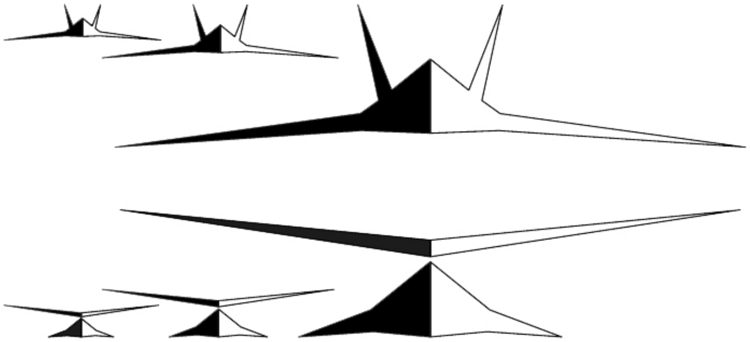


# “A Pilot-in-the-Loop Analysis of Several Kinds of Helicopter Acceleration/Deceleration Maneuvers”

Reprinted from *Helicopter Handling Qualities*, NASA CP 2219, April 1982

Robert K. Heffley

Robert Heffley Engineering
349 First Street, Suite H
Los Altos, CA 94022

http://www.RobertHeffley.com/

rhef@RobertHeffley.com

(650) 949-1747

# *A PILOT-IN-THE-LOOP ANALYSIS OF* SEVERAL KINDS OF HELICOPTER ACCELERATION/DECELERATION MANEUVERS

Robert K. Heffley
Principal Research Engineer
Systems Technology, Inc.
*Mountain View, California 94043*

## Abstract

It is becoming increasingly convenient to measure and analyze directly the control strategy of pilots involved in performing authentic tasks — both in simulators and in flight. As a result, it is now possible to begin compiling a catalog of engineering descriptions of various flight tasks, the associated piloting technique, and the perceptual pathways involved. This paper describes how a certain class of helicopter flight tasks, namely acceleration/ deceleration maneuvers, can be quantified and put to use in the fields of handling qualities, flight training, and evaluation of simulator fidelity. The three specific cases include the normal speed change maneuver, the nap-of-the-earth dash/ quickstop, and the decelerating approach to hover. All of these maneuvers share common generic features in terms of pilot adaptation and mathematical description; yet each differs in terms of the essential feedback loop structure, implications for handling qualities requirements, and simulator fidelity criteria.

## Notation

| | |
|---|---|
| $A$ | 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 |
| $K_U$ | 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 |
| $u$ | 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 |
| $\zeta$ | Damping ratio |
| $\zeta_{()}$ | Closed-loop damping ratio of () task |
| $r$ | Pitch attitude |
| $\theta_c$ | Pitch attitude command |
| $\theta_{pk}$ | Maximum pitch attitude during quickstop maneuver |
| $\phi_M$ | Phase margin |
| $\phi_{M_{()}}$ | Phase margin of () task |

| | |
|---|---|
| $\omega$ | Natural frequency |
| $\omega_{()}$ | Closed-loop natural frequency of () task |
| $\omega_c$ | Crossover frequency |
| $\omega_{c_{()}}$ | Effective crossover frequency of () task |

**Subscripts**

| | |
|---|---|
| a | Approach to hover task |
| f | Landing flare task |
| r | Dash/quickstop task |
| u | Normal speed change task |
| x | Fore-and-aft position regulation task |
| $\theta$ | Pitch attitude regulation task |

## Introduction

The purpose of this paper is to describe, using a set of examples, certain elements of an approach to handling qualities which can quantitatively account for the pilot-vehicle response needs in performing specific flight tasks or maneuvers. This is accomplished by modeling the flight task or maneuver in a way which permits the inference of the pilot's loop structure and the relative dependence of task performance on various essential and supporting loops. This complements and is fully compatible with the equivalent systems approach to describing the vehicle dynamics[1,2] and, in fact, provides the needed context for applying bandwidth criteria[3].

If handling qualities are "those stability and dynamic response characteristics of an aircraft and its control system which impact the pilot's ability to complete some useful task or mission,"[4] then we must be prepared to quantify not only the vehicle but also the task. Task quantification is the real subject of this paper; and we illustrate the concept using examples of several kinds of helicopter acceleration/deceleration maneuvers.

