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Vernon K. Merrick

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Vernon K. Merrick, Ames Research Center, Moffett Field, California

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Ames Research Center
Moffett Field, California 94035

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NOMENCLATURE

g	gravitational acceleration
h	altitude
$\dot{h}$	rate of climb
h_R	reference altitude of range R
$\dot{h}_R$	reference rate of climb at range R
$\ddot{h}_R$	reference vertical acceleration at range R
H_S	characteristic wave height
k_o, k_h, k_h, k_{2h}	vertical flight director gains
K_1, K_2	longitudinal flight director gains
R	distance from initial station-keeping point
s	Laplace transform variable
T_o	characteristic wave period
T/W	thrust/weight ratio
U_B, V_B, W_B	body axes airspeeds
V_x	longitudinal inertial velocity
$\dot{V}_x$	longitudinal inertial acceleration
V_y	lateral inertial velocity
V_{y_c}	lateral inertial velocity command
V_w	wind speed
V_{WOD}	speed of wind-over-deck
V_s	ship speed
$V_L, V_U, \dot{V}_L, \dot{V}_U$	longitudinal flight director parameters
β_{max}	maximum sideslip angle

$\Delta\beta_{ss}$	steady-state sideslip angle
ΔV_x	longitudinal velocity error
ΔV_x	longitudinal acceleration error
$\Delta V_U, \Delta V_L$	longitudinal flight director parameters
ζ	thrust vector (nozzle) angle (zero pointing aft)
$\dot{\zeta}$	thrust vector (nozzle) angle rate
ζ_ψ	yaw controller damping factor
μ_s	ship heading relative to wave direction
σ_ϕ	standard deviation of ship roll angle
σ_θ	standard deviation of ship pitch angle
σ_ψ	standard deviation of ship yaw angle
$\sigma_{x_{cg}}$	standard deviation of ship surge
$\sigma_{y_{cg}}$	standard deviation of ship sway
$\sigma_{z_{cg}}$	standard deviation of ship heave
$\sigma_{x_{\ell p}}$	standard deviation of landing point surge
$\sigma_{y_{\ell p}}$	standard deviation of landing point sway
$\sigma_{z_{\ell p}}$	standard deviation of landing point heave
$\sigma_{\dot{\phi}}$	standard deviation of ship roll rate
$\sigma_{\dot{\theta}}$	standard deviation of ship pitch rate
$\sigma_{\dot{\psi}}$	standard deviation of ship yaw rate
$\sigma_{\dot{x}_{cg}}$	standard deviation of ship surge velocity
$\sigma_{\dot{y}_{cg}}$	standard deviation of ship sway velocity
$\sigma_{\dot{z}_{cg}}$	standard deviation of ship heave velocity
$\sigma_{\dot{x}_{\ell p}}$	standard deviation of landing point surge velocity

$\sigma_{\dot{y}_{\ell p}}$	standard deviation of landing point sway velocity
$\sigma_{\dot{z}_{\ell p}}$	standard deviation of landing point heave velocity
τ_h	filter time constant in vertical flight director
ϕ	roll angle
ϕ_p	pilot-commanded roll angle
ϕ_{ss}	steady-state roll angle
ψ_w	wind heading relative to ship's axis
ψ_{WOD}	wind-over-deck heading relative to ship's axis
ω_o	frequency constant of translational rate command
ω_ψ	yaw controller frequency
ζ_ψ	yaw controller damping factor

Acronyms

CAA	Civil Aviation Authority
CTOL	conventional takeoff and landing
FSAA	Flight Simulator for Advanced Aircraft
HUD	head-up display
IMC	instrument meteorological conditions
RAE	Royal Aircraft Establishment
RCS	reaction control system
TVRS	thrust-vector-rate switch
VTOL	vertical takeoff and landing
WOD	wind over deck

SIMULATION EVALUATION OF TWO VTOL CONTROL/DISPLAY SYSTEMS IN IMC APPROACH AND SHIPBOARD LANDING

Vernon K. Merrick

Ames Research Center

SUMMARY

Two control/display systems, which differed in overall complexity but were both designed expressly for VTOL flight operations to and from small ships in instrument meteorological conditions (IMC), were tested using the Ames Flight Simulator for Advanced Aircraft (FSAA). Both systems have attitude command in transition and horizontal-velocity command in hover; the more complex system also has longitudinal-acceleration and flightpath-angle command in transition, and vertical-velocity command in hover. The most important overall distinction between the two systems from the viewpoint of implementation is that in one--the more complex--engine power and nozzle position are operated indirectly through flight controllers, whereas in the other they are operated directly by the pilot. Simulated landings were made on a moving model of a DD 963 Spruance-class destroyer. Acceptable transitions can be performed in turbulence of 3 m/sec rms using either system. Acceptable landings up to sea state 6 can be performed using the more complex system, and up to sea state 5 using the other system.

INTRODUCTION

In reference 1, two control/display systems, designed expressly for VTOL transition and shipboard landings in instrument meteorological conditions (IMC), were described, along with the results of a piloted simulation on the Ames Research Center's Flight Simulator for Advanced Aircraft (FSAA). The more complex Type 1 system had attitude command, vertical-velocity command, longitudinal-acceleration command in transition, and longitudinal-velocity command in hover, the translational-command modes being implemented through engine power and nozzle position. The Type 2 system had attitude command and direct pilot control of engine power and nozzle position.

Each control system was complemented by an appropriate head-up display (HUD) that included flight-director information. These control/display systems were applied to existing models of a conceptual lift-fan transport (ref. 2) and an AV-8A Harrier (ref. 3). Simulated landings were made on a moving model of a DD 963 destroyer. Of particular note was the inclusion of a representation of the ship-induced air-wake turbulence (ref. 4).

The overall simulated task (ref. 1) was divided into two parts: the approach transition from 120 knots to an initial station-keeping point, and the landing from the initial station-keeping point to touchdown. The transition tests showed that the Type 1 system was acceptable (Cooper-Harper rating less than 6-1/2) in free-air turbulence up to 2.25 m/sec (the highest tested), and the Type 2 system was acceptable up to a free-air turbulence of 1.5 m/sec. The landing tests showed thatthe Type 1 system was acceptable up to sea state 6 and wind-over-deck (WOD) of 43 knots and the Type 2 system was acceptable up to sea state 4 and WOD of 34 knots.

The simulation revealed several problems with both control/display systems, but particularly with the Type 2 system. Deficiencies were noted in the type of control modes provided, the flight-director laws, and the HUD format. It was clear that the Type 2 system would benefit from further development. Consequently, a small fixed-base simulator was used to investigate several new ideas regarding pilot control modes, HUD formats, and pilot controls. The result was two control/display systems that are variants of the Type 1 and Type 2 systems, and which are designated Type 1A and Type 2A.

This report addresses the basic problems with the Type 1 and Type 2 systems and describes the solutions, now incorporated into the Type 1A and Type 2A systems. The two new systems have, in turn, been incorporated into the model of the AV-8A Harrier. A piloted simulation has been carried out on the Ames FSAA to compare the performance of the two systems in IMC approaches and landings on the DD 963 destroyer. There are two significant differences between this latest simulation and that described in reference 1. The reference approach flightpath in the earlier simulation was straight, in plan-view, and was criticized as not requiring lateral pilot control inputs great enough to permit a proper evaluation of the lateral/directional handling characteristics of the aircraft. In the latest simulation the flightpath has an initial straight segment, followed by a curved segment, followed by a final straight segment. In addition, the three-degree-of-freedom motion base for the ship model used in the previous simulation has been expanded to a full six degrees of freedom in the latest simulation.

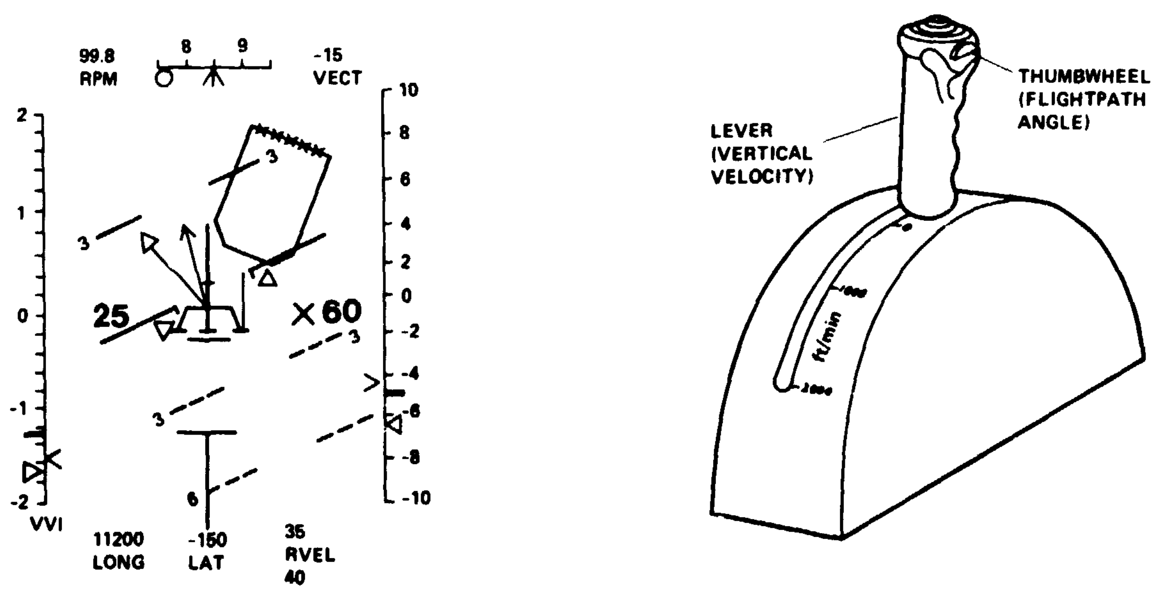
This report describes the latest simulation and compares the primary results with those obtained previously for the Type 1 and Type 2 systems.

TYPE 1A CONTROL/DISPLAY SYSTEM

The primary features of the Type 1A system are summarized in figure 1. The major differences between the Type 1A and Type 1 systems may be seen by comparing figure 1 with figure 2 of reference 1. The two systems differ significantly in the areas of longitudinal, vertical, and directional control in transition; and longitudinal, lateral, and vertical control in hover. Tables 1 and 2 compare the pilot-control modes, pilot controls, and flight-director provisions for the two systems. A detailed comparison of the HUD formats may be seen in figure 2 and figure 3 of reference 1. Following is a description of and rationale for these changes.

Vertical Control in Transition

It was noted in reference 1 (p. 57) that, when flying a straight approach using the Type 1 system, the pilot must gradually reduce the commanded rate of descent in order to maintain a constant glide slope during the deceleration. It was therefore suggested that a flightpath-angle command mode, rather than a vertical-velocity command mode, would reduce the pilot workload, since a single movement of the vertical control would establish the desired approach-path angle. Accordingly, the Type 1A system has a flightpath-angle command in transition. This control mode is derived from the Type 1 vertical control command mode by multiplying the pilot input by the inertial longitudinal velocity. Thus, for a fixed-control input, the commanded vertical velocity is proportional to the forward velocity, as required for a fixed-flightpath angle.



SYSTEM FEATURES

- ATTITUDE COMMAND
- LONGITUDINAL ACCELERATION AND FLIGHTPATH ANGLE COMMAND FOR TRANSITION
- HORIZONTAL AND VERTICAL VELOCITY COMMAND FOR HOVER AND TOUCHDOWN
- INTEGRATED FLIGHTPATH ANGLE AND VERTICAL VELOCITY CONTROLS
- HUD WITH THREE-AXIS FLIGHT DIRECTOR FOR TRANSITION

Figure 1.- Velocity command system (type 1A system).

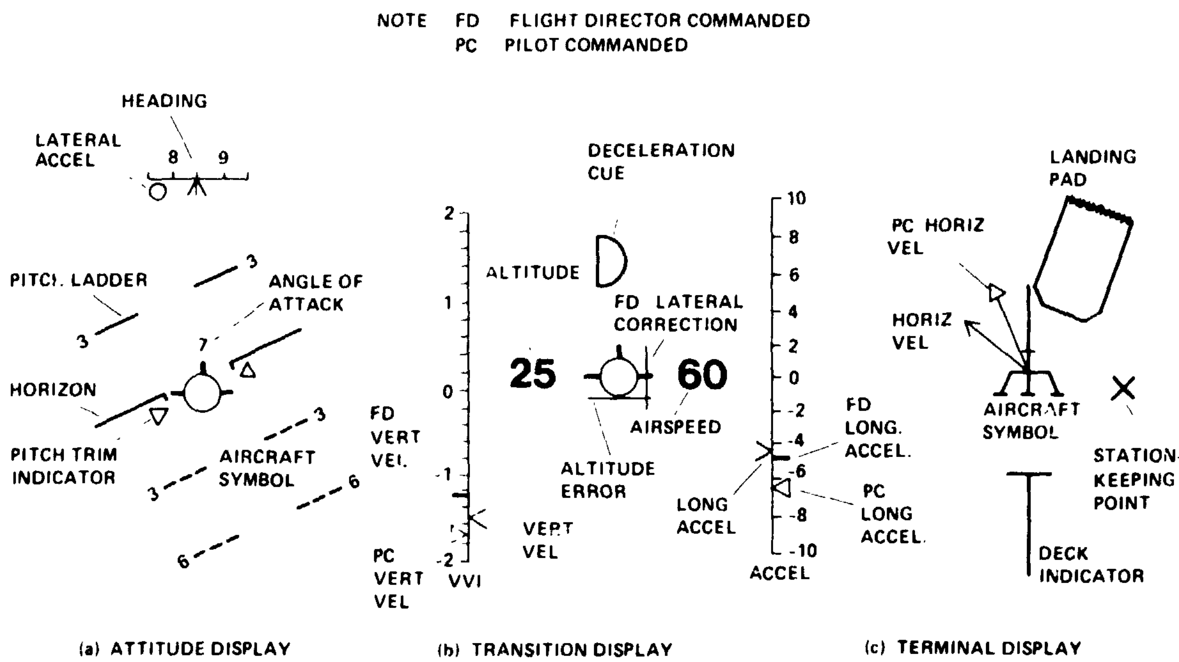


Figure 2.- HUD format breakdown for type 1A system.

TABLE 1. – TYPE 1A CONTROL SYSTEM SUMMARY

LANDING PHASE			DEGREE OF FREEDOM					
			X	Y	Z	PITCH	ROLL	YAW
HOVER AND FINAL DESCENT	CONTROL MODE (LAW)		V_x COMMAND	V_y COMMAND	$\dot{h}$ COMMAND h HOLD	$\dot{\theta}$ COMMAND (FIXED RATE) θ HOLD	NO DIRECT COMMAND MODE (SEE Y)	$\dot{\psi}$ COMMAND
	CONTROL FORCE PRODUCER		ENGINE NOZZLE DEFLECTION	ROLL ANGLE	ENGINE THRUST	RCS	RCS	RCS
	PILOT CONTROL		LONGITUDINAL STICK	LATERAL STICK	LEVER	STICK MOUNTED TRIM BUTTON	NONE (SEE Y)	PEDALS
	FLIGHT DIRECTOR		NO	NO	NO			
MODE BLEND OR SWITCH			SIMULTANEOUS SWITCH ON STICK BUTTON 1 (FIG 3)					BLEND 20KT < V_x < 30KT
TRANSITION	CONTROL MODE (LAW)		$\dot{V}_x$ COMMAND V_x HOLD	NO DIRECT COMMAND MODE (SEE ROLL)	γ COMMAND	θ COMMAND AND $\dot{\theta}$ COMMAND (FIXED RATE) θ HOLD	$\dot{\phi}$ COMMAND ϕ HOLD	WITH PEDALS CENTERED $\Delta\dot{\psi}$ COMMAND ON BASE OF $\dot{\psi} = \frac{g \tan\phi_p}{V_a}$ OTHERWISE n_y COMMAND
	CONTROL FORCE PRODUCER		ENGINE NOZZLE DEFLECTION	ROLL ANGLE	ENGINE THRUST	RCS	RCS	RCS
	PILOT CONTROL		STICK MOUNTED THUMBWHEEL	NONE (SEE ROLL)	LEVER MOUNTED THUMB WHEEL	STICK AND TRIM BUTTON	LATERAL STICK	PEDALS
	FLIGHT DIRECTOR		YES	YES	YES			

TABLE 2. – TYPE 1 CONTROL SYSTEM SUMMARY

LANDING PHASE		DEGREE OF FREEDOM: X	Y	Z	PITCH	ROLL	YAW
HOVER AND FINAL DESCENT	CONTROL MODE (LAW)	V_x COMMAND	NO DIRECT COMMAND MODE (SEE ROLL)	$\dot{h}$ COMMAND	θ COMMAND $\dot{\theta}$ COMMAND (FIXED RATE) θ HOLD	ϕ COMMAND	$\dot{\psi}$ COMMAND
	CONTROL FORCE PRODUCER	ENGINE NOZZLE DEFLECTION	ROLL ANGLE	ENGINE THRUST	RCS	RCS	RCS
	PILOT CONTROL	LEVER MOUNTED THUMB BUTTON	NONE (SEE ROLL)	LEVER	STICK AND TRIM BUTTON	LATERAL STICK	PEDALS
	FLIGHT DIRECTOR	NO	YES	NO			
MODE BLEND OR SWITCH		SIMULTANEOUS SWITCH ON STICK BUTTON 1 (FIG. 3)				BLEND 20KT < V_x < 30KT	
TRANSITION	CONTROL MODE (LAW)	$\dot{V}_x$ COMMAND V_x HOLD	NO DIRECT COMMAND MODE (SEE ROLL)	$\dot{h}$ COMMAND	θ COMMAND $\dot{\theta}$ COMMAND (FIXED RATE) θ HOLD	$\dot{\phi}$ COMMAND ϕ HOLD	$\Delta\dot{\psi}$ COMMAND ON BASE OF $\dot{\psi} = \frac{g \tan\phi}{V_x}$
	CONTROL FORCE PRODUCER	ENGINE NOZZLE DEFLECTION	ROLL ANGLE	ENGINE THRUST	RCS	RCS	RCS
	PILOT CONTROL	LEVER MOUNTED THUMB WHEEL	NONE (SEE ROLL)	LEVER	STICK AND TRIM BUTTON	LATERAL STICK	PEDALS
	FLIGHT DIRECTOR	YES	YES	YES			

Vertical Control in Hover

Flightpath-angle command, as described above for transition, cannot be used in hover, since if the velocity is zero then the flightpath-angle-control authority also is zero. Therefore, the Type 1 system vertical-velocity command mode is retained in the Type 1A for hover, with the switch from flightpath-angle mode to vertical-velocity mode being performed by the pilot. This switching procedure raises a problem (mentioned in ref. 1, p. 58); namely, that if the same pilot control is used throughout, the pilot would have to remember to center the control before pressing the mode-change switch to avoid inadvertently commanding a rate of descent. To overcome this problem, separate height controls are used for transition and hover. For transition, the lever thumb wheel is used to command flightpath angle (lever electrically disconnected), and in hover the lever is used to command vertical velocity (thumb wheel electrically disconnected).

