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PILOT MODELS FOR DISCRETE MANEUVERS

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ABSTRACT

Discrete maneuvers comprise a class of piloting tasks which can include fixed-wing landing flare; gross change of heading, altitude, or airspeed; helicopter or VTOL transition to hover; and helicopter nap-of-the-earth dash and quickstop. While these maneuvers may appear to differ fundamentally from basic tracking tasks, pilot models can be constructed using the same mathematical forms. Several examples of discrete-maneuver pilot models are presented along with accompanying flight and simulator data. The value of such models is discussed with regard to handling qualities, simulator fidelity, and pilot training. The main benefit is the ability to exploit pilot-in-the-loop analysis more effectively by formulating a complete pilot-vehicle-task context.

NOMENCLATURE

A	Gilinsky's perceived range constant
g	Gravity constant
h	Height
$\dot{h}$	Vertical velocity
$\dot{h}_{pk}$	Maximum sink rate during terminal landing maneuver
$\dot{h}_{td}$	Touchdown sink rate for landing maneuver
K_a	Pilot's effective gain in approach task
K_I	Pilot's integral gain in normal speed change maneuver
K_h	Pilot's height loop gain
K_U	Pilot's speed loop gain
K_R	Pilot's position gain in dash/quickstop
$K_{\dot{R}}$	Pilot's closure rate gain in dash/quickstop
R	Range (actual)
R_c	Position command
R_p	Perceived range
$\dot{R}$	Closure rate
$\dot{R}_{max}$	Maximum closure rate
$\ddot{R}$	Deceleration
T_I	Lag time constant
T_L	Lead time constant
u	Perturbation forward speed
U	Forward speed
U_c	Speed command
x	Fore-and-aft displacement
X_u	Speed damping stability derivative
$Y_{c()}$	Controlled element transfer function
$Y_{p()}$	Pilot control strategy transfer function
$\Delta\theta$	Perturbation pitch attitude
ε	General state variable
ζ	Damping ratio
$\zeta_{()}$	Closed-loop damping ratio of () task
θ	Pitch attitude
θ_c	Pitch attitude command
θ_{pk}	Maximum pitch attitude during quickstop maneuver
ϕ_M	Phase margin
$\phi_{M()}$	Phase margin of () task
ω	Natural frequency
$\omega_{()}$	Closed-loop natural frequency of () task
ω_c	Crossover frequency
$\omega_{c()}$	Effective crossover frequency of () task

Subscripts

a	Approach to hover task
c	Command
f	Landing flare task
pk	Peak value
r	Dash/quickstop task

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*Principal Research Engineer, Member AIAA u Normal speed change task

x Fore-and-aft position regulation task

θ Pitch attitude regulation task

INTRODUCTION

Discrete maneuvers comprise a class of piloting tasks which includes, for example, landing flare; gross change of heading, altitude, or airspeed; transition to hover; and helicopter nap-of-the-earth (NOE) dash, quickstop, or bob-up. These kinds of maneuvers differ fundamentally from steady-state or continuous compensatory or pursuit tracking tasks such as regulation of attitude, heading, flight director, or instrument landing system (ILS) flight path error.

Pilot modeling has traditionally centered on tracking tasks due to their relative ease of measurement in a laboratory environment. Describing function measurements involving artificial inputs are usually appropriate for tracking tasks and yield high quality data to support control strategy models. Modeling of discrete maneuvers has, to an extent, been avoided because of their short term nature and the difficulty in treating such tasks in an artificial laboratory scenario. For example, measurement of a visually guided landing flare control strategy must be accomplished during an actual landing maneuver, whether in a simulator or in flight; no surrogate laboratory tracking task to facilitate measurements would provide an acceptable and convincing substitute for a visually guided landing.

Progress has been made recently, however, in the modeling and measurement of discrete maneuvers. It has been found that certain nonintrusive pilot measurement techniques can effectively identify pilot feedback gains during the limited interval of a discrete maneuver[1]. For example, in the landing maneuver closed-loop response parameters can be measured within the 5- to 7-second duration of the flare. This corresponds to only one quarter of the period of the dominant closed-loop mode. From these measurements, the pilot's feedback height and sink rate gains can then be deduced.

This paper presents several examples of discrete-maneuver pilot models and accompanying justification from flight data, simulator data, or pilot training manual descriptions. It is shown that the form of most discrete-maneuver models can be identical to the closed-loop topology of tracking-task pilot models. In fact, for most examples shown, the pilot control strategy involves only stationary, pure-gain elements. A special case, a helicopter decelerating approach to hover, is presented in order to demonstrate how perceptual influences (in this case, range) may be primarily responsible for apparent nonstationary behavior while the pilot strategy actually remains invariant.

The value of discrete-maneuver pilot models will be illustrated by considering implications in the areas of handling qualities, simulator fidelity, and pilot training. For example, an analysis of the helicopter NOE quickstop maneuver implies a quantitative requirement for pitch attitude control bandwidth which is at least two or three times higher than for routine acceleration/deceleration maneuvers[2]. Recent measurements of DC-10 landing maneuvers performed in flight and in a simulator indicate excessive pilot lag or delay in commanding pitch attitude and a consequent hard landing tendency in the simulator. The same data are then used to show the relative training effectiveness for pilots transitioning to the DC-10 with flight training versus simulator training exclusively.

