 6 concerns the ability of the human to extract information from the system input at present time, which would allow the effective inversion of the vehicle dynamics over a relatively broad frequency range. Preview enters into these models as a means of compensating for inherent time delays in the man/machine system.

Finally, it is of interest to note that, automatic control system design techniques exhibiting the primary elements of manual preview control formulations have begun to appear in the literature. These automatic control techniques include... 1) prediction of future path, given current state and control information; 2) determination of future desired trajectory; and 3) calculation of control inputs leading to future path coinciding with desired trajectory. As in the case of Sheridan's second preview model, these techniques make use of an internal model concept and are referred to as "model predictive hueristic control," "model algorithmic control," or "output algorithmic control."[9]

Building on experimental results reported by Hess and Beckman,[10] the research to be described herein extends the single-loop preview model introduced in Ref. 6 to multiloop vehicular control. In particular, a model of the human pilot controlling the lateral-directional trajectory of a helicopter in near-Earth flight is proposed and evaluated using data from manned simulation and flight test. As will be seen, simplicity will be the key element in the model formulation.

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Preview Control Model

Figure 1 represents a structural model for compensatory/pursuit control introduced by Hess in Ref. 6. When the switch in this model is in position 0, the model is emulating compensatory control behavior, i.e., only system error information is being used by the human pilot. When the switch is in position 1, the model is emulating pursuit control behavior, as least as defined in Ref. 6. In this mode, the time rate of change of the input is used to drive the human's closed-loop neuromuscular system, defined as u_δ/u_c in Fig. 1. As outlined in Ref. 6, all the human's dynamic equalization is accomplished in the proprioceptive feedback loops shown in Fig. 1. When the model parameters are properly selected, the product $(u_\delta/u_c)Y_c$ in Fig. 1 will always resemble an integrator plus delay around the crossover frequency (as with the crossover model of the human operator). Thus, using the time rate of change of the input as a driving function means that the vehicle output will follow the vehicle input with a delay without the necessity of the human closing an error loop. Such a mode of operation on the part of the human has the potential for dramatic performance improvement as compared to compensatory behavior if preview allows the input rate to be sensed τ_p s into the future where $\tau_p = \tau_0$. This means that the human can cause the system output to follow the input over some limited but useful frequency range with essentially no delay.

As shown in Fig. 2, the vehicle control problem under study here involves multiloop feedback of vehicle motion quantities. Figure 2 represents loop closures that describe compensatory pilot control strategy in the lateral-directional control of an idealized helicopter. The idealization includes a roll-rate command system with infinite bandwidth and perfect turn coordination. Note that the structural model of Fig. 1 has been simplified considerably here. The u_δ/u_c transfer function has been replaced by an additional delay, which is then added to τ_0, and the sum is referred to as τ_e. This simplification is warranted, given the idealized $1/s$ roll attitude dynamics of the vehicle. The loop structure of Fig. 2 was experimentally verified by a manned laboratory simulation reported in Ref. 10. The question now becomes one of describing pursuit and preview behavior in the multiloop task of Fig. 2. Since the measurements of Ref. 10 indicated that the outer-loop equalization adopted by the pilot yielded an open-loop transfer function y/y_e, which also obeyed the crossover model, then pursuit behavior could possibly be described just as in Fig. 1, with the human using the time rate of change of y_c as a driving function. This is shown in Fig. 3a. With τ_e s of preview, the y/y_c transfer function is

$$\frac{y}{y_c}(s) = \frac{K_y \omega_c g (T_L s + 1)}{s(s + \omega_c e - {}^{\tau_e s})} \qquad (1)$$

Note that the $e - {}^{\tau_e s}$ term still appears in the denominator of Eq. (1).

As an alternative to Fig. 3a, consider that pursuit activity, as defined herein, occurs in the *inner* loop of Fig. 2, i.e., that the time rate of change of the roll attitude command is used in a manner completely analogous to the command signal in Fig. 1. This configuration is shown in Fig. 3b. Here, with τ_e s of preview, the y/y_c transfer function is

$$\frac{y}{y_c}(s) = \frac{K_y \omega_c g (T_L s + 1)}{s^2 + (K_y T_L \omega_c g)s + K_y \omega_c g} \qquad (2)$$

Note that Eq. (1) indicates poor low-frequency command following performance in the pilot/vehicle system. In addition, ω_c can be increased by the pilot in the preview system of Fig. 3b without incurring the stability limitations that would accompany such increases in the system of Fig. 3a. This is due to the persistence of the time delay in Eq. (1), even with preview activity. These considerations led the authors to favor the pursuit/preview structure of Fig. 3b over that of Fig. 3a in the helicopter flight control tasks to be discussed.

