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Summary

Using a generalized simulation model, a moving-base simulation of a lift-fan short takeoff/vertical landing fighter aircraft has been conducted on the Vertical Motion Simulator at Ames Research Center. Objectives of the experiment were to determine the influence of system bandwidth and phase delay on flying qualities for translational rate command and vertical velocity command systems. Assessments were made for precision hover control and for landings aboard an LPH type amphibious assault ship in the presence of winds and rough seas. Results obtained define the boundaries between satisfactory and adequate flying qualities for these design features for longitudinal and lateral translational rate command and for vertical velocity command.

Introduction

In the development of design concepts for advanced short takeoff and vertical landing (ASTOVL) configurations for the Joint Advanced Strike Technology (JAST) program, Ames Research Center has participated in the definition and evaluation of integrated flight/propulsion control concepts and design guidelines. Background for this work has come from the flight research program on NASA's V/STOL Systems Research Aircraft (VSRA) described in reference 1 and from a number of experiments on the Vertical Motion Simulator with different ASTOVL designs (refs. 2-5) that have addressed issues of control and display modes for different phases of STOVL operations, control power, thrust margin, transition acceleration, and control system dynamic response requirements. Most recently, a moving-base simulation of a lift-fan configuration was developed and used as another candidate ASTOVL configuration in the design guideline development (ref. 6). Through the course of these experiments, it has been evident that design criteria for the response characteristics for translational rate command and vertical velocity command systems in hover have not been sufficiently developed. Given the potential these systems have shown for significantly reducing pilot workload for precision hover and landing noted in the flying qualities results and pilot assessments presented in

references 1-6, the Joint Strike Fighter industry teams are seeking guidance from NASA for their design.

Two aspects of system design that require definition are the desired system bandwidth and the acceptable phase delay. Translational rate command system dynamic response was addressed in reference 7 but did not consider the thrust vectoring control of translation that characterize the longitudinal axis of ASTOVL aircraft and did not represent the shipboard landing task. Height control dynamics have been partially investigated for transition (ref. 8) but do not present a clear definition of the desired height control response. The influence of phase delay was not addressed in reference 8. The baseline systems evaluated in references 2-6 were considered to be fully satisfactory for precision hover and vertical landing tasks; however, a range of response characteristics was not explored rigorously to determine their effect for hover flying qualities. Thus the objective of this experiment was to examine sufficiently large variations in longitudinal, lateral, and vertical velocity response bandwidth and phase delay to permit the delineation between satisfactory and adequate (Level 1 and Level 2) flying qualities for precision hover control and vertical landing. These variations were not pursued to the point of identifying inadequate flying qualities since the unaugmented response in these axes to pitch and roll commands generated through attitude stabilized response types and to engine thrust for height control are generally accepted to provide adequate flying qualities for these tasks. As such, these more austere modes would form the basis for mode reversion in the event of failure of the more advanced modes.

The balance of this report provides a description of the aircraft and of the simulation experiment, followed by a discussion of results.

Nomenclature

h	altitude, ft
K_{RLN}	roll control power gain, lb/deg
P_B	body axis roll rate, rad/sec

\bar{q}	dynamic pressure, lb/ft ²
T_{cmd}	thrust command, lb
V	airspeed, knots
V_x	longitudinal inertial velocity, ft/sec
V_y	lateral inertial velocity, ft/sec
x	longitudinal position, ft
z	vertical position, ft
θ_N	resultant thrust deflection angle, deg
τ_p	phase delay, sec
ϕ	bank angle, deg
$\phi_{2\omega_{180}}$	Bode phase at the frequency $2 \times \omega_{180}$, deg
ω_{180}	frequency for Bode phase angle of -180 deg, rad/sec
ASTOVL	advanced short takeoff and vertical landing
CGI	computer generated image
HQR	handling qualities ratings
V/STOL	vertical or short takeoff and landing
VSRA	V/STOL Systems Research Aircraft

Description of the Lift-Fan ASTOVL Aircraft

The lift-fan ASTOVL aircraft is a single-place, single-engine fighter/attack aircraft (fig. 1) featuring a wing-canard arrangement with twin vertical tails and a lift-fan plus lift-cruise propulsion system. The aircraft and propulsion system has been described previously in references 9 and 10. For this simulation, the cruise engine dynamic characteristics were represented by a natural frequency $\omega_{core} = 10$ rad/sec and damping ratio $\zeta = 0.6$. Lift-fan dynamics were defined by a natural frequency $\omega_{LF} = 10$ rad/sec and a guide vane authority of 20 percent of maximum lift-fan thrust.

The basic flight control system consists of the canard, ailerons and twin rudders for aerodynamic effectors during forward flight. For powered-lift operation, control is provided by differential thrust transfer between the lift fan and lift nozzles, deflection of lift-fan and lift-nozzle thrust, and deflection of cruise nozzle thrust. Pitch control is achieved by a combination of canard deflection, thrust transfer between the lift fan and lift nozzles, and deflection of the cruise nozzle. Roll control is produced by the ailerons and differential thrust transfer between the lift nozzles. Yaw control is derived from the combination of rudder deflection, differential lift-nozzle deflection, and

lateral lift-fan thrust deflection. As an option, reaction control, powered by engine compressor bleed air, can provide additional control moments through nozzles located in the wing extremities and in the tail. Longitudinal acceleration is achieved through thrust transfer between the lift fan, lift nozzles and cruise nozzle and by deflection of the lift-fan and lift-nozzle thrust. The flight control system is described in reference 9.

A variety of control command modes are available depending on the phase of flight and the pilot's task (ref. 9). This experiment focused on the translational rate command and vertical velocity command modes that operate exclusively in the low-speed powered lift and hover flight regime. Propulsion system control in this mode consists of vertical velocity command through total thrust control and longitudinal velocity command through deflection of lift-fan and lift-nozzle thrust. Lateral velocity command is realized through roll control.

Simulation Experiment

Simulator Facility

This experiment was conducted on the Vertical Motion Simulator (fig. 2) at Ames Research Center. The simulator provides six degree-of-freedom motion that permits particularly large excursions in the vertical and longitudinal or lateral axes. Bandwidths of acceleration in all axes, including pitch, roll, and yaw, encompass the bandwidths of motion sensing that are expected to be of primary importance to the pilot in vertical flight tasks. The simulator cockpit orientation was chosen based on the task in this experiment to exploit the motion system authority. For longitudinal and vertical velocity command evaluations, the cockpit fore-and-aft axis was oriented along the motion system's translational beam; for lateral velocity command evaluations, this axis was oriented across the beam, the configuration that appears in figure 2. Appendix A lists the simulator motion system performance as well as the motion washout filter characteristics adopted for this experiment for each of the cockpit arrangements.

An interior view of the cockpit is shown in figure 3. A three-window, computer-generated imaging (CGI) system provided the external view. The CGI could present an airfield scene or a ship scene, the latter modeling an LPH type amphibious assault ship. A center stick and rudder pedal arrangement is seen in the figure, along with a left-hand throttle quadrant of the kind used in the Harrier. This quadrant contained both the power lever (throttle) and thrust vector deflection handle (nozzle lever). Overall frame time for output of the CGI in response to the pilot's control inputs was 0.065 sec. of which 0.02 sec was the host computer frame time.

Evaluation Tasks and Procedures

The pilot's operational tasks for evaluation during the simulation were (1) independent precision hover-position maneuvers in the longitudinal, lateral, and vertical axes carried out either at the airfield or aboard the LPH, and (2) translation from a hover station-keeping point adjacent to the LPH to hover over the deck followed by a vertical landing. Both tasks were accomplished in visual meteorological conditions using only external visual cues. A head-up display was not employed in this task since its dynamics would mask the effects of control bandwidth on position control; furthermore, the control system must be designed to achieve satisfactory performance in visual flight. Positioning maneuvers were carried out either at a taxiway site for the longitudinal assessment or aboard the LPH for lateral and vertical evaluations. Horizontal and vertical surfaces on buildings adjacent to the taxiway or on the ship's superstructure provided visual cueing for precise positioning. The task consisted of capturing and maintaining predefined positions starting from an offset. For the longitudinal positioning task, a reference point was established by two vertical edges that comprised the exterior and interior corners of a wing of the building that projected toward the taxiway 280 ft distant. These edges were offset from each other by 210 ft. Lateral positioning on the ship deck was accomplished with reference to the deck centerline. Vertical positioning cues were derived from a platform located on the ship's superstructure at 41 ft eyeheight above the deck and 44 ft to the right of deck centerline. Desired performance consisted of acquiring and maintaining position within 5 ft of the reference point. The shipboard landing was accomplished on Spot 5 1/2 on the aft deck of the LPH starting from a hover at a station-keeping point 100 ft aft and 100 ft to port from the landing spot. Desired landing performance was defined as touchdown within a 5 ft radius of the reference hover point over the deck with a sink rate of 3–5 ft/sec. Adequate performance was considered to be touchdown within 25 ft from the reference hover point at sink rates less than 12 ft/sec and with minimal lateral drift. For shipboard landings, sea state 3 was represented including a wind over deck of 20 knots aligned with the deck centerline. Taxiway positioning tasks were performed in calm winds.

Three pilots with V/STOL and powered-lift aircraft experience acted as evaluation pilots in this experiment. Handling qualities ratings and commentary were obtained, based on the Cooper-Harper rating scale (ref. 11).

Experiment Configurations

The experiment matrix consisted of variations in control system bandwidth and phase delay for the longitudinal,

lateral, and vertical velocity command systems. Block diagrams of each of these systems are presented in figures 4–6. Baseline system control gains are listed in table 1. System bandwidth is defined by the frequency for which the longitudinal, lateral, and vertical position response to the respective controller input achieves a phase margin of 45 deg. This bandwidth corresponds to the frequency for 45 deg phase lag for translational velocity response to the pilot's control command, as noted on the example in figure 7. Examples of longitudinal, lateral, and vertical velocity frequency responses for their respective baseline configurations, obtained from frequency sweeps for each axis, are shown in figures 8–10. These data were obtained using the frequency analysis program of reference 12. The composite runs shown in the figures were composed of the three individual data windows of 20, 40, and 50 sec out of a run of 180 sec duration. Bandwidth variations for the longitudinal, lateral, and vertical systems were achieved through changes in gains K_u , K_{ϕ_2} , and K_w , respectively.

Phase delay, as used in flying qualities specifications (e.g., refs. 8 and 13), is defined from the Bode plot of position response to control command by the following relationship:

$$\tau_p = -\frac{\phi_{2\omega_{180}} + 180}{57.3 \times 2\omega_{180}}$$

It is the slope of the phase curve with frequency at the bandwidth for a phase angle of -180 deg. Phase delay variations were achieved through transport delays inserted in the pilot's controller input path, as shown in figures 4–6, that added to the inherent delays in the control system and simulation system. The added delay would represent physical contributions of the aircraft to delay such as would arise from sensor, filter, and servo lags, propulsion system component thrust lags, digital computation frame time, and analog-digital or digital-analog conversion. The baseline configuration delay in this simulation consisted of high-order effects of the airframe and propulsion system dynamics, such as actuators and engine thrust transient response, and of the simulation computer frame time, input/output delays, and visual system delays. The total delays for each axis of the baseline configuration were identified from frequency sweeps for each respective axis to be 0.18 sec for longitudinal, 0.56 sec for lateral, and 0.34 sec for vertical, of which 0.065 sec was associated with visual system and computer frame time delays. The appreciably larger delay for the lateral axis is attributed to the dynamics of the bank angle control inner loop and the contribution to delay that it produces at lateral velocity control frequencies. The vertical delay comes, in part, from the dynamics of total thrust control in the propulsion system.