A significant aspect of modeling discrete maneuvers is that we can exploit pilot-in-the-loop analysis techniques in a natural context. Along with this is the ability to apply nonintrusive measurement procedures which require a general control strategy framework.

DEFINITION OF A DISCRETE MANEUVER

Several examples of discrete maneuvers have been cited such as commanded changes in heading, altitude, speed, or position. In each case it is the "transitory" nature of a discrete maneuver which distinguishes it from the "steady-state" quality of a tracking task. A simple heading change in cruising flight is a discrete occurrence in terms of the decision to turn, initiation of the command, the turn itself, and the eventual settling on to the new heading. Beyond a certain point, though, regulation of that new heading becomes equivalent to a steady-state tracking task, and there may not necessarily be a precise boundary separating the short term discrete task and the longer term regulatory task.

The beginning of a discrete maneuver also can be vague. In the case of a decelerating approach to hover, the start of the maneuver is not clear, at least not in terms of vehicle state or control response[3]. The initial deceleration is accomplished by a very gradual pitch attitude change, yet taken as a whole, the maneuver has a clear transient response associated with it.

One useful definition for a discrete maneuver is simply the limited-term transition from one task to another. Thus a heading change would be the transition from holding one heading to holding another, or a decelerating approach to hover would be transition from holding a steady approach speed to maintaining a steady hover over the landing area.

In the following pages the transitory aspect of a discrete maneuver will be quantified in terms of specific mathematical models and the parameters associated with those models.

TASK MODELS VERSUS PILOT MODELS

It is necessary to distinguish the dynamics associated with execution of a task from those of the pilot, per se. The task model includes the inputs, loop structure, and the overall closed-loop response of the pilot plus vehicle as well as the effect of any environmental features such as gusts. The pilot model is a single element in that chain which includes piloting technique and the perceptual features associated with the pilot. These distinctions are shown in Fig. 1.

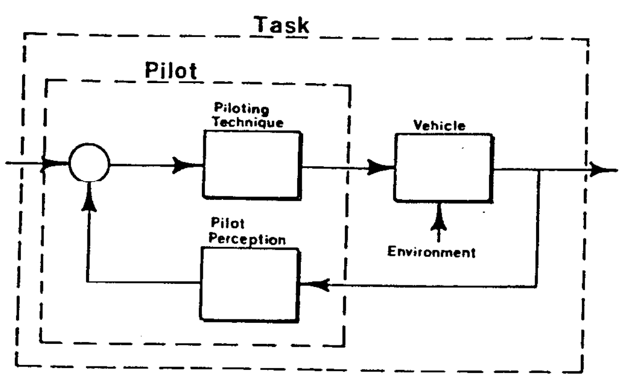


Figure 1. Block Diagram of Pilot-Vehicle-Task System

In dealing with discrete maneuvers it is useful to concentrate first on the task. If the task can be quantified adequately, then the pilot aspects, per se, can be addressed. The examples which will be presented illustrate this.

TOOLS FOR ANALYZING DISCRETE MANEUVER TASK DYNAMICS

In the course of analyzing various discrete maneuvers it has been found that identification of the dominant closed-loop response mode is useful. At the same time, as the definition offered above implies, the discrete maneuver is transient. Thus the dominant mode may appear during only a fraction of its effective period or time constant.

One technique for identifying a mode during a limited interval is to use a phase plane trajectory, i.e., a plot of rate versus displacement of a given state. The particular state to be considered is that of the discrete command. For a heading change maneuver one would choose to inspect heading rate plotted against heading displacement; for hover position, closure rate versus range; or for altitude change, vertical velocity versus height. Examples of such command-loop phase planes will be presented in the following pages.

For a second order response, the closed-loop damping and natural frequency parameters, ζ and ω, can be found using rigorous parameter identification procedures; however, even simple phase plane estimation methods work well. The sketch in Fig. 2 outlines one technique that has been found particularly useful for a variety of discrete maneuvers. Thus natural frequency can be extracted from the aspect ratio of the phase plane. A large number of landing maneuvers was so analyzed in Ref. 1.

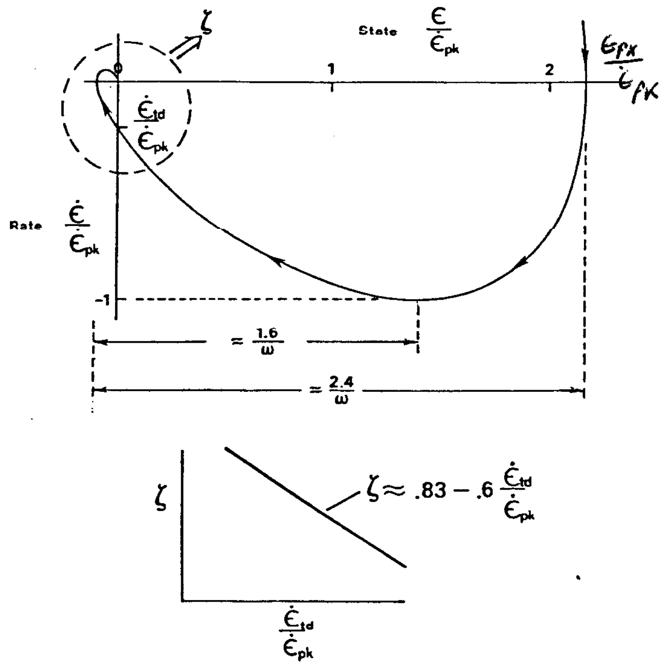


Figure 2. Normalized Phase Plane and Relationships for Extracting Closed-Loop Damping and Natural Frequency