Historically, handling qualities requirements have not been very closely tied to specific flight tasks. This holds for fixed-wing[5], V/STOL[6], and rotary-wing aircraft[7]. Perhaps the closest that existing specifications come to dealing with individual flight tasks is the fixed-wing handling qualities specification, MIL-F-8785C, and its three "flight phase categories;" however, we shall be dealing with at least one or two additional tiers of detail in the individual task or maneuver description (i.e., specific flight tasks and then individual axes of control for each task). With regard to the rotary-wing specification, MIL-H-8501A, there is the mention of specific flight tasks in connection with various power and speed conditions but, again, no quantitative definition. Hence, as specialized environments such as NOE have entered the scene, it has been necessary to consider significantly more stringent response standards such as those suggested by Edenborough and Wernicke[8]. An example of the level of task breakdown which should be considered is shown in Table 1[9]. This is based, in part, on careful tabulation of Army training objectives.

Table 1. Army Flight Tasks and Maneuvers (Rotary- and Fixed-Wing)

BASIC FLIGHT
  Straight and Level
  Climb/Descent
  Level Turns
  Climb/Descending Turns
• Acceleration/Deceleration
  Traffic Pattern
  Slow Flight
  Stalls

HOVERING
  Takeoff to Hover
  Hover
  Hover Checks
  Hover Turns
  Forward Hover
  Land from Hover
  Hover Out of Ground Effect
  Confined Area
  Pinnacle/Ridgeline
  Slope

TAKEOFF
  Normal Takeoff
  Maximum Performance
  Short Field
  Obstacle Clearance
  Terrain Flight Takeoff

APPROACH/LANDING
• Normal Approach/Landing
  Steep Approach
  Shallow Approach
  Go Around
  Short Field
  Obstacle Clearance
  Terrain Flight Approach
  VASI Approach

LOW ALTITUDE OPERATIONS
  Terrain Flight Navigation
  Low Level Flight
  Contour Flight
  NOE Flight
  Unmask/Remask
• Dash/Quickstop
  Evasive Maneuvers

WEAPON DELIVERY
  Hover Fire
  Running Fire
  Diving Fire
  ACM

INSTRUMENT FLIGHT
  Takeoff
  Level Flight
  Turns
  Timed Turns
  Climbs/Descents
  Climb/Descending Turns
  Acceleration/Deceleration
  Autorotation
  VOR Navigation
  ADF Navigation
  Holding
  Unusual Attitude Recovery
  Navaid Approach
  GCA Approach
  Tactical Instrument Takeoff
  Tactical Instrument Approach

EMERGENCIES
  Hover Autorotation
  Standard Autorotation
  Standard Autorotation with Turn
  Low-Level Autorotation
  Hydraulic Malfunction
  Anti-Torque Malfunction
  Engine Failure at Altitude
  Engine Failure at Hover
  Flight at VMC (Single Engine)
  Single Engine Landing
  Single Engine Go Around
  Engine Failure at Takeoff
  Engine Failure During Approach

---

• Cases considered in this paper.

The aim of this paper, then, is to show how a more thorough treatment of individual flight tasks and maneuvers can result in better understanding of the piloting technique, the perceptual pathways, crucial vehicle characteristics, and the role of supporting pilot loops. The hope is to arrive at a more rational and selective approach to handling qualities which looks after the key ingredients of any particular piloting task. This approach can also be useful in judging the validity of simulator investigations of handling qualities.

In order to illustrate the above concepts we shall consider one class of helicopter flight tasks, namely speed changes. Representing this class are three rather specific maneuvers:

1) Normal speed change maneuvers
2) NOE dash/quickstop
3) Decelerating approach to hover.

As we shall see, each involves a unique combination of abruptness, pilot compensation, essential loop structure, and crucial vehicle features. In effect, *each maneuver represents a particular* context for judging handling qualities.

## Technical Approach

The approach to analyzing the speed change maneuvers listed above is adapted from a particularly successful and insightful analysis of the landing flare for a DC-10 jet transport[10]. Based on a direct estimation of closed-loop flight path response for the flare maneuver, pilot control strategy was quantified in considerable detail. This resulted, in turn, in identifying differences between landings performed in flight and in a simulator, the effects of training pilots in flight as opposed to on a simulator, and the key features in the pilot or aircraft responsible for any landing difficulties.