Results

Effects of System Bandwidth

Longitudinal velocity control— Effects of longitudinal control bandwidth on the pilot's evaluations of precision longitudinal position control are shown in figure 11. Consistently satisfactory flying qualities were obtained for bandwidths between 0.4 and 0.9 rad/sec, whereas below 0.22 or above 1.1 rad/sec flying qualities were considered only adequate. The boundary between satisfactory (Level 1) and adequate (Level 2) flying qualities falls at 0.3 and at 1.0 rad/sec based on the trends of the data in the figure. Although no inadequate (Level 3) ratings were obtained for the configurations explored, from the data shown, bandwidth would likely have to fall below 0.1 rad/sec before Level 3 would be reached. Results obtained recently from the flight experiments on the VSRA Harrier (ref. 1) for this task showed a similar demarcation between Level 1 and Level 2 at the lower bandwidths. Pilot commentary indicates that precise position control can be easily achieved for bandwidths in excess of 0.4 rad/sec. At the higher bandwidths shown, abrupt or jerky response becomes objectionable and eventually demands compensation by the pilot to effectively filter control inputs. For bandwidths of 0.22 rad/sec and below, lags in response are evident, and fine tracking becomes difficult. Response seemed more like acceleration than velocity command, and lead compensation is required to perform the task. Desired precision of longitudinal position control was achieved in all instances. In fact, given the accuracy with which the pilots could establish their position from visual alignment of the vertical edges, it was possible to achieve position capture and holding tolerances on the order of 1–2 ft with the better system dynamics compared to the stated desire of 5 ft. This level of precision was obtained as a result of the pilots intentionally tightening their control of position in order to expose deficiencies in system response, such as tendencies for pilot-induced oscillations.

Shipboard landing results for longitudinal control system variations are shown in figure 12. In contrast to the previous case (where nearly full concentration was placed on the longitudinal axis), these data do not show a clear trend of ratings with variations in bandwidth or demarcation between Level 1/2 characteristics. Instead, the allocation of only adequate ratings and associated commentary reflect the difficulty with the more demanding multi-axis, split-attention task of recovery to the ship in weather. The lack of variation with bandwidth reflects an insensitivity to this of the accuracy requirement of ± 5 ft for hover positioning.

The only formal flying qualities specifications for translational rate command systems are those contained in reference 13 for rotary-wing aircraft. The current specification and user's guide for fixed-wing V/STOL aircraft (ref. 14) offer no guidance in this regard. The rotary-wing specification is stated in the form of an equivalent rise time of a qualitative first-order type response and defines Level 1/2 boundaries for rise times greater than 2.5 sec and less than 5 sec. Bandwidths of 0.4 and 0.2 rad/sec can be inferred for these rise times if the response is nearly first order. The lower bandwidth contrasts with 0.3 rad/sec determined from this experiment; the upper bandwidth contrasts with 1 rad/sec as noted above. Alternatively, data for this simulation are replotted in terms of rise time in figure 13 and indicate that the Level 1/2 boundary would allow rise times no greater than 3.5 sec. The conflict between these two criteria likely arises from the differences in implementation of the longitudinal velocity command systems in this simulation versus the experiment on which the reference 13 data are based. In the latter case (ref. 8), longitudinal translation was achieved through commands for pitch attitude adjustments, and the pilots were reported to be reticent to accept what they considered to be aggressive changes in pitch attitude. This would, in turn, influence the assessment of different rise times for the longitudinal velocity response. Further, in that simulation experiment, the external visual scene was much lower in fidelity than that used in the current experiment and would not have allowed the pilot to judge position as precisely. The data from X-22 flight experiments (ref. 7), though not obtained from shipboard operation, produce an upper boundary on rise time of 2.2 sec which is more in accord with those ratings obtained in the current experiment.

Lateral velocity control— Results of the pilots' assessments of lateral position control bandwidth are indicated in figure 14. Satisfactory flying qualities were achieved over the range of bandwidths from 0.4 to 0.66 rad/sec. On the low side, only adequate ratings were obtained for bandwidths of 0.35 rad/sec and below; one adequate rating was given at higher bandwidths, that being at 0.66 rad/sec. It appears that a Level 1/2 boundary would be justified for a lower frequency around 0.37 rad/sec and for an upper frequency at 0.7 rad/sec, although the latter has marginal justification in the data. VSRA results generally support the lower boundary although they indicate a somewhat lower bandwidth of 0.25 rad/sec could be accepted. Comments from the pilots show similarity to those for longitudinal control, in that precise position control was easy to achieve for bandwidths above 0.4 rad/sec. Abrupt response was criticized for bandwidths of 0.55 rad/sec and above and rapid initial roll

was noted at the highest bandwidth. For bandwidths below 0.35 rad/sec, the pilots noticed lag in the response and a tendency to chase the hover point. Moderate to considerable amounts of lead were required to stop the translation at the intended position. Desired precision was obtained in all cases. As in the case of longitudinal control, alignment with the deck centerline could be achieved with accuracies around 2 ft in comparison with the desired objective of 5 ft, reflecting the pilots pressing for a higher level of performance to expose poor response characteristics.

Results for the shipboard landing are shown in figure 15. As in the longitudinal case, the ratings for the two pilots who evaluated this case do not show the clear trend that was evident for the lateral control case alone (fig. 14). One pilot did identify a clear preference for bandwidths in excess of 0.4 rad/sec for the landing task, which was comparable to that for the basic lateral positioning task discussed above. Comments indicated that lead compensation was required when correcting to the centerline for the low bandwidth case. This suggests that the two tasks are comparable in the cues to execute them and the demands they place on the pilot.

Flying qualities specifications from reference 13 for the lateral axis are the same as those for longitudinal axis. Thus the specification for the lower boundary on bandwidth of 0.2 rad/sec is also less demanding than that from this experiment (0.37 rad/sec). Considering the current results in terms of rise time (fig. 16) shows a clear Level 1/2 boundary around 2.7 sec in contrast to the 5 sec requirement in reference 13. It is clear from the commentary in this experiment that the pilots did not have the aversion to bank angle changes to achieve the lateral translation that was expressed by the subjects of the earlier test. Consequently, quicker response and more aggressive lateral maneuvers were acceptable to the pilots to achieve the desired tracking performance. Again, these results are more in accord with the flight data of reference 7.

Vertical velocity control—Evaluations of height control bandwidth are presented in figure 17. Satisfactory flying qualities were only achieved for a bandwidth of 0.93 rad/sec. All ratings at lower bandwidths were considered only adequate and one rating at a bandwidth of 0.14 rad/sec was inadequate. This simulation data suggest a Level 1/2 boundary of 0.93 rad/sec in contrast to results from the earlier flight experiments which seemed to be somewhat less demanding of system response. In those VSRA experiments, a bandwidth of 0.6 rad/sec was considered to be satisfactory. Pilots' comments reflected the need to provide leading throttle inputs to control vertical speed to achieve a precise altitude capture for all

but the highest bandwidth configuration. For the lower bandwidth cases, lag in vertical speed response was apparent and for the lowest bandwidth case tendencies to chase the hover height were present, especially for aggressive maneuvers. Desired precision was achieved in all instances, with the pilot's being able to track to 2 ft accuracies in most cases. In general, one of the more attention demanding aspects of the altitude hold task was the ability to achieve precisely zero rate of climb since the throttle did not have a reference detent for a null command. This characteristic was a factor in the adequate ratings given by some of the pilots for the higher bandwidth configurations. This was not the case for the VSRA experiment since the inceptor for vertical velocity control, a thumbwheel on the throttle handle, incorporated a detent as a null for vertical velocity command.

Shipboard landing results, shown in figure 18, are somewhat less demanding than for the height control task alone. A Level 1/2 boundary is reasonably drawn around 0.6 rad/sec compared to the 0.93 rad/sec noted above. For the shipboard landing, the 5 ft height precision was readily achieved when establishing the hover over the deck. The vertical control aspect of the landing task concentrated more on establishing and maintaining a reasonable sink rate during the descent to touchdown. This was easy to accomplish at the higher bandwidths but elicited familiar criticism of lags and imprecise response for the low bandwidths.

Reference 13 specifications are based on bob up and down maneuvers by helicopters. The Level 1/2 boundary is based on a first-order time constant of 5 sec, which equates to an altitude control bandwidth of 0.2 rad/sec. Both the bandwidth data of figure 17 and the rise time data of figure 19 show that the pilots in this experiment were more demanding of vertical axis response than is called for in the specification. Rationale is evident in their comments which note a demand for precision in vertical positioning and intolerance for lags in response that could produce oscillatory tracking. Considering the VSRA flight results along with the shipboard landing data from this experiment, a Level 1/2 boundary of 0.6 rad/sec is warranted for operational tasks.

Effects of Phase Delay

Longitudinal velocity control—Results for the evaluation of longitudinal phase delays for the precision longitudinal control task are shown in figure 20. Delays were increased to as high as 0.78 sec before flying qualities degraded to adequate. Pilot comments indicated that they were aware of the delay beginning at the intermediate values and consciously compensated for it, but that the amount of compensation was not significant except for the more

extreme delay. At 0.78 sec delay, pulse-type control applications were required and the system was clearly susceptible to pilot-induced oscillations. Based on these data, a Level 1/2 boundary at 0.6 sec would be warranted in order to obtain precision control without any concern for inducing any oscillatory control tendencies.

At first glance, the data shown in figure 21 for shipboard landing on the LPH appear to impose a more stringent limit on phase delay than indicated for the longitudinal velocity control task alone. Phase delays of 0.47 sec or greater were considered to yield only adequate flying qualities for this task, and the data trend would suggest a Level 1/2 boundary around 0.4 sec. However, given the difficulty of the task, borderline Level 1/2 ratings are likely warranted, regardless of the velocity command system delay. Of more interest is the amount of delay at which the ratings become appreciably worse and where pilot commentary directly or subtly reflects the influence of added delay. This further degradation clearly occurs for delays of 0.6 sec and greater. Thus, the effects for the shipboard task would appear to be similar to those for the precision control task noted above. The specification in reference 13 has no recommendation for a phase delay requirement. The fact that the amount of delay that can be accepted for position control exceeds considerably that which would be acceptable for attitude control can be attributed to the lower gain at which the positioning task is performed and to a lower sensitivity to variation in phase margin for the task.

Lateral velocity control— Evaluations of lateral phase delays show a disparity between the assessments of the data from two pilots (fig. 22). While one pilot's ratings fall into the adequate range for delays of 0.7 sec and greater, the other pilot could accept delays as large as 0.96 sec as satisfactory. Thus the Level 1/2 boundary could range from 0.68 sec to 1.06 sec for this collection of data. Delays less than 0.66 sec were not apparent to either of the pilots. Greater delays began to be evident to the more critical pilot in the form of a tendency to chase or oscillate about the centerline in an attempt to capture that position. That tendency became pronounced at a delay of 0.86 sec and led to the HQR 6 point. This tendency was not exposed to the other pilot until delays of 1.06 sec were reached. Based on these comments, a conservative choice for the Level 1/2 boundary would be 0.7 sec, which would keep it comparable to that for the longitudinal axis.

