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Flight Investigation of Variations in Rotorcraft Control and Display Dynamics for Hover

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This paper describes a flight investigation of the handling qualities issues associated with variations in display dynamics for varying levels of vehicle augmentation. The experiment was conducted on the NASA/Army CH-47B Variable-Stability Research Helicopter using its model-following control system and a color, panel-mounted display. A display law design method developed and flight tested previously was refined and expanded to account for guidance effects. Specifically, for rate, attitude, and velocity command vehicle response types, both integrator-like and gain-like display controlled element dynamics were evaluated in two hovering tasks conducted in simulated zero-visibility conditions. The tasks were performed both with and without automation of the vertical and directional axes to assess the impact of divided attention on performance and work load. Quantitative and subjective data describing the pilots' ability to perform the tasks were collected and analyzed, and pilot-vehicle-display dynamics were identified. Results indicated that gain-like display dynamics were generally preferred and resulted in better inner-loop tracking and higher inner-loop crossover frequencies, while not degrading outer-loop position performance.

Introduction

MODERN requirements for rotorcraft to operate in near-terrain environments in conditions of reduced visibility have led to the widespread use of vision aids. Images provided by helmet-mounted, forward-looking, infrared sensors have been enhanced through the superposition of symbology to increase pilot situational awareness. For hover and near-hover maneuvering, symbolic displays implemented operationally have provided symbols of aircraft position, velocity, and in most cases, estimates of linear acceleration. Such is the case, for example, for the AH-64 Apache Pilot Night Vision System (PNVS) hover symbology, described in Ref. 1. As demonstrated in the simulation experiment of Ref. 2, these status displays provide information vital to mission performance. However, as implemented operationally, they do not take advantage of the large body of theoretical and experimental work that treats the displayed element dynamics as an integral part of the pilot-in-the-loop control design. As outlined in detail in Ref. 3, manual control theory provides principles for the design of displayed element drive laws that integrate command and status information for the optimization of pilot work load and task performance.

In applying manual control theory to display design, much of the work has concentrated on flight director requirements for approach and landing tasks for conventional, short takeoff and landing (STOL)[4] and vertical takeoff and landing (VTOL)[5] aircraft. In addition, the complementary relationship between display and control augmentation has been well established, which demonstrates that display augmentation can compensate, to a point, for vehicle deficiencies.[5]

Although low-altitude hover maneuvering tasks are not by nature as well defined as the instrument approach, manual control theory can still be applied to the specification of display elements that the pilot is controlling. The importance of proper specification of display dynamics for hover was demonstrated in Ref. 6. That flight experiment documented the handling qualities degradation resulting from controlled element dynamics that were not tuned to the dynamics of the vehicle.

The experiment described herein is derived from that of Ref. 6, with an overall objective of investigating, in flight, the application of the theory of manual control displays to the hover maneuvering environment. In particular, this experiment examined the effects of gain-like vs integrator-like display controlled element characteristics on pilot work load, compensation, and performance for two hover positioning tasks.

As in the first experiment, the display symbology used was essentially that of the PNVS (Fig. 1), and the experiment was conducted on the NASA/Army CH-47B Variable-Stability Research Helicopter. The display law design technique developed in Ref. 6 was refined, and analysis models were developed to predict the effects of display parameter variations on task performance for later comparison with flight data. The display laws were derived and evaluated for a range of vehicle augmentation levels both with and without automation of the secondary control axes. The resulting handling qualities data provided information on the merits of the two display law sets.

Display Format

The display format (Fig. 1) was superimposed on a color artificial horizon display. It was presented on a head-down cathode-ray tube mounted on the CH-47B instrument panel. The symbology combines planview, attitude, and altitude information on a single plane. Fixed at the center of the display is a reticle that represents the aircraft horizontal position in the planview sense. The velocity vector is the vector sum of the aircraft's forward and sideward ground velocities. The acceleration symbol, though not actually driven by aircraft acceleration in this experiment or in the operational PNVS, provides a prediction of velocity and is referenced to the tip of the velocity vector. For a constant velocity, the acceleration symbol rests at the tip of the vector. The hover position symbol, or hover pad, moves as necessary to represent the desired hover position relative to the aircraft, or the fixed reticle.

The PNVS symbology can be considered a pursuit format since both the acceleration symbol and the error between it

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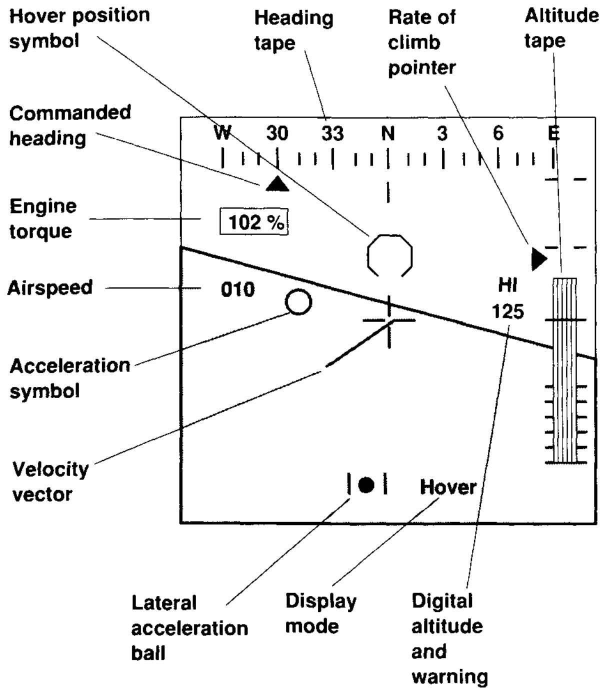

Fig. 1 Hover display symbology.

and the hover pad are presented. However, one distinction from pursuit displays is that, since the hover pad is driven by aircraft motion itself, it is not an independent target in the conventional pursuit tracking sense. In any case, it is assumed that the display format allows pursuit-type pilot behavior and its attendant benefits, as discussed in Ref. 7.

Considerations for Controlled Element Dynamics

Both operationally for the PNVS symbology and for this study, the acceleration symbol, or ball, is the pilot's controlled element for aircraft horizontal position. To achieve a hover over the pad, the pilot may adopt a guidance strategy in which he places the ball on the pad, through appropriate control actions, and maintains it there as the pad converges to the display center, indicating that the aircraft has reached the desired position. The ease and precision with which the pilot is able to maintain the acceleration ball on the pad, and the dynamics of the resulting aircraft position response, are functions of the pilot, vehicle, and acceleration ball dynamics and the display position and velocity scalings.