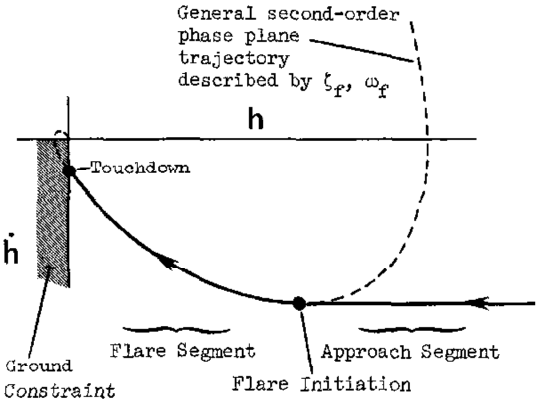
The analysis procedure applied to the DC-10 landing flare consisted of identifying the effective second-order closed-loop response parameters (e.g., frequency and damping) and subtracting the open-loop aircraft response in order to infer the pilot's control strategy. Each of these components, of course, has value, i.e.,

1) **Closed-loop pilot-vehicle response**: abruptness or urgency of the task and specific context for supporting loops or pilot actions.

2) **Open-loop aircraft response**: specific roles or influences of vehicle stability, control, and performance characteristics.

3) **Pilot control strategy**: availability of cues, ease of compensation, and level of skill.

One important tool in the DC-10 analysis was the use of a phase plane plot of the "command loop" (extreme outer loop) — in that case height versus height rate-of-change. Based on the phase plane trajectory, it was observed that the landing flare was equivalent to an unforced second-order response beginning with a set of state initial conditions and a set of state commands appropriate to touchdown. This is shown in the sketch in Fig. 1.



$$\ddot{h} + 2\zeta_f\omega_f\dot{h} + \omega_f^2 h = 0$$

Figure 1. Phase Plane Depiction of Landing Flare

The closed-loop damping and natural frequency parameters, $\zeta_f$ and $\omega_f$, can be found using rigorous parameter identification procedures, although even simple phase plane estimation methods work well. The sketch in Fig. 2 outlines all that we shall need in order to address the speed change maneuvers of interest here.

For the 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. In terms of an effective bandwidth (crossover frequency) and phase margin, the DC-10 flare was found to have:

Crossover Frequency, $\omega_{c_f} \approx 0.2$ to 0.33 rad/sec

Phase Margin, $\phi_{M_f} \approx 70$ to 90 deg

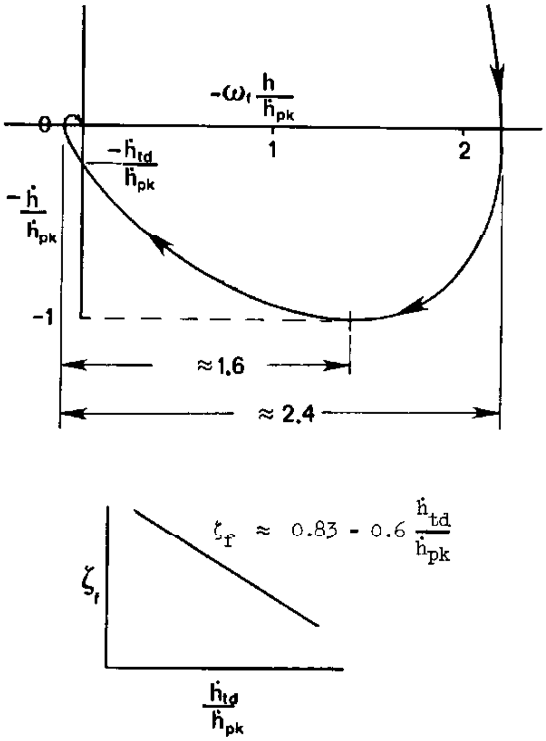


Figure 2. Normalized Phase Plane and Relationships for Extracting Closed-Loop Damping and Natural Frequency

These values therefore establish a highly quantitative context by which to judge basic airplane response characteristics and the degree of precision and control of pitch attitude required for support of the landing maneuver. As an example we might apply a factor-of-five rule of thumb for setting the necessary inner-loop pitch response bandwidth. Hence the equivalent-system pitch attitude bandwidth requirement for landing in the DC-10 should be at least 1 to 1.7 rad/sec —— a reasonable range of values.