It was noted in reference 1 (p. 58) that when the Type 1 system was used in hover and in high turbulence, the aircraft gradually lost altitude, even though the commanded vertical velocity was zero. This phenomenon occurred because the thrust available was insufficient to maintain altitude during down gusts. To overcome the problem, the Type 1A system has an altitude-hold feature that is active only when the vertical-velocity-command lever is in this detent position (zero vertical-velocity command).

Longitudinal Control in Transition

The longitudinal-command mode remains the same for the Type 1A system as for the Type 1 system. Longitudinal pilot control for the Type 1A system is through a thumb wheel mounted on the stick (fig. 3). This additional pilot control is required because the lever-mounted thumb wheel, used for longitudinal control in the Type 1 system, is used for flightpath-angle control in the Type 1A system.

Longitudinal Control in Hover

With the Type 1 system, longitudinal translation in hover (using thrust deflection at constant pitch attitude) is controlled with the left hand through a lever-mounted thumb button (ref. 1, fig. 2); and in the case of the AV-8A, lateral translation (using roll angle) is controlled with the right hand through the stick. This arrangement has led to criticism that the controls were poorly harmonized (ref. 1, p. 46). The problem is overcome in the Type 1A system by controlling longitudinal translation with the right hand through the stick. Thus, the stick controls both longitudinal and lateral translation in hover, similar to a helicopter. Control of pitch attitude in the Type 1A system is through the stick-grip-mounted trim button only, at a constant rate of 2°/sec.

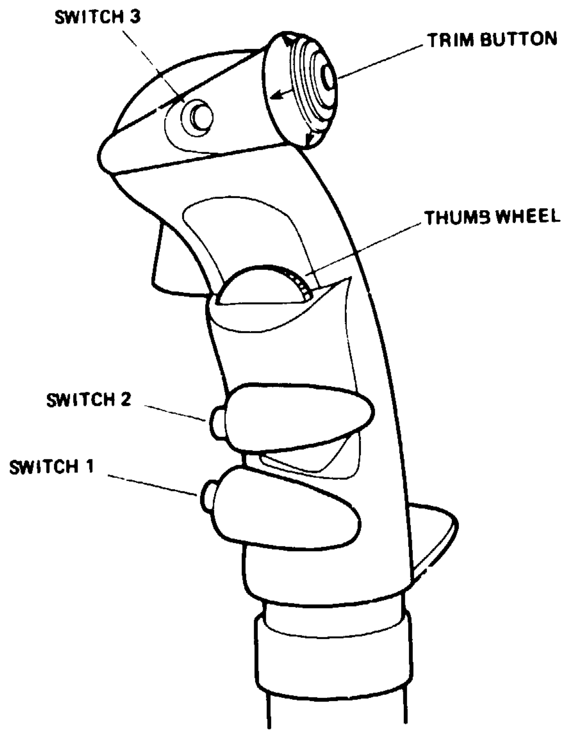


Figure 3.- Stick grip.

Lateral Control in Hover

When applied to the AV-8A (no lateral-thrust deflection), the Type 1 system uses roll-attitude command and a flight director to position the aircraft laterally in hover. This approach was shown to result in high pilot workload, especially in high turbulence (ref. 1, p. 58). The problem is largely due to lack of translational damping aggravated by lack of visual cues, and can be compensated for only partially by the use of a flight director. To overcome this problem, the Type 1A system is provided with a lateral-velocity command mode through roll angle. The relationship between the pilot command, V_{y_c}, and lateral velocity, V_y, is given the transfer function

$$\frac{V_y}{V_{y_c}} = \frac{\omega_o^3}{(s + \omega_o)^3} \quad (1)$$

where s is the Laplace transform variable and ω_o is the characteristic frequency of the lateral-velocity command mode. The technique used to design a self-triming lateral flight controller with the characteristics given by equation (1) is described in reference 5. Following a preliminary fixed-base simulator evaluation, a value for

ω_o of 1.75 rad/sec was selected. This value of ω_o is consistent with results reported in reference 6.

The well-known superior handling qualities associated with a system with characteristics given by equation (1), coupled with a self-trimming feature, obviate the need for a lateral flight director in the Type 1A system for hover.

Yaw Control in Transition

Although the Type 1 system yaw-control mode was not criticized in the last simulation (ref. 1), this does not necessarily mean that the mode is generally satisfactory. Because the flightpath used in the last simulation was straight, the pilot did not need to make large lateral maneuvers of the type that would expose weakness in the yaw-control mode. Fixed-base simulations during the development phase of the Type 1A system using a curved approach path, however, exposed yaw-control-mode deficiencies noted in a previous simulation (ref. 2), and led to a search for a better control mode.

The yaw-control mode of the Type 1 system is yaw-rate command complemented by a turn-coordination input added downstream of the pilot's input and equal to $g \tan \phi / V_x$ where g is the acceleration due to gravity, ϕ is the roll angle, and V_x is the inertial longitudinal velocity. The simulation results reported in reference 2 indicated that the turn-coordination feature works reasonably well at speeds above 60 knots and in the absence of winds. However, in the presence of winds, large sideslip angles develop because the use of inertial velocity V_x in the turn-coordination input produces a yaw rate that maintains the longitudinal axis of the aircraft tangential to the flightpath (in plan view), rather than along the direction of the airstream (ref. 2, fig. 42). A crude estimate of the magnitude of this effect may be obtained from

$$\beta_{max} = \frac{V_w}{\sqrt{V_w^2 + V_x^2}} \qquad (2)$$

where β_{max} is the maximum sideslip angle and V_w is the wind speed. At an inertial speed of 30 knots with a wind of 15 knots, the sideslip angle can be as high as 25°. A simple solution to the problem is to replace V_x in the turn-coordination input with the airspeed, V_a. With this modification the yaw rate commanded by the turn-coordination input is that required to maintain longitudinal axis coincident with the airspeed vector. At speeds below 60 knots, even this correction is insufficient to keep the sideslip angle acceptably low. The problem at these very low speeds is that yaw rates required for turn coordination are relatively high (15°/sec), and in the turn entry, the lag in the yaw-controller response to the turn-coordination input causes the aircraft's yaw angle to lag behind that required to produce zero-sideslip. An estimate of this effect is given by

$$\Delta\beta_{ss} = \frac{2\zeta_\psi g \phi_{ss}}{\omega_\psi V_x} \quad (3)$$

where $\Delta\beta_{ss}$ is the steady sideslip following a turn entry, ϕ_{ss} is the steady roll angle in the turn, and ω_ψ and ζ_ψ are the undamped frequency and the damping factor of the yaw-controller mode. It should be noted that equation (3) is independent of the time history of the roll angle during the turn entry. With $\omega_\psi = 2$ rad/sec and $\zeta_\psi = 0.75$ (table 3 of ref. 1) the steady-state sideslip angle after entering a 30° banked turn at 30 knots is 14.3°. A simple solution to this problem is to replace ϕ in the turn-coordination input with the pilot-commanded roll angle ϕ_p. Since the roll and yaw controller are designed to have the same dynamic characteristics, ϕ_p leads ϕ by just the correct amount to counter the yaw lag. Tests were carried out on the fixed-base simulator using the turn-coordination input signal $g \tan \phi_p / V_a$. Pedal-free 360° turns at a constant 30-knot inertial speed, in a wind of 15 knots, using a roll angle of 30°, resulted in sideslip angles of less than 5°.

During the simulation reported in reference 2, tests were carried out using a sideslip-angle command mode. Such a yaw-controller mode automatically provides turn coordination. In smooth air the mode was well-liked because of its speed-independent sideslip characteristics, and excellent turn coordination. Unfortunately, in turbulent air the lateral accelerations at the pilot's station made the ride quality unacceptable. One way to minimize the ride-quality problem is to provide a sideslip-angle command mode only when a nonzero sideslip is required (pedals out of the center dead band), and a yaw-rate-command mode with turn-coordination assist when zero sideslip is desired (pedals in the center dead band). The rationale for these arrangements is that most of the time, if the turn coordination is acceptable the pilot will maintain the pedals in the center. This hybrid yaw-controller mode is employed in the Type 1A system. In the implementation of the system it is assumed that the output of a lateral accelerometer located at the lateral center of rotation of the aircraft provides an adequate measurement of sideslip. It follows that the yaw-controller mode is more accurately described as a lateral-acceleration command. The parameters of the yaw controller were set to provide an undamped frequency of 2 rad/sec and a damping factor of 1.

HUD Format

Differences between the Type 1A and Type 1 and HUD formats (fig. 2, and fig. 3 of ref. 1) are identified below under the headings of the three major display subformats.

Attitude display- To aid in differentiating positive and negative pitch attitude, the Type 1A system pitch attitude "ladder" uses dashed lines to identify negative attitudes. In addition, the horizontal "wings" of the fixed airplane symbol are lengthened to aid in resolving small bank angles (figs. 2(a) and 2(b)).

Transition display- Digital altitude and airspeed are provided next to the fixed airplane symbol (fig. 2(b)). In this position this important information falls within the horizontal-scan pattern of the pilot as he or she reads the three flight directors.

To advise the pilot that the time to start the deceleration is imminent (ref. 1, p. 57), a large D is presented on the HUD (fig. 2(b)). This symbol appears 5 sec before the start of deceleration and disappears after a further 5 sec.

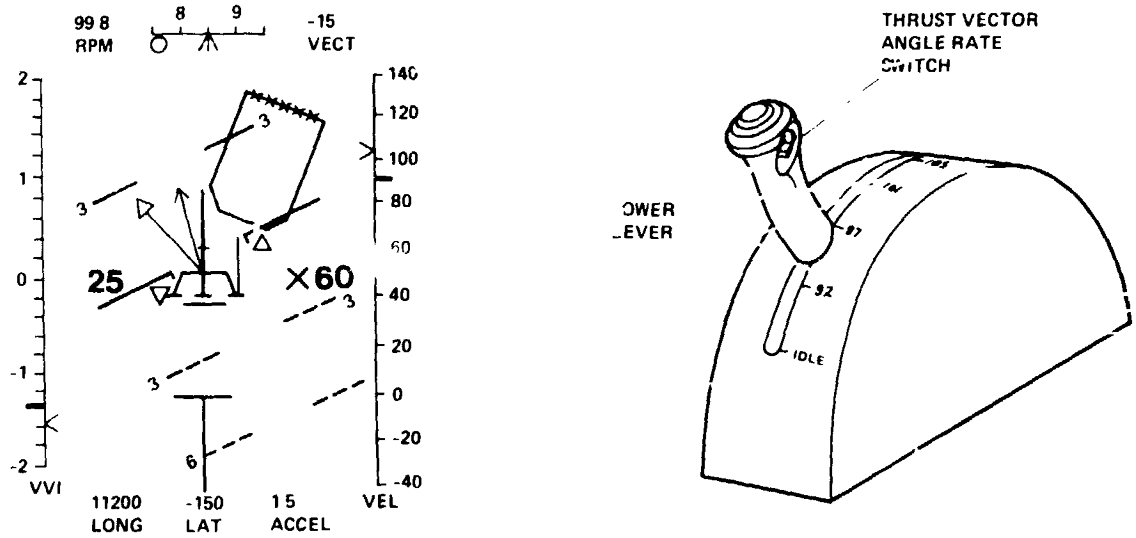
Terminal display- One of the most important deficiencies of the Type 1 terminal display (ref. 1, fig. 3(c)) is that the pilot is unable to judge how far the aircraft's wheels are from the edge of the landing pad and how far the aircraft's nose is from the hangar. To provide this information, the Type 1A terminal display (fig. 2(c)) uses a landing-pad symbol that is geometrically similar to the actual pad and, when the hover-control system is selected, a fixed-aircraft symbol appears that is a "stick" drawing of the aircraft's plan view, including wheel position, to the same scale as the landing-pad symbol. Furthermore, when the nose of the aircraft is within 3 m (10 ft) of the hangar, a row of crosses on the hangar edge of the pad symbol flashes repeatedly. The distance from the T-bar (fig. 2(c)) to the bottom of the aircraft symbol represents the altitude of the wheels above the deck.

TYPE 2A CONTROL/DISPLAY SYSTEM

A summary of the primary features of the Type 2A system is shown in figure 4. The major differences between the Type 2A and Type 2 systems may be seen by comparing figure 4 with figure 4 of reference 1. The systems differ significantly in the areas of longitudinal and vertical flight directors in transition, and in longitudinal and lateral control in hover. The control differences may be seen by comparing tables 3 and 4, which specify the pilot-control modes, pilot controls, and flight-director provisions for the two systems. A detailed comparison of the HUD formats is shown in figure 5 and figure 5 of reference 1. A description of the changes to the Type 2 leading to the Type 2A system and the rationale for these changes is given below.

Longitudinal and Lateral Control in Hover

In hover, both the longitudinal and lateral control modes of the Type 2 system are attitude command. It was reported in reference 1 that although the dynamics of the attitude command were satisfactory, the IMC precision-landing task, even when conducted using flight directors, was difficult, especially in high turbulence. Some of this difficulty was due to deficiencies in the flight-director laws, but the high workload was usually a direct consequence of the low translational damping of the aircraft (see "Type 1A Control/Display System, Lateral Control in Hover"). To overcome this problem, both the longitudinal and lateral control modes of the Type 2A system are translational velocity command through attitude. The implementation and



SYSTEM FEATURES

- ATTITUDE COMMAND IN TRANSITION
- TRANSLATIONAL VELOCITY COMMAND THROUGH ATTITUDE IN HOVER
- THRUST AND THRUST VECTOR ANGLE RATE COMMAND
- INTEGRATED POWER AND THRUST VECTOR ANGLE RATE CONTROLS
- HUD WITH THREE AXES FLIGHT DIRECTORS FOR TRANSITION, AND POWER FLIGHT DIRECTOR FOR HOVER MANEUVERS AND FINAL DESCENT

Figure 4.- Thrust and thrust vector angle rate command system (type 2A system).

modal dynamic characteristics for both the longitudinal and the lateral degrees of freedom are identical to those described for the Type 1A system lateral control in hover. Because of the recognized superior characteristics of translational-velocity command systems, the Type 2A system, like the Type 1A system, does not employ longitudinal or lateral flight directors for hover maneuvers and descent.

Vertical (Throttle) Flight Director in Transition

The Type 2 system vertical flight director is too sensitive to turbulence during transition (ref. 1). This sensitivity is due to the relatively high bandwidth designed into the director. The high bandwidth was provided to overcome the effects of rapidly varying aerodynamic lift during the deceleration.