DISCRETE MANEUVER MODELS

A reasonable mathematical model of the discrete maneuver can be obtained by direct transient response analysis methods. That is, a characteristic equation can be evaluated starting with a set of initial conditions and the commands appropriate to the final condition. The first step is to obtain a reasonable estimate of the closed-loop response type. This can be accomplished through the phase plane analysis suggested above. For example a first-order dominant mode can be distinguished from a second-order one depending upon the relative curvature of the trajectory. (Various texts can be consulted for an in-depth treatment of phase plane analysis, e. g., Ref. 4 or 5.) Ref. 6 describes how pilot training manuals can be exploited to obtain estimates of the discrete maneuver dynamics.

The following are several examples of discrete maneuvers which illustrate aspects of the general closed-loop analysis technique. These examples include a conventional fixed-wing landing flare and various rotary-wing speed change maneuvers.

Landing Flare

Consider the landing flare maneuver. First, based on observation of the closed-loop dynamics, the basic response appears to be second order—a damped sinusoid. Fig. 3 is a sample of a landing phase-plane which illustrates the second-order-like behavior, at least during the latter portion of the trajectory.

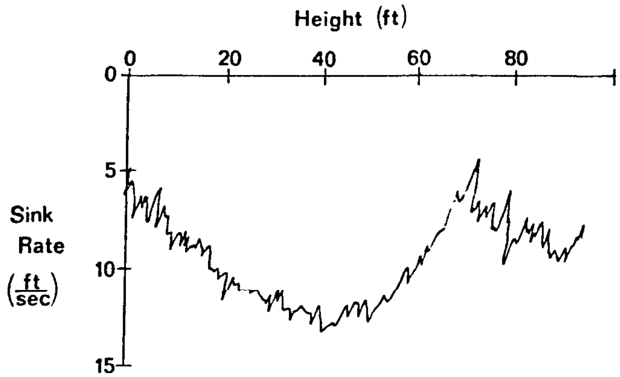


Figure 3. Sample Landing Phase Plane Trajectory

Hence a second-order transient response starting with a given height and sink rate should yield a comparable phase plane. If the second-order characteristic equation is assumed to be $\ddot{h} + 2\zeta_f\omega_f\dot{h} + \omega_f^2 h = 0$, then the Laplace transform can be written as

$$\left(s^2 + 2\zeta_f\omega_f s + \omega_f^2\right) h(s) = \left(s + 2\zeta_f\omega_f\right) h_o + \dot{h}_o \tag{1}$$

where h_o and $\dot{h}_o$ are the height and vertical velocity at any point during the flare maneuver. Thus a family of general solutions could be constructed from the parameters ζ_f and ω_f and particularized using h_o and $\dot{h}_o$. The appropriate command for height would presumably be zero, and this does appear to agree with comparisons of the above model to actual flight data. An example of a DC-10 landing and the matched second-order model parameters are shown in Fig. 4.

For the DC-10 landing flare, it was found that a fairly large sample of pilots preferred a closed-loop damping ratio of about 0.7 ± 0.1 and a closed-loop natural frequency of about 0.4 ± 0.1 rad/sec. It should be noted that a closed-loop response with these properties tends

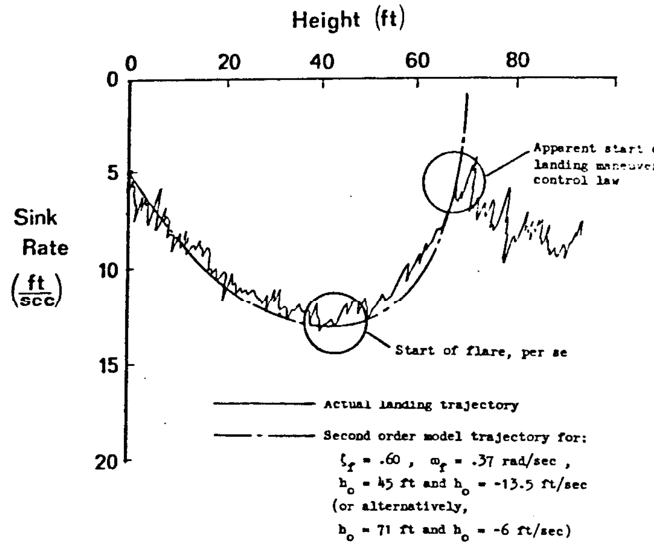


Figure 4. Typical Landing Maneuver Performed in the Actual Aircraft

to provide consistently good decay of sink rate from a wide range of initial conditions, from off-nominal aircraft flight conditions, or from a variation in flare maneuver aggressiveness.

If the closed-loop response can be evaluated as shown above, then it may be possible to deduce something about the pilot control strategy and the perceptual pathways. In Ref. 1 it was shown that the combined pilot-vehicle system during landing has the general properties of a lag-lead network. Further, using ensemble landing data and knowledge of the aircraft flight path dynamics, one can deduce the use of lead-compensated height variation and the existence of a significant lag or decay in addition to the airframe flight path lag.