The shipboard landing results (fig. 23) show a clear trend only for one pilot; for the other pilot, the difficulty of this task dominated the ratings regardless of the delay. Taking the trend of the one pilot's ratings, control begins to deteriorate for delays of 0.86 sec and greater. The effect of delay on this pilot's ability to perform the task is more

pronounced for the shipboard task compared to the lateral precision control task alone and is reflected in a difficulty to align with the centerline during descent to the deck. It would be prudent to retain 0.7 sec as defining the Level 1/2 boundary, similar to the conservative approach noted in the previous paragraph.

Vertical velocity control— As illustrated by the data of figure 24, the pilots were least tolerant of delays in the vertical axis. Flying qualities for precision height control were only adequate for delays of 0.4 sec and greater. Comments from the pilots exposed a difficulty in nulling the vertical speed to capture and hold the desired height for delays in excess of 0.35 sec. In some cases, several throttle control reversals were needed to capture the desired altitude. For the larger delays, pilot-induced oscillations were encountered frequently. Based on these results, a Level 1/2 boundary at 0.3 sec is justified.

The shipboard landing data shown in figure 25 reflect the difficulty of the task and show a subtle influence of degrading flying qualities for phase delays around 0.4 to 0.5 sec. A more pronounced degradation is evident for large delays exceeding 0.9 sec. Pilot comments began to reflect the effects of the delay in terms of oscillatory control for delays of 0.5 sec. All pilots were aware of degraded control when delays of 0.94 sec were reached. Over the intervening range, one pilot was more sensitive to the presence of delays than the other. To assure Level 1 flying qualities, it would be prudent to allow delays no greater than 0.4 sec.

Conclusions

Using a generalized simulation model, a moving-base simulation of a lift-fan short takeoff/vertical landing fighter aircraft has been conducted on the Vertical Motion Simulator at Ames Research Center. Objectives of the experiment were to determine the influence on flying qualities for translational rate command and vertical velocity command systems of system bandwidth and phase delay. Assessments were made for precision hover control and for landings aboard an LPH type amphibious assault ship in the presence of winds and rough seas.

Data indicate that the boundaries for Level 1/2 flying qualities call for system bandwidths for translational rate command of at least 0.3 rad/sec for precision longitudinal control, 0.37 rad/sec for lateral control, and 0.93 rad/sec for height control. Recent flight data from the VSRA Harrier at Ames support the longitudinal and lateral boundaries but indicate that a lower bandwidth of 0.6 rad/sec could be accepted for the vertical axis. In addition, Level 1/2 boundaries are also indicated for

bandwidths exceeding 1 rad/sec for longitudinal and 0.7 sec for lateral control.

Results of the simulation also show that Level 1/2 boundaries on phase delay fall at 0.6 sec for longitudinal control, 0.7 sec for lateral control, and 0.3 sec for vertical control.

Appendix A

Vertical Motion Simulator Motion Characteristics

The Vertical Motion Simulator used in this experiment is capable of producing large translational and rotational motion cues over frequency ranges that encompass the bandwidths of control of the tasks associated with transition and vertical flight. Longitudinal, lateral, and

vertical motion limits were ± 20 ft, ± 4 ft, and ± 30 ft, respectively, with the cockpit oriented for the longitudinal and vertical task. Values for the longitudinal and lateral limits are interchanged for the cockpit orientation used for the lateral task. Motion system bandwidth (frequency for 45 deg phase lag) is 8 rad/sec for the vertical axis. The rotational limits in pitch, roll, and yaw are 18, 18, and 24 deg. Bandwidths are 10 rad/sec for pitch and roll and 6 rad/sec for yaw. Motion drive logic for each axis commands accelerations through second order high pass (washout) filters that are characterized by their gain, natural frequency, and damping ratio. In all cases, damping ratios of 0.7 were used. Filter gains and natural frequencies are presented in table A1 for cockpit orientations associated with the longitudinal/vertical tasks and with the lateral tasks.

Table A1. Motion system gains and natural frequencies

Motion axis	Longitudinal/vertical case		Lateral case	
	Gain	Frequency rad/sec	Gain	Frequency rad/sec
Pitch	0.5	0.7	0.5	0.7
Roll	0.3	0.2	0.7	0.3
Yaw	0.5	0.2	0.5	0.2
Longitudinal	0.7	0.7	0.3	1.2
Lateral	0.5	1.2	1.0	0.3
Vertical	0.8	0.2	0.8	0.2

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Table 1. Translational rate command control gains

Longitudinal velocity	Roll
Control limits = ± 2.25 in.	Control limits = ± 4.2 in.
Force gradient = 1.0 lb/in.	Force gradient = 0.7 lb/in.
Breakout = 0.225 in.	Breakout = 0.05 in.
$K_2 \dot{U} = 0.1$	$K_1 = 1.2$ rad/in.
$K_{V1} = 20.0$ sec ⁻¹	$K_{333} = 1.6$ rad/sec/in.
$K_V = 14.0$ ft/sec ² /in.	$K_\phi = 9.0$ rad/rad
$K_U = 0.69$ sec ⁻¹	$K_{\dot{\phi}} = 6.0$ sec
$K_{3U} = 1.0$	$K_3 = 15.0(100/KRLN)/(1 + 0.029 \bar{q})$ deg/rad
$\tau_U = 0.35$ sec	$\tau_8 = 0.05$ sec
Vertical velocity	Lateral velocity
$K_\gamma = 0.00545$ rad/deg	$K_6 = 10.0$ ft/sec/deg
$K_w = 0.71$ sec ⁻¹	PR = 5.25
$K_{3W} = 0.14$	$K_{\phi_2} = 0.58$ rad/ft/sec
$K_h = 0.0$	$K_9 = 0.285$ rad/rad
$\tau_{CNT} = 0.1$ sec	

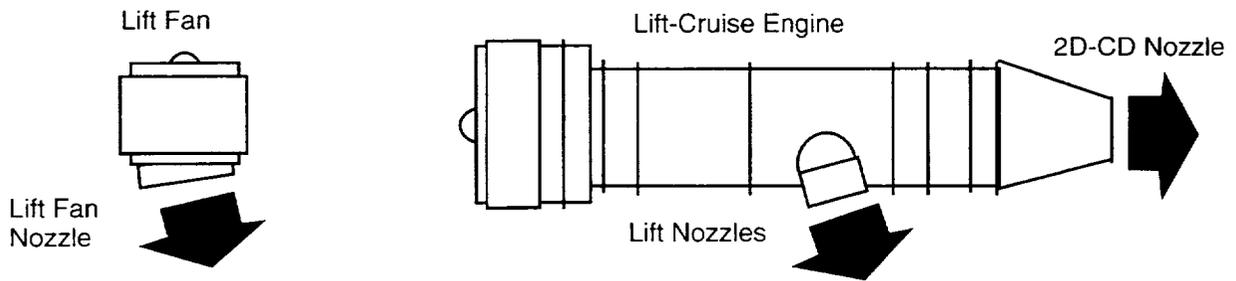
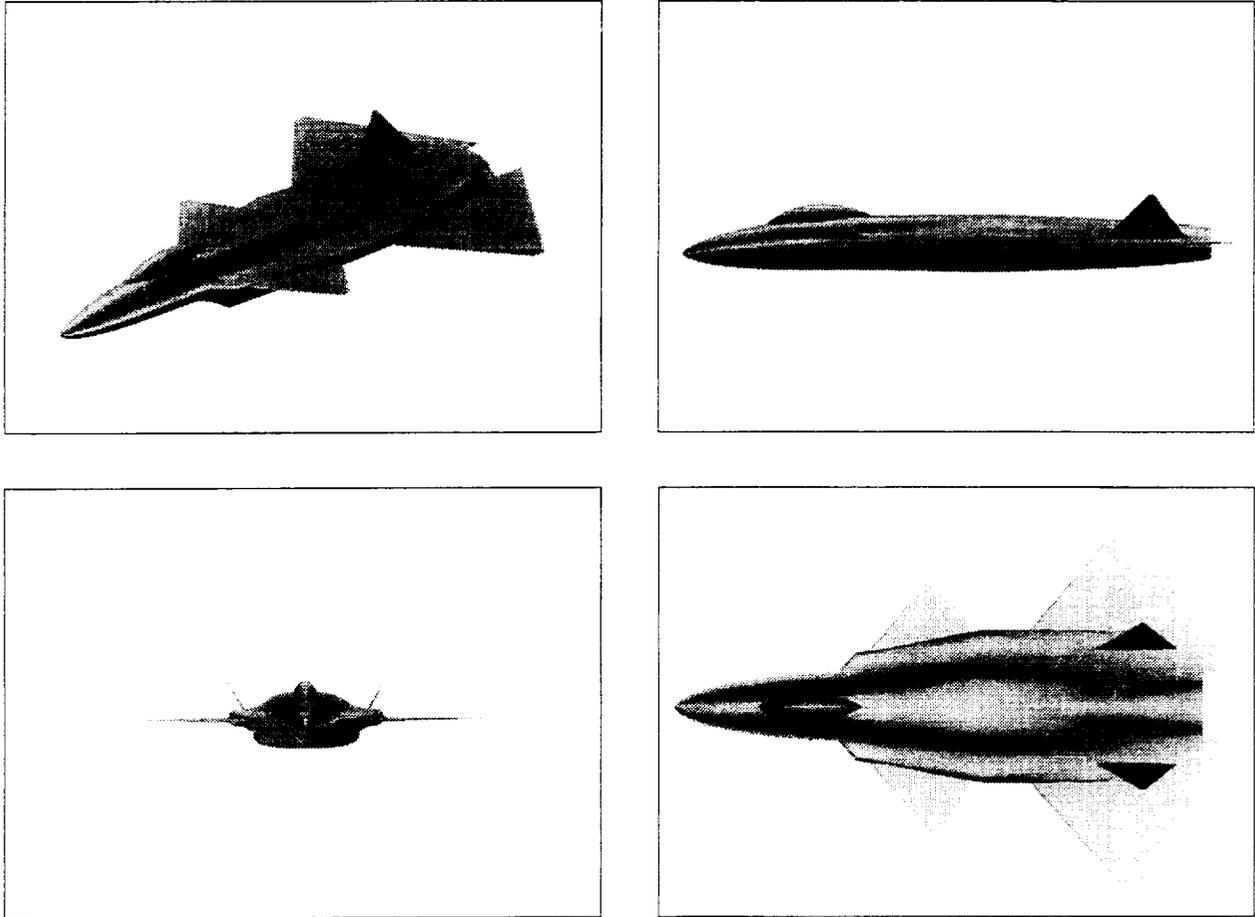


Figure 1. ASTOVL lift-fan aircraft and propulsion system.