A block diagram of the Type 2A system vertical flight director and the associated parameter values are shown in figure [illegible]. A comparison of figure 6 with figure 11 of reference 1 shows that the vertical acceleration feedback has been

TABLE 3. – TYPE 2A CONTROL SYSTEM SUMMARY

LANDING PHASE			DEGREE OF FREEDOM					
			X	Y	Z	PITCH	ROLL	YAW
LANDING PHASE	HOVER AND FINAL DESCENT	CONTROL MODE (LAW)	V_x COMMAND	V_y COMMAND	ENGINE THRUST COMMAND	$\dot{\theta}$ COMMAND (FIXED RATE) θ HOLD	NO DIRECT COMMAND MODE (SEE Y)	$\dot{\psi}$ COMMAND
		CONTROL FORCE PRODUCER	PITCH ANGLE	ROLL ANGLE	ENGINE THRUST	RCS AND ENGINE NOZZLE DEFLECTION	RCS	RCS
		PILOT CONTROL	LONGITUDINAL STICK	LATERAL STICK	POWER LEVER	STICK MOUNTED TRIM BUTTON	NONE (SEE Y)	PEDALS
		FLIGHT DIRECTOR	NO	NO	YES			
	MODE BLEND OR SWITCH		SIMULTANEOUS SWITCH ON STICK BUTTON 1 (FIG. 3)					BLEND 20KT $< V_x <$ 30KT
	TRANSITION	CONTROL MODE (LAW)	ENGINE NOZZLE RATE COMMAND	NO DIRECT COMMAND MODE (SEE ROLL)	ENGINE THRUST COMMAND	θ COMMAND AND $\dot{\theta}$ COMMAND (FIXED RATE) θ HOLD	$\dot{\phi}$ COMMAND ϕ HOLD	WITH PEDALS CENTERED $\Delta\dot{\psi}$ COMMAND ON BASE OF $\dot{\psi} = \frac{g \tan\phi_p}{V_a}$ OTHERWISE n_y COMMAND
		CONTROL FORCE PRODUCER	ENGINE NOZZLE DEFLECTION	ROLL ANGLE	ENGINE THRUST	RCS	RCS	RCS
		PILOT CONTROL	POWER LEVER MOUNTED SWITCH	NONE (SEE ROLL)	POWER LEVER	STICK AND TRIM BUTTON	LATERAL STICK	PEDALS
		FLIGHT DIRECTOR	YES	YES	YES			

TABLE 4. – TYPE 2 CONTROL SYSTEM SUMMARY

LANDING PHASE			DEGREE OF FREEDOM					
			X	Y	Z	PITCH	ROLL	YAW
HOVER AND FINAL DESCENT		CONTROL MODE (LAW)	ENGINE NOZZLE COMMAND	NO DIRECT COMMAND MODE (SEE ROLL)	ENGINE THRUST COMMAND	θ COMMAND $\{\dot{\theta}$ COMMAND $\{\theta$ HOLD	ϕ COMMAND	$\dot{\psi}$ COMMAND
		CONTROL FORCE PRODUCER	ENGINE NOZZLE DEFLECTION	ROLL ANGLE	ENGINE THRUST	RCS	RCS	RCS
		PILOT CONTROL	LEVER MOUNTED THUMB BUTTON	NONE (SEE ROLL)	POWER LEVER	STICK AND TRIM BUTTON	LATERAL STICK	PEDALS
		FLIGHT DIRECTOR	YES	YES	YES	X	X	X
MODE BLEND OR SWITCH			SIMULTANEOUS SWITCH ON STICK BUTTON 1 (FIG. 3)			X	BLEND $20KT < V_x < 30KT$	
TRANSITION		CONTROL MODE (LAW)	ENGINE NOZZLE RATE COMMAND	NO DIRECT COMMAND MODE (SEE ROLL)	ENGINE THRUST COMMAND	θ COMMAND $\{\dot{\theta}$ COMMAND $\{\theta$ HOLD	$\dot{\phi}$ COMMAND ϕ HOLD	$\Delta\dot{\psi}$ COMMAND ON BASE OF $\dot{\psi} = \frac{g \tan\phi}{V_x}$
		CONTROL FORCE PRODUCER	ENGINE NOZZLE DEFLECTION	ROLL ANGLE	ENGINE THRUST	RCS	RCS	RCS
		PILOT CONTROL	POWER LEVER MOUNTED SWITCH	NONE (SEE ROLL)	POWER LEVER	STICK AND TRIM BUTTON	LATERAL STICK	PEDALS
		FLIGHT DIRECTOR	YES	YES	YES	X	X	X

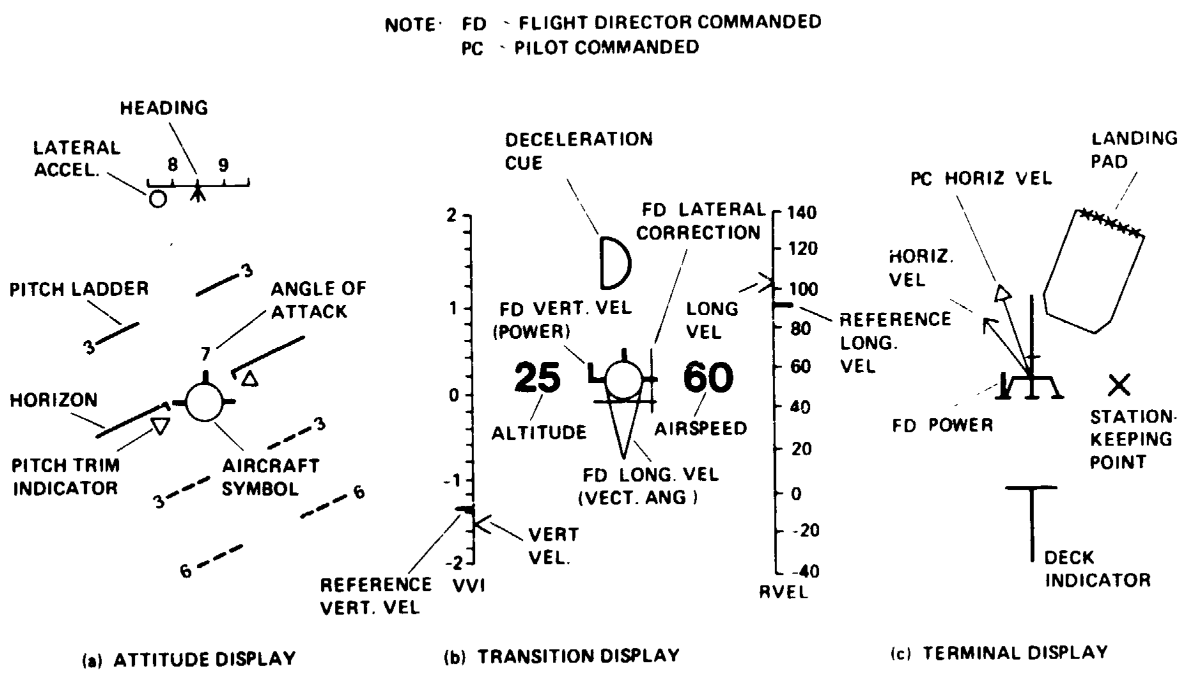


Figure 5.- HUD format breakdown for type 2A system.

PARAMETER VALUES

PARAMETER	TRANSITION	HOVER MANEUVERS AND FINAL DESCENT
k_o	-3.0 $sec^2\ m^{-1}$	0
k_h	0.149 sec^{-2}	0.132 sec^{-2}
$k_{\dot{h}}$	1.0 sec^{-1}	1 0 sec^{-1}
k_{2h}	3.022 deg $sec^2\ m^{-1}$	7.785 deg $sec^2\ m^{-1}$
τ_h	6.130 sec	7.231 sec

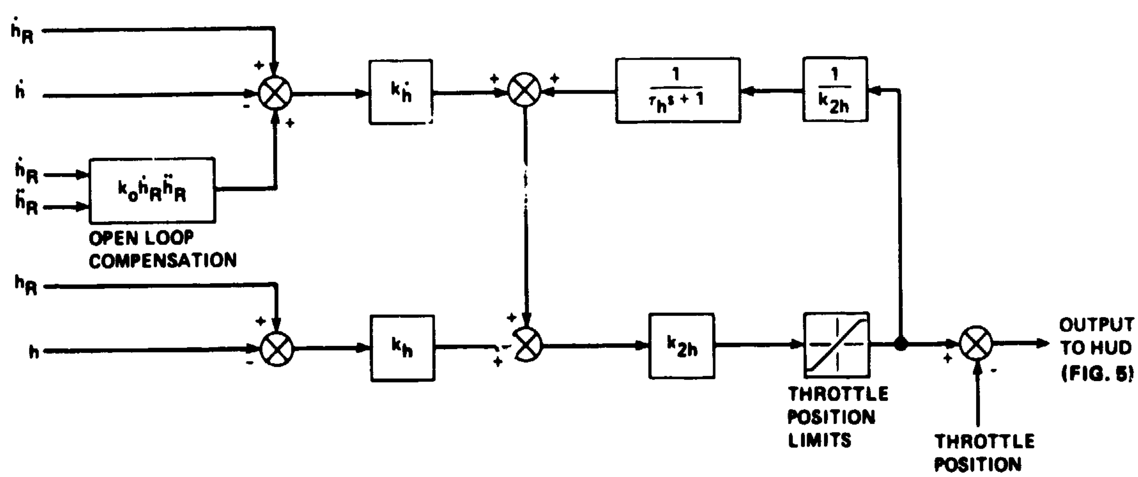


Figure 6.-Vertical (throttle) flight director.

omitted, an open-loop lift-loss compensation term has been added, and the parameter values have been markedly changed. These modifications were recommended in reference 1 and are discussed here.

The sensitivity of the flight director to external disturbances is reduced not only by eliminating the vertical acceleration feedback, but also by increasing the time constant of the trim loop, τ_h, from 0.333 to 6.13 and adjusting the remaining parameters to increase the overall system (direct coupled, without pilot) time constant from 8 sec to 10 sec. This reduction of sensitivity is apparent in figure 7, which shows the altitude and throttle error time histories for transitions using first the old flight director (fig. 7(a)) and then the new flight director without the lift-loss compensation (fig. 7(b)). A comparison of figures 7(a) and 7(b) shows that throttle errors using the new flight director are roughly one-third of those using the old flight director. However, the modifications to achieve this result have the undesirable effect of permitting altitude errors to accumulate during deceleration even though the sensitivity of the new flight director to altitude errors (measured by $k_h k_{2h}$) is increased by a factor of 4.4. This phenomenon points to the

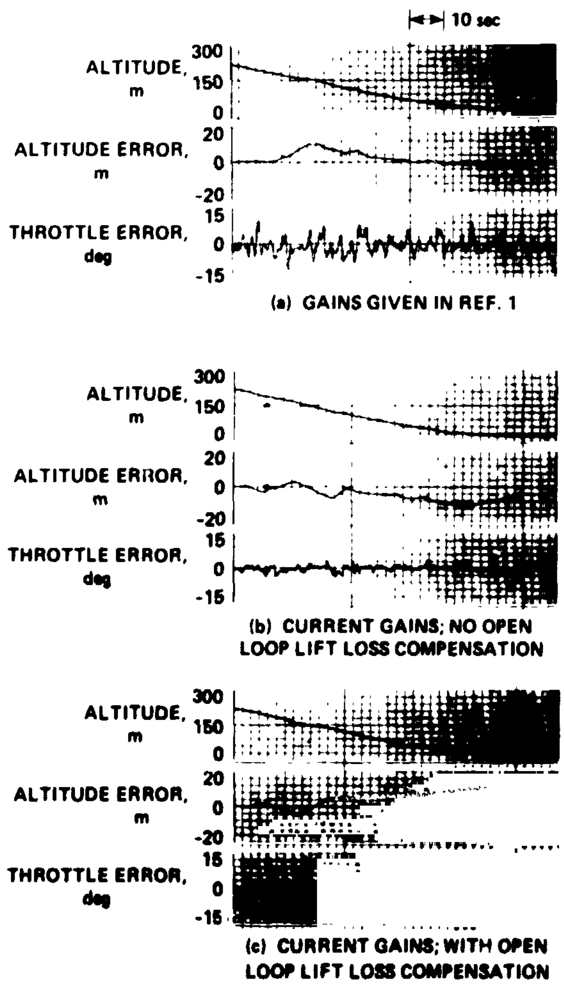


Figure 7.- Effect of throttle flight director changes (transition).

need for the open-loop lift-loss compensation signal provided in the new flight director (fig. 6). The form of this signal is $k_o h_R h_R$, where h_R and h_R are the reference vertical velocity and acceleration, and k_o is a constant. It should be noted here that the lift-loss compensation is a function only of the distance from the initial station-keeping point. The effect of this compensation is to reduce the altitude droop significantly. For example, a comparison of figures 7(b) and 7(c) shows a reduction of altitude droop from 10 m to 4 m measured at an altitude of 30 m.

Vertical (Throttle) Flight Director in Hover

In the Type 2 system, a vertical flight director was provided for both the hover maneuvers and the final descent phases. For the final descent, the pilot could activate a hover-point reference-descent schedule (Appendix A of ref. 1) and the flight director provided throttle-position direction to follow this schedule. In practice, the idea of following a specific reference descent proved to be too inflexible. If the pilot made the decision to descend from the usual 15-m (50-ft) height above the deck, this decision had to be made about 20 sec before touchdown. However, it is not possible to predict the motion of the deck 20 sec into the future, and in high sea states the pilot followed the director for only a short distance during the descent, after which he moved the throttle solely on the information provided by the T-bar. It was decided, therefore, to delete the reference-descent schedule and the associated flight-director information.

The throttle flight director for hover maneuvers is retained in the Type 2A system, and is of the same form as for transition, but with different parameters (fig. 6). In hover, the sensitivity of the Type 2A flight director to altitude change is 20 times greater than that of the Type 2, while maintaining the same 10-sec time constant. This increase of sensitivity can be achieved only by accepting a large increase in the value of the trim-loop time constant, τ_h, from 0.3333 to 7.231. This increase of τ_h is acceptable in hover, since the vertical force change on the aircraft caused by external disturbances and maneuvering is much less in hover than in transition.

Longitudinal (Thrust-Vector-Angle) Flight Director

The major problem with the Type 2 system longitudinal flight director (ref. 1, p. 59) is that substantial residual velocities and accelerations (3 m/sec and 1 m/sec^2) can exist at the end of transition, making it difficult for the pilot to acquire the initial station-keeping point. Two conceptual modifications to improve the director are advanced in reference 1, and a combination of the two is incorporated into the Type 2A system longitudinal flight director. These modifications and their implementation are described here.

One way to reduce the terminal transition errors is to reshape the switching lines (ref. 1, fig. 7) to maintain a tighter control along the upper switching line. This reshaping attempts to increase the amount of lead information from acceleration, especially in the region of small acceleration errors, by adding a linear term to the equations defining the switching lines. The shapes of the switching lines used for the Type 2A and Type 2 longitudinal flight directors are shown in figure 8. The general analytical form for these lines is

$$\left.\begin{aligned}
\text{Line AB:}\quad \Delta V_x &= \Delta V_U - \frac{K_1(\Delta\dot{V}_x)^2}{2g|\dot{\xi}|} - K_2|\Delta\dot{V}_x| \\
\text{Line BC:}\quad \Delta V_x &= \Delta V_U + \frac{K_1(\Delta V_x)^2}{2g|\dot{\xi}|} + K_2|\Delta\dot{V}_x| \\
\text{Line DE:}\quad \Delta V_x &= \Delta V_L - \frac{K_1(\Delta V_x)^2}{2g|\dot{\xi}|} - K_2|\Delta\dot{V}_x| \\
\text{Line EF:}\quad \Delta V_x &= \Delta V_L + \frac{K_1(\Delta V_x)^2}{2g|\dot{\xi}|} + K_2|\Delta\dot{V}_x|
\end{aligned}\right\} \qquad (4)$$

where

ΔV_x longitudinal velocity error

ΔV_U upper longitudinal velocity error at zero acceleration error

ΔV_L lower longitudinal velocity error at zero acceleration error

$\Delta\dot{V}_x$ longitudinal acceleration error

g acceleration due to gravity

$\dot{\xi}$ thrust vector angle rate (fixed) in rad/sec

K_1, K_2 constant gains

Note that with $K_1 = 1$ and $K_2 = 0$, equation (4) becomes identical with equation (1) given in reference 1.

Tests were performed on the fixed-base simulator to establish suitable values of K_1 and K_2. With $K_1 = 1$ and $K_2 = 2$, and the thrust-vector-angle rate increased from 1°/sec to 2°/sec, the velocity and acceleration errors occurring at the end of transition were reduced to about one-half of those made when using the Type 2 system director, although the number of operations of the thrust-vector-rate switch (TVRS) was doubled.