A general effective lag-lead pilot-vehicle form for the landing maneuver is shown in Fig. 5. Assumption of such a form can be based

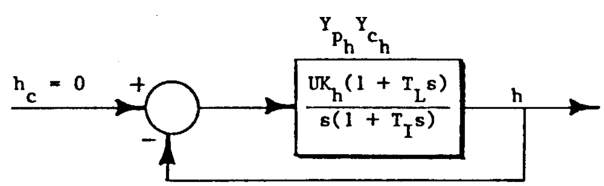


Figure 5. Block Diagram of Equivalent Pilot-Vehicle System for Flare

on knowledge of the vehicle flight path dynamics and the deduction that the rate feedback or its equivalent must be involved to explain the relatively large amount of closed-loop damping. By expanding the closed-loop characteristic equation for this network, the open-loop parameters T_L and T_I can be related to the closed-loop parameters ζ_f and ω_f in the following manner:

$$0 = 1 + Y_{P_h} Y_{c_h} =$$

$$s^2 + \frac{1}{T_I}(1 + UK_h T_L)s + \frac{UK_h}{T_I} = s^2 + 2\zeta_f \omega_f s + \omega_f^2 \quad (2)$$

or

$$2\zeta_f \omega_f = \frac{1}{T_I} + \omega_f^2 T_L \quad (3)$$

Hence if true lead compensation were involved in a fixed amount, even for varying pilot gain; there should be a trend in ensemble landing data suggested by the latter equation, namely, ensemble landing data, when plotted in terms of $2\zeta_f\omega_f$ versus ω_f^2, should have a slope equal to T_L and an intercept equal to $1/T_I$ as shown in Fig. 6.

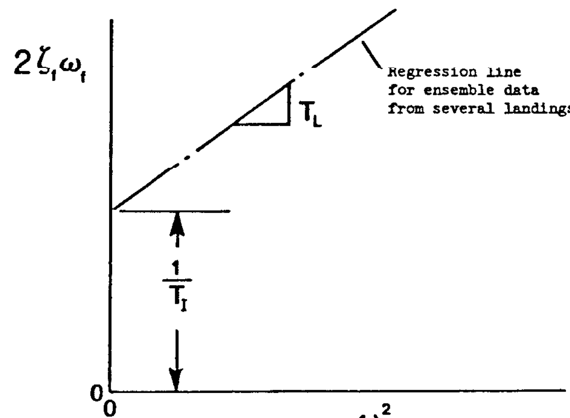


Figure 6. Regression Line Analysis Scheme for Ensemble Landing Data

Such was shown to be the case in Ref. 1 In fact a more detailed analysis based on this concept was conducted resulting in the suggestion of lead higher than first order (perhaps involving vestibular feedback) and the indication of a substantial lag or delay beyond that of just the airframe and closed-loop pitch response. For actual landings, this lag was not detrimental, but for simulator landings it was excessive and could be used to explain the tendency for hard landings. Thus this analysis procedure permitted an assessment of simulator fidelity and even training effectiveness of the simulator through direct comparison of simulator landings with those made in the actual aircraft.

Normal Speed Change Maneuver

The normal speed change maneuver in a helicopter might include takeoff as well as up-and-away flight. It is not unlike the corresponding maneuver in a fixed-wing aircraft. Cyclic pitch (or elevator) and collective (or throttle) are coordinated so as to effect an x-axis acceleration with minimal disturbance to flight path. In a helicopter the normal technique for slowing down is to pitch up and lower the collective simultaneously. (The relative amount of collective control change tends to be in direct proportion to the airspeed; but collective control is a separate issue which can be handled apart from the pitch attitude control, per se.)

The main determinant of a helicopter speed change is the use of pitch attitude since it can be shown that to a good first-order approximation[7]:

$$\Delta\dot{u} = X_u \Delta u - g\Delta\theta \quad (4)$$

To this we can add the pilot's closed-loop control of attitude in terms of a first-order lag approximation involving pitch crossover frequency, ω_{c_θ}, i.e.,

$$\frac{\Delta\dot{\theta}}{\omega_{c_\theta}} = -\Delta\theta + \Delta\theta_c \quad (5)$$

Thus a pilot control law can be expressed in terms of a pitch attitude command rather than a cyclic pitch control command, per se.

The basic control strategy for either regulating or changing speed will involve a speed feedback in the "command loop," i.e., as shown in Fig. 7. The job of the pilot is to adopt a speed

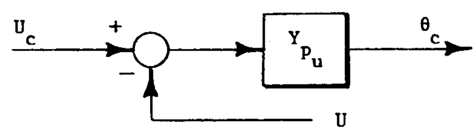


Figure 7. Control Strategy for the Normal Speed Change Maneuver

control strategy, Y_{P_u}, which will result in an effective management of speed, and we can obtain strong clues of the pilot's control strategy by observing a phase plane plot of speed versus acceleration. In several available flight cases, it can be observed that the phase plane trajectory of a speed change is essentially second order. Figure 8 shows some examples.