It is interesting to note that the configuration of Fig. 3a, with preview, falls into Sheridan's first preview model category in that the human is generating a control signal by operating on future input. In addition, with τ_p representing the preview time, the previewed time rate of change of roll attitude command in Fig. 3b can be written as

$$\begin{aligned}\dot\phi_c(t+\tau_p) &= K_y[T_L \ddot y_e(t+\tau_p) + \dot y_e(t+\tau_p)] \\ &= K_y\{T_L[\ddot y_c(t+\tau_p) - \ddot y(t+\tau_p)] \\ &\quad + [\dot y_c(t+\tau_p) - \dot y(t+\tau_p)]\}\end{aligned} \qquad (3)$$

Because $\ddot y(t+\tau_p)$ and $\dot y(t+\tau_p)$ must be obtained by the human as *predictions* of future vehicle trajectory characteristics, the configuration if Fig. 3b falls into Sheridan's second preview model category.

The preview control formulation of Fig. 3b will now be applied to the helicopter flight control problem diagrammed in Fig. 4. Here, the pilot of a helicopter with idealized dynamics is attempting to follow a command ground track represented by a two-dimensional projection of the vehicle flight path onto a plane parallel to a flat Earth. It is assumed that the magnitude of the vehicle velocity vector is constant and that the vehicle heading angle satisfies small angle approximations. Note that the product of the preview time and the vehicle velocity represents the length of predicted and command ground tracks subject to pilot preview.

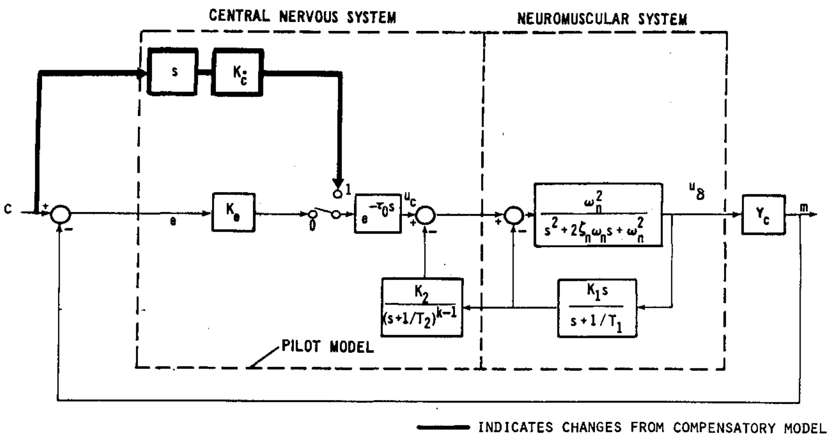

Fig. 1 Structural model of the human pilot.

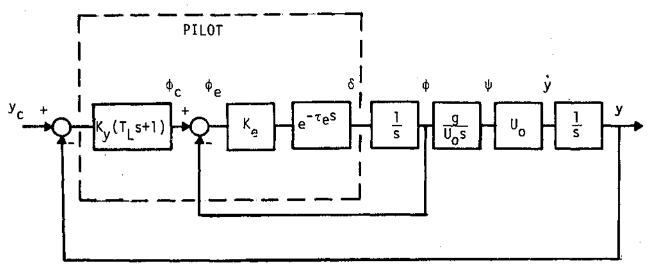

Fig. 2 Compensatory pilot/vehicle system for lateral-directional flight control.

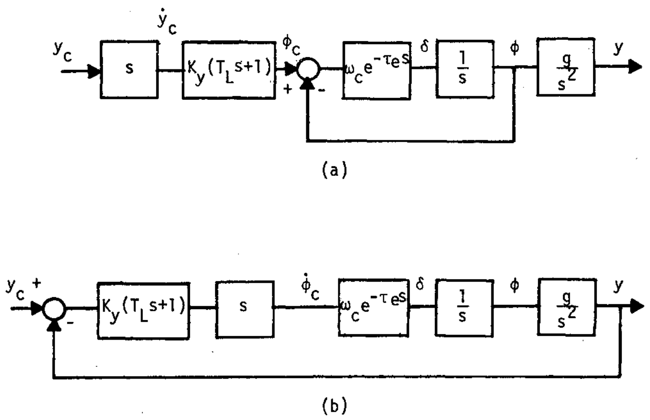

Fig. 3 Pursuit control possibilities for the system of Fig. 2; a) outer-loop pursuit control, b) inner-loop pursuit control.