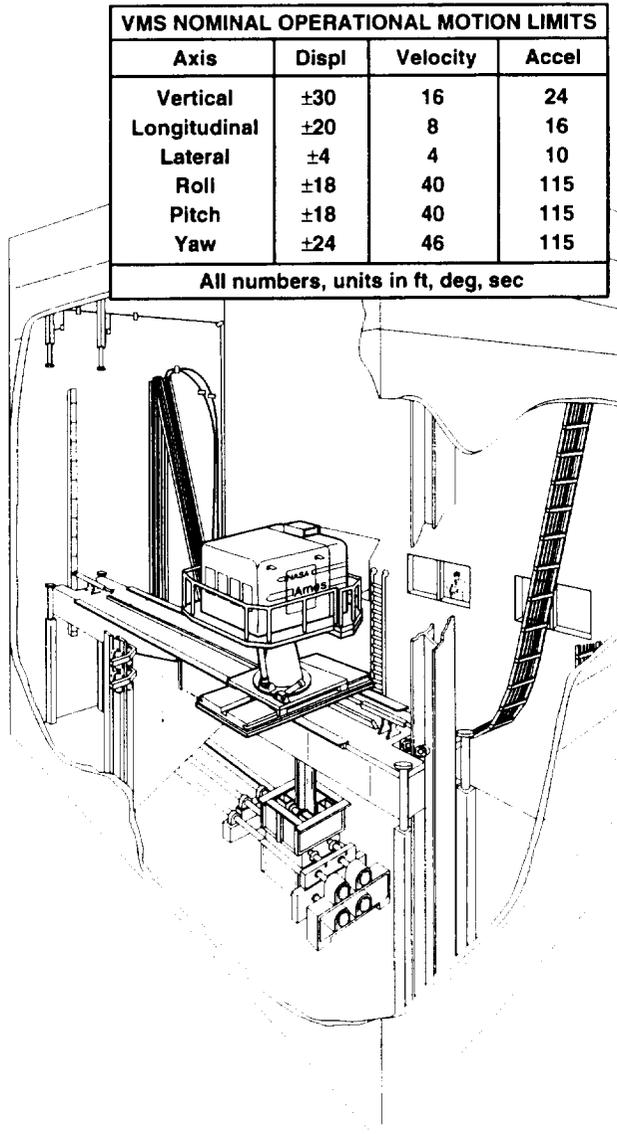


Figure 2. Vertical Motion Simulator.

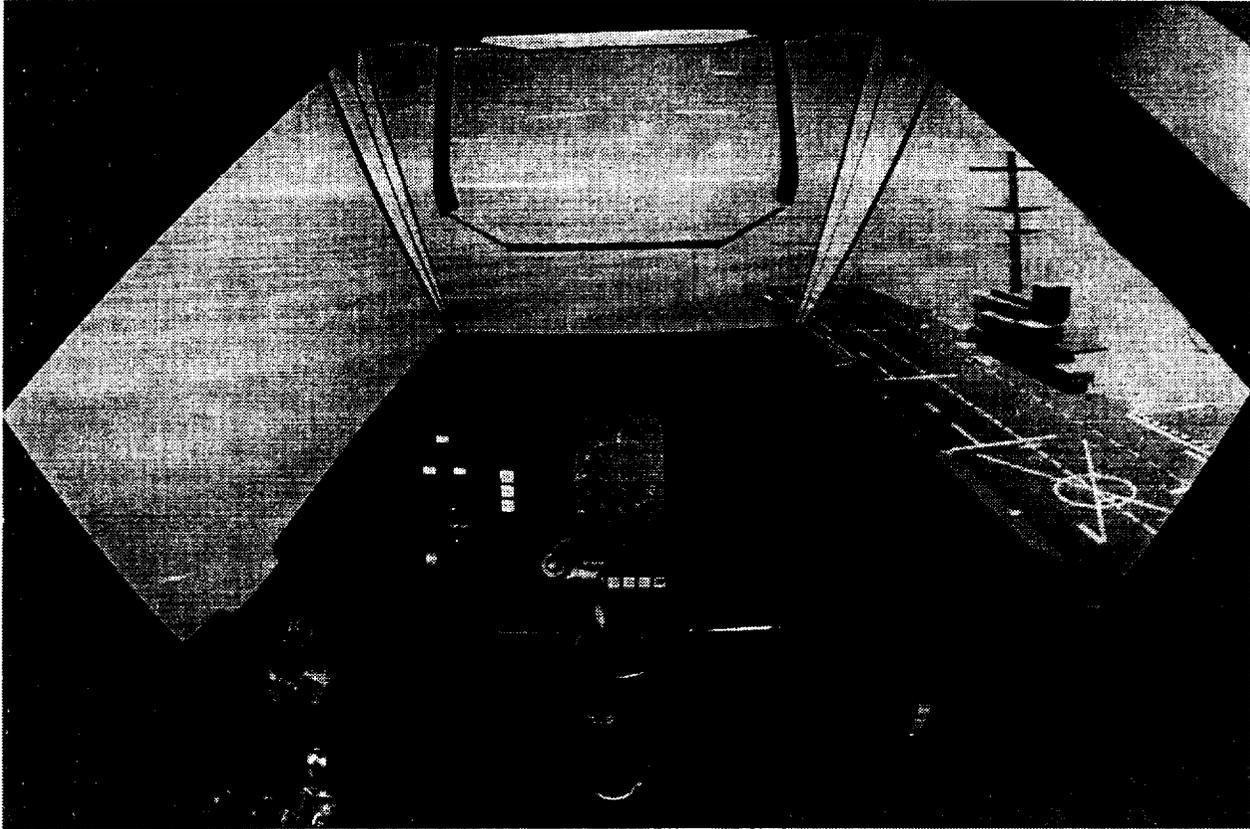


Figure 3. Simulator cockpit interior view.

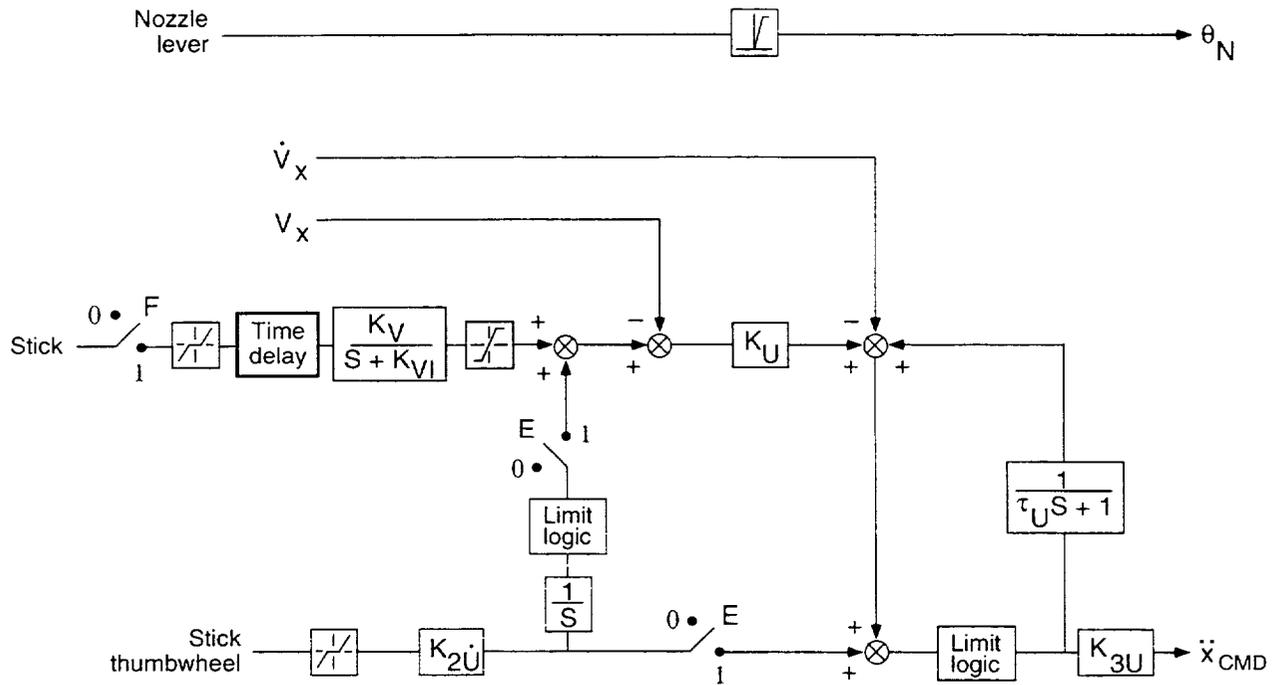


Figure 4. Longitudinal velocity stabilization and command augmentation system.

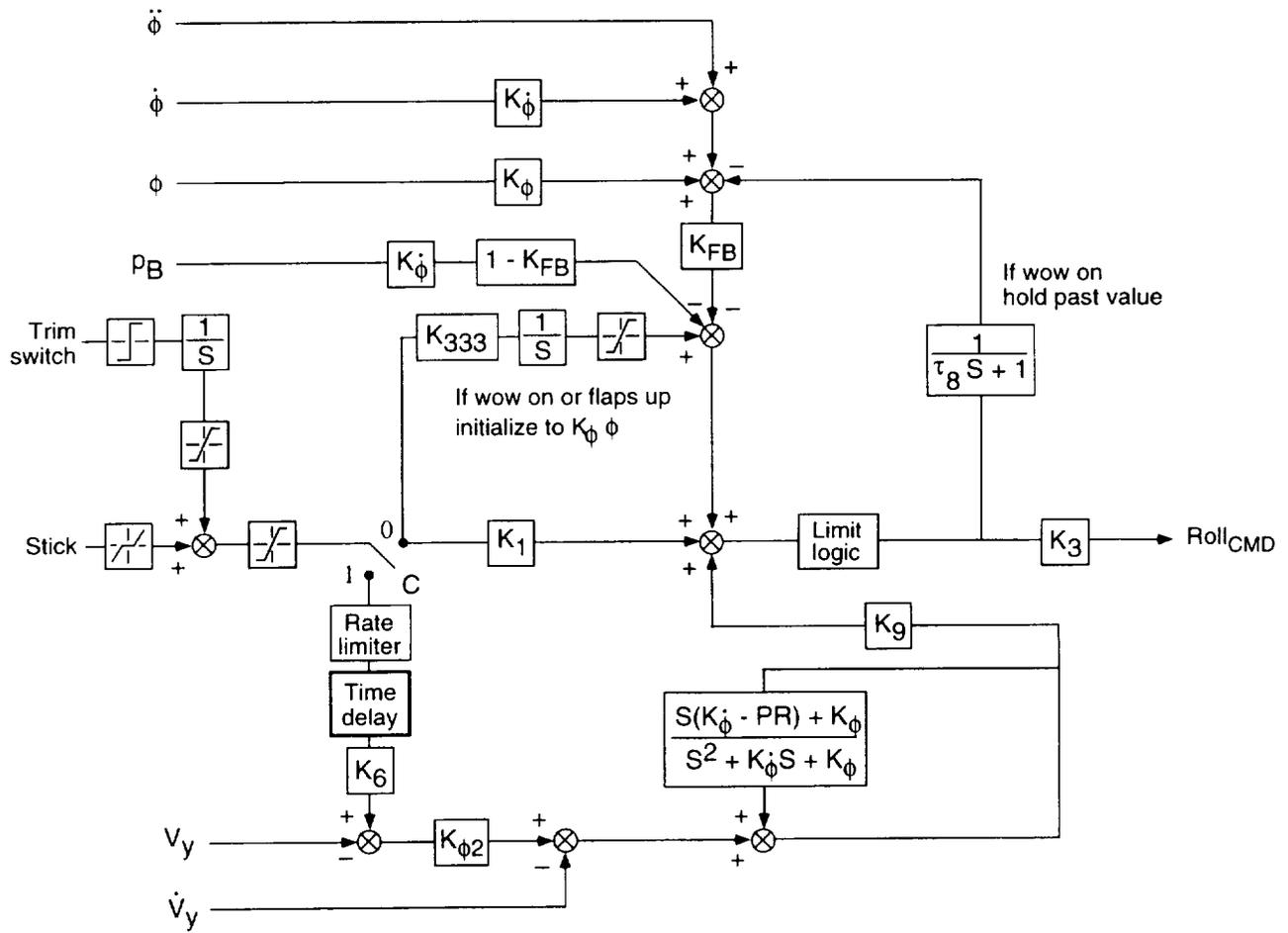


Figure 5. Roll stabilization and command augmentation system.