The kind of data shown in Fig. 8 can be replotted in conventional phase plane terms as shown in Fig. 9, even though good definition of the terminal condition is lacking. Where it is so ill-defined, we must estimate or assume a closed-loop damping ratio, ζ_u. A value of 0.7 to 0.9 is probably reasonable in view of the desire to avoid significant overshoot in any discrete maneuver. (Recall that for the landing flare a

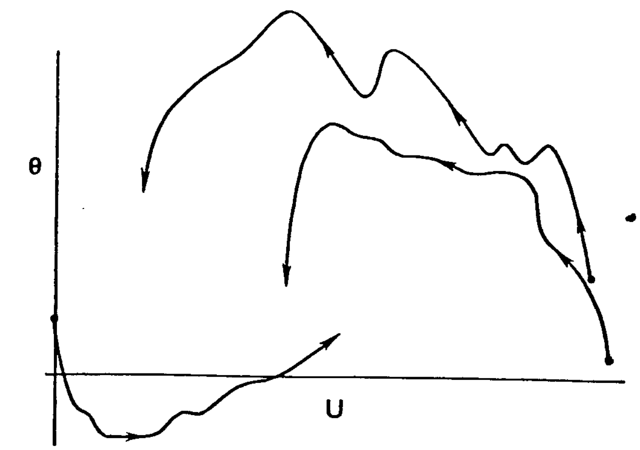
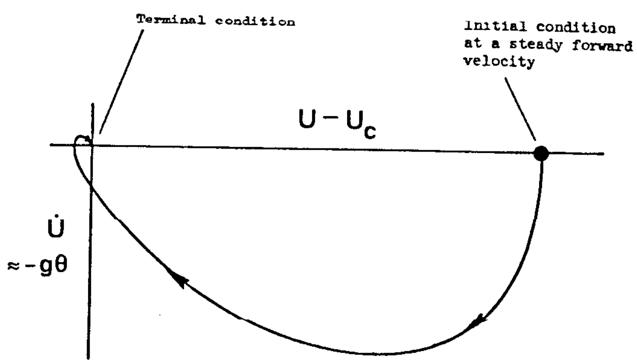


Figure 8. Typical Flight Examples of Normal Speed Changes



$$\ddot{U} + 2\zeta_u\omega_u\dot{U} + \omega_u^2 U = 0$$

Figure 9. Typical Phase Plane of a Normal Speed Change

damping ratio of 0.7 was measured.) The ratio of peak pitch attitude change (or x-acceleration) to total speed change is directly related to the closed-loop natural frequency. According to the relationships shown in Fig. 2,

$$\omega_u \doteq 2.4\, g\, \frac{\Delta\theta_{pk}}{\Delta U} \doteq 2.4\, \frac{\Delta u}{\Delta u} \qquad (6)$$

Using the predominant closed-loop response and the essential helicopter dynamics, it is thus possible to solve directly for the pilot's control law, Y_{p_u}, i.e.,

$$0 = 1 + Y_{p_u} Y_{c_u} \doteq s^2 + 2\zeta_u\omega_u s + \omega_u^2 \qquad (7)$$

where

$$Y_{c_u} \doteq \frac{g}{s - X_u} \cdot \frac{1}{1 + \frac{s}{\omega_{c_\theta}}} \qquad (8)$$

Airframe Speed Response   Closed-loop Pitch Response

and, assuming an integral-plus-proportional speed control,

$$Y_{p_u} \doteq K_U \left(1 + \frac{K_I}{s}\right) \qquad (9)$$

then

$$\frac{s^3}{\omega_{c_\theta}} + \left(1 + \frac{X_u}{\omega_{c_\theta}}\right) s^2 + \left(gK_U - X_u\right) s + gK_U K_I = 0 \qquad (10)$$

It can be shown that for $\omega_{c_\theta} >> \omega_u$, the s^3 term is negligible and the s^2 coefficient is nearly unity. (Also X_u is often negligible.)

Thus

$$K_U \doteq \frac{2\zeta_u\omega_u + X_u}{g} \text{ and } K_I \doteq \frac{\omega_u^2}{2\zeta_u\omega_u + X_u} \qquad (11),(12)$$

Typical flight data may show a 10 deg pitch change for an 80 kt speed change which therefore corresponds to an ω_u of 0.1 rad/sec according to Eq. 6. For a ζ_u of 0.7, this would yield a speed gain crossover frequency of also about 0.1 rad/sec. It should also be noted that only a pitch attitude cue and a speed cue (i.e., indicated airspeed) are needed to accomplish this task. The integral term implies a trimming function in parallel with the basic pitch attitude command. Thus the basic pilot gains (assuming a typically negligible X_u for helicopters) would be

$$K_U \doteq 0.4 \frac{\text{deg}}{\text{kt}} \text{ and } K_I \doteq 0.07/\text{sec} \qquad (13),(14)$$

In retrospect it can be seen that the usual closed-loop pitch attitude bandwidth (ω_{c_θ}) of about 1 rad/sec is not critical to the performance of a the normal speed change maneuver; in fact, it could possibly be as low as 0.3 rad/sec and still provide adequate support to the task. (Clearly this task would not be critical to the specification of pitch response characteristics.) Takeoff time histories for a UH-60[8] seem to substantiate these estimates well in that an airspeed inverse time constant of about 0.1/sec and an attitude inverse time constant of about 0.33/sec can be observed.

NOE Dash/Quickstop Maneuver

This is a far more aggressive variety of speed change maneuver than that considered above. The NOE speed change--really a position change--also involves timely use of collective pitch to offset height changes and prevent ground contact. As before, though, we shall treat only the x-axis, i.e., the pilot's control law for effecting a speed change through use of pitch attitude control, and set aside the important collective control aspects. (At the same time, we are establishing the context of the collective control task.)

The basic control strategy for the NOE speed change maneuver involves a range command-loop (Fig. 10) since position is of ultimate importance. A phase plane portrait of the dash/quickstop is therefore correctly depicted in the $\dot{R}$ - R plane of Fig. 11. Note that we can handle either the dash-quickstop combination or the quickstop alone depending upon how we pick initial conditions, but the family of phase plane trajectories would be the same.