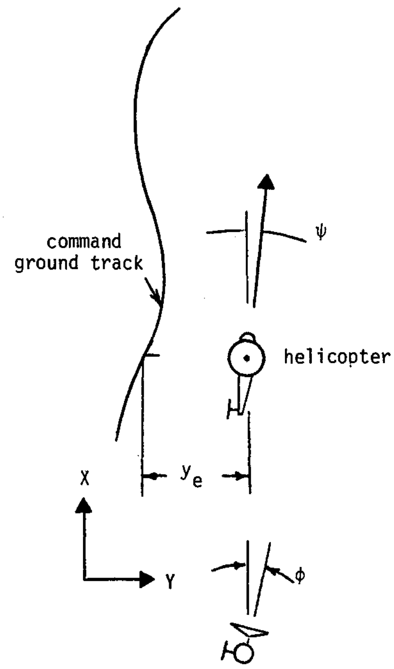

Fig. 4 Helicopter near-Earth maneuvering task.

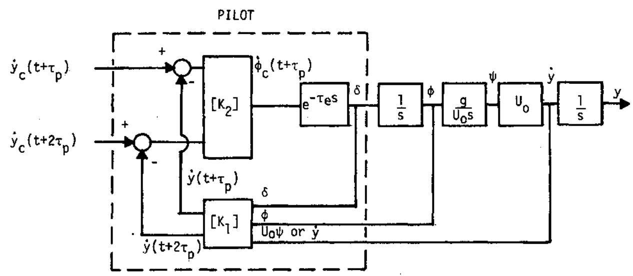

Fig. 5 Lateral-directional preview control model.

Before proceeding, one last important assumption will be made in the multiloop preview model. The term $\ddot{y}_e(t+\tau_p)$ in Eq. (3) will be approximated as

$$\ddot{y}_e(t+\tau_p) = \frac{\dot{y}_e(t+2\tau_p) - \dot{y}_e(t+\tau_p)}{\tau_p} \tag{4}$$

The approximation of Eq. (4) was invoked for two reasons: First, this relation is a convenient, albeit approximate, means of placing limitations on the accuracy of human preview control. Such limitations are important since, without them, the preview configuration of Fig. 3b summarized by Eq. (2) would permit unrealistically large bandwidths in the path following dynamics of the simplified pilot/vehicle system adopted here. Second, Eq. (4) obviated the necessity of creating command ground tracks with continuous second-order derivatives in the simulations to follow. Obviously, more realistic means of modeling human preview limitations would be a worthwhile topic for future research. It is interesting to note that, with the introduction of Eq. (4), the preview problem has been transformed into a "two-point" or "two-viewing-distance" problem. A similar problem, emphasizing visual field cues, was studied analytically and experimentally by Grunwald and Merhav in the context of the lateral-directional *compensatory* control of a remotely piloted vehicle.[11]

The pilot's ground track prediction activity was modeled by allowing

$$\dot{y}(t+\tau_p) = \dot{y}(t) + \tau_p\ddot{y}(t) + \frac{\tau_p^2\dddot{y}(t)}{2!}$$

$$\dot{y}(t+2\tau_p) = \dot{y}(t) + 2\tau_p\ddot{y}(t) + \frac{(2\tau_p)^2\dddot{y}(t)}{2!} \tag{5}$$

These expressions were then used in Eq. (4). Figure 5 shows the complete pilot/vehicle preview system. The gain matrices $[K_1]$ and $[K_2]$ are given by

$$[K_1] = \begin{bmatrix} g(\tau_p^2/2) & 2g\tau_p^2 \\ g\tau_p & 2g\tau_p \\ 1.0 & 1.0 \end{bmatrix}$$

$$[K_2] = \begin{bmatrix} [1-(T_L/\tau_p)]K_y \\ (T_L/\tau_p)K_y \end{bmatrix} \tag{6}$$

such that $[\dot{y}(t+\tau_p)\ \dot{y}(t+2\tau_p)] = [\delta\ \phi\ y][K_1]$ and $\phi_c(t+\tau_p) = [\dot{y}_e(t+\tau_p)\ \dot{y}_e(t+2\tau_p)][K_2]$. The matrix $[K_1]$ and its inputs are identified as the "internal model" in Fig. 5 since they are responsible for generating predictions of vehicle velocity components. Although the pilot/vehicle model of Fig. 5 is very simple in form, it will be shown to be an acceptable descriptive model of pilot/vehicle performance in realistic near-Earth maneuvering flight tasks.