Two types of controlled element responses to control inputs, namely gain-like and integrator-like characteristics, were examined for this experiment. The use of integrator-like characteristics is founded on the well-known principle of manual control theory—the crossover model.[8] It postulates that in a compensatory tracking task, the human operator will provide the necessary compensation such that the open-loop pilot-vehicle-display system will have the characteristics of an integrator plus an effective time delay in the crossover frequency range. A result of the model is that, if the vehicle-display combination provides integrator response, the pilot need only provide gain equalization, plus his unavoidable time delay. The integrator characteristics of the controlled element provide for good closed-loop stability, reduced work load, high-frequency noise attenuation, and good tracking performance. Equivalently, if the controlled element possesses gain-like characteristics, the crossover model predicts that the pilot would provide low-frequency lag equalization. Also, the use of gain characteristics can lead to noise amplification and reduced display sensitivities that may degrade tracking performance.[3] These principles provided the foundation for the integrator-like display designs used in the simulation experiment of Ref. 9, which employed the same format, tasks, and aircraft characteristics as had been used in Ref. 6.

In spite of the potential disadvantages of gain characteristics, several flight investigations have demonstrated that pilots prefer the sense of immediate controllability that results from a display element with gain characteristics at frequencies near or beyond the typical crossover region (here referred to as gain-like). The Ref. 4 flight experiment, for example, demonstrated the benefits of gain-like characteristics for the throttle bar of a compensatory flight director in a multiaxis curved decelerating approach task. In addition, the Ref. 10 flight experiment used washed-out pitch attitude command to quicken the flight-path symbol of a STOL pursuit approach display with excellent results. The authors pointed out that the resulting pure gain dynamics reduced pilot work load and may have allowed for more division of attention to other scanning or control tasks since the pilot command does not have to decay exponentially as it would with an integrator-like element. A gain-like display element was also used successfully, for hover, in the flight investigation of Ref. 11.

Vehicle Response Dynamics

The vehicle responses studied for this experiment were mechanized using the variable-stability capability of the CH-47B helicopter through an explicit model-following control system (MFCS).[12] Pilot inputs are used to drive a state-space model of desired characteristics. The MFCS forces the aircraft to follow the model states as closely as possible. The response types for the pitch and roll axes were, in order of increasing augmentation, rate command/attitude hold, attitude command/attitude hold, and velocity command. The directional response was yaw rate command with optional heading hold, whereas the vertical response was vertical rate command with optional altitude hold. All of the responses were decoupled. Their transfer functions are presented in Table 1. It can be seen that the velocity system was essentially a feed-forward shaping of attitude response to approximately replace the basic vehicle velocity-response time constants with desired new characteristics. No velocity feedback for long-term stabilization was included; however, the attitude shaping did provide constant velocity response to pilot input for the frequency range of the evaluation tasks.

Display Law Design

The display law design specified the acceleration ball dynamics with consideration of the outer-loop position performance, especially as determined by the relative scaling of the velocity vector and hover pad. These guidance considerations will be discussed subsequently. The objectives of the inner-loop design were to achieve ball dynamics that exhibited either gain-like K or integrator-like K/s response characteristics to pilot input over as broad a frequency range as possible. The following discussion concerns only the longitudinal display design; the lateral axis is analogous. First, the general form of

Table 1 Model-following control system model response dynamics

Control response type	$\frac{\theta}{\delta_b}$, $\frac{\text{rad}}{\text{in.}}$	$\frac{\phi}{\delta_a}$, $\frac{\text{rad}}{\text{in.}}$	$\frac{r}{\delta_r}$, $\frac{\text{rad/s}}{\text{in.}}$	$\frac{\dot{h}}{\delta_c}$, $\frac{\text{ft/s}}{\text{in.}}$
Rate	$\frac{0.21}{s(s+2.0)}$	$\frac{0.21}{s(s+2.0)}$	$\frac{0.12}{s+1.0}$	$\frac{6.33}{s+0.33}$
Attitude	$\frac{0.28}{s^2+2s+2}$	$\frac{0.28}{s^2+2s+2}$	$\frac{0.12}{s+1.0}$	$\frac{6.33}{s+0.33}$
Velocity	$\frac{0.26(s+0.02)}{(s+0.3)(s+1.4)^2}$	$\frac{0.44(s+0.12)}{(s+0.5)(s+1.4)^2}$	$\frac{0.12}{s+1.0}$	$\frac{6.33}{s+0.33}$

the drive law for the acceleration symbol with respect to the display center (Fig. 2) is

$$A_x = K_{\dot{x}}\dot{x} + K_\theta\theta_{\rm wo} + K_q q + K_{\delta_b}\delta_{b\rm wo}$$

where the subscript wo refers to washout. Inputs to the drive law are readily available quantities and effectively represent successive differentiations from which the desired controlled element equalization can be generated. The velocity term $K_{\dot{x}}\dot{x}$ references the acceleration symbol to the tip of the velocity vector. The washed-out attitude term $K_\theta\theta_{\rm wo}$ approximates the short-term linear accelerations that result from tilting the vehicle. As will be shown, the angular rate term $K_q q$ provides the lead necessary to achieve K/s dynamics, and the control input term $K_{\delta_b}\delta_{b\rm wo}$ provides for a pure gain response above a desired frequency not accounting for system delays. The washout filters on the attitude and control input ensure that in any trimmed flight condition the ball rests at the tip of the vector.

Including the washout terms and dividing through by the control input yields

$$\frac{Ax}{\delta_b}(s) = K_{\dot{x}}\frac{\dot{x}}{\delta_b}(s) + K_\theta\left(\frac{s}{s+1/T_\theta}\right)\frac{\theta}{\delta_b}(s) + K_q\frac{q}{\delta_b}(s) + K_{\delta_b}\left(\frac{s}{s+1/T_{\delta_b}}\right) \qquad (1)$$

The vehicle response to control inputs is contained in the first three terms of the ball dynamics specification. For this experiment, the vehicle response transfer function used was the model that the CH-47B's MFCS was commanding the aircraft to follow. The inclusion of high-order effects in the form of equivalent time delays is ignored in the design, but it will be discussed subsequently.