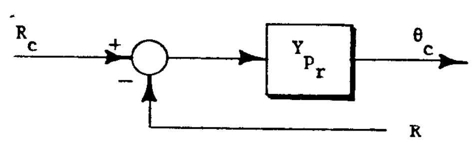


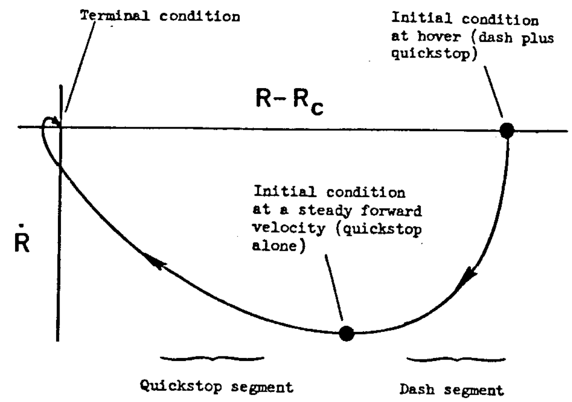
Figure 10. Command Loop for the NOE Speed (Position) Change

If the NOE speed change is assumed to involve both a range and a velocity feedback, then

$$Y_{p_r} = K_R + K_{\dot{R}}s \qquad (15)$$

The controlled element is the same as before except for an additional integration, i.e.,

$$Y_{c_r} \approx -\underbrace{\frac{g}{s(s - X_u)}}_{\substack{\text{Airframe}\\ \text{x-Position}\\ \text{Response}}} \cdot \underbrace{\frac{1}{1 + \frac{s}{\omega_{c_\theta}}}}_{\substack{\text{Closed-Loop}\\ \text{Pitch Response}}} \qquad (16)$$



$$\ddot{R} + 2\zeta_r\omega_r\dot{R} + \omega_r^2 R = 0$$

Figure 11. Range Phase Plane Assuming Second-Order Closed-Loop Behavior

$$\text{thus } 0 = Y_{p_r}Y_{c_r} + 1 \approx s^2 + 2\zeta_r\omega_r s + \omega_r^2 \qquad (17)$$

and

$$\frac{s^3}{\omega_{c_\theta}} + \left(1 - \frac{X_u}{\omega_{c_\theta}}\right)s^2 + \left(gK_{\dot{R}} - X_u\right)s + gK_R = 0 \qquad (18)$$

and with the same simplifying conditions as before for the s^3 and s^2 terms,

$$K_{\dot{R}} \approx \frac{2\zeta_r\omega_r}{g} \quad \text{and} \quad K_R \approx \frac{\omega_r^2}{g} \qquad (19),(20)$$

Observations made for a UH-1H performing quickstops in flight[9] were that

$$\frac{\theta_{pk}}{\dot{R}_{max}} \approx 1\ \frac{\text{deg}}{\text{kt}} \qquad (21)$$

e.g., starting from 40 kt, the peak pitch-up during the deceleration was about 40 deg. Based on these observations,

$$K_{\dot{R}} \approx 4\ \frac{\text{deg}}{\text{kt}} \quad \text{and} \quad K_R \approx 1\ \frac{\text{deg}}{\text{ft}} \qquad (22)(23)$$

This corresponds to $\omega_r \approx 0.8$ rad/sec which is also about equal to the effective crossover frequency. This is an extraordinarily high bandwidth for an x-axis task! Again applying a factor-of-three bandwidth requirement for pitch attitude, an NOE dash/quickstop should require about 2.5 rad/sec ω_{c_θ} --nearly an order of magnitude higher than the normal speed change task. Also, this value agrees well with the pitch damping (essentially pitch attitude bandwidth) suggested by Edenborough and Wernicke[10] for the NOE regime. This bandwidth requirement, of course, is at great variance with the pitch damping specified in MIL-H-8501A[11].

Decelerating Approach to Hover

This is a flight task for which the estimation of a simple pilot control strategy is obscured by the effects of visual perception of range. Moen, et al.[12], collected numerous approach profiles, such as those shown in Fig. 12; but it is not possible to fit simple linear, constant-coefficient models as in the previous two cases.

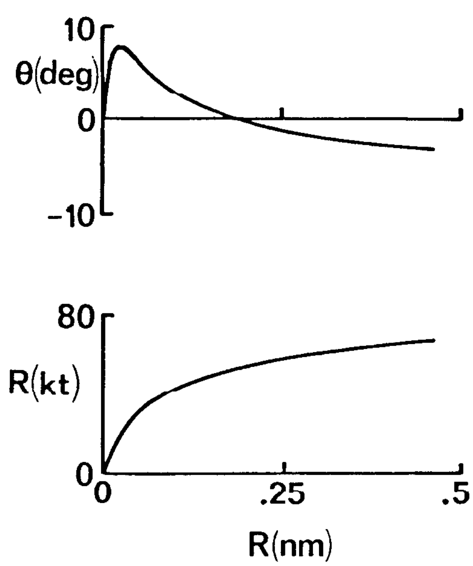


Figure 12. Typical Approach Profiles Measured by Moen, et al.[12]

It was found, however, that if the "perceived range" function of Gilinsky[13] was assumed to be operating, i.e.,

$$\text{Perceived Range,} \quad R_p = \frac{R}{1 + R/A}, \qquad (24)$$

where A is an empirically obtained perceived-range constant and R is the actual range, then the pilot control strategy for the entire approach followed by hover is a simple, stationary form such as shown in Fig. 13.