Application of the Preview Model to Simulation and Flight Test Data

Manned Simulation Data

Tomlinson and Padfield[12] conducted piloted, moving base simulation studies of helicopter nap-of-the-Earth (NOE) flight. The usual definition of NOE flight is flight in which

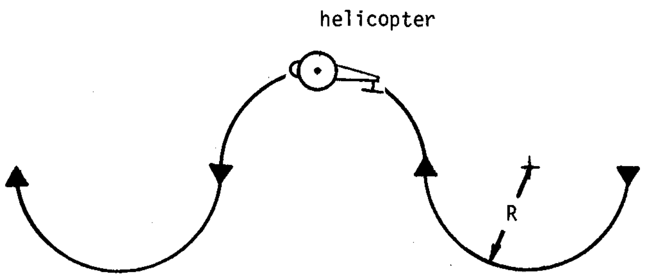

Fig. 6 Triple-bend geometry from Ref. 12.

Table 1 Triple-bend geometry and assumed outer-loop pilot model parameters

R, ft	U_0, ft/s	ω_0, rad/s	ω_{cy}, rad/s	T_L, s	K_y
200	101	0.51	1.02	10.0	0.0025
500	67.4	0.13	0.26	10.0	0.00095
500	101	0.20	0.40	10.0	0.0010
500	135	0.27	0.54	10.0	0.0010
500	168	0.34	0.68	10.0	0.0018

features of the terrain and vegetation are used for concealment. The nature of the terrain and flight altitude in Ref. 12 was such that the desired or command ground track was constrained to a curvilinear triple bend consisting of three semicircles of radius R. A televised terrain board provided visual cues for the pilot. As shown in Fig. 6, a "small" and "large" triple bend were used in the simulation, and the task was conducted with a variety of nominal airspeeds. Table 1 gives the pertinent task information, along with pilot model parameters for the preview control model of Fig. 5. For the analysis, it was assumed that the pilot has stabilized the helicopter in a coordinated steady turn along one semicircular path segment with a bank angle $\phi = 2\tan^{-1}(U_0/gR)$ and then initiates a roll reversal onto the next semicircular segment to a new steady-state bank angle of equal magnitude but opposite sign. The temporal frequency of the command ground track when traversed at a constant airspeed U_0 is $\omega_0 = 2\pi U_0/R$.

The third column of Table 1 lists the frequencies ω_0. For the sake of comparison, a compensatory pilot/vehicle system was also modeled for this task. To be conservative, the outer-loop crossover frequency ω_{c_y} for the compensatory system (Fig. 2) was chosen as twice the appropriate ω_0 values. The pilot lead time constant T_L was chosen as 10 s to give a broad K/s-like region to cover the range of outer-loop crossover frequencies evident in the table, whereas K_y was chosen to give the desired crossover frequency for each combination of triple-bend radius and airspeed. The roll attitude open-loop transfer function was chosen as a simple $1/s$. Thus, the dynamics of the particular vehicle that was simulated in Ref. 12 did not enter into this analysis.

For the preview pilot/vehicle system of Fig. 5, the model parameters just given for the compensatory model were left unchanged. The preview time τ_p was set equal to the effective time delay of 0.3 s. It is obvious that ψ
$\sin\psi$ for this task. However, one can still compare simulation and model results by focusing attention on the roll reversal points and comparing roll rates obtained in the manned simulation with those predicted by the compensatory and preview pilot/vehicle systems. In this analysis, the maximum $\dot{\phi}$ that would be evident at the roll reversal points was calculated from $\dot{y}(t+0.3)$ and $\dot{y}(t+0.6)$ as determined from the triple-bend geometry. Then, it was assumed that $\dot{\phi}_{MAX} = \dot{\phi}_{c_{MAX}}$. Thus, for the preview case, a simulation of the