For small perturbations about hover, the velocity response transfer function is assumed to be

$$\frac{\dot{x}}{\delta_b}(s) \approx -\frac{g}{(s+1/T_u)}\frac{\theta}{\delta_b}(s)$$

and the body pitch rate transfer function is assumed as

$$\frac{q}{\delta_b}(s) \approx s\frac{\theta}{\delta_b}(s)$$

Under these assumptions, Eq. (1) becomes

$$\frac{A_x}{\delta_b}(s) = \left[\frac{-gK_{\dot{x}}}{s+1/T_u} + K_\theta\left(\frac{s}{s+1/T_\theta}\right) + K_q s\right]\frac{\theta}{\delta_b}(s) + K_{\delta_b}\left(\frac{s}{s+1/T_{\delta_b}}\right) \qquad (2)$$

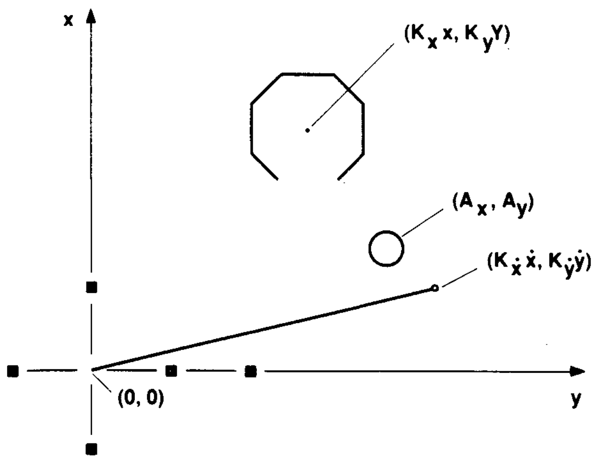

Fig. 2 Central symbology deflections.

Given the expressions for the vehicle attitude and velocity responses, the remaining parameters may be specified so that the previous equations exhibit K/s-like characteristics without the control-input term and K-like characteristics with the control-input term included. The procedure for achieving K/s and then K characteristics will be presented only for the attitude response type. The rate response design is detailed in Ref. 13.

Display Design for K/s Controlled Element Dynamics

To achieve K/s characteristics, the control-input term of Eq. (2) is removed, which results in the following expression:

$$\frac{A_x}{\delta_b}(s) = \frac{K_q}{(s+1/T_u)(s+1/T_\theta)}\left\{s^3 + \left(\frac{K_\theta}{K_q} + \frac{1}{T_\theta} + \frac{1}{T_u}\right)s^2 + \left[-g\frac{K_{\dot{x}}}{K_q} + \frac{1}{T_uT_\theta} + \frac{K_\theta}{K_q}\left(\frac{1}{T_u}\right)\right]s - g\frac{K_{\dot{x}}}{K_q}\left(\frac{1}{T_\theta}\right)\right\}\frac{\theta}{\delta_b}(s) \qquad (3)$$

The attitude response to control input for an ideal attitude system is

$$\frac{\theta}{\delta_b}(s) = \frac{M_{\delta_b}}{(s^2 + 2\zeta_\theta\omega_\theta s + \omega_\theta^2)}$$

If the portion of the numerator term in brackets of Eq. (3) is set equal to

$$\left(s + \frac{1}{T_u}\right)(s^2 + 2\zeta_\theta\omega_\theta s + \omega_\theta^2)$$

then the resulting form for A_x/δ_b is

$$\frac{A_x}{\delta_b}(s) = \frac{K_qM_{\delta_b}}{(s+1/T_\theta)} \times \frac{(s+1/T_u)(s^2 + 2\zeta_\theta\omega_\theta s + \omega_\theta^2)}{(s+1/T_u)(s^2 + 2\zeta_\theta\omega_\theta s + \omega_\theta^2)} \qquad (4)$$

Equation (4) has the desired K/s response characteristics for frequencies beyond $1/T_\theta$ rad/s. Setting Eq. (4) equal to Eq. (3) and matching coefficients yields the relationships for the display parameters necessary to achieve these K/s characteristics for an attitude system:

$$\frac{1}{T_\theta} = \frac{1}{T_u}$$

$$K_q = -g\frac{K_{\dot{x}}}{\omega_\theta^2}$$

$$K_\theta = -g\frac{K_{\dot{x}}}{\omega_\theta^2}\left(2\zeta_\theta\omega_\theta - \frac{1}{T_u}\right)$$

Note that the display design parameter $K_{\dot{x}}$ appears on the right side of the last two equations. Thus, $K_{\dot{x}}$ acts as a scale factor on the principal display parameters K_q and K_θ. Methods for its determination will be described subsequently.

Extension of Display Design to K Controlled Element Dynamics

Once the procedure for achieving K/s dynamics has been completed, the extension to K is made by simply adding the washed-out control-input term to the expression for A_x/δ_b. The resulting ball response transfer function for the attitude system is then,

$$\frac{A_x}{\delta_b}(s) = \frac{K_qM_{\delta_b}}{s+1/T_\theta} + K_{\delta_b}\left(\frac{s}{s+1/T_{\delta_b}}\right) \qquad (5)$$

The new design parameters K_{δ_b} and T_{δ_b} must next be determined. Equation (5) can be rewritten as

$$\frac{A_x}{\delta_b}(s) = \frac{K_{\delta_b}s^2 + (K_qM_{\delta_b} + K_{\delta_b}/T_\theta)s + K_qM_{\delta_b}/T_{\delta_b}}{(s+1/T_\theta)(s+1/T_{\delta_b})}$$