## 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 simultaneously pitch up and lower the collective. 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[11]:

$$\Delta\dot{u} \approx X_u \Delta u - g\Delta\theta \qquad (1)$$

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, $\omega_{c_\theta}$, i.e.,

$$\frac{\Delta\dot{\theta}}{\omega_{c_\theta}} \approx -\Delta\theta + \Delta\theta_c \qquad (2)$$

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. 3. The job of the pilot is to adopt a speed 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 4 shows some examples.

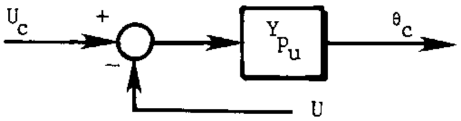


Figure 3. Control Strategy for the Normal Speed Change Maneuver

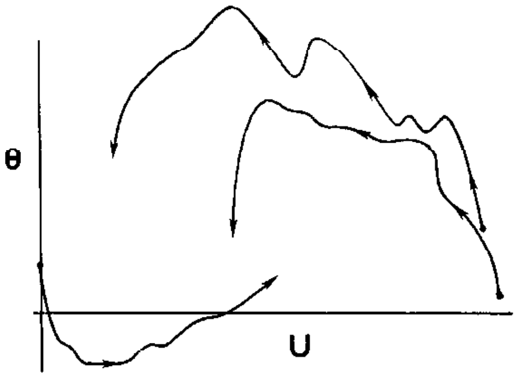


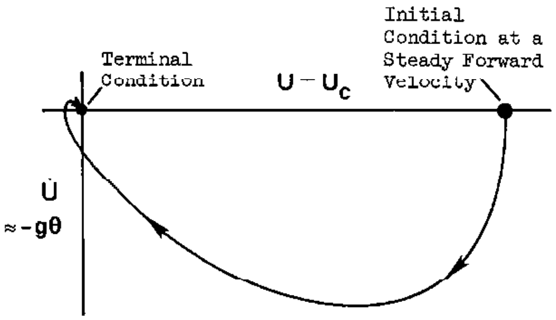
Figure 4. Typical Flight Examples of Normal Speed Changes

The kind of data shown in Fig. 4 can be replotted in conventional phase plane terms as shown in Fig. 5, 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, $\zeta_u$. 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 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.

$$\omega_u \approx 2.4\, g\, \frac{\Delta\theta_{pk}}{\Delta U} \qquad (3)$$

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

$$\text{i.e., } 0 = 1 + Y_{P_u} \cdot Y_{c_u} \approx s^2 + 2\zeta_u\omega_u s + \omega_u^2 \qquad (4)$$



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

Figure 5. Typical Phase Plane of a Normal Speed Change

where

$$Y_{c_u} \approx \underbrace{\frac{g}{s - X_u}}_{\text{Airframe Speed Response}} \cdot \underbrace{\frac{1}{\left(1 + \frac{s}{\omega_{c_\theta}}\right)}}_{\text{Closed-loop Pitch Response}} \qquad (5)$$

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

$$Y_{P_u} \approx K_U\left(1 + \frac{K_I}{s}\right) \qquad (6)$$

then

$$\frac{s^3}{\omega_{c_\theta}} + \left(1 + \frac{X_u}{\omega_{c_\theta}}\right)s^2 + (gK_U - X_u)\,s + gK_UK_I = 0 \qquad (7)$$

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

Thus

$$K_U \approx \frac{2\zeta_u\omega_u + X_u}{g} \quad \text{and} \quad K_I \approx \frac{\omega_u^2}{2\zeta_u\omega_u + X_u} \qquad (8),(9)$$

Typical flight data may show a 10 deg pitch change for an 80 kt speed change which therefore corresponds to an $\omega_u$ of 0.1 rad/sec according to Eqn. (3). For a $\zeta_u$ of 0.7, this would yield a crossover frequency of 0.07 rad/sec and a phase margin of about 85 deg. 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

$$K_U \approx 0.4\,\frac{\text{deg}}{\text{kt}} \quad \text{and} \quad K_I \approx 0.07/\text{sec} \qquad (10),(11)$$

In retrospect it can be seen that the usual closed-loop pitch attitude bandwidth ($\omega_{c_\theta}$) of about 1 rad/sec is not critical to the performance of a the normal speed change maneuver; in fact, it could be as low as 0.35 rad/sec and still provide adequate support to the task. Takeoff time histories for a UH-60[12] 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 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 maneuver involves a range command-loop (Fig. 6) 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. 7. 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.