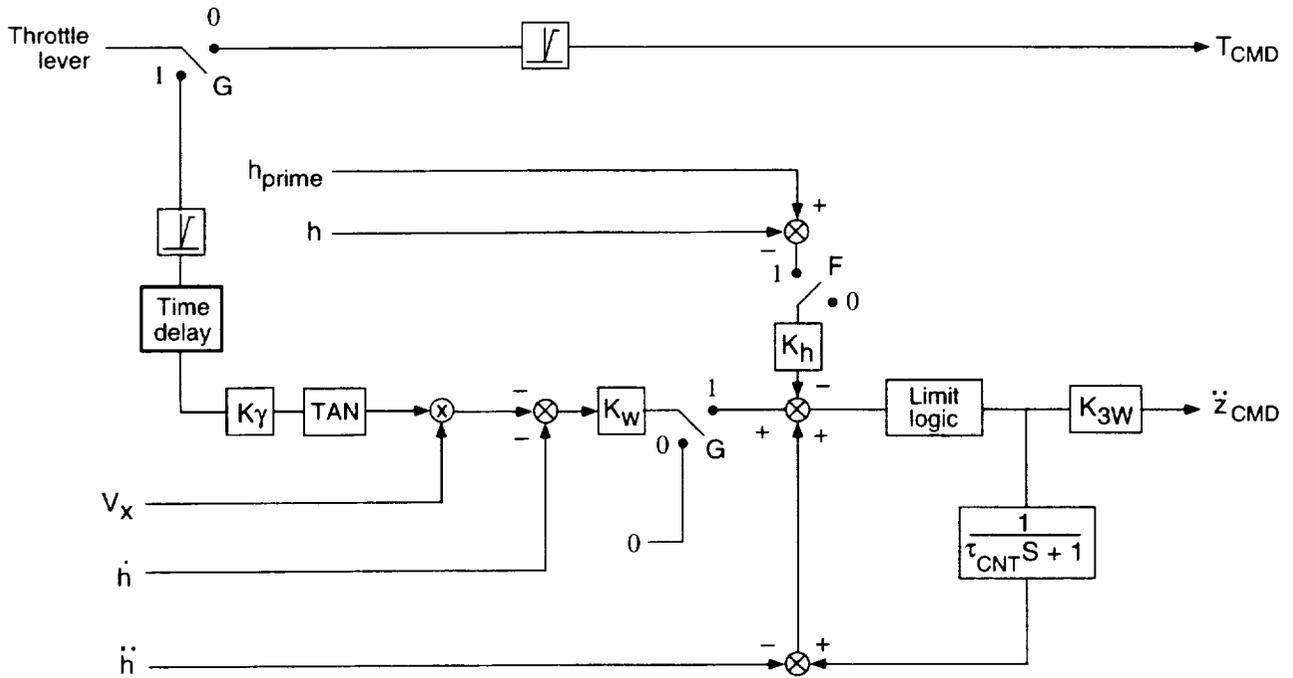


Figure 6. Vertical velocity stabilization and command augmentation system.

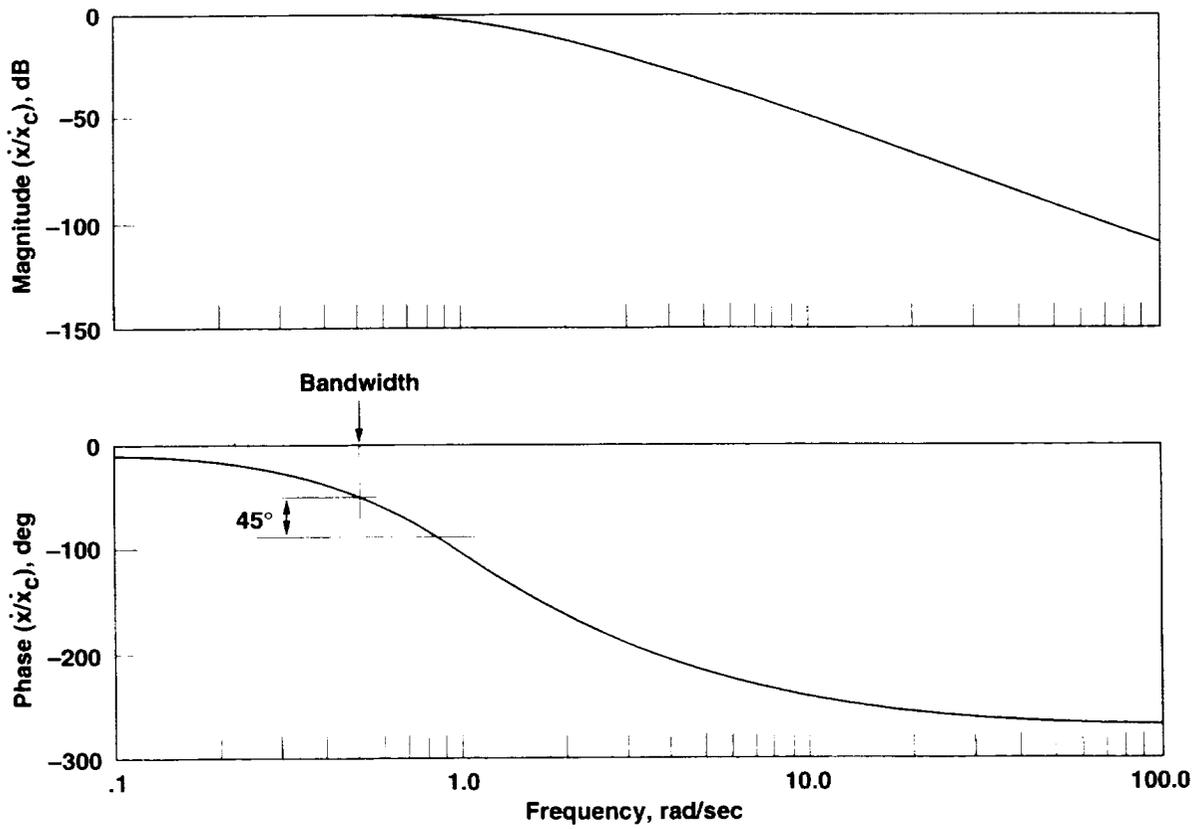


Figure 7. Definition of bandwidth for position control from closed-loop frequency response of translational rate.

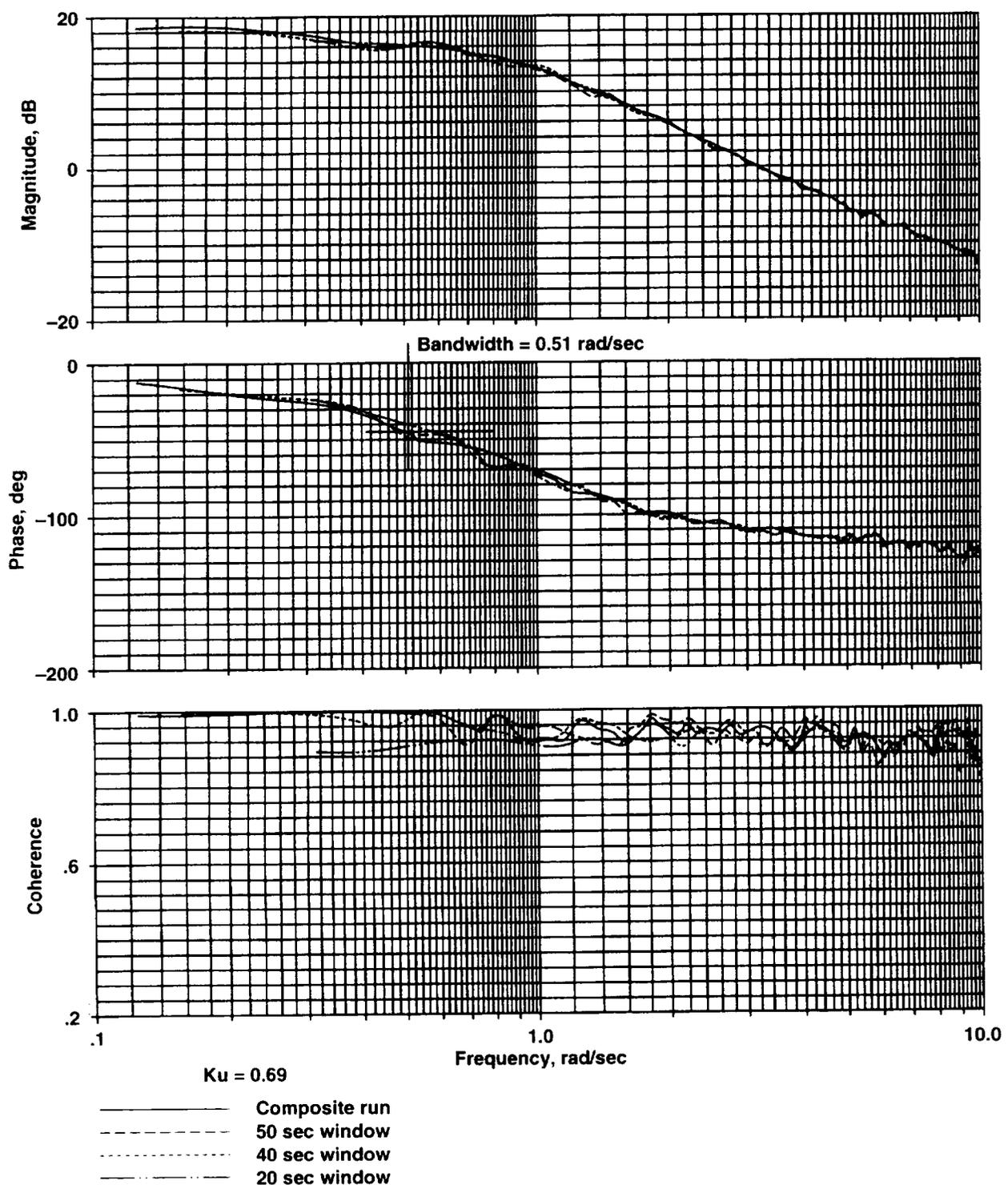


Figure 8. Longitudinal translational rate command system frequency response.