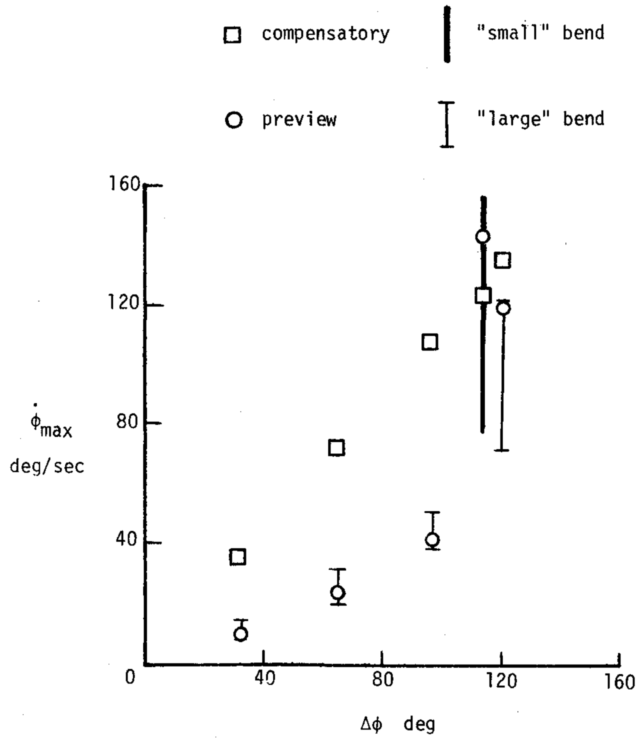

Fig. 7 Comparison of preview control model and manned simulation results.

Table 2 Predicted maximum roll rates for triple-bend maneuver

R, ft	U_0, ft/s	$\dot{y}_e(t+\tau_p)$, ft/s	$\dot{y}_e(t+2\tau_p)$, ft/s	$\dot{\phi}_c$, deg/s	$\Delta\phi$, deg
200	101	30.3	59.6	144	115
500	67.4	5.5	10.9	10	32
500	101	12.1	24.2	24	65
500	135	21.6	43.2	42	97
500	168	33.6	67.2	119	121

system of Fig. 4 was not involved. The results of this analysis are shown in Table 2 and Fig. 7. The superiority of the preview model over the compensatory model in matching the manned simulation data is evident in the figure. This comparison emphasizes the importance of considering preview behavior in modeling pilot/vehicle systems in near-Earth maneuvering flight.

Flight Test Data

Corliss and Carico[13] conducted an investigation of helicopter handling qualities in a low-altitude slalom task, in which a helicopter was flown in a series of s-turns between alternating 1000-ft markers on each side of a runway 200 ft wide. The vehicle was the NASA/Army variable stability UH-1H helicopter. The pilots maintained a nominal airspeed and altitude of 60 kn and 100 ft, respectively. Although not included in Ref. 13, time histories of vehicle roll attitude, roll rate, and heading were obtained from NASA Ames Research Center for this study.

Attention will be focused on two sets of roll attitude dynamics used in the flight test and simplified for this study:

Basic vehicle:

$$\frac{\phi}{\delta}(s) = \frac{e^{-0.3s}}{s} \tag{7}$$

Augmented vehicle:

$$\frac{\phi}{\delta}(s) = \frac{1}{s} \tag{8}$$

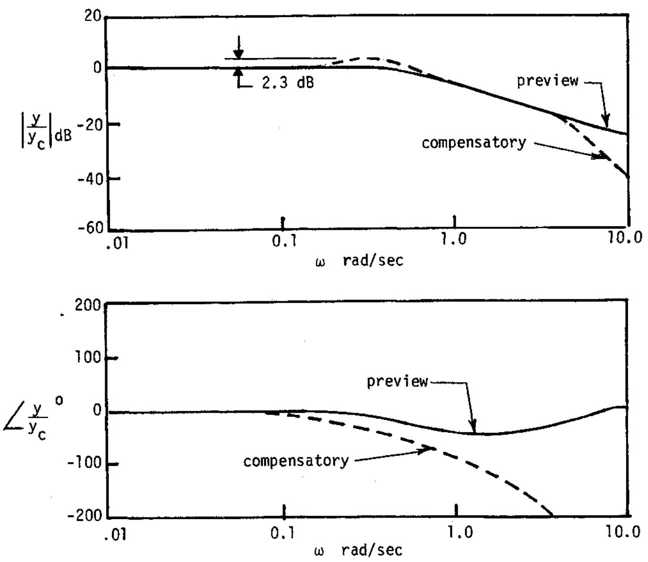

Fig. 8 Closed-loop pilot/vehicle characteristics with compensatory and preview control.