Table 2 Final display and related aircraft parameters

Display parameter	Units	Rate K/s	Rate K	Attitude K/s	Attitude K	Velocity K/s	Velocity K
K_x	deg/ft	0.04359	0.04359	0.04359	0.04359	0.04359	0.04359
$K_{\dot{x}}$	deg/ft/s	0.3300	0.3300	0.3300	0.3300	0.3300	0.3300
K_θ	deg/rad	− 16.16	− 16.16	− 10.52	− 10.52	− 11.12	− 11.12
T_θ	s	5.326	5.326	50.0	50.0	4.657	4.657
K_q	deg/rad/s	− 6.234	− 6.234	− 5.314	− 5.314	− 3.880	− 3.880
K_{δ_b}	deg/in.	0.0	− 0.8044	0.0	− 1.716	0.0	− 1.506
T_{δ_b}	s	—	4.0	—	3.333	—	3.333
K_y	deg/ft	0.04359	0.04359	0.04359	0.04359	0.04359	0.04359
$K_{\dot{y}}$	deg/ft/s	0.3300	0.3300	0.3300	0.3300	0.3300	0.3300
K_ϕ	deg/rad	18.15	18.15	9.989	9.989	10.17	10.17
T_ϕ	s	4.495	4.495	8.333	8.333	3.039	3.039
K_p	deg/rad/s	7.388	7.388	5.314	5.314	3.568	3.568
K_{δ_a}	deg/in.	0.0	0.9281	0.0	1.716	0.0	2.306
T_{δ_a}	s	—	4.0	—	3.333	—	2.5
M_{δ_b}	rad/s^2/in.	0.21	0.21	0.28	0.28	0.26	0.26
$1/T_u$	s^{-1}	0.02	0.02	0.02	0.02	0.02	0.02
L_{δ_a}	rad/s^2/in.	0.21	0.21	0.28	0.28	0.44	0.44
$1/T_v$	s^{-1}	0.12	0.12	0.12	0.12	0.12	0.12

The values of the stick washout time constant and stick gain determine both the sensitivity of the ball to stick inputs and the frequency beyond which gain-like dynamics prevail. A tradeoff exists between this gain break frequency and the amount of true aircraft state present in the ball response because the K-like characteristics are due to the stick input rather than to the aircraft response. A ball that is driven excessively by control input may not yield good positioning accuracy. In addition, K_{δ_b} and T_{δ_b} must be chosen to provide adequate numerator damping to assure that the velocity response dynamics to a fixed ball position will not be oscillatory.

Guidance Considerations and the Selection of Velocity Vector Gains

Consider a pad capture task, in which the pilot wants to acquire a new position over the hover pad symbol, which is offset some distance from the display center. Without an acceleration symbol, if the pilot were able to place the tip of the velocity vector on the hover pad and maintain it there, an exponential closure would result with a time constant determined by the ratio of the velocity vector and hover position display scaling gains. The effects of the velocity vector gain would then be immediately apparent. However, with the acceleration symbol as the controlled element, the character of the pad closure is not a simple exponential, but instead could be oscillatory convergent or even divergent. The velocity vector scaling still has a strong effect on the trajectory dynamics.

The impact of velocity vector scaling on task guidance can be predicted analytically[13] by modeling the pilot's strategy of maintaining the acceleration symbol at the center of the hover pad throughout a pad capture. The trajectory resulting from using this guidance law can be determined for the vehicle-display combination of interest. A block diagram illustrating this analysis is presented in Fig. 3. The pilot is represented by a simple gain on the error between the ball and the pad, where the pad location is the difference between the actual and commanded aircraft positions, referenced to a common point and scaled for screen displacement. The pilot gain K_p is selected to yield reasonable control deflections, and a limit of ± 5 in. is placed on the pilot control to prevent unattainable inputs. The aircraft and display blocks are the simple transfer functions discussed in the display design section.

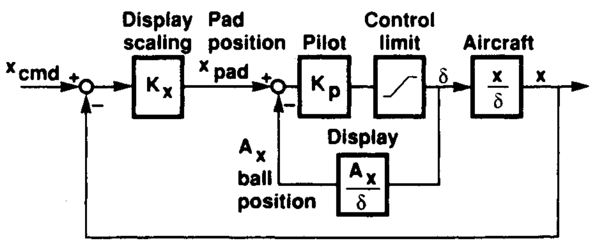

Fig. 3 Block diagram of pilot-vehicle-display system.

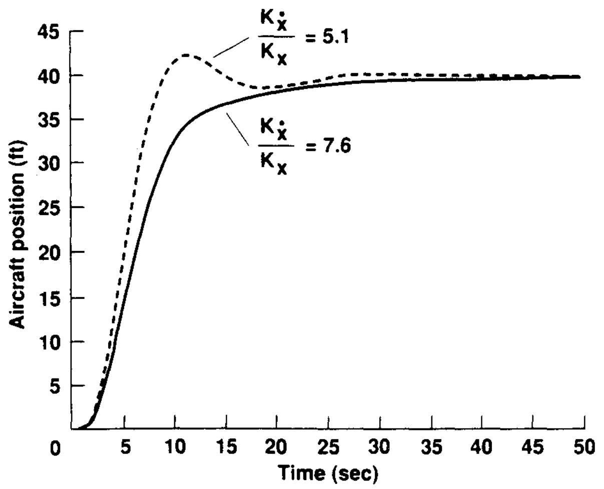

Fig. 4 Position trajectories for two vector gains.

This analysis is illustrated for the attitude command, K dynamics configuration, for a 40-ft step command in position and a K_p of 1.45 in./deg, where the display deflection is defined as degrees subtended at the nominal pilot eye station (full scale is ± 4.4 deg). Figure 4 presents the resulting position trajectories for values of $K_{\dot{x}}$ that are 5.1 and 7.6 times the value of K_x. It can be seen that the 50% change results in very different characteristics. The tradeoff between oscillation and capture time is evident. This tradeoff should be considered when selecting the display scalings in the context of the operating environment and the attendant demands on the pilot.

Summary of Design Choices

The hover pad was scaled to be approximately 28 ft in diameter, with a full-scale deflection of $\pm$ 101 ft. This value was reasonable considering the size of the CH-47B. Based on initial flight tests, $K_{\dot{x}}$ was chosen based on a $K_{\dot{x}}/K_x$ ratio of 7.6 s, which resulted in a slow pad acquisition with no noticeable vehicle position oscillation.