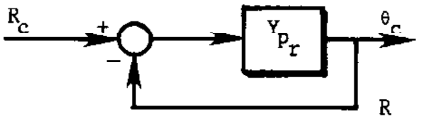
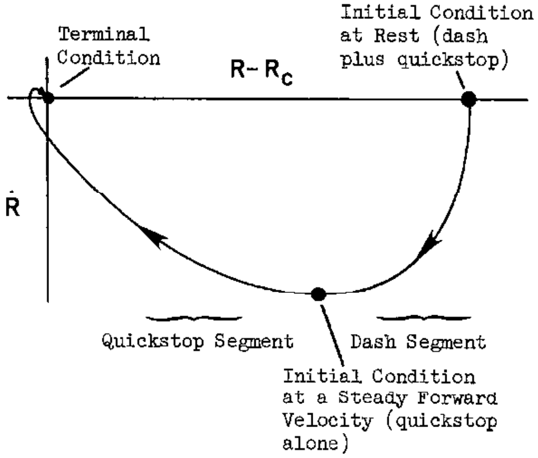


Figure 6. Command Loop for the NOE Speed (Position) Change



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

Figure 7. Range Phase Plane Assuming Second-Order Closed-Loop Behavior

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

$$Y_{P_r} = K_R + K_{\dot{R}}s \qquad (12)$$

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

$$Y_{c_r} \approx \underbrace{-\frac{g}{s(s-X_u)}}_{\text{Airframe x-Position Response}} \cdot \underbrace{\frac{1}{\left(1+\frac{s}{\omega_{c_\theta}}\right)}}_{\text{Closed-Loop Pitch Response}} \qquad (13)$$

thus $0 = Y_{p_r}Y_{c_r} + 1 \approx s^2 + 2\zeta_r\omega_r s + \omega_r^2$ (14)

and

$$\frac{s^3}{\omega_{c_\theta}} + \left(1 - \frac{X_u}{\omega_{c_\theta}}\right)s^2 + (gK_{\dot{R}} - X_u)s + gK_R = 0 \qquad (15)$$

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

$$K_{\dot{R}} \approx \frac{2\zeta_r\omega_r}{g} \quad \text{and} \quad K_R \approx \frac{\omega_r^2}{g} \qquad (16),(17)$$

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

$$\frac{\theta_{pk}}{\dot{R}_{max}} \approx 1\,\frac{\text{deg}}{\text{kt}} \qquad (18)$$

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

$$K_{\dot{R}} \approx 4\,\frac{\text{deg}}{\text{kt}} \quad \text{and} \quad K_R \approx 1\,\frac{\text{deg}}{\text{ft}} \qquad (19)$$

This corresponds to $\omega_r \approx 0.8$ rad/sec and, for $\zeta_r \approx 0.7$, the effective crossover frequency is 0.5 rad/sec and the phase margin is 85 deg. This is an extraordinarily high bandwidth for an x-axis task! Again applying a factor-of-five bandwidth requirement for pitch attitude, an NOE dash/quickstop should require about 2.5 rad/sec $\omega_{c_\theta}$ — 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[8] for the NOE regime. This bandwidth requirement, of course, is at great variance with the pitch damping specified in MIL-H-8501A (see Ref. 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.,[13] collected numerous approach profiles, such as those shown in Fig. 8; but it is not possible to fit simple linear, constant-coefficient models as in the previous two cases.