As opposed to the pilot/vehicle analysis of the preceding section, some care was taken in modeling the vehicle dynamics for this task since the results of a *continuous* simulation were to be used in assessing the preview pilot/vehicle system. The crossover frequencies for the roll attitude loop for the compensatory pilot/vehicle systems were chosen so that the ϕ/ϕ_e open-loop transfer functions for both the basic and augmented vehicles had identical phase margins of approximately 50 deg. This meant a lower crossover frequency for the basic, as opposed to the augmented, vehicle (1.25 compared to 2.5 rad/s). This crossover frequency regression was included to model the effects of time delays in compensatory systems.[14] Outer-loop crossover frequencies for both the basic and augmented pilot/vehicle systems were chosen as 0.5 rad/s. This led to a K_y value of 0.003, with a T_L chosen as 5 s to give K/s-like characteristics around the outer-loop crossover frequency.

It should be noted that the inclusion of the 0.3-s time delay in the vehicle dynamics for the basic vehicle means that the control input to the internal model in Fig. 5 should be $\delta(t-0.3)$, not $\delta(t)$. However, the ground track performance decrement introduced by using $\delta(t)$ was found to be negligible because the δ input to the internal model represents a higher-order term in the Taylor series expansion of Eq. (5).

After choosing the preview time as the sum of the pilot and vehicle time delays, values for K_y for the preview pilot/vehicle system were chosen on the basis of a tradeoff between ground track performance and stability, where the latter was determined by Nyquist stability analyses. As expected, the approximation of Eq. (4) led to decreasing closed-loop stability as K_y was increased. As an example of the benefits of preview, Fig. 8 shows a comparison between typical y/y_c transfer functions for the compensatory and preview pilot/vehicle systems for the augmented vehicle. The superiority of the preview system over the compensatory one is evident when one compares the phase lags in each system in the frequency range beyond 0.1 rad/s. Also, note the 2.3-dB amplitude peak for the compensatory system around 0.3 rad/s. As a point of reference, the temporal frequency of the command ground track traversed at 60 kn and enclosing alternate 1000-ft markers is approximately 0.3 rad/s.

Figures 9 and 10 show a comparison between representative flight test results and the simulation of the preview pilot/vehicle system for the basic and augmented vehicles. No flight data were available for the vehicle ground tracks, and the dotted curve on the y trace represents the command ground

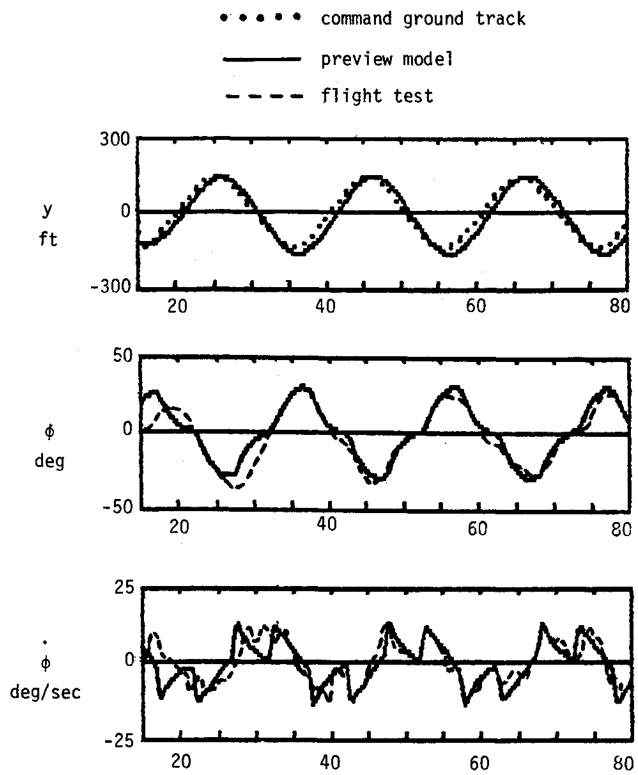

Fig. 9 Comparison of preview control model and flight test results; basic vehicle.