The display parameter values used for this experiment appear in Table 2. The analytical longitudinal-axis frequency responses of the ball for the rate, attitude, and velocity sys-

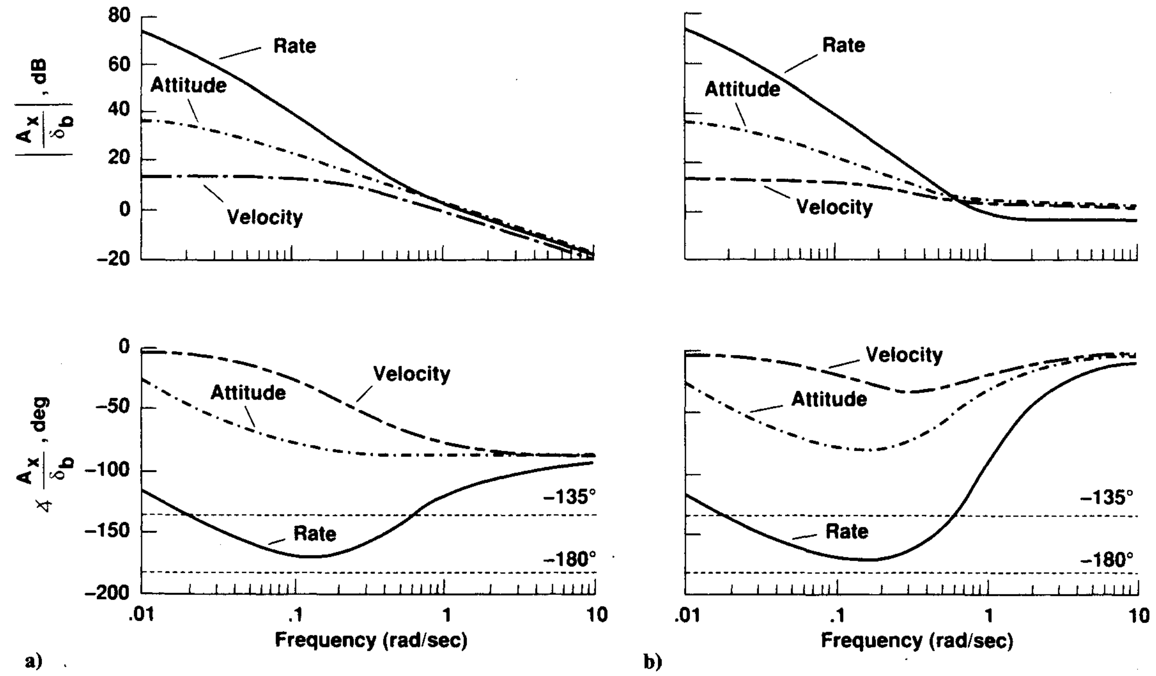

Fig. 5 Analytical frequency responses: a) for K/s designs, b) for K designs.

tems, K/s and K configurations, are presented in Fig. 5. Note that the three responses for each configuration are not the same. In particular, at low frequencies, the rate system has K/s^2 characteristics. It was not possible with the display law to completely mask the low-frequency aircraft characteristics, partially as a result of the feedback nature of the display compensation (see Fig. 3), in contrast with a flight director display implemented in the forward path in which all aircraft dynamics can be analytically canceled.

Impact of High-Order Dynamics on Displayed Element Response

The design technique provides for either K/s or K acceleration ball dynamics under the assumption that the low-order models of the aircraft response are representative. In reality, the high-order dynamics of the aircraft actuators, rotors, sensor filters, and the time delays of the digital computers and output devices will impact the controlled element response. For low-order equivalent system matching, these high-order dynamics may be combined into a time delay on the aircraft response to pilot input. Using frequency domain identification techniques[14] for this experiment and in previous analyses of the MFCS,[12] the identified equivalent time delay was found to be approximately 0.175 s. In addition, it is necessary to model the simple computational and transport delays between aircraft response and displayed symbology movement; for the CH-47B system these delays totaled 0.09 s. Finally, preliminary flights revealed that the pilot control-input signals present in the ball for the K configurations contained noise from motion-induced vibration through the center-stick controller. The noise was reduced by applying a first-order 10-rad/s filter on the entire acceleration ball response for all of the K configurations. The actual acceleration ball transfer function of Eq. (2) can therefore be written including the delay and filter terms:

$$\frac{A_x}{\delta_b} = \left\{\left[\frac{-gK_{\dot{x}}}{s+1/Tu} + K_\theta\left(\frac{s}{s+1/T_\theta}\right) + K_q s\right]\frac{\theta}{\delta_b}e^{-0.175s} + K_{\delta_b}\left(\frac{s}{s+1/T_{\delta_b}}\right)\right\}\left(\frac{10}{s+10}\right)e^{-0.09s}$$

where the K/s case results by removing both the K_{δ_b} term and the 10-rad/s filter. Figure 6 presents the frequency responses resulting for the attitude system K/s and K configurations with these time delays included (in the form of second-order Padé approximations). Evident is the larger phase margin of the K system vs the K/s system in the expected crossover frequency region (1–4 rad/s, from identification data to be discussed subsequently).

This analysis reveals that the in-flight ball configurations actually had K or K/s dynamics only in the magnitude sense in the crossover region, whereas the phase characteristics for both were degraded vs ideal dynamics. The term K dynamics more properly describes, then, the addition of lead compensation for high-frequency phase lags. The phase margin degradation is unavoidable, but must be considered, when a simple display law design technique is applied to a high-order vehicle. In any case, the interpretation and generalization of the flight results must be tempered by the true vehicle/display dynamics that were tested. The use of the terms K and K/s in the paper

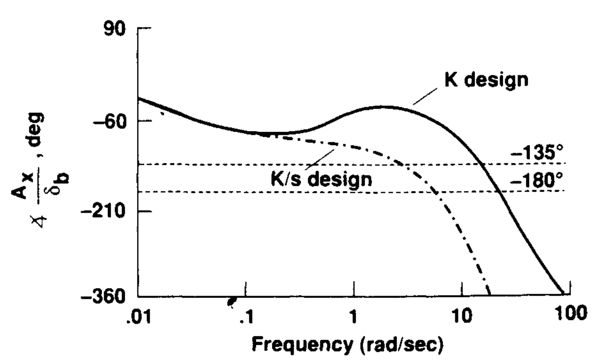

Fig. 6 Attitude K and K/s designs including system delays.

is in this context a simplification, but is still the most suitable characterization of the differences between the two designs.

Flight Experiment Design

Experimental Variables

The primary experimental variables were the vehicle pitch/roll response type (rate, attitude, or velocity command) and the acceleration ball dynamics (K or K/s) for each response type. The secondary variable, which was intended to further expose the relative merits of K vs K/s controlled element dynamics, was the regulation of the directional and vertical axes. With heading hold and altitude hold activated, the pilot was able to supply full, or undivided, attention to the task of positioning the helicopter in the horizontal plane. Heading and altitude performance were then not of concern to the pilot. When those axes were not regulated automatically by the control system, the pilot was forced to divert his attention from the central symbology to the heading and altitude tapes to control them. In this case he gave divided attention to the positioning task.