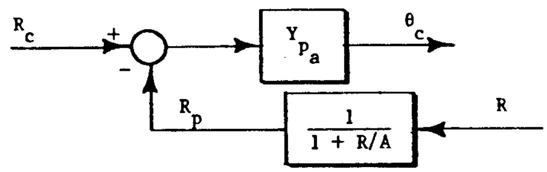


Figure 13. Decelerating Approach-to-Hover Control Strategy

A closed-form solution of the approach profile can be derived[3] in terms of deceleration or pitch attitude versus range:

$$g\Delta\theta \approx \ddot{R} \approx \frac{K_a^2 R}{(1 + R/A)^3} \qquad (25)$$

where K_a is an effective pilot control strategy gain and the effective crossover frequency can be expressed as a function of range by

$$\omega_{c_a} \approx K_a \cdot \frac{1}{1 + R/A} \qquad (26)$$

The goodness of this model is shown in Fig. 14 along with two fittings to a set of flight data--one slightly better at long range and the other at short range.

Note that a value of 0.25 for K_a and 500 ft for A would give a crossover equal to about 0.035 rad/sec at 0.5 nm, 0.065 rad/sec at 0.25 nm, and 0.25 rad/sec at hover, i.e., a steadily increasing bandwidth. It is particularly interesting that the model applies to a steady hover as well as to the entire speed transition. Furthermore, the above estimated value of ω_{c_a} at hover agrees well with the simulator measurements made by Ringland, et al.[14], using an open cockpit on the NASA Ames Research Center S.01 six-degrees-of-freedom simulator. Those data showed hover position bandwidth $\omega_{c_x} \approx 0.2$ rad/sec for three pilots.

One last observation for this case is that the supporting pitch attitude bandwidth requirement would be about 1 rad/sec, and crucial only during the very last portion of the maneuver. This agrees with Ringland's data[14] (the measured ω_{c_θ} was about 1.4 rad/sec) and other multiloop analytical approaches as exemplified by Craig, et al.[15].

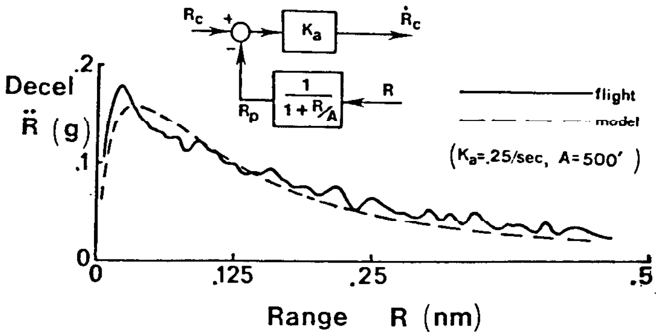


Figure 14. Comparison of Deceleration Profiles Between Analytical Model and Flight Test Data

Table 1. Summary of Helicopter Speed Change Characteristics

Maneuver	Loop Structure, Pilot Cues	Effective Crossover Frequency in Outer Loop	Implied Bandwidth Requirement for Pitch Attitude
Normal Speed Change	$U \rightarrow \theta_c$ (Integral-Plus-Proportional Compensation)	0.1 rad/sec	0.3 rad/sec
Decelerating Approach to Hover	$R_p \rightarrow \theta_c$ (Pure Gain Using "Perceived Range")	Increasing to 0.3 rad/sec	Increasing to 1.0 rad/sec
NOE Dash/ Quickstop	$R, \dot{R} \rightarrow \theta_c$	0.8 rad/sec	2.5 rad/sec

HANDLING QUALITIES IMPLICATIONS

The discrete maneuver analysis demonstrated above provides the potential for predicting handling qualities needs or problem areas. In effect the quantitative definition of a discrete maneuver establishes the context for use of supporting controls or inner loops.

For the landing maneuver a nominal closed loop natural frequency of 0.4 rad/sec implies that the pilot should be able to establish easily a pitch attitude bandwidth of about 1.2 rad/sec, i.e., about three times the outer loop bandwidth.

For the x-axis control in each of three basic helicopter speed change maneuvers, there were variations in cues used and in the abruptness required in the attitude response. This is summarized in Table 1. It should be noted that certain handling qualities requirements having fair agreement with present standards have been derived from a direct, simple analysis of basic discrete-maneuver flight tasks. Furthermore, the parameters used to characterize the outer-loop discrete maneuvers are identical in form to the inner-loop regulatory or tracking functions such as attitude control. For example we can deal with pilot control strategy gains, pilot compensation, crossover frequencies, and phase margins.

The very limited depth of the foregoing analysis must be recognized, however. The amount and quality of flight data supporting the numerical results presented is grossly inadequate for setting design standards. Data for individual flight tasks must be gathered systematically for reasonably large populations of skilled pilots and various vehicle types. As shown, analysis methods do not require large arrays of vehicle state records, therefore extensive flight test instrumentation is not really needed. To an extent, existing flight and simulator data could be reanalyzed. Useful data can also be obtained nonintrusively from flight and simulator investigations having other primary objectives.