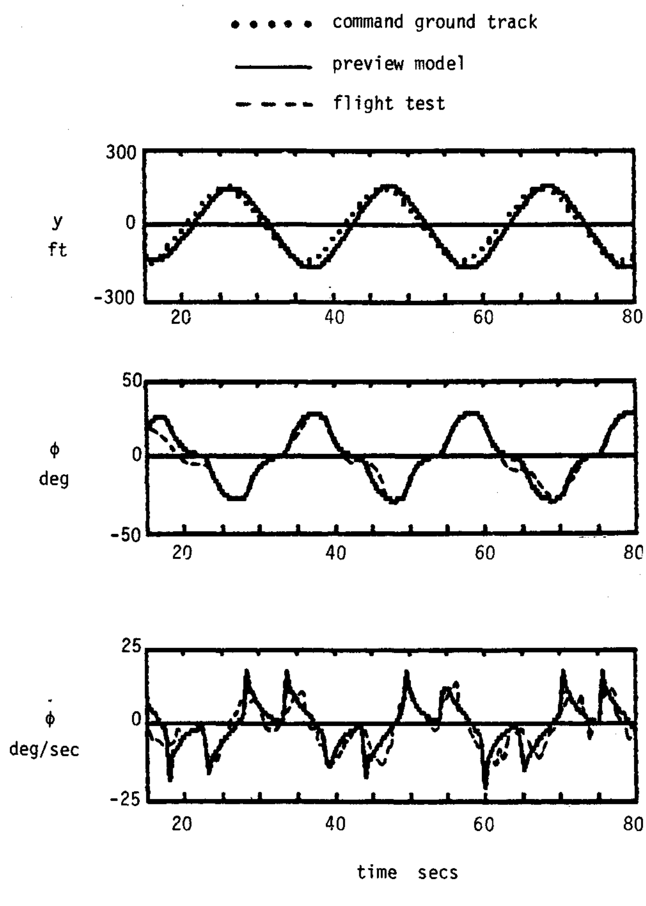

Fig. 10 Comparison of preview control model and flight test results; augmented vehicle.

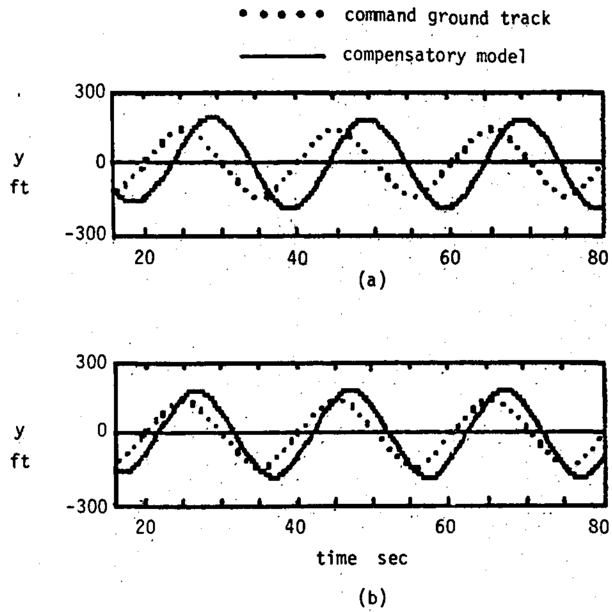

Fig. 11 Compensatory control model performance; a) basic vehicle, b) augmented vehicle.

track synthesized by the authors and used throughout this simulation. The quality of the comparisons between model and flight test is quite good. In contrast to these results, Fig. 11 shows ground track performance for the simulated compensatory systems for both basic and augmented vehicles. The performance is poor and is not qualitatively representative of flight test results. Even shifting the ground track traces by a suitable amount (over 4 s in the case of the basic vehicle) will not yield command vs output ground track matches comparable to those of Figs. 9 and 10 because the output has a larger amplitude than the command. This, of course, was predicted by the amplitude plot of the compensatory system in Fig. 8. Once again, one sees the importance of considering preview behavior in modeling pilot/vehicle systems in near-Earth maneuvering flight.