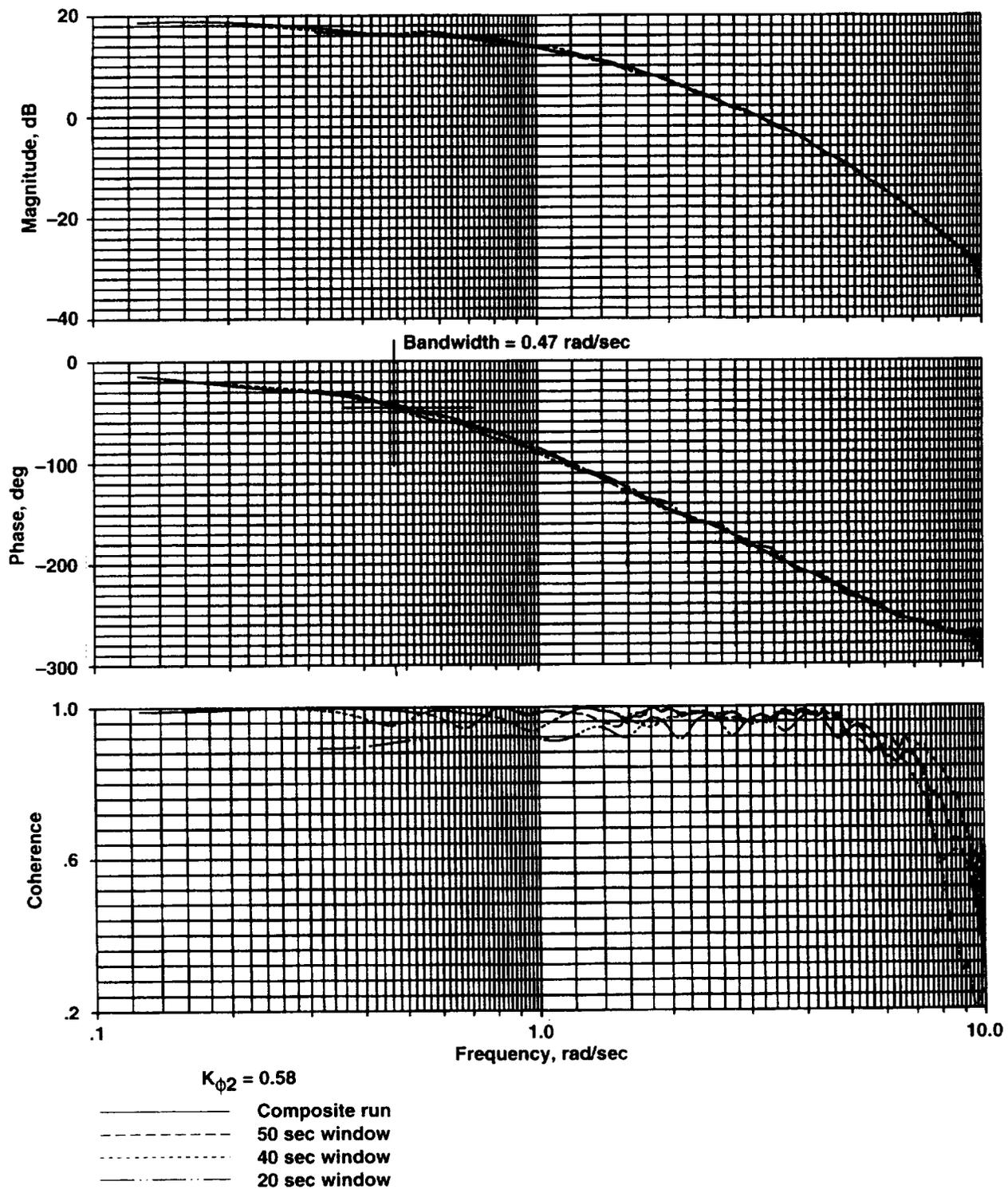


Figure 9. Lateral translational rate command system frequency response.

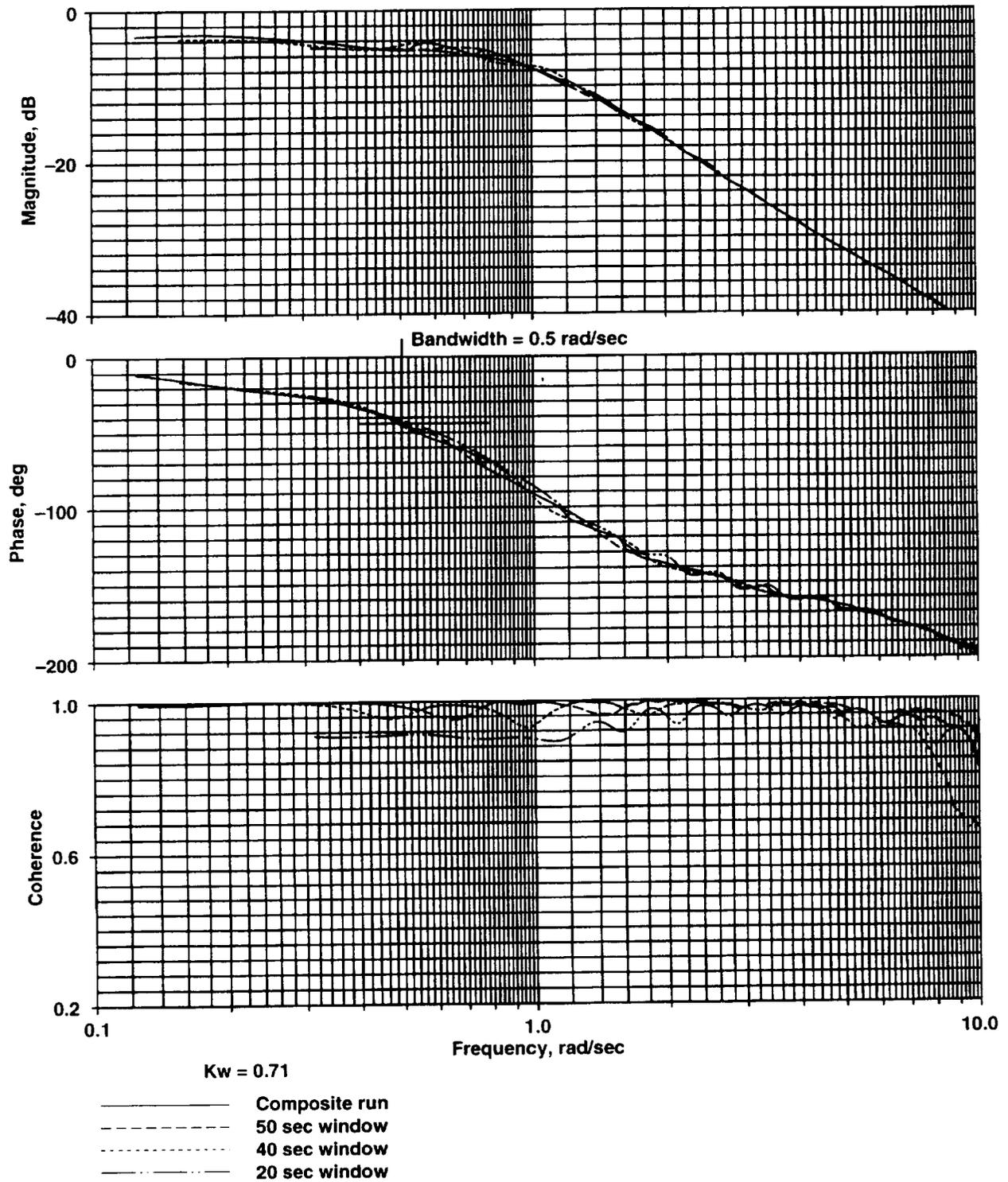


Figure 10. Vertical translational rate command system frequency response.

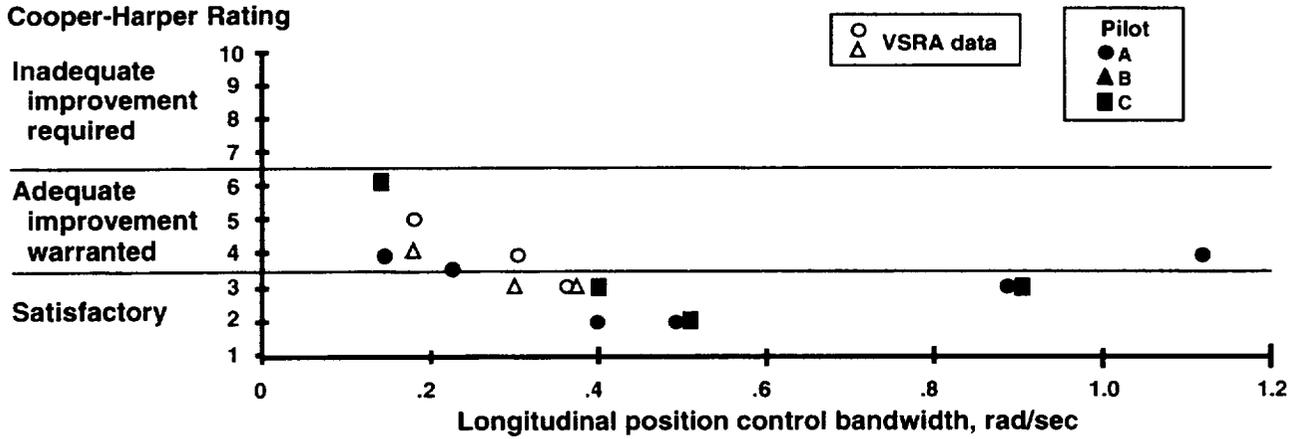


Figure 11. Effect of longitudinal position control bandwidth on precision hover.

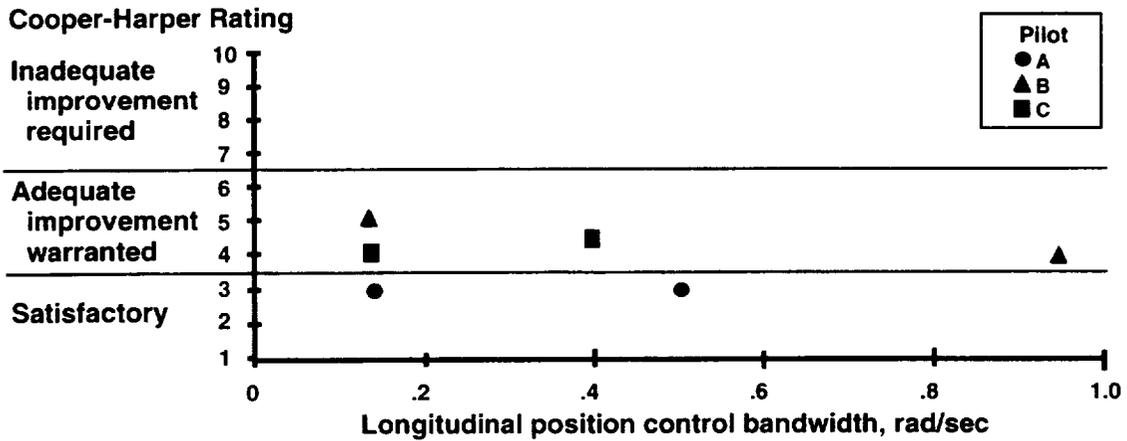


Figure 12. Effect of longitudinal position control bandwidth on hover and vertical landing on LPH.