Flight Tasks

Hover Pad Capture

The pad capture was chosen both because it is a representative hover maneuver and because it exposed position tracking and guidance law issues, since it is an outer-loop control task. In this task, the hover position symbol was displaced (via software) a total of 57 ft diagonally, or 2 pad diameters, both forward/rightward and rearward/leftward from the aircraft. The pilot was instructed to achieve a stable hover over the pad within 25 s by quickly placing the acceleration symbol on the hover pad symbol and maintaining it there as the pad converged to the center of the screen. The standards for desired performance were to achieve final position within one-third of the pad center (10 ft), without significant over- or undershoot. For the divided-attention cases, desired heading performance was $\pm$ 5 deg and altitude was $\pm$ 10 ft. Standards for adequate performance were twice those for desired performance.

Hover Pad Tracking Task

The pad tracking task was chosen because it was a well-defined, repeatable maneuver and to provide data for identifying pilot-vehicle-display dynamics. It also exposed acceleration symbol controllability issues apart from the outer-loop aircraft position performance. For this task, the hover pad symbol was driven by a sum-of-sinusoids forcing function that added to the pad motion resulting from aircraft movement. The equations used to drive the pad, derived for use with Fourier transform analysis techniques, were as follows:

$$x\text{pad} = 8.75\ [\sin(0.1983t) + \sin(0.3304t) + \sin(0.5287t) + \sin(0.8591t)] + 0.875\ [\sin(1.256t) + \sin(1.916t) + \sin(3.040t)] + 0.438\ [\sin(5.022t) + \sin(7.468t)]$$

$$y\text{pad} = 8.75\ [\sin(0.2643t) + \sin(0.4626t) + \sin(0.7269t) + \sin(0.9913t)] + 0.875\ [\sin(1.520t) + \sin(2.445t) + \sin(4.031t)] + 0.438\ [\sin(6.146t) + \sin(8.393t)]$$

where $x$pad and $y$pad are the commanded inertial hover pad positions in feet and t is the time in seconds since the start of the maneuver. The maximum pad command generated by the signals was approximately 42 ft, or 1.5 pad diameters from the screen center.

The pilot's objective for the 95-s task was to keep the center of the acceleration symbol within the hover position symbol, as close as possible to its center. The performance standards were to keep the center of the ball within the hover pad for at least 80% of the run for desired performance and for 50–80% of the run for adequate performance. The heading and altitude standards for the divided-attention case were the same as for the pad capture task. The performance measure of ball-to-pad error was specified rather than aircraft position error for two reasons. First, it was far easier for the pilot to estimate his ball-on-pad tracking performance than his position performance. Second, since he was instructed as part of the task to keep the ball on the pad, the position performance was uniquely determined by his ability to do that and by the combined vehicle-display dynamics. Aircraft position could not be independently controlled, so it would have been inconsistent to insist on his keeping the ball on the pad and at the same time defining a desired maximum position deviation.

Experiment Conduct and Piloted Evaluations

Reference 15 provides a description of the CH-47B variable-stability system and its operations. Reference 16 summarizes the configuration for this experiment.

The flight evaluations were performed by two experimental test pilots with extensive fixed- and rotary-wing experience. In nine flights, 62 evaluations were obtained, totaling approximately 12 flight hours. The tasks were conducted with the pilot fully hooded to eliminate external visual cues that could influence the evaluation. The control/display configurations were not disclosed to the evaluation pilot, although he was informed whether the task was to be performed with undivided or divided attention, i.e., heading and altitude hold on or off. All relevant signals, pilot comments in response to a questionnaire, and Cooper-Harper pilot opinion ratings[17] were recorded. For the pad capture task, one rating was taken for a series of at least four captures, two diagonally forward and two diagonally rearward.

Results

Pad Capture Task

All of the pilot ratings for the pad capture task are shown in Fig. 7. Several trends can be noted. First, on examining the K/s configurations, for the undivided attention case, it is seen that the attitude system was generally preferred, followed by velocity and then rate. Regarding the dispersion of ratings for pilot B for the attitude system and pilot A for the velocity system, the poorer ratings were given on each pilot's first evaluation flight, so that training may have been a factor. Pilot comments for the attitude system, undivided case indicated that the acceleration ball was, in general, controllable,

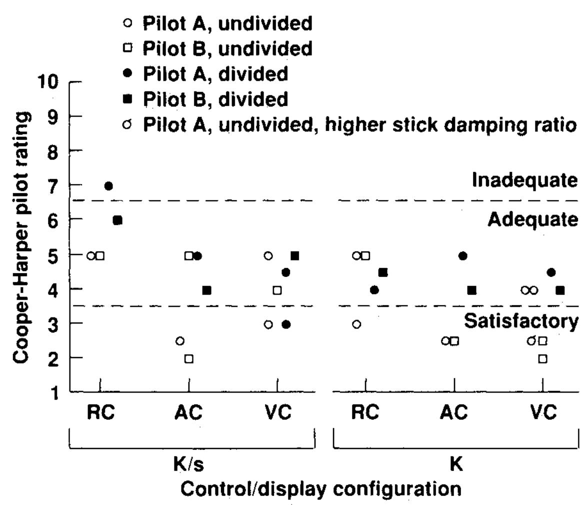

Fig. 7 Pilot rating results, pad capture task.

but appeared to be sluggish. Initial impressions were that the ball required constant attention to assure that it was maintained within the pad. Significant, although not objectionable, control and aircraft motions were required to move the ball to the pad initially. For example, pitch attitude changes of 6 deg from trim were seen as opposed to 4 deg for the attitude system with a *K* display law. The aircraft was slow to converge on the final hover point, but this could be compensated by placing the ball slightly to the other side of the pad center. The task was, in general, easy, and the compensation was minimal or not a factor.

Negative factors seen with the attitude system were slightly more pronounced for the velocity system. In particular, the sluggishness of the ball led to a sense of unpredictability and, in some cases, a position oscillation about the desired hover point owing to the difficulty of precisely controlling the ball about the pad center.

Comments for the rate system indicated that it was notably worse than the others in terms of ball controllability, predictability, aircraft motion, and position oscillation. The compensation was considerable, and the configuration was level 2 (adequate) in all respects.