Discussion

In the preceding analyses of preview models of the helicopter pilot, the preview time τ_p was selected as the sum of pilot and vehicle effective time delays appearing in the simplified pilot/vehicle models at hand. The preview time involved were either 0.3 or 0.6 s which, given Eq. (4), translates into 0.6 or 1.2 s of required preview information. Although such values compare favorably with the optimum values obtained in the single-loop laboratory tasks of Reid and Drewell[3] and Tomizuka and Whitney,[4] a caveat is in order. The preview model developed here is intended only to describe pilot behavior appropriate for constant velocity vehicular control in a restricted class of rather aggressive near-Earth maneuvers. Noncontrol tasks such as near-term flight path planning (generating the command ground tracks that have been assumed to be given quantities in this work) or self-paced flight path control, where vehicle velocity is a control variable, have not been addressed. These tasks would obviously require much longer preview times.

Preview Control in Vertical Maneuvering Flight

The preview control model introduced here can, of course, be applied to the control of vehicle dynamic modes other that lateral-directional. For example, Fig. 12 and 13 show compensatory and preview control models for the vertical flight path

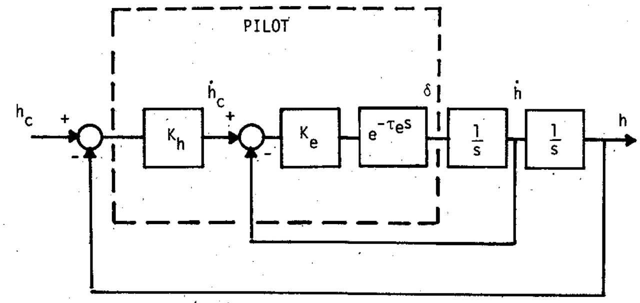

Fig. 12 Compensatory pilot/vehicle system for vertical flight control.

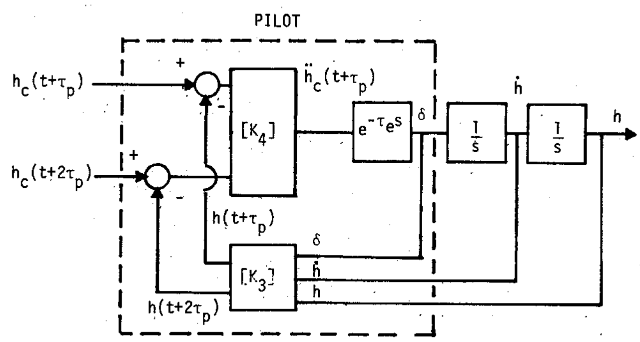

Fig. 13 Vertical preview control model.

control of a helicopter. The time rate of change of the inner-loop altitude rate command of the preview model is given by

$$\ddot{h}_c(t+\tau_p) = K_h[\dot{h}_e(t+\tau_p)] \tag{9}$$

As in Eq. (4), limitations on the accuracy of preview control can be introduced by approximating the first derivative in Eq. (9) as

$$\dot{h}_e(t+\tau_p) = \frac{h_e(t+2\tau_p) - h_e(t+\tau_p)}{\tau_p} \tag{10}$$

As in Eq. (5), the pilot's ground track prediction activity can be modeled as

$$h(t+\tau_p) = h(t) + \tau_p\dot{h}(t) + \frac{\tau_p^2\ddot{h}(t)}{2!}$$
$$h(t+2\tau_p) = h(t) + 2\tau_p\dot{h}(t) + \frac{(2\tau_p)^2\ddot{h}(t)}{2!} \tag{11}$$

Note that, in general, the preview times in different axes of control may be different. In Fig. 12, the gain matrix $[K_3]$ is identical to $[K_1]$ in Eq. (6), and $[K_4]$ is given by

$$[K_4] = \begin{bmatrix} -K_h/\tau_p \\ K_h/\tau_p \end{bmatrix} \tag{12}$$

Conclusions

1) A structural model of the human pilot, used to describe compensatory and pursuit control behavior, can provide a basis for modeling preview control activity. With the structural model, preview control is viewed as a natural extension of pursuit control in which preview is used to compensate for inherent delays in the man/machine system.

2) Although the preview model was very simple in form, it was successfully applied to modeling realistic near-Earth flight control tasks for which limited manned simulation and flight test data were available. The results emphasized the importance of including the preview model in the pilot/vehicle analyses of such tasks.

3) The preview model can be easily extended to the control of vehicle dynamic modes other than lateral-directional.

4) Future research should be aimed at incorporating more realistic vehicle dynamics and the complete structural model of the human pilot into the preview model. In addition, more realistic models of human preview limitations should be investigated.

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