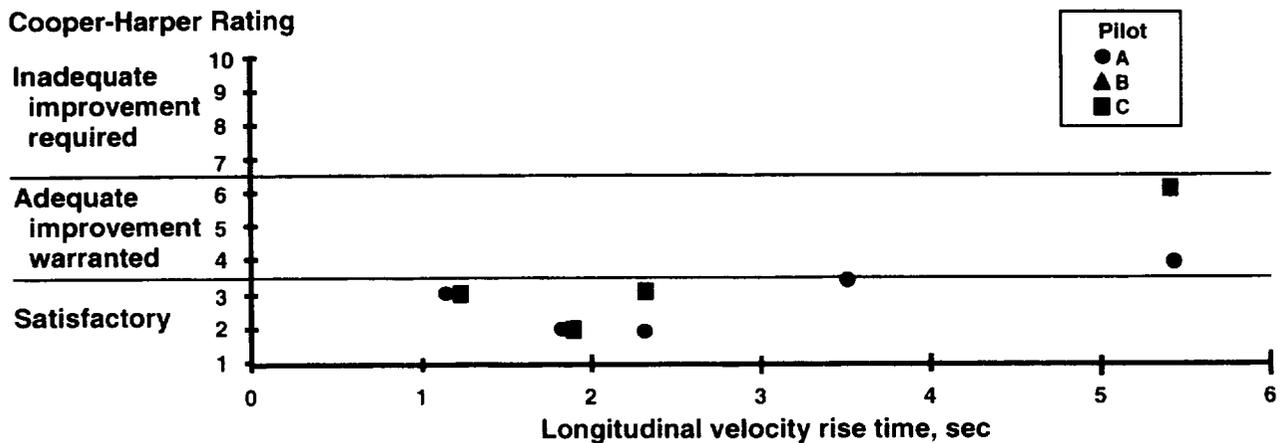


Figure 13. Effect of longitudinal velocity rise time on precision hover.

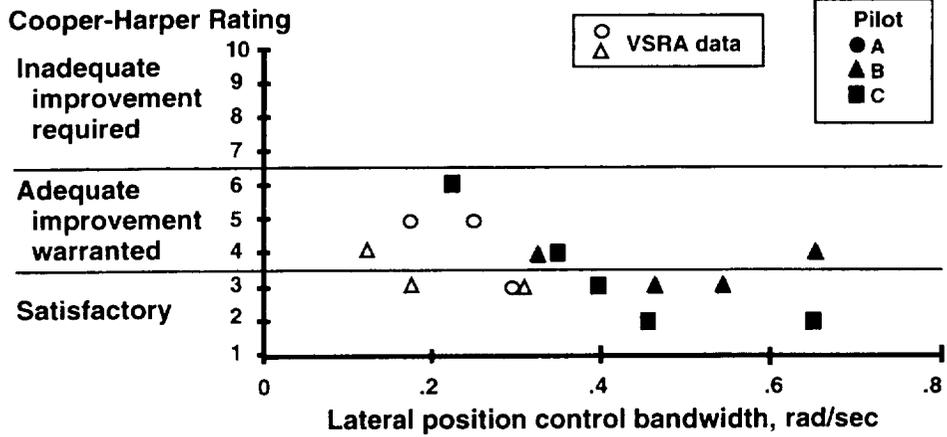


Figure 14. Effect of lateral position control bandwidth on precision hover.

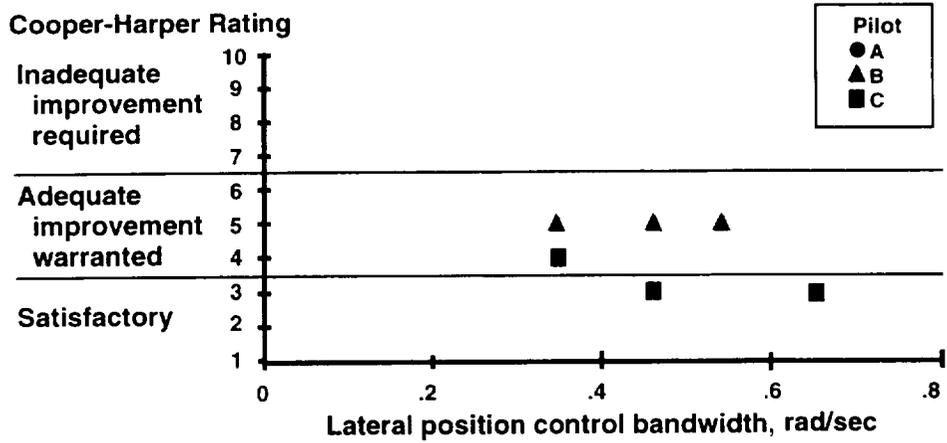


Figure 15. Effect of lateral position control bandwidth on hover and vertical landing on LPH.

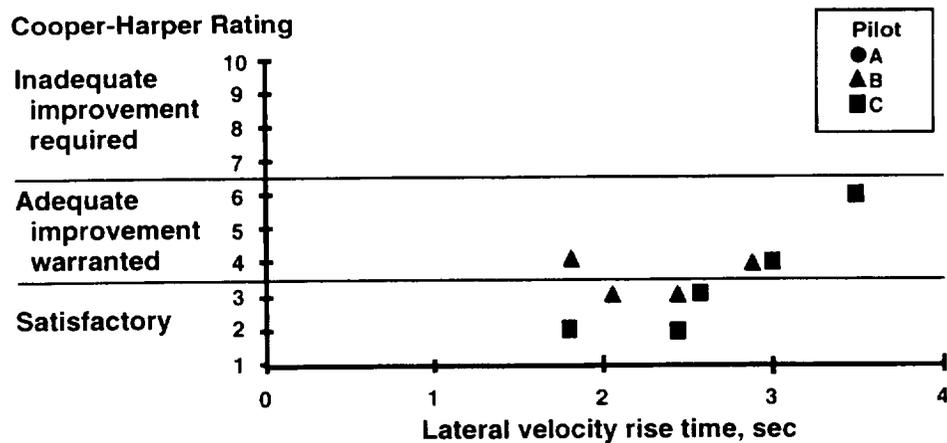


Figure 16. Effect of lateral velocity rise time on precision hover.

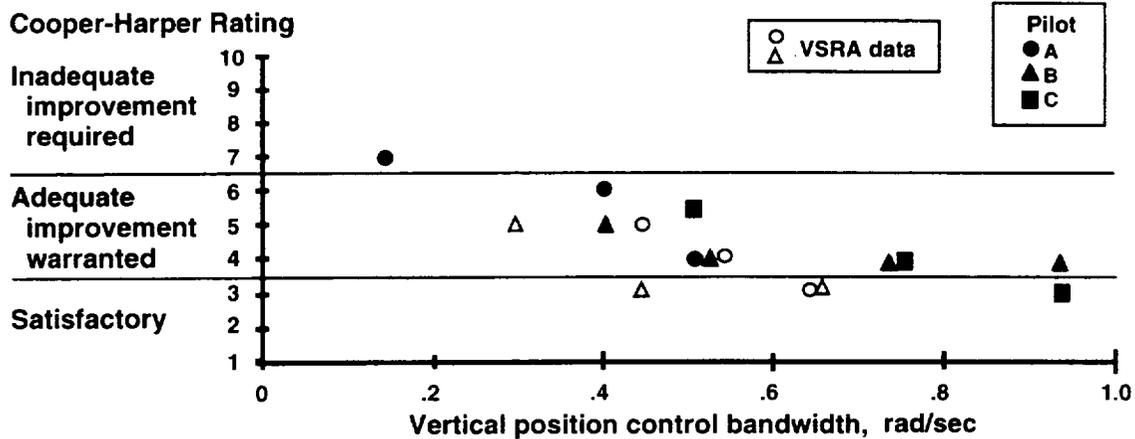


Figure 17. Effect of vertical position control bandwidth on precision hover.

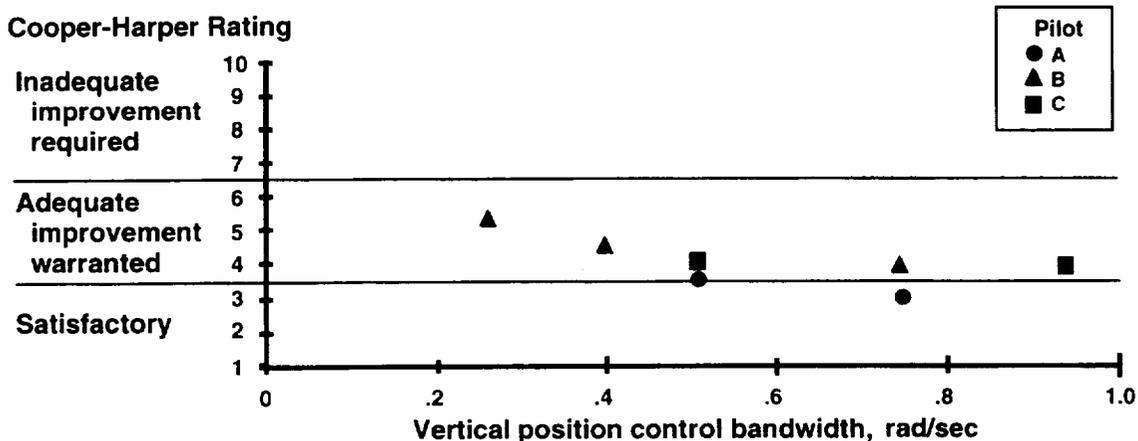


Figure 18. Effect of vertical position control bandwidth on hover and vertical landing on LPH.

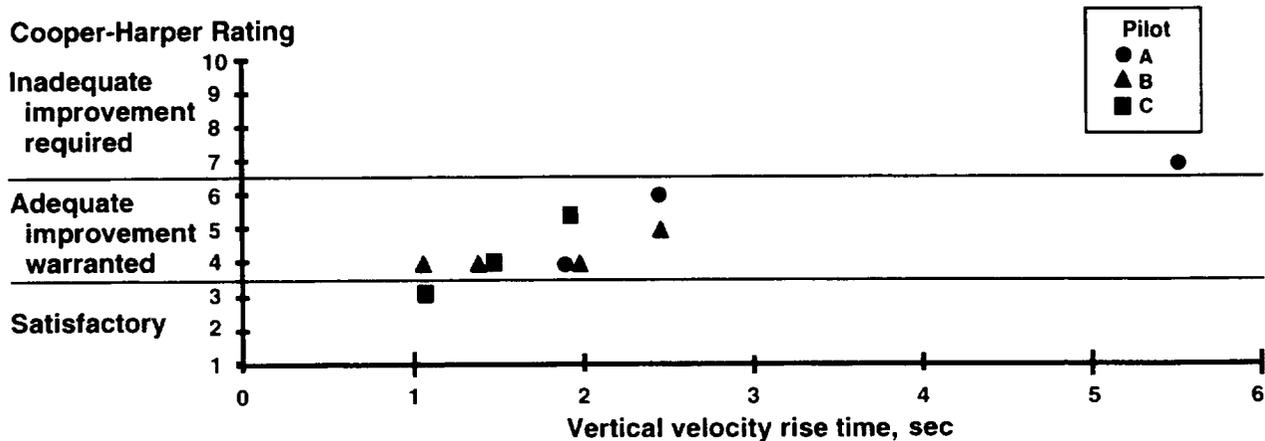


Figure 19. Effect of vertical velocity rise time on precision hover.