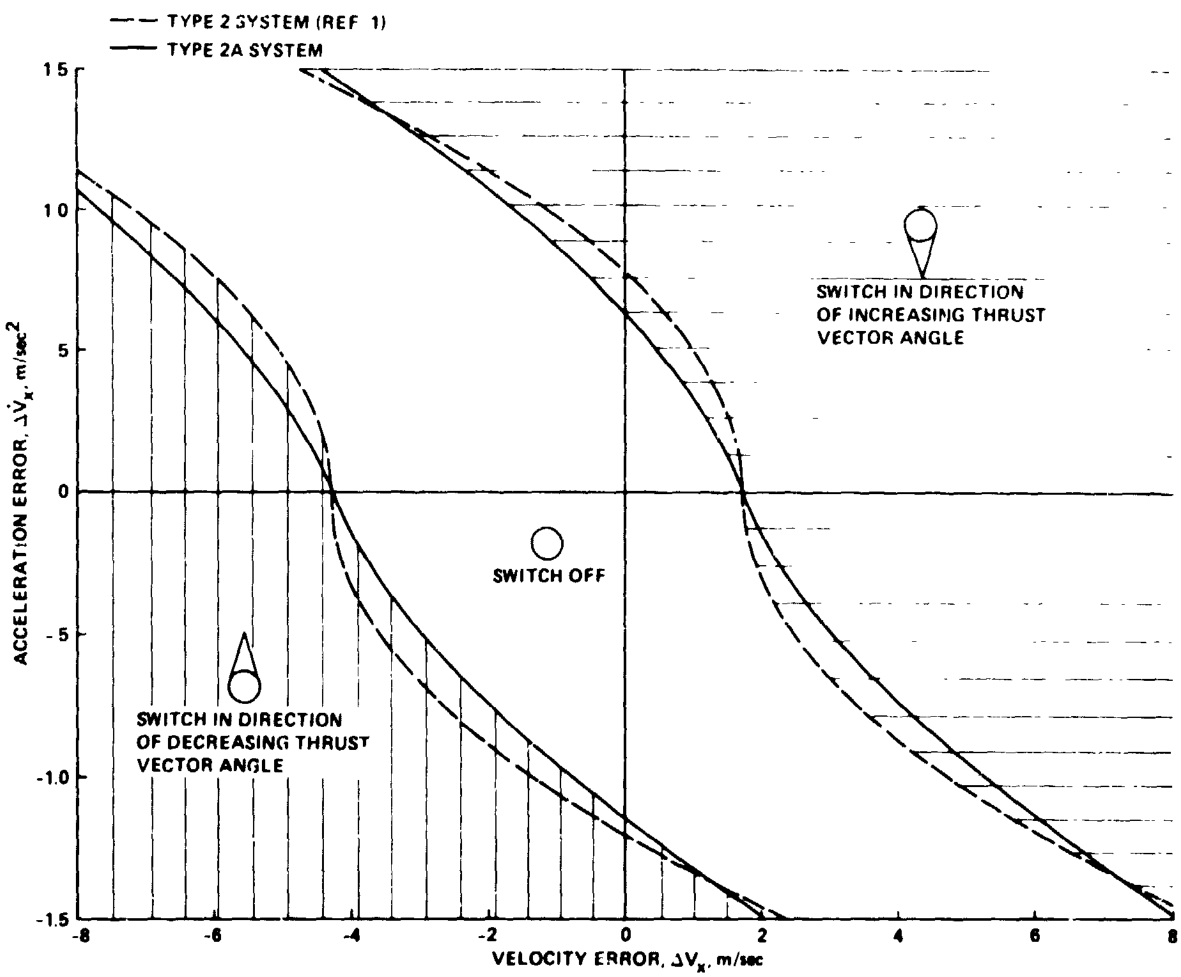


Figure 8.- Comparison of longitudinal flight director switching lines.

Although the reduction in both velocity and acceleration errors made it easier to acquire the initial station-keeping point, the pitch transients that occurred upon switching to the Type 2A translational-velocity system were often unacceptable (±5°). These pitch transients are caused by the nonzero velocity and acceleration at the control-mode switch point. The need to further reduce the velocity and acceleration at the control-mode switch point clearly demonstrates the need to implement the second suggestion of reference 1; namely, an automatic switch to a second set of switching lines defined on the phase-plane of velocity and acceleration errors relative to the initial station-keeping point. The switch from one set of switching logic to the other takes place at a fixed predetermined distance from the initial station-keeping point (tests resulted in the selection of 5 m).

The terminal switching diagram is shown in figure 9, and the analytical forms of the switching lines are

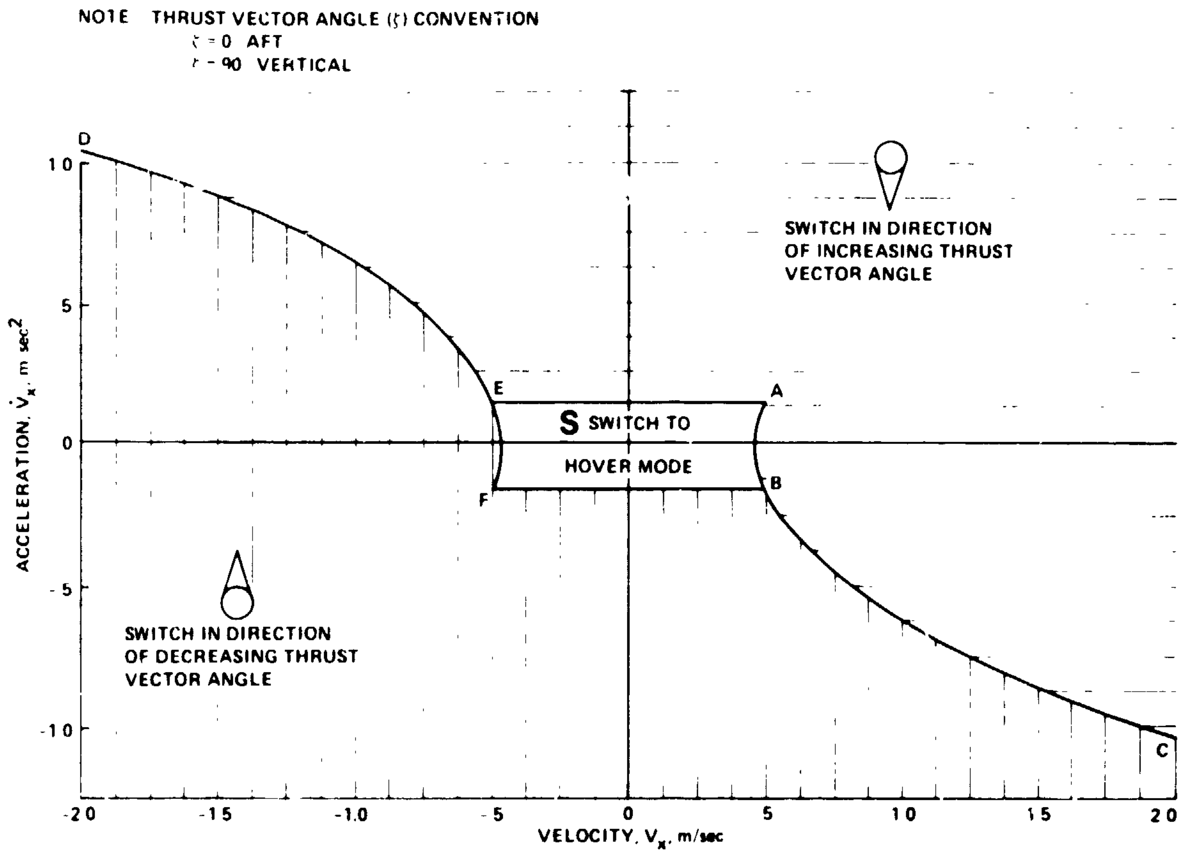


Figure 9.- Longitudinal flight director switching lines when close to initial station-keeping point.

$$
\left.
\begin{aligned}
&\text{Line ABC:} \quad \dot{V}_x = \dot{V}_U - \frac{V_x^2}{2g|\xi|} \\
&\text{Line DEF:} \quad \dot{V}_x = \dot{V}_L + \frac{V_x^2}{2g|\xi|} \\
&\text{Line EA:} \quad \dot{V}_x = \dot{V}_U \\
&\text{Line FB:} \quad \dot{V}_x = \dot{V}_L
\end{aligned}
\right\} \qquad (5)
$$

where

V_x longitudinal velocity relative to the initial station-keeping point

V_U upper longitudinal velocity at zero acceleration

V_L lower longitudinal velocity at zero acceleration

$\dot{V}_x$ longitudinal acceleration relative to the initial station-keeping point

$\dot{V}_U, \dot{V}_L$ constant limit values of longitudinal acceleration

When the phase-plane trajectory is in the area above the line DEABC of figure 9, the pilot is directed by the HUD (see HUD Format) to press the TVRS in the direction of increasing thrust vector angle (decelerate), whereas if the trajectory is in the area below the line DEFBC, the pilot is directed to accelerate. When the trajectory passes into the area ABFE, the pilot is directed to switch to the hover mode. A series of tests carried out on the fixed-base simulator resulted in the following selection of the parameter values: $V_U = -V_L = 0.457$ m/sec (1.5 ft/sec) and $V_U = -V_L = 0.152$ m/sec^2 (0.5 ft/sec^2). With these parameter values, the pitch transient following the mode switch is always less than 1°.

HUD Format

Differences between the Type 2A and Type 2 HUD formats (fig. 5 and fig. 5 of ref. 1) largely parallel those between the Type 1A and Type 1 HUD formats. One element was added to the Type 2A HUD format: a large S which appears in the same position as the large D (fig. 5(b)), and indicates to the pilot that the aircraft's acceleration and velocity are sufficiently small that the switch can be made to the hover mode without incurring a large pitch transient.

OPERATIONAL DESCRIPTION OF CONTROL/DISPLAY SYSTEMS

In operation, the Type 1A and Type 2A systems differ from the Type 1 and Type 2 systems in many details. To facilitate a full appreciation of these differences, a complete step-by-step description is given of the intended piloting procedures during a typical approach and landing. This description may be compared with that given in reference 1 for the Type 1 and Type 2 systems.

Typical Landing Using Type 1A System

It is assumed that at the start of the approach the aircraft is on the glide slope with the scheduled speed and rate of descent, but is displaced laterally from the flightpath and trimmed at a pitch attitude which is different from that required at touchdown. With these conditions, the pilot will have the flightpath-angle-command thumb wheel (fig. 1) and the longitudinal-acceleration thumb wheel (fig. 3) positioned so that the two pilot-command symbols on the left and right scales of the HUD (fig. 2(b)) match the corresponding flight-director symbols.

The actions taken by the pilot during the approach and landing are detailed below.

1. The pilot acquires the flightpath using the lateral stick in conjunction with the lateral flight director (fig. 2(b)). When the curved segment of the flightpath is reached, the lateral flight director makes a sudden move to signal the need to bank the aircraft. The pilot uses the lateral stick to recenter the flight director, thereby establishing the bank angle required to track the curved segment.

2. At a predetermined distance from the initial station-keeping point (this distance depends on the preselected level of longitudinal deceleration during transition), the large D (for decelerate) appears on the HUD (fig. 2(b)), and 5 sec later the acceleration flight-director (right scale of fig. 2(b)) moves from zero to indicate the required deceleration. The pilot, alerted by the D to the imminent need to decelerate, moves the stick-mounted thumb wheel (fig. 3) until the pilot acceleration-command symbol matches the acceleration flight-director symbol. Five seconds after the start of deceleration, the D disappears from the HUD.

3. Since the desired flightpath angle is constant, the vertical-velocity flight director will indicate a gradually reducing rate-of-descent requirement as the aircraft decelerates. However, with flightpath-angle command, the aircraft automatically reduces its rate of descent to maintain the flightpath angle constant. Therefore, the actual and flight-director indicated rates of descent deviate only slightly, and often only a single, small, additional pilot input is required during the entire transition.

4. At about 100 knots, the pilot retrims the aircraft, in pitch, to the touchdown attitude. The pilot may retrim in either of two ways: by using the trim button (fig. 3), which changes the pitch attitude at 2°/sec; or by pressing the trim reset button (switch 3 in fig. 3), so that the control system automatically retrims at 2°/sec to the preset touchdown attitude. When either technique is used, the final trimmed pitch attitude is indicated on the display (fig. 2(a)). It should be noted here that the trim rate for the Type 1 system is 4°/sec. The reduction to 2°/sec for the Type 1A system reflects a preference among the pilots for a lower trim rate.

5. The transition continues with the pilot following the three flight-director symbols (lateral, longitudinal, and vertical) with the appropriate controls, while using the pedals to keep the lateral-acceleration symbol (fig. 2(a)) centered.

6. At 100 m (328 ft) from the initial station-keeping point, the symbol representing the station-keeping point appears on the HUD; and, when the aircraft's speed relative to the station-keeping point is less than 10 m/sec (32.8 ft/sec), the horizontal relative-velocity arrow appears on the HUD (fig. 2(c)). This arrow is the projection of the relative-velocity vector in the horizontal plane. Assuming that

the pilot has followed the flight directors reasonably closely, the initial station-keeping point will approach the fixed aircraft symbol with reducing relative velocity. Eventually, the vertical-velocity and acceleration flight directors will both indicate zero, the relative velocity vector will be small, and the pilot will usually have the longitudinal-acceleration thumb wheel in the detent, but the flightpath-control thumb wheel may not be in the detent. In any event, the position of these thumb wheels at the switch point is not important to subsequent events.

7. At this point in the landing, the pilot changes control modes and hand controls by pressing switch no. 1 on the stick (fig. 3). This action changes the control system from longitudinal-acceleration command through the stick thumb wheel to longitudinal-velocity command through the stick, from roll-rate command through the stick to lateral-velocity command through the stick, and from flightpath-angle command through the lever thumb wheel to vertical-velocity command through the lever (table 1). Since the stick is usually in the center position when the switch is made, the residual velocity of the aircraft relative to the initial station-keeping point is automatically reduced to zero. The pressing of switch No. 1 also introduces the pilot-command horizontal-velocity arrow on the HUD (fig. 2(c)).

8. With the vertical-velocity lever in the detent (altitude-hold feature active), the pilot moves the stick so that the pilot-command arrow on the HUD points to the initial station-keeping point. In this manner, the pilot brings the aircraft symbol and initial station-keeping-point symbol together.

9. The pilot then presses switch No. 2 on the stick (fig. 3), and the station-keeping-point symbol on the HUD jumps to the center of the landing pad.

10. The pilot moves the stick to bring the aircraft symbol and station-keeping-point symbol (now in its final position) together.

11. When the altitude is less than 30 m (100 ft) above the deck, the deck-altitude-indicator symbol (T-bar) appears on the HUD (fig. 2(c)). The pilot uses the vertical-velocity indicator and T-bar to judge the final descent to touchdown. At the instant of touchdown, the pilot pulls back the vertical-velocity lever to reduce the engine speed to idle.

Typical Landing Using Type 2A System

The aircraft's state at the start of the approach is assumed to be the same as that in the description of the use of the Type 1A system. The pilot is assumed to have the power and thrust-vector-angle levers positioned correctly for the start-of-approach conditions.

The actions taken by the pilot during the approach and landing are detailed below.

1. The pilot acquires and maintains position on the flightpath using the lateral stick in conjunction with the lateral flight director (fig. 5(b)).

2. At a predetermined point, the large D appears on the HUD to signal that the start of deceleration is imminent. Five seconds later, the longitudinal (thrust-vector-angle) flight director indicates the start of deceleration by a broad arrow on the HUD, pointing downward (fig. 5(b)). The pilot has the option of pressing the TVRS, or, if a nose-up trim change is required to reach the landing attitude, of making the trim change. Executing either or both of these options causes the aircraft to decelerate. Eventually the arrow symbol will disappear, indicating that the speed/acceleration error criterion is satisfied. While starting to decelerate, the pilot must follow the vertical (power) flight director to maintain position on the glide slope.

3. The transition continues with the pilot following the lateral, longitudinal, and vertical flight directors using the stick, power lever, and TVRS, respectively. The longitudinal flight director will indicate a downward-pointing arrow (increase the thrust-vector angle) six to eight times and may, under some circumstances, indicate an up arrow (decrease the thrust-vector angle).

When the aircraft is close to the initial station-keeping point (less than 5 m), the terminal thrust-vector-angle flight director becomes active and usually signals to the pilot for two or three activations of the TVRS in fairly rapid succession, after which the velocity and acceleration are small enough that a switch to the hover mode can be made. The switch point is indicated by a large S on the HUD.

4. The pilot then presses switch No. 1 on the stick grip. This action changes the control system from pitch-attitude and roll-rate commands through the stick to longitudinal- and lateral-velocity commands through the stick. Pitch-rate command is retained through the trim button, but is attained by rotating the thrust-vector angle at 2°/sec. The pressing of switch No. 1 also introduces the pilot-command horizontal-velocity arrow on the HUD (fig. 5(c)).

5. The pilot commands the appropriate longitudinal and lateral velocities to bring the aircraft close to the initial station-keeping point.

6. The pilot then presses switch No. 2 on the stick grip, and the station-keeping-point symbol on the HUD jumps to the center of the landing pad.

7. The pilot moves the stick to bring the aircraft symbol and station-keeping-point symbol (now in its final position) together while simultaneously following the vertical flight director with the throttle to maintain a constant altitude.

8. Once satisfied with the location of the aircraft over the deck, the pilot presses switch No. 2 a second time. This action deactivates the throttle flight director, and the pilot performs the final descent using throttle and T-bar only.

SIMULATION

Simulation Models

The models used for the AV-8A Harrier, Spruance-class destroyer (DD 963), ship air-wake, and isotropic turbulence were the same as those used in the simulation reported in reference 1.