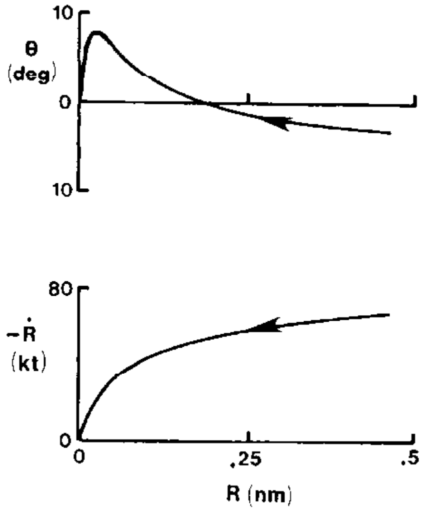


Figure 8. Typical Approach Profiles Measured by Moen, et al.[13]

It was found, however, that if the "perceived range" function of Gilinsky[14] was assumed to be operating, i.e.,

$$\text{Perceived Range,} \quad R_p = \frac{R}{1 + R/A}, \qquad (20)$$

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. 9.

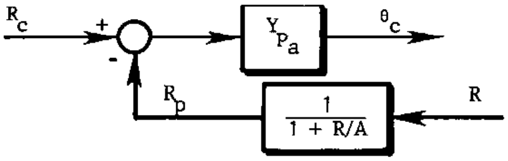


Figure 9. Decelerating Approach-to-Hover Control Strategy

A closed-form solution of the approach profile can be derived[15] in terms of deceleration or pitch attitude versus range:

$$g\Delta\theta \approx \ddot{R} \approx \frac{K_a^2 R}{(1 + R/A)^3} \tag{21}$$

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

$$\omega_{c_a} \approx K_a \cdot \frac{1}{1 + R/A} \tag{22}$$

The goodness of this model is shown in Fig. 10 along with two fittings to a set of flight data — one slightly better at long range and the other at short range.

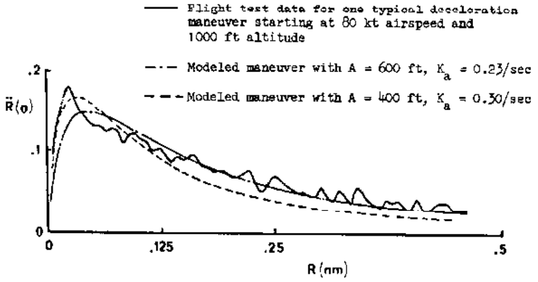


Figure 10. Comparison of Deceleration Profiles Between Analytical Model and Flight Test Data

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 $\omega_{c_a}$ at hover agrees well with the simulator measurements made by Ringland, et al.,[16] 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 1.3 rad/sec, and crucial only during the very last portion of the maneuver. This agrees with the Ringland data[16] (the measured $\omega_{c_\theta}$ was about 1.4 rad/sec) and other multiloop analytical approaches as exemplified by Craig, et al.,[17].

## Handling Qualities Implications

As a result of the above analysis, we have defined the x-axis control for three basic helicopter speed change maneuvers. In each case there were variations in cues used and in the abruptness and, therefore, the quickness required in the attitude response. This is summarized in Table 2.

Table 2. Summary of Helicopter Speed Change Characteristics

| MANEUVER | LOOP STRUCTURE, PILOT CUES | EFFECTIVE CROSSOVER IN OUTER LOOP | IMPLIED BANDWIDTH REQUIREMENT FOR PITCH ATTITUDE |
|---|---|---|---|
| NORMAL SPEED CHANGE | $u + \theta_c$<br>(INTEGRAL-PLUS-PROPORTIONAL COMPENSATION) | ≈0.07 RAD/SEC | ≈0.35 RAD/SEC |
| DECELERATING APPROACH TO HOVER | $R_p + \theta_c$<br>(PURE GAIN USING "PERCEIVED RANGE") | INCREASING TO ≈0.25 RAD/SEC | INCREASING TO ≈1.3 RAD/SEC |
| NOE DASH/QUICKSTOP | $R, \dot{R} + \theta_c$ | ≈0.5 RAD/SEC | ≈2.5 RAD/SEC |

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, phase margins, etc.

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 include those listed in Table 1 with special emphasis on the critical mission segments such as NOE or air-to-air combat or 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 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 $\omega_r$ or $\omega_{c_r}$) implied by the quickstop analysis presented here is likely to lead to the rotor drive-system/fuel-control coupling discussed in Ref. 18. 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. This was done in the case of the DC-10 landing maneuver[10] 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.

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. 11, describe a quickstop maneuver as performed by an instructor flying at low altitude over a runway.