For the *K* configurations, the undivided attention case ratings were roughly similar to those for *K/s*, but pilot comments described large differences in the character of the ball dynamics. First, for all of the configurations there was some degree of objection to the amount of noise in the ball response caused by biodynamic feedback through the control-input term. Even with the 10-rad/s filter on the ball response, the noise on the velocity system's ball was enough to force pilot A's rating to a 4. (Note that the velocity system had the highest lateral ball-to-stick gain of the three systems.) As an expedient solution, the damping ratio of the variable force-feel center stick was increased from 0.75 to 1.25; pilot A's rating then improved to 2.5. Other comments for the velocity and attitude systems indicated that the ball was easily controllable, desired performance was easily attainable, and compensation was minimal or not a factor.

The rate system *K* configuration elicited inconsistent comments and ratings. Pilot A did not particularly like the configuration, but he could not identify specific deficiencies. Since desired performance was attained, he assigned a rating of 3. For the ratings of 5, both pilots commented that the ball at first appeared controllable, but then tended to overshoot the pilot input. It was difficult to keep the ball on the pad after placing it there initally, and it was difficult to stabilize the aircraft in a precise hover.

The divided attention cases generally evoked similar comments from the pilots for all of the configurations, namely that the requirement to scan and control the heading and altitude axes forced the pilot compensation to at least a moderate level. The degradation was the worst for the rate system *K/s* configuration. For the cases where performance degraded to adequate for divided attention, the violated standard was usually the altitude.

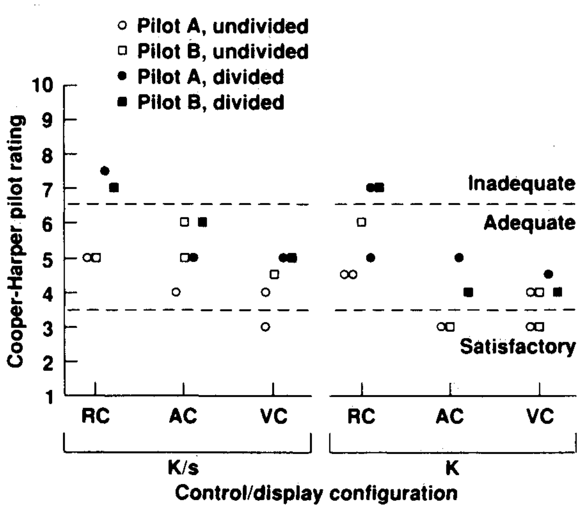

Fig. 8 Pilot rating results, pad tracking task.

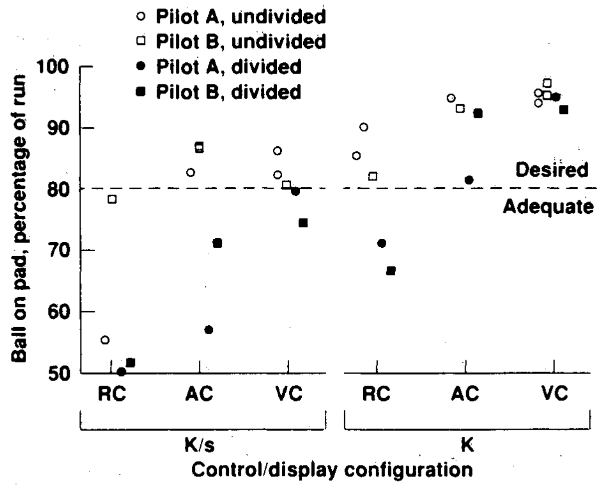

Fig. 9 Inner-loop pad tracking performance, percent of run.

It is interesting that these deficiencies were not as clearly identified for the divided attention cases as for the rate *K* system, which were actually given better ratings than the undivided case. It was felt that the work load for four-axis control in effect masked the ball deficiencies; desired performance was achieved, and the pilots did not feel compelled to give a rating worse than 4.5. In fact, all three response types resulted in essentially equal pilot ratings for the divided attention *K* case, implying that *K* dynamics mask the response details when all four axes require pilot attention.

Comparing the rating results for the *K* and *K/s* cases, it is seen that both the rate and velocity systems are somewhat better accepted with *K* dynamics than with *K/s*, whereas the attitude system is virtually unchanged.

Pad Tracking Task

The pilot rating results for the pad tracking task are shown in Fig. 8. First, the ratings generally improve with increasing levels of augmentation for both the *K* and *K/s* configurations. One exception is the velocity *K* configuration, undivided case. Pilot comments indicate that this configuration was satisfactory in performance and work load, except for the ball noise from the center-stick controller. The noise forced the ratings of 4 on the first evaluations by both pilots. Unfortunately, the increased stick damping solution was not examined for this task.

The second trend noted is that for any one response type, and for both the undivided and divided attention cases, the *K* configuration was preferred over the *K/s* configuration. Pilot comments indicate that, with the *K/s* dynamics, the ball was sluggish and could not be moved quickly enough to keep up with the pad, and so extra compensation was required to judge the velocity of the pad to generate lead for controlling the ball. Also, the amount of aircraft attitude response associated with chasing the pad was, in some cases, uncomfortable. This latter characteristic was particularly true of the rate system, in which peak-to-peak pitch attitude changes of up to 17 deg were seen. Conversely, with *K* dynamics, the ball could be placed easily near the center of the pad without a sense of chasing, and the resulting aircraft excursions were not objectionable.

Pilot comments for the divided attention cases were similar to those for the pad capture, namely that the requirement to scan and control the other axes degraded performance and greatly increased pilot compensation requirements, precluding level 1 (satisfactory) ratings.

Since its objectives are well defined, the tracking task performance can be assessed quantitatively for each 95-s run.

First, as a correlation of configuration and task performance, Fig. 9 shows the measured percentage of the run for which the center of the acceleration ball was within the hover pad, with the boundaries for desired and adequate performance. Within each display set, performance improves with increasing vehicle augmentation. For any one vehicle response type, performance is better for the K than for the K/s display dynamics. The negative impact of divided attention on performance is also clearly evident, but it decreases for both display sets as vehicle augmentation increases. For the velocity K configuration, there is essentially no performance degradation due to divided attention.