Scope of the Simulation

The areas of evaluation and comparison of the control/display systems are summarized in the following sections.

1. Operational acceptability of the task

2. Pilots' evaluations of transitions and landings

3. Task performance parameters

4. Control use

5. Evaluation of the HUD formats

6. Evaluation of the pilot-control modes

7. Evaluation of the flight directors

8. Evaluation of the pilot controls (inceptors)

9. Simulation equipment limitations

Following the lead established in reference 1, the approach and landing task was divided into two parts. One part was the approach transition starting at 120 knots and ending at the initial station-keeping point. The other was the hover maneuvers and final descent starting at the initial station-keeping point and ending at touchdown. These two parts will be termed "transition" and "landing," respectively.

The reference approach path used throughout the simulation is shown in figure 10. This path has an initial straight segment, a curved segment 2553 m (8377 ft) long with a radius of 2438 m (8000 ft), and a final straight segment 305 m (1000 ft) long. The final segment terminates at the initial station-keeping point. The flightpath has a constant -3° slope, and the headings of the initial and final straight segments are 30° and 90°, respectively. Since the ship is heading due east, the final segment is parallel to the ship (fig. 11).

In the previous simulation (ref. 1), the pilots noted that the initial station-keeping point was located in the ship air-wake for some test conditions, and such a location may be operationally unacceptable for these conditions. Despite this

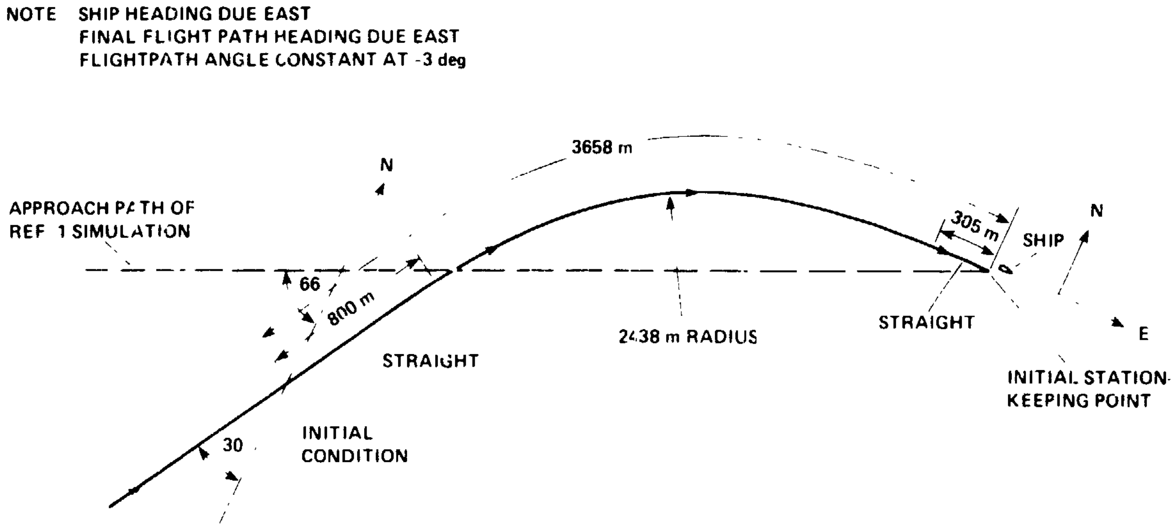


Figure 10.- Plan view of approach path.

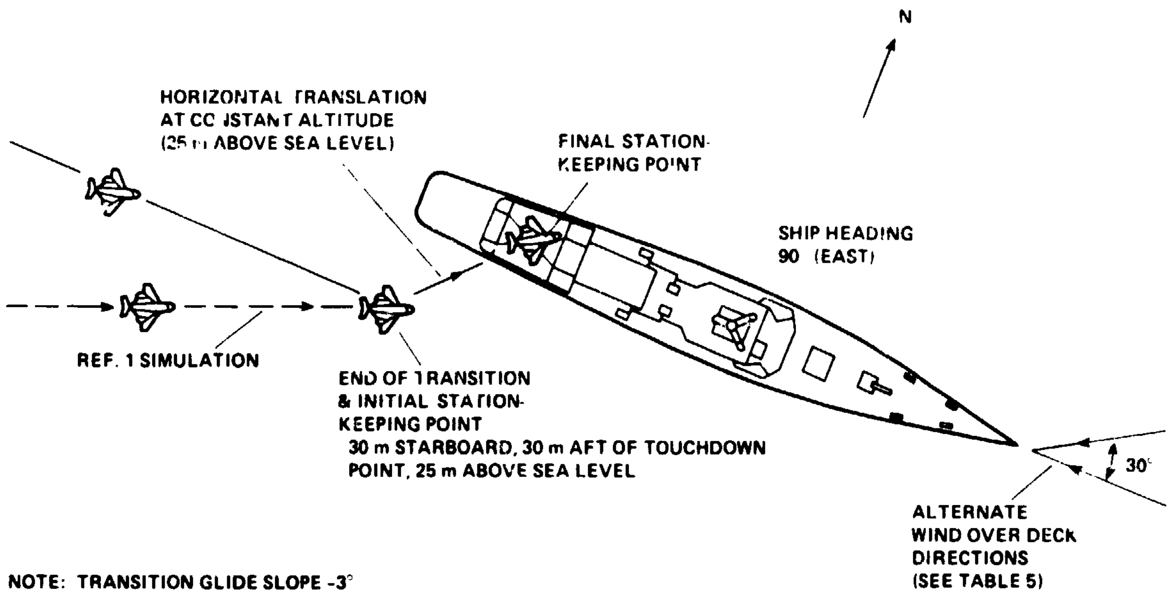


Figure 11.- Geometry of final approach.

possible objection, the same location of the initial station-keeping point was used; namely, 30 m (100 ft) to starboard, 30 m (100 ft) aft of the touchdown point, and 25 m (82 ft) above sea level. The decision to retain the same location was motivated by the desire to provide continuity between the two simulations.

Throughout the tests the aircraft was assumed to start the approach 3658 m (12,000 ft) from the initial station-keeping point at a speed of 120 knots relative to the ship. The reference flightpath altitude at the 3658-m (12,000-ft) point is 217 m (712 ft) above sea level. A reference longitudinal deceleration of 0.91 m/sec^2 (3 ft/sec^2) was standard throughout the tests. The rate-of-descent variation with altitude corresponding to the initial relative speed of 120 knots and 0.91 m/sec^2 deceleration is shown in figure 16 of reference 1.

The two environmental variables associated with the transition task are air turbulence and visibility. Free-air turbulence levels were varied up to a maximum of 3.05 m/sec (10 ft/sec) rms. Visibility conditions were the same as those used in reference 1; namely, a ceiling of 30 m (100 ft) and a runway visual range (RVR) of 213 m (700 ft). With the -3° flightpath angle, the ship becomes visible at a range of about 150 m (500 ft). All transitions were started with the aircraft displaced from the reference flightpath 46 m (150 ft) laterally and 15 km (50 ft) vertically.

The geometry of the nominal landing is shown in figure 11. The environmental conditions in the vicinity of the ship were identical to those used in the tests described in reference 1. These conditions are given in table 5. To facilitate an appreciation of the effect of sea state on the landing task, the standard deviations of the deck angles and landing point displacements are given in table 6, and the standard deviations of the associated velocities are given in table 7. It is not possible to characterize adequately the ship-air-wake turbulence with one or two parameters, as can be done with ship motion, because the turbulence and mean airspeeds vary considerably with position. However, some indication of the magnitude of the air disturbances is shown in figure 12, which gives the airspeeds in the aircraft's x, y, and z body-fixed axes system during typical landings for each of the environmental conditions given in table 5. Of particular note is the rapid reduction of longitudinal airspeed in the final descent due to the shielding effect of the hangar.

TABLE 5.- SIMULATION ENVIRONMENTAL CONDITIONS

Condition no.	Sea state	V_s, knots	μ_s, deg	ψ_w, deg	ψ_{WOD}, deg	V_w, knots	V_{WOD}, knots	H_s, m	T_o, sec
1	6	25	120	-60	-30	25.00	43.30	5.49	15.13
2	5	25	120	-60	-30	25.00	43.30	3.66	13.50
3	5	20	120	-60	-30	20.00	34.64	3.66	13.50
4	5	10	135	-45	-30	19.32	27.32	3.66	13.07
5	5	25	180	0	0	20.00	45.00	3.66	12.07
6	5	5	180	0	0	20.00	25.00	3.66	11.51
7	4	25	105	-75	-30	17.68	34.15	2.10	10.60
8	3	25	105	-75	-30	17.68	34.15	1.40	8.80
9	3	20	105	-75	-30	14.14	27.32	1.40	8.80
10	3	25	90	-90	-30	14.43	28.87	1.40	8.80
11	3	15	120	-60	-30	15.00	25.98	1.40	8.80
12	3	25	180	0	0	14.00	39.00	1.40	8.80
13	3	5	180	0	0	14.00	19.00	1.40	8.80
14	0	10	-	-68.6	-30	8.07	15.00	0	-

TABLE 6.- STANDARD DEVIATIONS OF SHIP POSITION

Condition no.	σ_{ϕ}, deg	σ_{θ}, deg	σ_{ψ}, deg	$\sigma_{x_{cg}}$, m	$\sigma_{y_{cg}}$, m	$\sigma_{z_{cg}}$, m	$\sigma_{x_{\ell p}}$, m	$\sigma_{y_{\ell p}}$, m	$\sigma_{z_{\ell p}}$, m
1	3.13	1.05	0.45	0.24	0.71	1.51	0.45	0.63	1.67
2	2.03	.77	.30	.15	.42	1.02	.30	.40	1.17
3	2.38	.80	.34	.16	.44	.96	.32	.46	1.12
4	2.92	.97	.36	.23	.32	.72	.43	.91	.98
5	0	.93	0	.13	0	.81	.31	0	1.09
6	0	.90	0	.25	0	.44	.43	0	.72
7	1.11	.34	.17	.05	.27	.60	.12	.18	.65
8	.57	.24	.11	.03	.14	.39	.06	.16	.44
9	.65	.26	.12	.03	.15	.38	.08	.18	.43
10	.65	.09	.04	.01	.23	.36	.03	.22	.37
11	.62	.35	.13	.04	.08	.29	.11	.18	.41
12	0	.21	0	.02	0	.17	.06	0	.25
13	0	.24	0	.04	0	.09	.09	0	.20
14	0	0	0	0	0	0	0	0	0

TABLE 7.- STANDARD DEVIATIONS OF SHIP VELOCITY

Condition no.	$\sigma_{\dot{\phi}}$, deg/sec	$\sigma_{\dot{\theta}}$, deg/sec	$\sigma_{\dot{\psi}}$, deg/sec	$\sigma_{\dot{x}_{cg}}$, m/sec	$\sigma_{\dot{y}_{cg}}$, m/sec	$\sigma_{\dot{z}_{cg}}$, m/sec	$\sigma_{\dot{x}_{\ell p}}$, m/sec	$\sigma_{\dot{y}_{\ell p}}$, m/sec	$\sigma_{\dot{z}_{\ell p}}$, m/sec
1	2.00	0.90	0.36	0.15	0.41	1.10	0.32	0.46	1.31
2	1.39	.69	.26	.10	.27	.82	.23	.35	.98
3	1.57	.69	.28	.11	.27	.72	.24	.38	.91
4	1.82	.75	.24	.14	.18	.47	.29	.53	.73
5	0	.90	0	.11	0	.75	.27	0	1.05
6	0	.63	0	.14	0	.29	.27	0	.52
7	.88	.32	.18	.04	.21	.53	.10	.20	.59
8	.55	.25	.14	.02	.13	.38	.06	.20	.44
9	.59	.26	.14	.03	.13	.36	.07	.21	.42
10	.50	.09	.04	.01	.18	.31	.03	.18	.32
11	.54	.35	.13	.03	.07	.28	.10	.18	.40
12	0	.23	0	.02	0	.19	.06	0	.28
13	0	.20	0	.03	0	.08	.07	0	.17
14	0	0	0	0	0	0	0	0	0

The test parameters and configuration assumed for the AV-8A are given in table 8. The weight of 77,840 N (17,500 lb) and maximum thrust of 85,628 N (19,250 lb) give a maximum, free-air, hovering thrust/weight ratio of 1.1. This maximum engine thrust was kept constant throughout the tests. The aircraft weight was varied only for those tests used to evaluate the effects of reduced thrust/weight ratio during landing. Throughout the tests, the effects of engine rating, time limits, and fuel consumption on the aircraft's parameters were suppressed. Also

TABLE 8.- AV-8A TEST PARAMETERS CONFIGURATION;
NO STORES, GEAR DOWN, FLAPS AT 50°

Parameter	Value
Weight	77,840 N (17,500 lb)
Maximum thrust	85,628 N (19,250 lb)
X moment of inertia	7,807 kg m^2 (5,758 slug ft^2)
Y moment of inertia	39,476 kg m^2 (29,116 slug ft^2)
Z moment of inertia	43,769 kg m^2 (32,282 slug ft^2)
XZ product of inertia	1,971 kg m^2 (1,454 slug ft^2)
Maximum RCS pitch control power (nose up)	0.56 rad/sec^2
Maximum RCS pitch control power (nose down)	0.86 rad/sec^2
Maximum RCS roll control power	1.68 rad/sec^2
Maximum RCS yaw control power	0.44 rad/sec^2

Note: RCS ‑ reaction control system. All control powers are for singular demand.

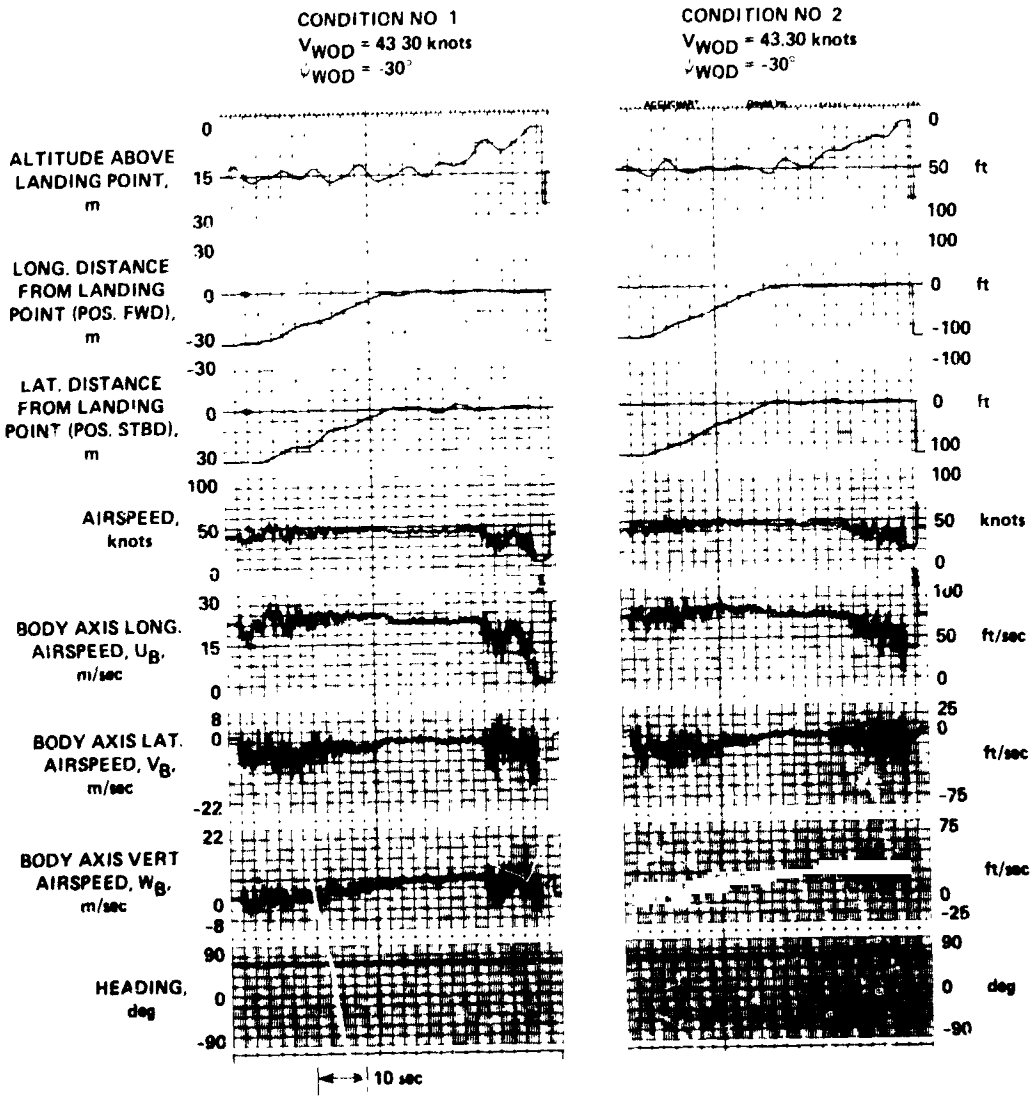
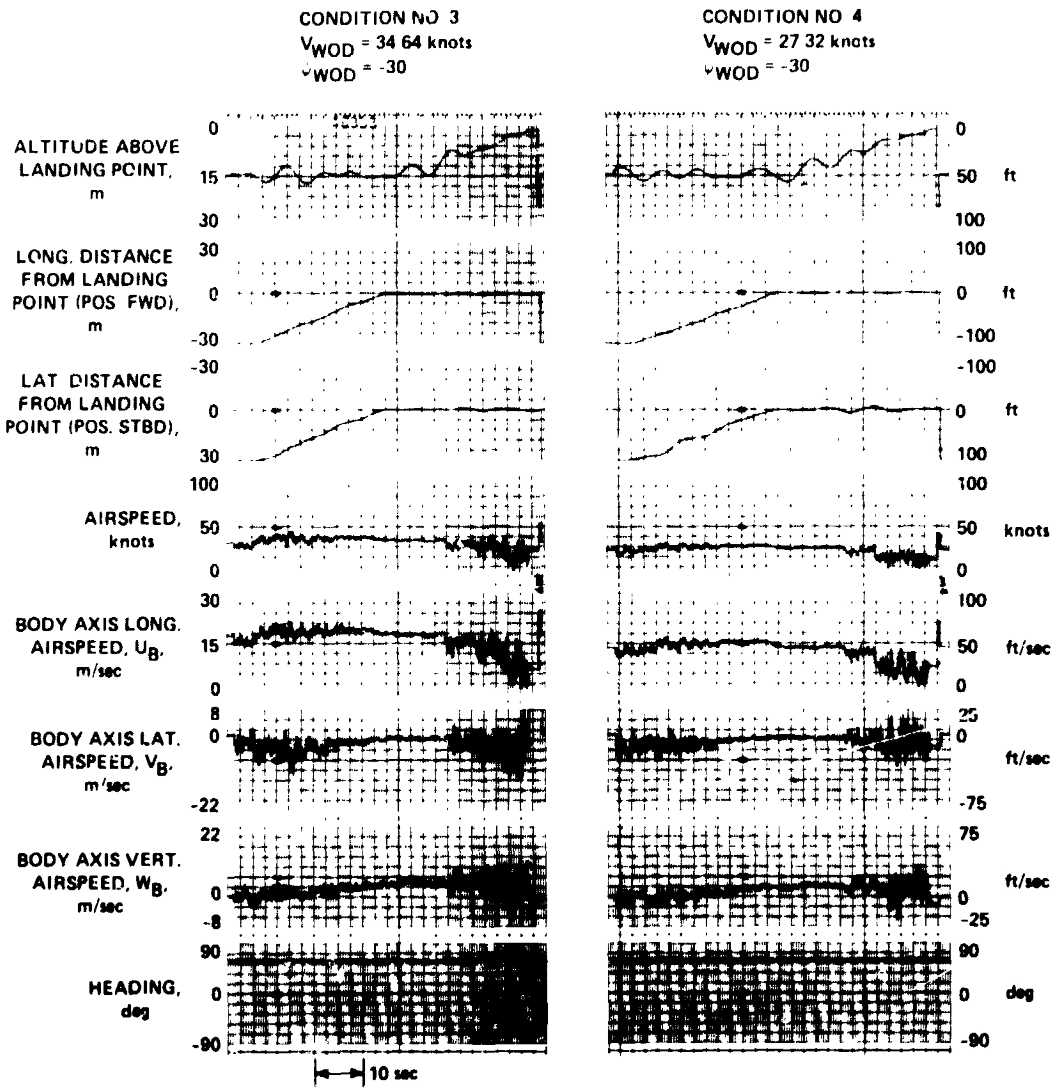