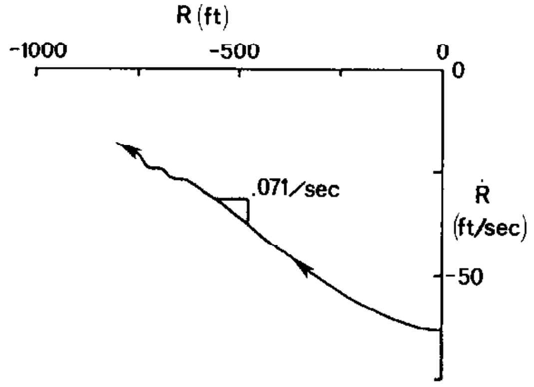


Figure 11. Quickstop Phase Plane Data From UH-60 Training Simulator

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 (15) can thus be used to estimate $K_{\dot{R}}$ and $K_R$, i.e.,

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

$$\approx \frac{s^3}{\omega_{c_\theta}} + \left(1 + \frac{0.071}{\omega_{c_\theta}}\right) s^2 + 0.065 s \qquad (22)$$

Hence

$$K_{\dot{R}} \approx 0.2\,\frac{\text{deg}}{\text{kt}} \quad \text{and} \quad K_R \approx 0 \qquad (23),(24)$$

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[19] this was 18 deg, and the maximum pitch attitude recorded during the maneuver was 13 deg.

## Conclusions

Using, as an example, three specific kinds of helicopter speed change maneuvers, we have demonstrated how each of the maneuvers can be modeled and interpreted in terms of its own individual pilot control strategy. The normal speed change maneuver relies only on a speed feedback loop with some proportional-plus-integral compensation. The maneuver is mild and requires minimal response bandwidth in the supporting pitch attitude regulation.

The NOE dash/quickstop contrasts greatly with the normal speed change maneuver in terms of abruptness and requires both range and closure-rate feedbacks. The pilot's aggressiveness in the maneuver calls for a very large pitch attitude bandwidth in order to adequately control the vehicle. In addition, the collective pitch control response required to support the maneuver in terms of height regulation may precipitate engine/fuel-control deficiencies in adequately controlling rotor rpm.

The third maneuver, the decelerating approach to hover, is intermediate to the other two in terms of abruptness but involves pilot perception in a special way. It is shown that the pilot control strategy can remain relatively invariant throughout the approach and ensuing hover and that the main source of closed-loop variation arises from the nonlinear effect of range perception.

Handling qualities implications can be drawn in each case by inspecting the role of vehicle dynamics either in the direct response (in these cases, speed response) or in the response of supporting axes or controls (e.g., pitch attitude due to cyclic pitch change). This was demonstrated for the simple cases considered here by applying a "factor-of-five" inner-loop/outer-loop bandwidth criterion. A more thorough, systematic treatment would, of course, be required to set firm handling qualities requirements.

Simulator fidelity was also addressed in terms of the analysis approach illustrated here. The main fidelity criterion used was the direct, quantitative comparison of the pilot control strategy induced in a particular simulator versus that induced by an actual aircraft counterpart. Discrepancies in control strategy can then be used to aid in searching for specific sources of deficiencies in the simulator motion or visual systems or in the computer mathematical models of the vehicle and environment.

It is suggested that the general approach illustrated here be applied in a broader, more thorough manner to the field of handling qualities. The approach provides a rational way to account for the handling-qualities needs in supporting a given flight task. It also offers a means for evaluating the validity and effectiveness of flight simulation tools which must be used in establishing handling qualities requirements.