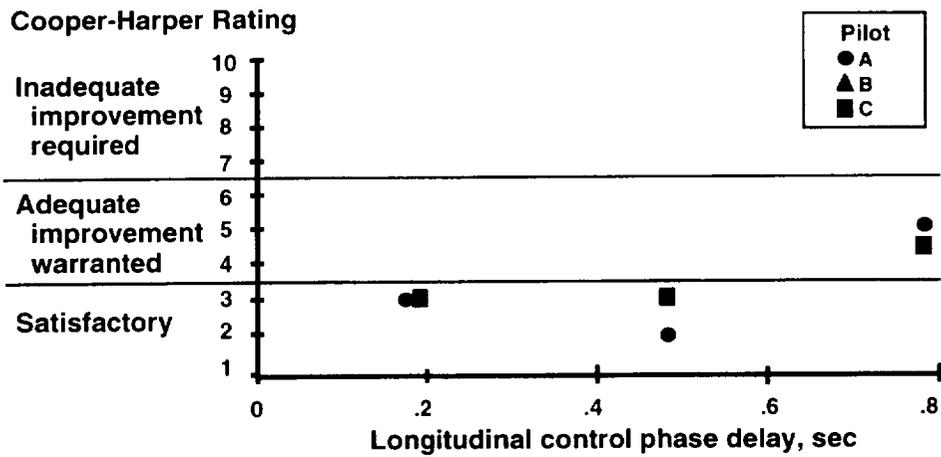


Figure 20. Effect of longitudinal control phase delay on precision hover.

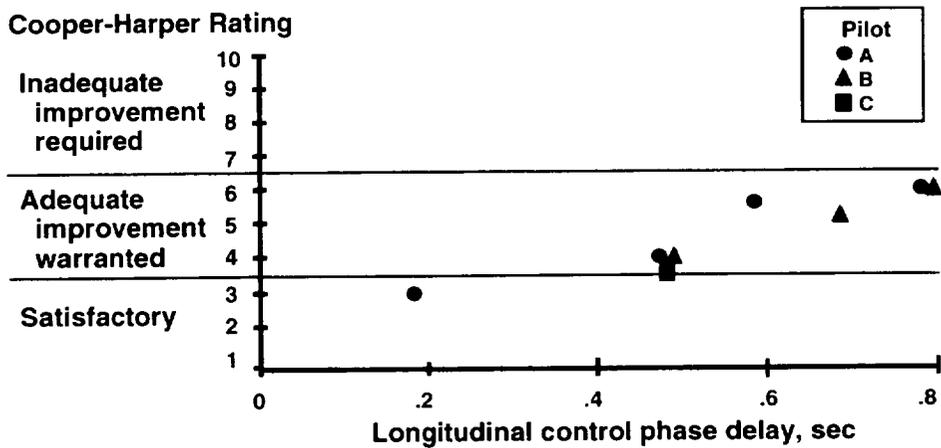


Figure 21. Effect of longitudinal control phase delay on hover and vertical landing on LPH.

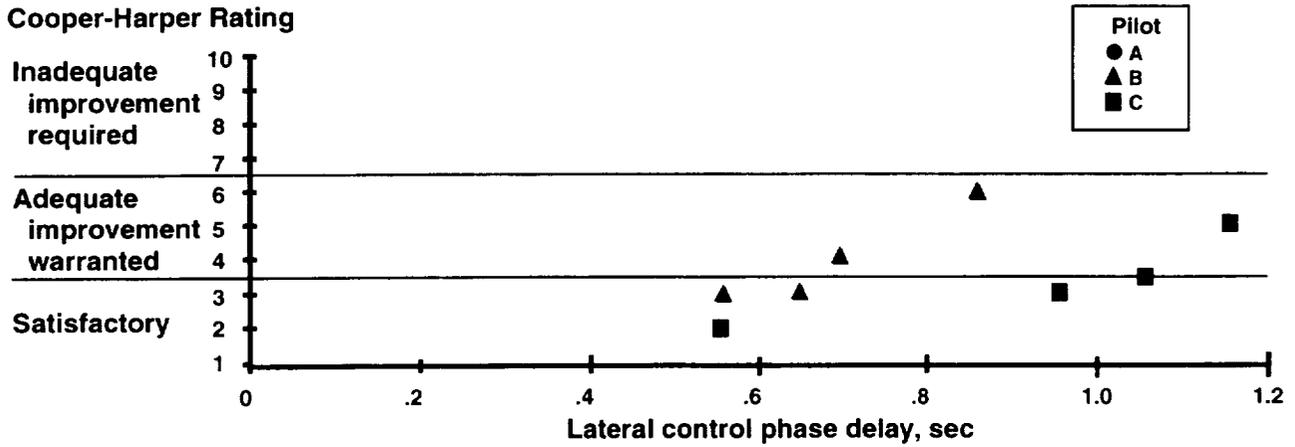


Figure 22. Effect of lateral control phase delay on precision hover.

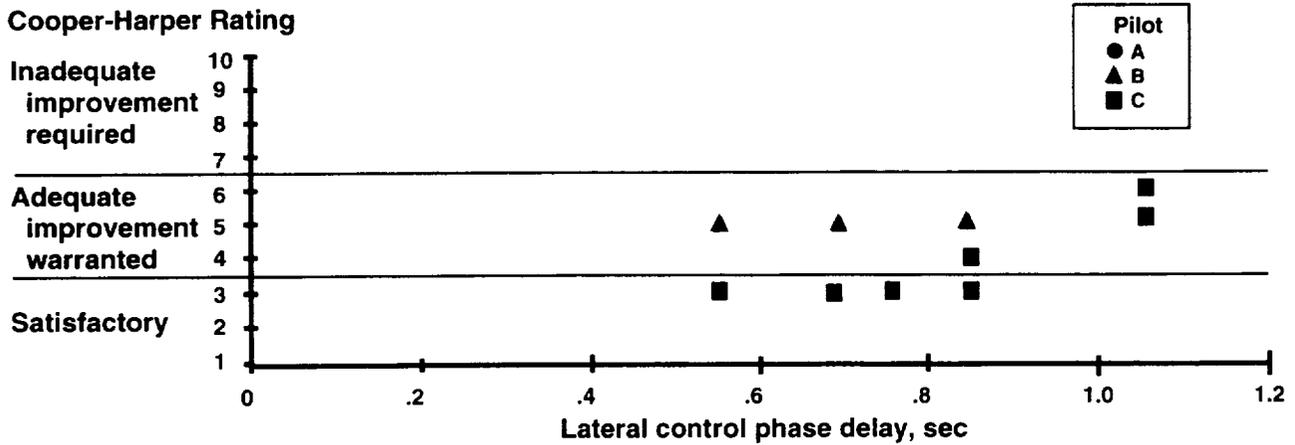


Figure 23. Effect of lateral control phase delay on hover and vertical landing on LPH.

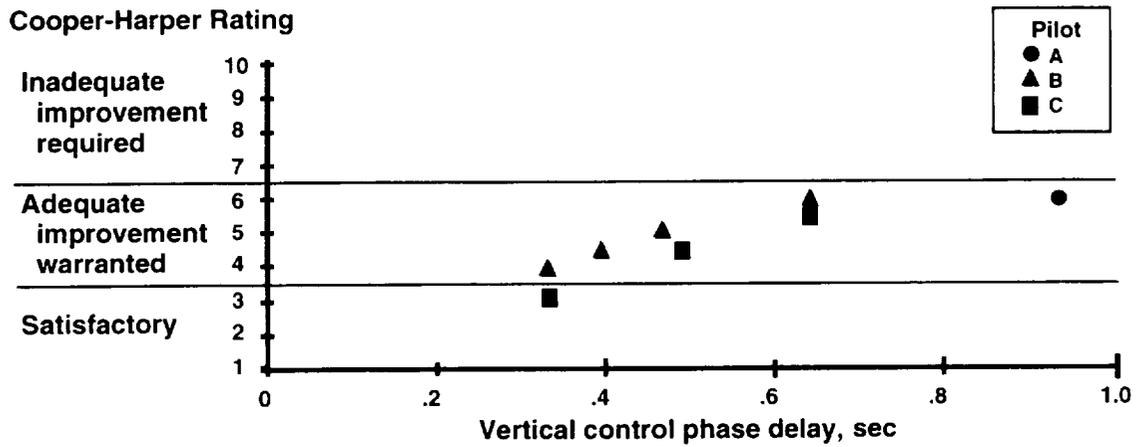


Figure 24. Effect of vertical control phase delay on precision hover.

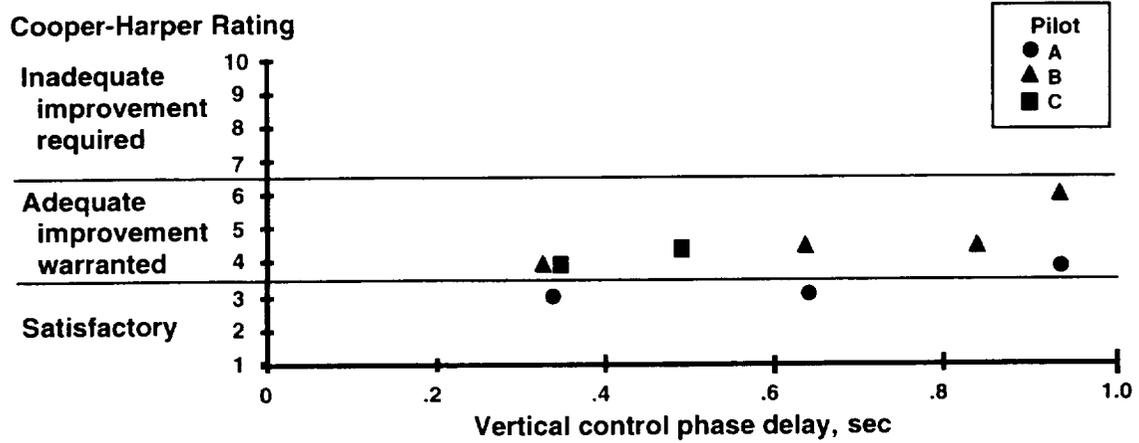


Figure 25. Effect of vertical control phase delay on hover and vertical landing on LPH.

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13. ABSTRACT (Maximum 200 words) Using a generalized simulation model, a moving-base simulation of a lift-fan short takeoff/vertical landing fighter aircraft has been conducted on the Vertical Motion Simulator at Ames Research Center. Objectives of the experiment were to determine the influence of system bandwidth and phase delay on flying qualities for translational rate command and vertical velocity command systems. Assessments were made for precision hover control and for landings aboard an LPH type amphibious assault ship in the presence of winds and rough seas. Results obtained define the boundaries between satisfactory and adequate flying qualities for these design features for longitudinal and lateral translational rate command and for vertical velocity command.			
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