Figure 12.- Turbulence in typical landing from initial station-keeping point to touchdown.



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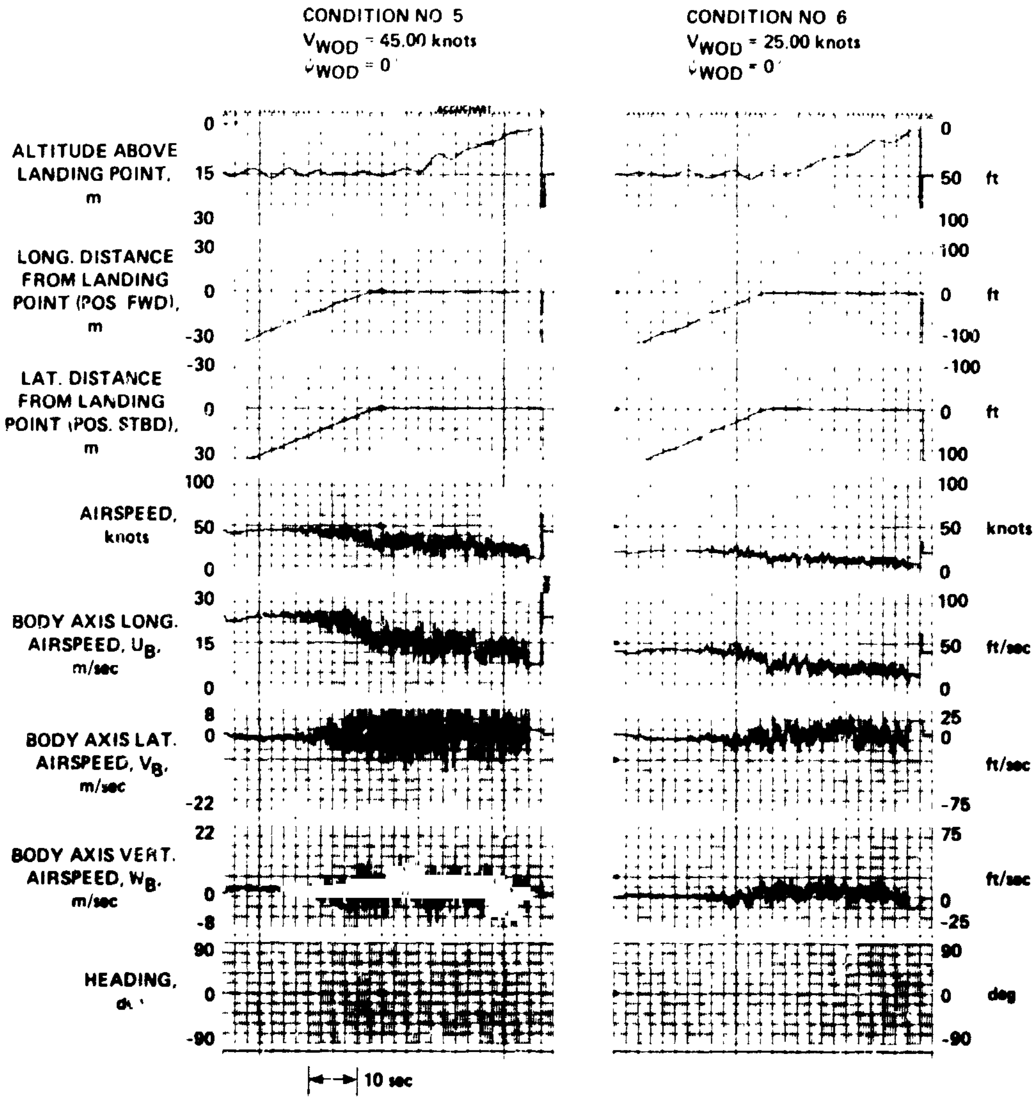

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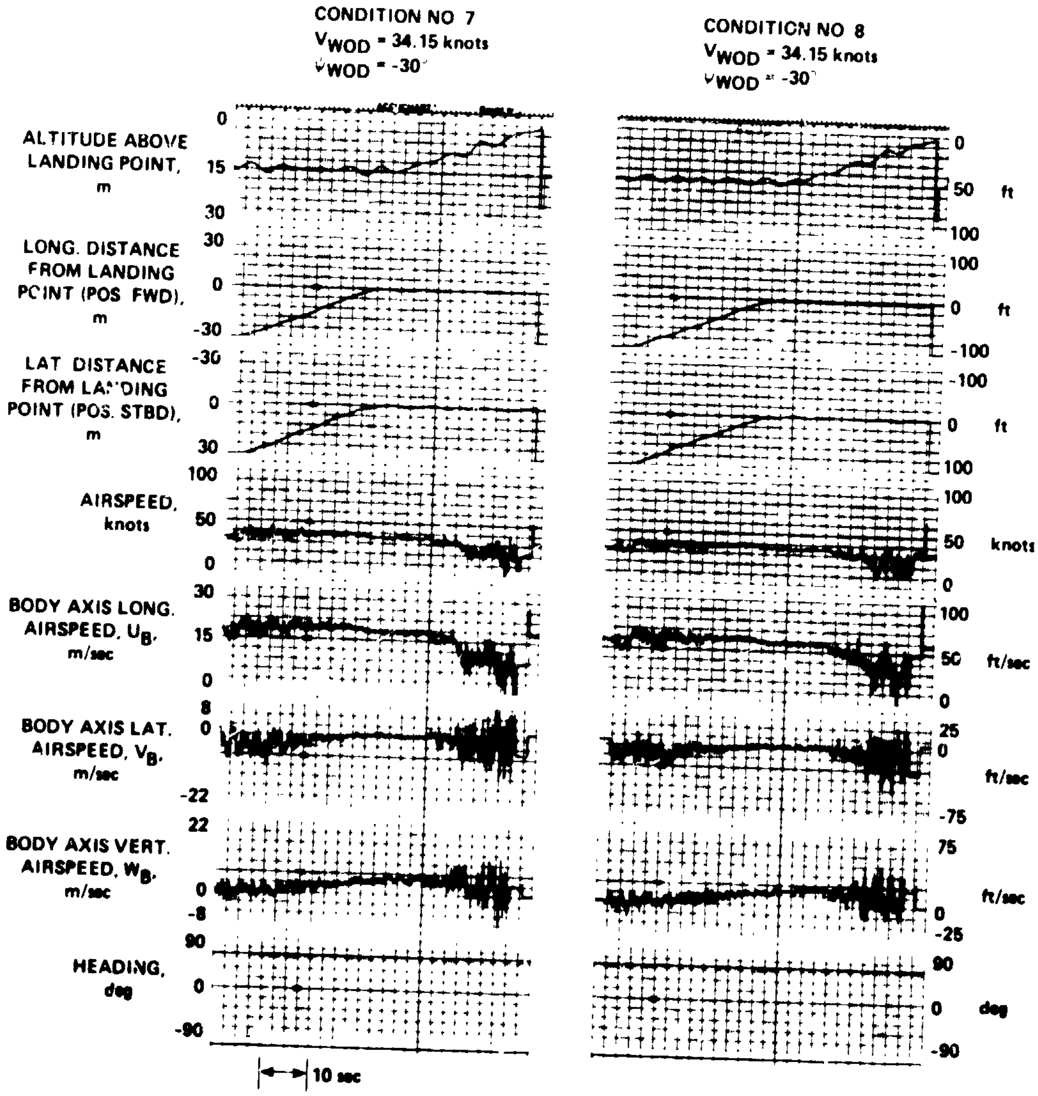

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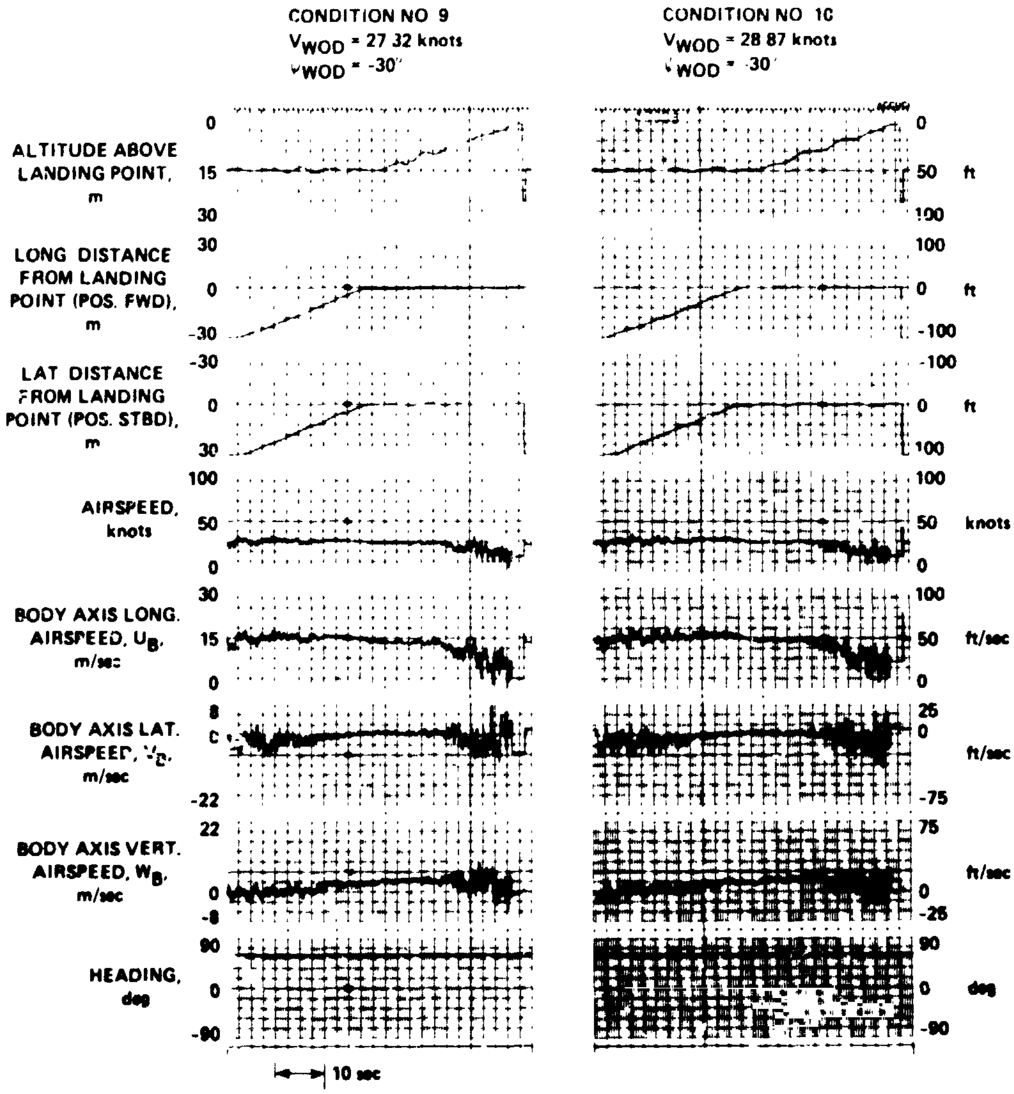

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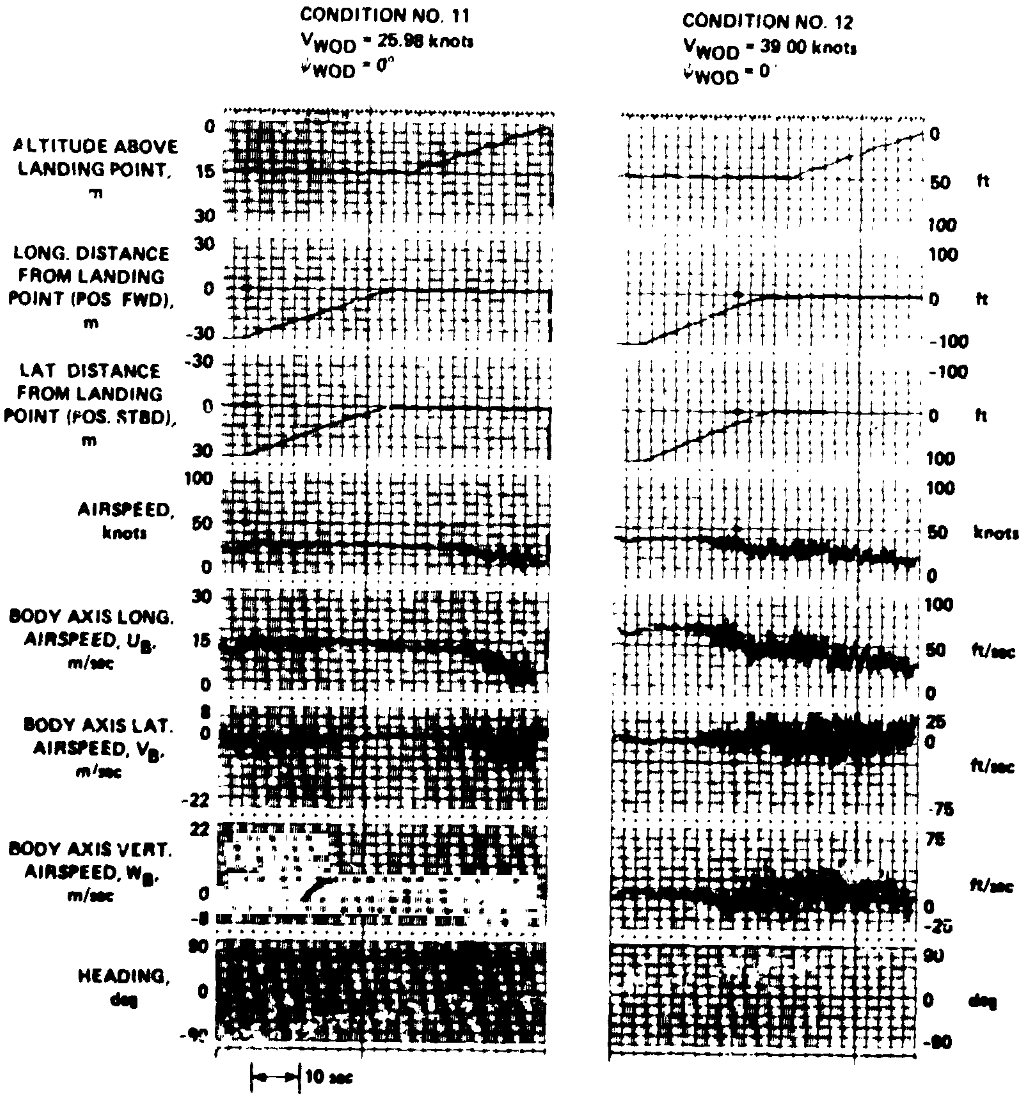