A thorough quantitative definition of helicopter flight tasks and maneuvers should be compiled with special emphasis on the critical mission segments for fixed- and rotary-wing aircraft such as approach and landing, terrain following, formation flight, and NOE air-to-air combat or for difficult operating environments such as nighttime, instrument meteorological conditions, or extreme atmospheric disturbances.

Handling qualities are not solely tied to "stability and control" but can also impact "performance" aspects, especially in extreme maneuvers. For example in the case of helicopters, in normal speed change maneuvers (including takeoff) or in an approach to hover, large torque transients due to the pilot's use of collective pitch are not likely. Performance of a very abrupt quickstop, on the other hand, requires collective pitch applied with commensurate quickness to avoid ground-tail contact or excessive increase in altitude. The specific amount of maneuver abruptness (in terms of ω_r) implied by the quickstop analysis presented here is likely to lead to the rotor drive-system/fuel-control coupling discussed in Kuczynski[16]. The result may be significant rotor underspeed/ overspeed transients which, in effect, limit just how aggressively the pilot performs in a critical situation. It should be further noted that the pilot model arising from the flight task analysis can also be used as a tool for unmanned computer simulation in very early design stages. Thus realistic closed-loop investigations can be conducted into "stability and control" and "performance" interactions.

The main handling-qualities-related objective of the analysis approach presented has been to emphasize the rational, direct relationship between a task and its supporting handling qualities features.

SIMULATOR FIDELITY

Simulator fidelity is a basic issue in the field of handling qualities when flight simulation is the main source of pilot and performance data. Normally simulator fidelity is established by focusing on the correctness of dynamic response of the simulator motion and visual systems and the vehicle mathematical model. The result is frequently great simulator system sophistication and model complexity.

One criterion for simulator fidelity is the extent to which the simulator induces the same piloting technique or control strategy for a given task as does the actual aircraft[9]. Thus we might measure pilot control strategy in the simulator in the manner suggested here and compare it to flight. As mentioned earlier, this was done in the case of the DC-10 landing maneuver and found to reveal significant differences accounting for landing performance problems. In addition, certain adverse training effects were spotted in terms of pilot control strategy. For example, a large number of pilots training on the simulator carried over into flight excessive amounts of control lag or improper lead compensation.

A simulator fidelity effect which relates to the speed change maneuvers analyzed here was found in a recent set of unpublished data obtained from an Army UH-60 training simulator. These data, shown in Fig. 15, describe a quickstop maneuver as performed by an instructor flying at low altitude over a runway.

Direct inspection of the phase plane of $\dot{R}$ versus R reveals a constant slope of 0.071 ft/sec/ft with no apparent preference for range. The approximate closed-loop roots are therefore $(s + \omega_{c_\theta})(s + 0.065)s$. Equation (18) can thus be used to estimate $K_{\dot{R}}$ and K_R, i.e.,

$$0 = \frac{s^3}{\omega_{c_\theta}} + s^2 + g\, K_{\dot{R}} s + g K_R$$

$$= \frac{s^3}{\omega_{c_\theta}} + \left(1 + \frac{0.071}{\omega_{c_\theta}}\right) s^2 + 0.065s \qquad (27)$$

Hence

$$K_{\dot{R}} = 0.2\ \frac{\text{deg}}{\text{kt}} \quad \text{and} \quad K_R = 0 \qquad (28),(29)$$

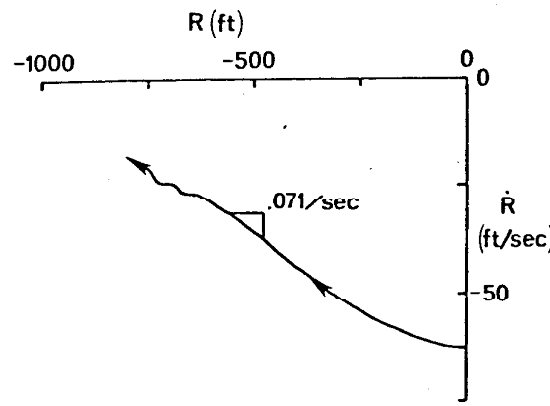


Figure 15. Quickstop Phase Plane Data From UH-60 Training Simulator

Comparing these values to the 4 deg/kt and 1 deg/ft, respectively, estimated from flight, we see that in the simulator the closure-rate feedback was more than an order of magnitude smaller and that the range feedback was essentially nonexistent. Having such a disparity should, of course, discourage any use of the simulator for that particular maneuver, but it also can help to diagnose the source of simulator fidelity problems. In the case cited above, it is likely that the main limiting feature was the downward field of view over the nose. According to the simulator specification[17] this was 18 deg, and the maximum pitch attitude recorded during the maneuver was 13 deg.

CONCLUSIONS

It is feasible to address the performance of discrete maneuvers in terms of conventional closed-loop pilot models. The maneuver task itself can be described in terms of the dominant response modes and commanded states. This task performance description can then be used to deduce the pilot element features such as effective loop gains, compensation, and perceptual pathways.

While this technique has been applied to a variety of fixed- and rotary-wing aircraft tasks, much remains to be done to define adequately each of the various piloting tasks crucial to the full range of civil and military missions. Data for individual flight tasks should be systematically gathered for reasonably large populations of skilled pilots and various aircraft types.

The availability of such data would enhance the development of handling qualities standards, the determination of simulator fidelity and velocity, and the evaluation of the effectiveness of pilot training programs.

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