## References

1. Stapleford, R. L.; McRuer, D. T.; Hoh, R. H.; Johnston, D. E.; and Heffley, R. K., "Outsmarting MIL-F-8785B(ASG), the Military Flying Qualities Specification," Systems Technology, Inc., Technical Report No. 190-1, August 1971.
2. Hodgkinson, J., "Equivalent Systems Approach for Flying Qualities Specification," SAE Control and Guidance Systems Committee Meeting, Denver, CO, March 1979, (MCAIR Paper 79-017).
3. Hoh, R. H.; Mitchell, D. G.; and Hodgkinson, M., "Bandwidth - A Criterion for Highly Augmented Airplanes," AIAA Paper No. 81-1890, AIAA Atmospheric Flight Mechanics Conference, Albuquerque, NM, August 19-21, 1981.
4. George, Frank L.; and Moorhouse, David J., "Relationship of the Flying Qualities Specification to Task Performance," AIAA Workshop on Flight Testing to Identify Pilot Workload and Pilot Dynamics, AFFTC, Edwards AFB, CA, January 19-21, 1982.
5. Anon., "Military Specification -- Flying Qualities of Piloted Airplanes," MIL-F-8785C, November 5, 1980.
6. Chalk, Charles R.; Key, David L.; Kroll, John, Jr.; Wasserman, Richard; and Radford, Robert C., "Background Information and User Guide for MIL-F-83300-Military Specification -- Flying Qualities of Piloted V/STOL Aircraft," AFFDL-TR-70-88, March 1971.
7. Anon., "Military Specification -- Helicopter Flying and Ground Handling Qualities; General Requirements For," MIL-H-8501A, Amendment 1, April 3, 1962.
8. Edenborough, H. K.; and Wernicke, K. G., "Control and Maneuver Requirements for Armed Helicopters," AHS Twentieth Annual National Forum, Washington, D. C., May 13-15, 1964.
9. Heffley, Robert K.; Clement, Warren F.; Ringland, Robert F.; Jewell, Wayne F.; Jex, Henry R.; McRuer, Duane T.; and Carter, Vernon E., "Determination of Motion and Visual System Requirements for Flight Training Simulators," Systems Technology, Inc., Technical Report No. 1162 1, August 1981 (forthcoming ARI report).
10. Heffley, Robert K.; Schulman, Ted M.; Randle, Robert J., Jr.; and Clement, Warren F., "An Analysis of Airline Landing Flare Data Based on Flight and Training Simulator Measurements," Systems Technology, Inc., Technical Report No. 1172-1R, March 1982 (forthcoming NASA TM).
11. Heffley, Robert K., "A Compilation and Analysis of Helicopter Handling Qualities Data. Volume Two: Data Analysis," NASA CR-3145, August 1979.
12. Nagata, John I.; Skinner, Gary L.; Buckanin, Robert M.; Robbins, Robert D.; and Williams, Robert A., "Airworthiness and Flight Characteristics Evaluation, UH-60A (Black Hawk) Helicopter," Final Report on USAAEFA Project No. 77-17, September 1981.
13. Moen, Gene C.; DiCarlo, Daniel J.; and Yenni, Kenneth R., "A Parametric Analysis of Visual Approaches for Helicopters," NASA TN D-8275, December 1976.
14. Gilinsky, Alberta S., "Perceived Size and Distance in Visual Space," Psychological Review, Vol. 58, 1951, pp. 460-482.
15. Heffley, Robert K., "A Model for Manual Decelerating Approaches to Hover," Proceedings of the Fifteenth Annual Conference on Manual Control, AFFDL-TR-79-3134, November 1979, pp. 545-554.

16. Ringland, R. F.; Stapleford, R. L.; and Magdaleno, R. E., "Motion Effects on an IFR Hovering Task -- Analytical Predictions and Experimental Results," NASA CR-1933, November 1971.

17. Craig, Samuel J.; and Campbell, Anthony, "Analysis of VTOL Handling Qualities Requirements. Part I: Longitudinal Hover and Transition," AFFDL-TR-67-179, Part I, October 1968.

18. Kuczynski, W. A.; Cooper, D. E.; Twomey, W. J.; and Howlett, J. J., "The Influence of Engine/Fuel Control Design on Helicopter Dynamics and Handling Qualities," Journal of the American Helicopter Society, Vol. 25, No. 2, April 1980, pp. 26-34.

19. Schalow, P. S., "Specification for the UTTAS Helicopter Synthetic Flight Training System, Device 2B38," NTEC 2222-1152, October 30, 1975.

*NASA Conference Publication 2219*

# Helicopter Handling Qualities

Proceedings of a Specialists Meeting on
Helicopter Handling Qualities sponsored by
the NASA Ames Research Center and the
American Helicopter Society and held at
NASA Ames Research Center
Moffett Field, California
April 14-15, 1982

NASA
National Aeronautics
and Space Administration

**Scientific and Technical**
**Information Branch**

1982