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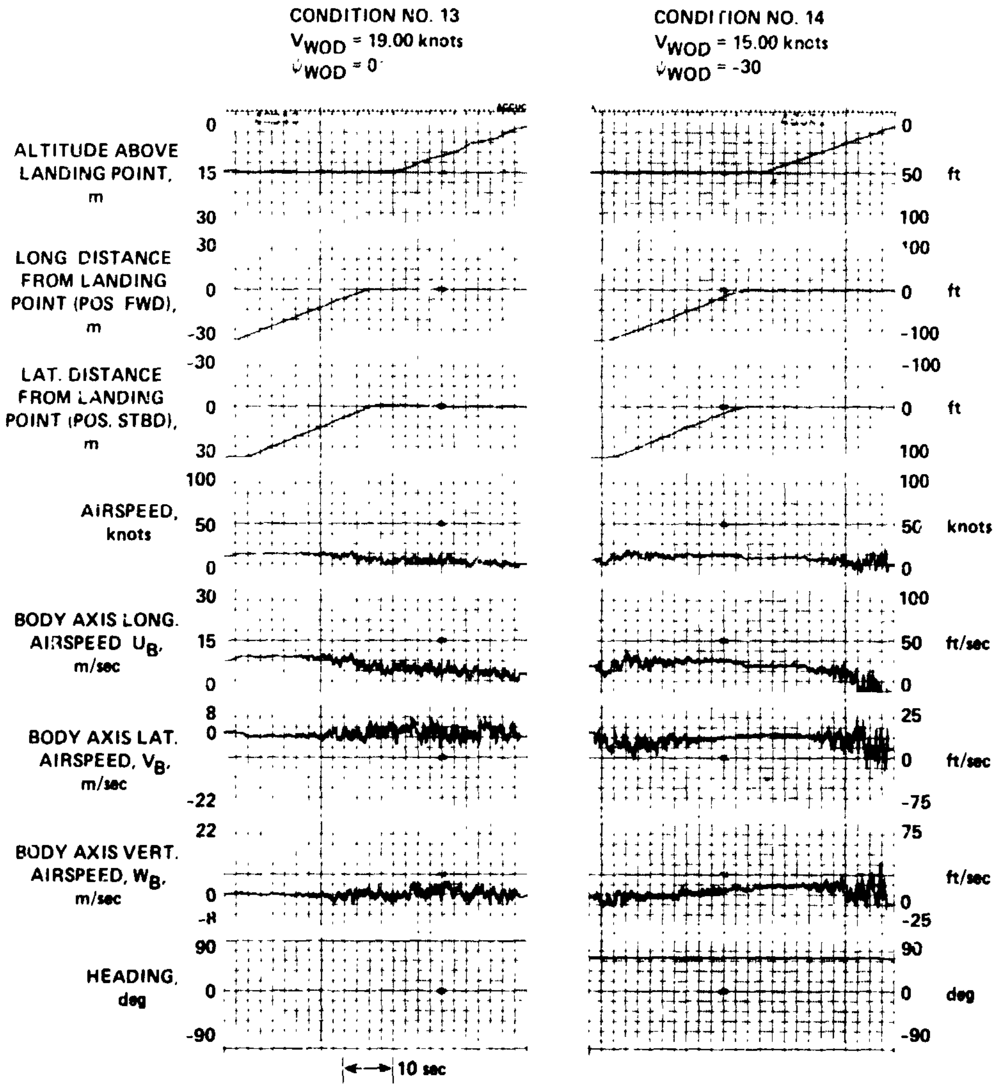

Figure 12.- Concluded.

given in table 8 are the maximum attitude-reaction-control powers for singular demand.

In addition to the tests of the Type 1A and Type 2A systems, a series of variants of the Type 1A system were tested to compare different arrangements of pilot controls (inceptors) for the control of altitude and speed. Any two of the four available Type 1A pilot controls (lever, lever thumb wheel, stick, and stick thumb wheel) were selected to perform the entire approach and landing, for a total of 12 combinations. These tests were performed in a turbulence of 1.22 m/sec (4 ft/sec) and ship environmental condition 7 (sea state 4) using the pilot control modes of the Type 1A system. Prior to the evaluation of each control combination, the pilot performed at least two constant-altitude visual approaches and landings to determine the most natural "sense" of the control (e.g., thumb wheel forward for descent). These preliminary tests were very important for unusual control arrangements.

Also evaluated during the tests were the transition yaw-controller mode used both in the Type 1A and Type 2A systems, and an alternate flightpath-angle rate-command system for vertical control in the Type 1A system during transition.

Before recording data for each major test phase, the pilots were given some time in the simulator to familiarize themselves with the control/display system and the task. All the pilot ratings for the various tests were based on the standard Cooper-Harper handling-qualities rating scale given in figure 13.

Simulation Equipment

The tests were conducted using the Ames FSAA. This simulator and its dynamic performance are fully described in reference 7. Details of the simulator motion-drive-washout logic used in the tests are given in appendix C of reference 1.

The cockpit instrument panel used for the tests is shown in figure 14. This instrument panel differed somewhat from that used in the tests described in reference 1. Although this panel does not duplicate that of an AV-8A Harrier, it is a closer representation than that used in the previous tests. In any case, the primary source of information required by the pilot is provided by the HUD. Force and displacement characteristics of the stick and pedals are given in reference 1.

The equipment used to provide a view out of the cockpit and of the HUD was the same as that used in the previous tests.

The 1/250-scale model of a DD 963 Spruance-class destroyer used in the previous tests was again used, but the ship-motion drive mechanism provided a full six degrees of freedom.

As in the previous simulation, a Xerox Corporation Sigma-8 computer operating at a frame time of 55 msec was used for overall control of the simulation, and a Digital Equipment Corporation PDP-11/55 was used to generate the HUD at an update frame time of 110 msec.

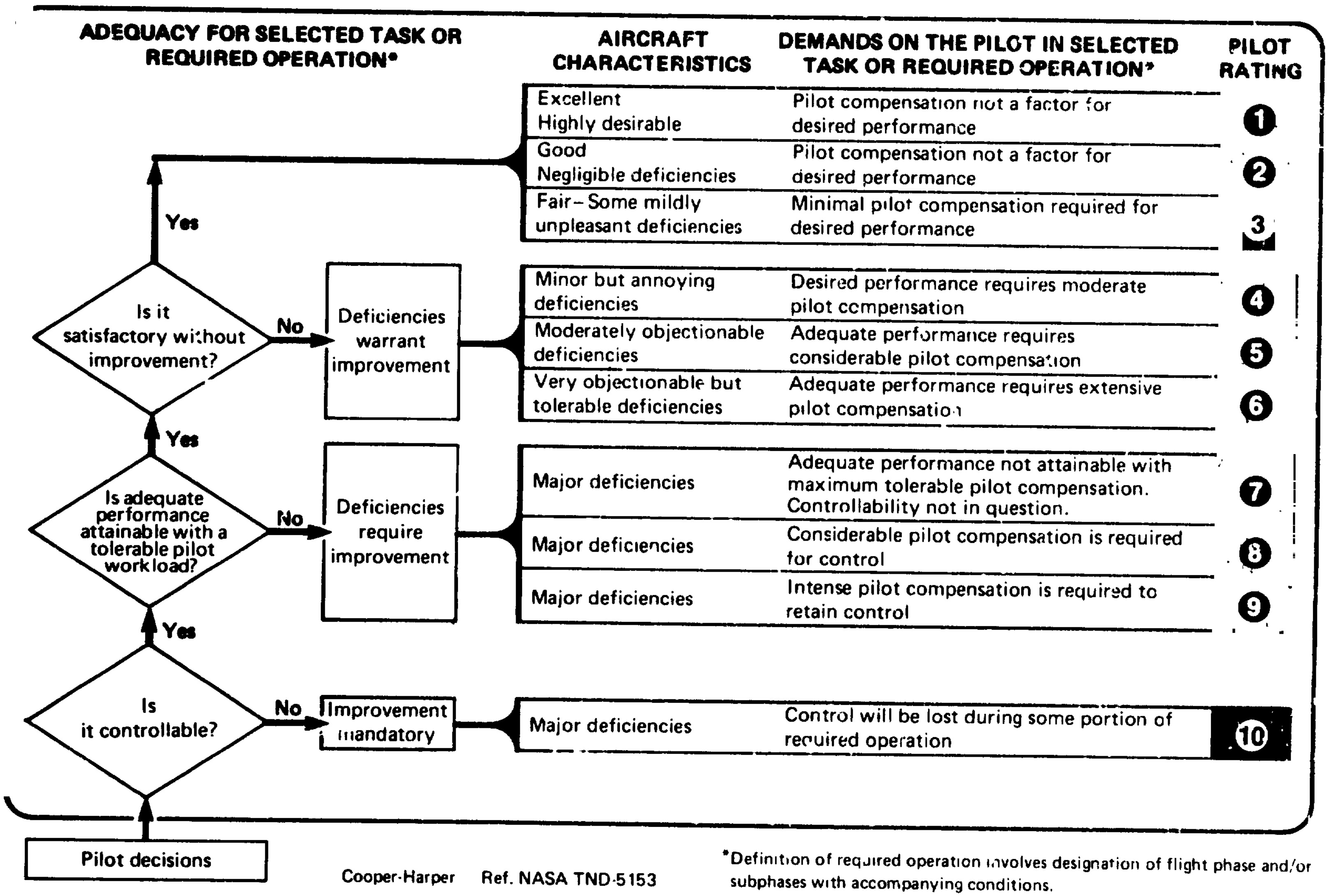

Figure 13.- Handling-qualities rating scale.

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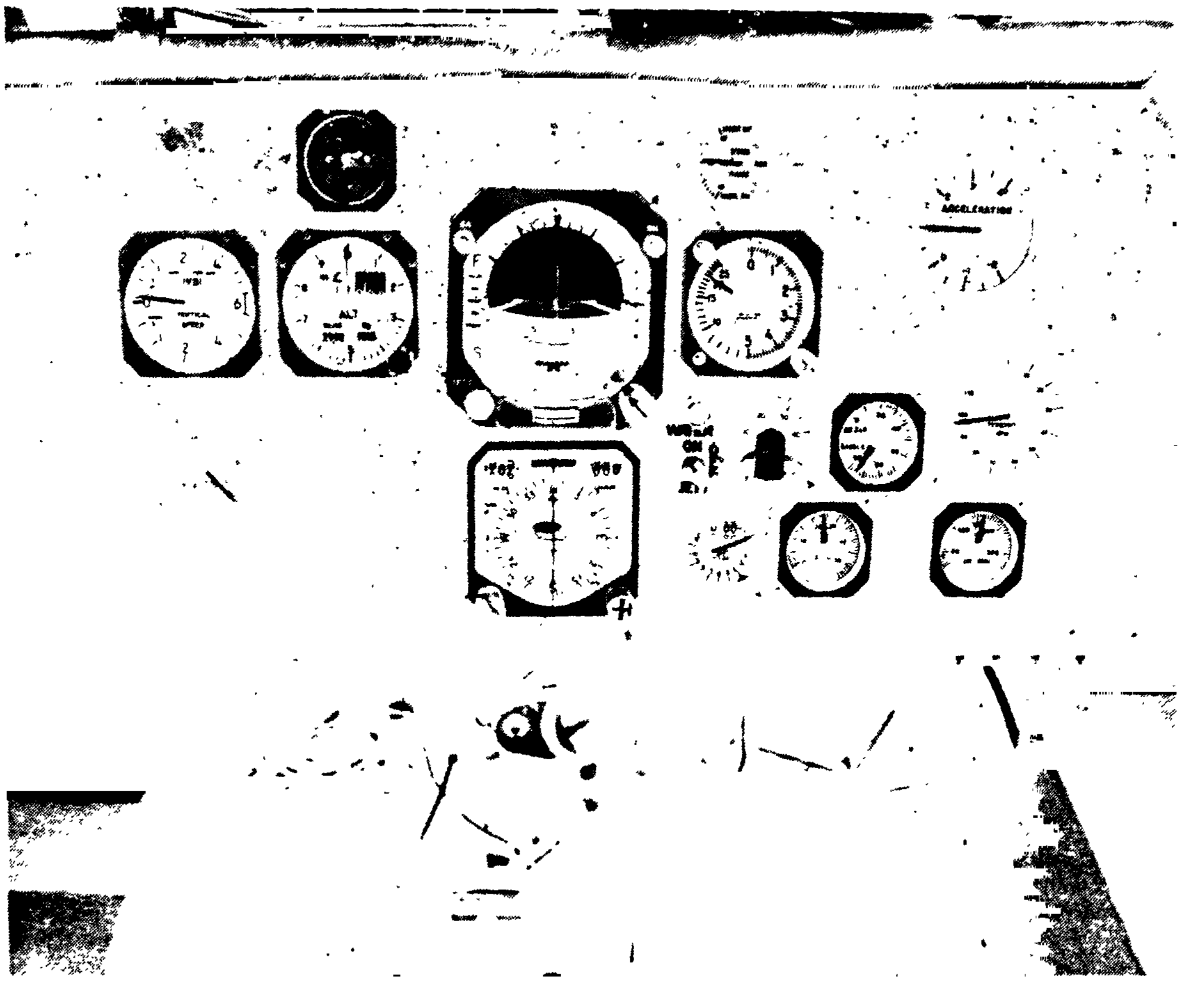


Figure 14.- Photograph of instrument panel.

Pilot Experience

Three pilots participated in the simulation: one from United Kingdom's Royal Aircraft Establishment (RAE), Bedford, England; one from United Kingdom's Civil Aviation Authority (CAA); and one from NASA Ames Research Center.

The RAE pilot had a total flight experience of 2300 hr, including 1200 hr in various marks of Harrier aircraft in the VSTOL, ground attack, reconnaissance, and test-flying roles. He participated in the sea trials to develop HUD formats and operational techniques now used for the recovery of Sea Harriers to Invincible-class ships in poor weather and at night. He also participated in the October 1979 simulation study at NASA Ames Research Center (ref. 1).

The CAA pilot had a total flight experience of 4600 hr of which 4000 hr were in helicopters. He had no jet VTOL experience and only minimal HUD experience. His participation in the current simulation was restricted to evaluating various pilot-control (inceptor) arrangements.

The NASA Ames pilot had a total flight experience of 7600 hr and had participated in a variety of VTOL research projects, including the X-14, X-22, and XV-5. He also had about 5 hr of Harrier experience, and had participated in the previous simulation.

In the results section of the report, the pilots are identified by their initials: PD is the RAE pilot, PH is the CAA pilot, and RG is the NASA Ames pilot.

SIMULATION RESULTS AND DISCUSSION

Results presented here are organized under the headings listed earlier in "Scope of the Simulation." Additional comments of the RAE pilot are presented in reference 8.

Operational Acceptability of the Task

Even though for some test conditions the initial station-keeping point was in the ship's air wake (see "Scope of the Simulation"), the pilots regarded the task as both an operationally acceptable and a well-balanced test of all the important control/display elements.

Although the deceleration schedule used in the current tests was identical to that used in the previous tests, the pilots reported significantly less workload just prior to the switch to the hover mode. The reasons for this improvement are to be found in the particular characteristics of the Type 1A and Type 2A systems, as discussed later. This reduced workload was a significant factor in the judgment of the operational acceptability of the task.