Figure 10 presents the root-mean-square (rms) error in the tracking of the hover pad by the ball for all of the pad tracking runs. Once again, a steady improvement is evident as the level of vehicle augmentation increases and for K vs K/s dynamics. As with the pilot ratings and ball-on-pad performance, rms performance for the divided attention cases was generally worse than for the undivided case. The rms aircraft position errors are shown in Fig. 11. Although not under direct control by the pilot, the position data represent the outer-loop guidance resulting from inner-loop tracking for each configuration. The positioning performance did not vary significantly among the configurations. Taken together, Figs. 10 and 11 demonstrate that the K configurations allowed better inner-loop tracking, yet did not penalize outer-loop position performance as might have been expected from using control input to quicken the ball response. Combining these data with the pilot ratings and their comments on reduced work load, it is reasonable to conclude that K dynamics are preferable for this task.

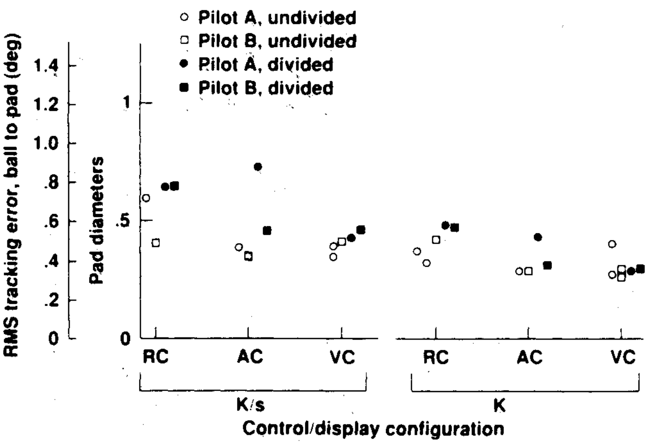

Fig. 10 Root-mean-square inner-loop tracking performance, ball to pad.

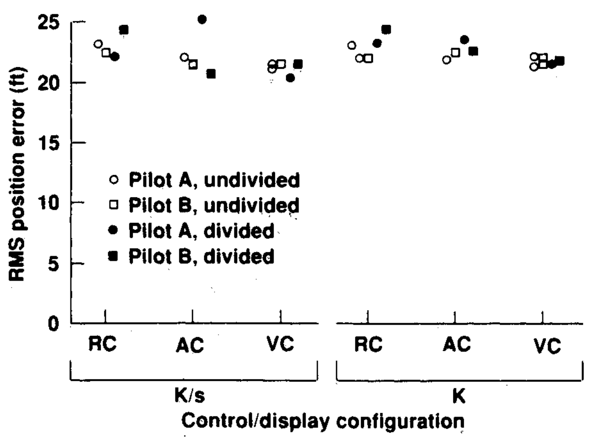

Fig. 11 Root-mean-square outer-loop tracking performance, aircraft to pad.

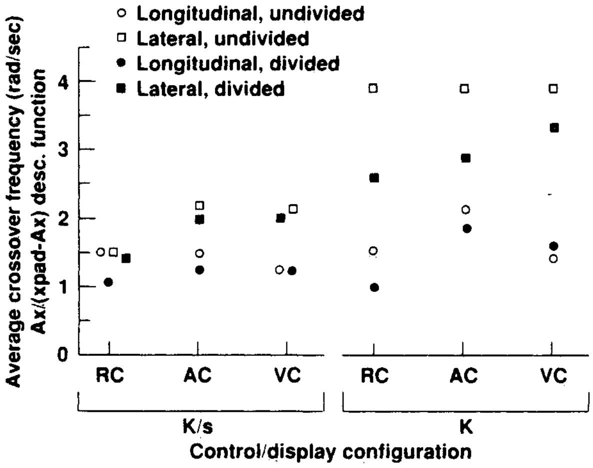

Fig. 12 Identified inner-loop crossover frequencies.

Pilot Identification for Pad Tracking Task

Fourier analysis techniques were used to identify pilot-vehicle-display dynamics for the pad tracking task for each configuration. Referring to Fig. 3, the describing functions of interest are x/x_c and $A_x/(x_{\text{pad}} - A_x)$. An alternative loop structure for this task was proposed in Ref. 18 and included a more explicit pursuit strategy for the pilot. However, the assumption of compensatory behavior here allows an easily measured describing function, $A_x/(x_{\text{pad}} - A_x)$, to provide information about comparative tracking aggressiveness. For this describing function, the crossover frequencies were determined for each configuration; the average longitudinal and lateral crossover frequencies for all runs are shown in Fig. 12. First, it is seen that the crossover frequencies were lower for the longitudinal axis than for the lateral, even though the display, control, and controller configurations were essentially symmetric. It is postulated that this difference was chiefly because of the large distance between the pilot station and the longitudinal center of gravity of the CH-47B (17 vs 1.5 ft laterally). Thus, equal angular rates in pitch and roll would generate considerably more normal than lateral acceleration for the pilot, perhaps inhibiting his willingness to be equally aggressive in pitch.

Considering the lateral axis only, there is a marked increase in crossover frequency for the K configurations vs the K/s configurations for the undivided attention case. For the divided case, the lateral crossover frequency is always less than for the undivided case, but it also increases with increasing augmentation and in going from K/s to K dynamics. These trends are in good agreement with the rms tracking error data shown in Fig. 10. The data also agree with previous work[19] documenting the decrease in crossover frequency for divided- vs undivided-attention tasks. Finally, the data may reflect the larger crossover frequency and increased phase margin available for the K relative to the K/s configurations in the presence of system delay (Fig. 6).

Conclusions

A flight experiment was conducted that examined pilot-vehicle-display performance and work-load differences between gain and integrator-like controlled element dynamics. These differences were examined for three levels of vehicle augmentation.

When gain-like dynamics were used in conjunction with the attitude and velocity response types in undivided attention tasks, level 1 handling qualities were consistently achieved. The level 2 ratings encountered with the velocity response type were always attributed to noise that could be eliminated by increasing the damping ratio of the pilot control stick. Level 1 handling qualities were only occasionally achieved with integrator-like dynamics combined with the same response types in undivided attention tasks. The rate response type did not yield level 1 handling qualities, independent of the controlled element dynamics, though the gain-like dynamics were preferred over the integrator-like dynamics.

Performance data for the pad tracking task confirmed that gain-like dynamics yielded improved inner-loop tracking performance and reduced the effects of dividing attention while not affecting outer-loop positioning performance as might have been expected from using control input to quicken the controlled element response.

Identification of pilot-vehicle-display dynamics, especially for the lateral axis, showed a higher crossover frequency for gain-like than for integrator-like controlled element dynamics and a reduction in inner-loop crossover frequency for divided- vs undivided-attention tasks.

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