Pilots' Evaluations of Transitions and Landings

Transition (Type 1A System)- The variation of pilot ratings with turbulence level (fig. 15) shows excellent agreement between the two pilots, with ratings of less than 3-1/2 (satisfactory without improvement) up to turbulence levels of about 2.5 m/sec (8.2 ft/sec) rms. These results show a 1/2 to 1 pilot-rating improvement over those for the Type 1 system (summarized in fig. 15), which was rated less than 3-1/2 up to turbulence levels of about 1.4 m/sec (4.6 ft/sec) rms. However, the overall workload reduction using the Type 1A relative to the Type 1 system is even more pronounced than is indicated in figure 15, since the curved flightpath used in

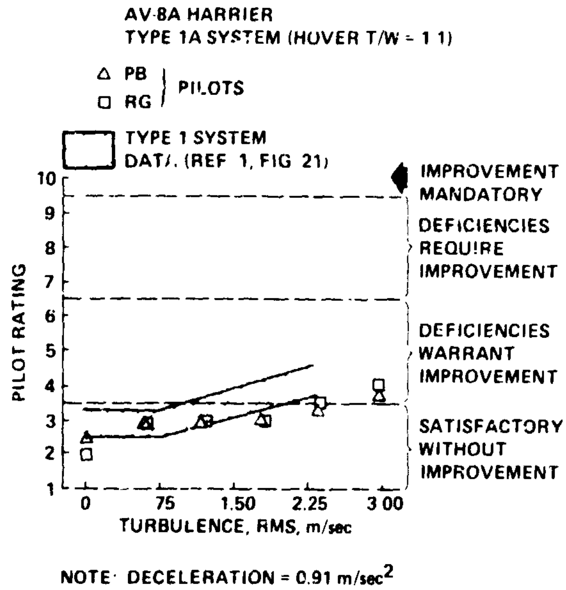


Figure 15.- Pilot ratings for transition (various turbulence levels).

the current tests required more attention be given by the pilot to the lateral-tracking task.

The significant reduction in workload using the Type 1A system is due entirely to the use of a flightpath-angle command mode. The pilots found it easy to correct any altitude error, and, once having acquired the correct -3° glide slope, often found it unnecessary to make further corrections for the remainder of the transition. Of particular note is that a flightpath-angle command mode reduces the workload in the altitude-control task during the critical period at the end of transition when the pilot is attempting to acquire a unique point in space (the initial station-keeping point) with zero velocity and acceleration. Even a small reduction of workload in any of the individual subtasks can have a large impact on the pilot's perception of the difficulty of the overall task.

Transition (Type 2A System)- It was pointed out in reference 1 that the problems with the Type 2 system during transition were largely due to deficiencies in the vertical and longitudinal flight directors. Significant changes were made to improve these flight directors in the Type 2A system (see "Type 2A Control/Display System"). The effect of these changes on pilot ratings may be seen in figure 16, which, in addition to results from current simulation, provides a summary of corresponding results for the Type 2 system from reference 1. Pilot ratings in calm air are about the same for the Type 2 and Type 2A systems; however, the Type 2 system becomes unacceptable (pilot rating >6-1/2) in turbulence greater than 2 m/sec (6.6 ft/sec) rms, whereas the type 2A system remains acceptable up to 3 m/sec (10 ft/sec) rms, the highest value tested.

The pilots noted the large reduction in the sensitivity to turbulence of the vertical flight director, and the increase in effectiveness of the longitudinal flight-director terminal-switching logic. These directors enabled the pilots to consistently bring the aircraft to a hover close (within 2 m) to the initial station-keeping point. Furthermore, the pitch and roll following the switch to the hover mode were always acceptably small (less than 2°).

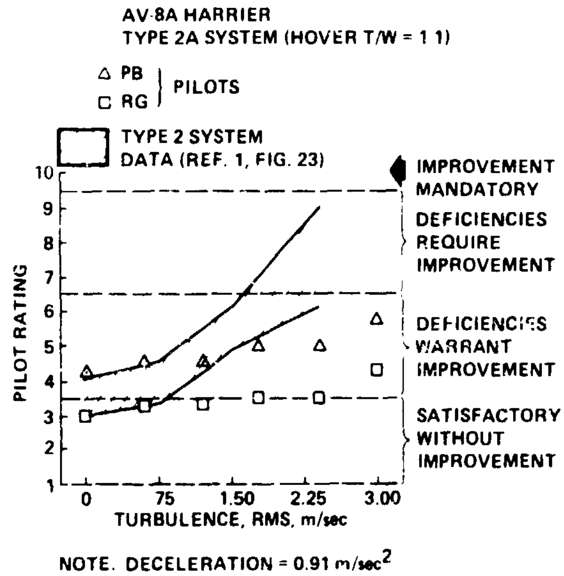


Figure 16.- Pilot ratings for transition (various turbulence levels).

It is interesting to note that pilot RG gave the Type 2A system pilot ratings only 1/2 point higher (worse) than the much more sophisticated Type 1A system, independent of the turbulence level. On the other hand, pilot PB consistently rated the Type 2A system two points higher (worse) than the Type 1A system. Pilot PB was of the opinion that the number of times the TVRS had to be pressed was excessive, being about 10 times per transition. He was influenced in this opinion by his experience flying the AV-8A using the current operational transition technique, which requires a single movement of the thrust-vector-angle (nozzle) lever to the so-called "hover stop." However, the current operational technique is a far less precise maneuver than the task specified for the simulation. In particular, the final approach to the ship is strictly visual with no unique station-keeping point defined. Moreover, with the operational technique, additional thrust-vector-angle changes relative to the true vertical are made through pitch-attitude changes. Nevertheless, it is important to reduce the number of times the TVRS needs to be pressed, and this reduction can probably be achieved with further refinement of the longitudinal flight-director switching lines.

<u>Landing (Type 1A System)</u>- Pilot ratings for landings in various sea states (fig. 17) show that the Type 1A system is acceptable (PR 6-1/2) for this task up to the most severe environmental condition tested. These results show a pilot-rating improvement of about 1 point compared with the Type 1 system (summarized in fig. 17) for all environmental conditions. This improvement is particularly significant since the inclusion of ship sway and yaw motion in the current simulation increased the lateral movement of the landing pad by about 60% (in sea state 6, lateral movements up to about 2.5 m (8.2 ft) were observed).

Listed below in order of importance are the differences between the Type 1 and Type 1A systems that influenced the pilot ratings for the landing task:

1. Lateral positioning in the Type 1 system is by roll-attitude command with a flight director, whereas in the Type 1A system, lateral positioning is by lateral-velocity command (using roll angle) without a flight director.

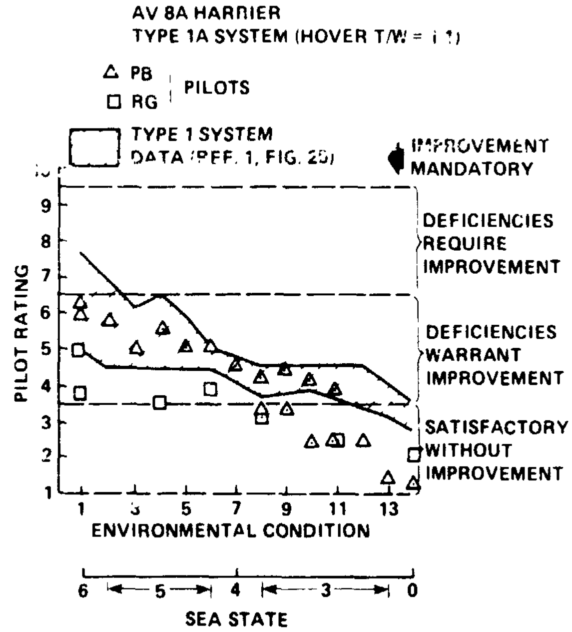


Figure 17.- Pilot ratings for landing from initial station keeping point.

2. With the Type 1 system, longitudinal translation is controlled through a lever-mounted, force-proportional thumb button (left hand), and lateral control is through the stick (right hand). With the Type 1A system, both longitudinal and lateral translation are controlled through the stick.

3. The Type 1 HUD horizontal-situation display uses a landing-pad symbol whose size is a function of altitude, whereas the Type 1A HUD uses a fixed-size landing-pad symbol with an aircraft symbol whose scale is the same as that of the landing pad.

4. The Type 1A system has an altitude-hold feature when the vertical-velocity-command lever is in the detent (zero velocity command).

The differences given in (1) and (2) above were responsible for most of the pilot-rating improvement. The combined use of lateral- and longitudinal-velocity command through the stick provided a well-harmonized helicopter-like behavior with pilot workload balanced between the two hands. Moreover, the self-trimming feature of the control modes in both the longitudinal and lateral axes gave the aircraft position-holding characteristics such that, even in the most severe wind-over-deck condition, no stick inputs were needed during the vertical descent. Under these conditions, the incremental increase in pilot rating for any given sea state above that for calm conditions is due solely to the pilot workload required in the vertical axis to achieve a satisfactory rate of descent at touchdown.

The Type 1A system applied to the AV-8A is comparable to the Type 1 system applied to the lift-fan transport described in reference 1. In the latter, the lateral-velocity command mode operates through lateral thrust deflection (zero roll angle), and both lateral and longitudinal translation are controlled by the pilot through a two-axis, force-proportional thumb button located on the vertical-velocity lever (fig. 2 in ref. 1). A comparison of figure 17 with figure 24 of reference 1 shows that the Type 1A system applied to the AV-8A received pilot ratings about one-half unit less than for the Type 1 system applied to the lift-fan transport. The main reason for this improvement is that the pilots preferred to control horizontal translation through the stick, which permitted much more precise inputs than are possible with the force-proportional thumb button. In addition, the pilots were much more receptive to the Type 1A AV-8A scheme of controlling all horizontal motion with the right hand and vertical motion with the left hand, than they were with the Type 1 lift-fan transport scheme of controlling both horizontal and vertical motion with the left hand

The effect of free-air maximum thrust/weight ratio on pilot ratings is shown in figure 18. This test was exploratory and was performed only by pilot PB. The results show that in calm sea conditions (sea state 0), the thrust/weight ratio had no effect on pilot rating down to the lowest value tested (1.02). Moreover, in calm sea conditions, the pilot did not notice any effect of thrust saturation, although saturation did occur at the low thrust/weight ratios for short periods of time following stick inputs during the horizontal translation. During the vertical descent, however, no saturation occurred. The pilot simply selected a rate of descent of about 1 m/sec (200 ft/min), and let the aircraft descend to touchdown without

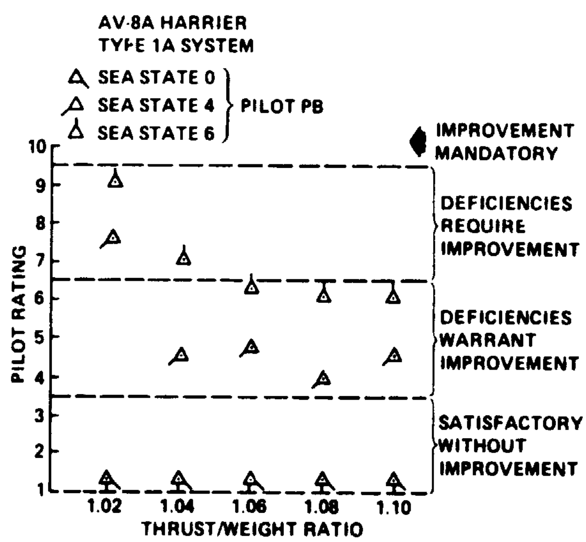


Figure 18.- Pilot ratings for landings with various thrust/weight ratios.

further inputs. With this technique, the thrust/weight ratio during the descent was always slightly below unity. Again, in the sea state 4 and 6 conditions, no noticeable effect of thrust saturation was apparent to the pilot during the horizontal translation. During the vertical descent at these two sea states, however, the technique used for calm conditions was not feasible, and the pilot became aware of thrust limitation while attempting to reduce the rate of descent when the deck was moving upward. It is clear from figure 18 that for sea states 4 and 6 the thrust limitation influences the pilot's ability to perform the task for thrust/weight ratios below 1.04 and 1.06, respectively.

It should be recognized that firm conclusions cannot be drawn from such a small sample of data, especially since the motion of the ship is random. However, the results do give some hope that thrust/weight-ratio requirements for vertical landings may be reduced below the usually accepted value of 1.1.

Landing (Type 2A System)- Pilot ratings for landings in various sea states (fig. 19) show that the Type 2A system provides acceptable handling qualities (PR < 6-1/2) for this task up to the most severe environmental condition associated with sea state 5. Also included in figure 19 is a summary of the data for the Type 2 system from figure 26 of reference 1, showing that the Type 2A system provides handling-qualities improvements equivalent to 1-1/2 to 2 pilot-rating units. This improvement is due solely to the use of translational-rate command for both the longitudinal and lateral degrees of freedom, as suggested in reference 1. In reference 1, it was noted that the use of pitch-attitude command for longitudinal positioning caused piloting problems because of conflicting visual cues from the HUD. As a result of this problem, a vernier thrust-vector-angle control (nozzle nudger) was provided in the Type 2 system for longitudinal positioning. It is significant that although pitch attitude is used in the Type 2A system, the HUD-cues conflict observed with the Type 2 system was no longer a problem because the translational control used in the Type 2A system enables the pilot to make longitudinal translations with lower amplitude, smoother, pitch-attitude changes than appear to be possible using pitch-attitude command. Pilot PB adopted a technique of translating between the initial and final station-keeping points by maintaining a fairly constant acceleration followed by a deceleration of similar magnitude. This technique results

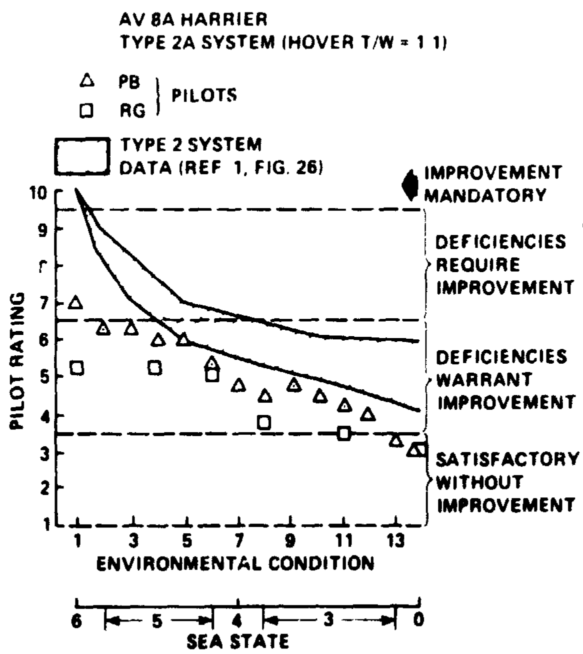


Figure 19.- Pilot ratings for landing from initial station-keeping point.

in the smallest possible pitch-attitude changes for a given translation time. Translation times of 20 sec could be achieved without exceeding pitch attitude changes of 5°. With smooth pitch-attitude changes of this magnitude, the conflicting HUD cues, although undesirable, were acceptable.

Since both the Type 1A and Type 2A systems use translational velocity command for longitudinal and lateral positioning, the major difference between the two systems from a piloting viewpoint lies in the height-control mode; namely, vertical-velocity command for the Type 1A system and thrust command for the Type 2A system. A comparison of figures 17 and 19 shows that the pilot ratings for the Type 2A system are only about one-half unit worse than for the Type 1A system in moderate and high sea states, and about one unit worse in low sea states. These somewhat unexpected results occur because, when using the Type 1A system, the pilot adopts a different technique of descent at low sea states than at moderate and high sea states. In low sea states, the pilot merely commands an acceptable rate of descent involving a single movement of the vertical velocity command lever, and then waits for the aircraft to land. At moderate and high sea states (environmental conditions from 1 to 11), the pilot continuously adjusts the vertical-velocity command lever to maintain an acceptable rate of descent relative to the deck. When using the Type 2A system with its thrust command, the pilot must continuously adjust the throttle to attain an acceptable rate of descent, even in low sea states. Therefore, in low sea states, the Type 2A system is significantly more difficult to use than the Type 1A system, but the difference between the two becomes less as the flying technique becomes the same for both systems. The surprising result here is that even in high seas the Type 1A system vertical-velocity command, with its excellent damping, was rated only one-half of a pilot-rating unit better than the Type 1A system thrust command with its virtually zero damping. However, handling qualities in high seas are dictated not only by vertical damping but also by speed of response to pilot inputs, and, in this latter respect, the vertical-velocity controller of the Type 1A system has a considerably larger time constant (1.15 sec) than the basic engine thrust (0.15 sec).

The effect of free-air maximum thrust/weight ratio (T/W) on pilot rating is shown in figure 20. As in the case of the Type 1A system, any thrust saturation during the horizontal maneuvers was imperceptible to the pilots even down to the thrust/weight ratios of 1.02. Some credit for this result must be given to the power flight director, which quickly tells the pilot that the aircraft is deviating from the planned altitude, thus obviating large corrective throttle inputs. In the vertical descent, in both calm and sea state 4 conditions, thrust limitations became apparent to the pilot below a thrust/weight ratio of 1.06, and in the sea state 6 condition, below a thrust/weight ratio of 1.08. These results (fig. 20), compared with those for the Type 1A system (fig. 18), seem to indicate that the use of a highly augmented height-control mode may permit reductions in the required thrust/weight ratio below those required using thrust command by at least 0.02, and possibly by as much as 0.04 for landing on a fixed landing pad.

It is important to recognize here that some of the credit for the thrust/weight-ratio results for the Type 2A system in general, and for the Type 1A system in moderate and high sea states, may be due to the precise indication of height-above-deck

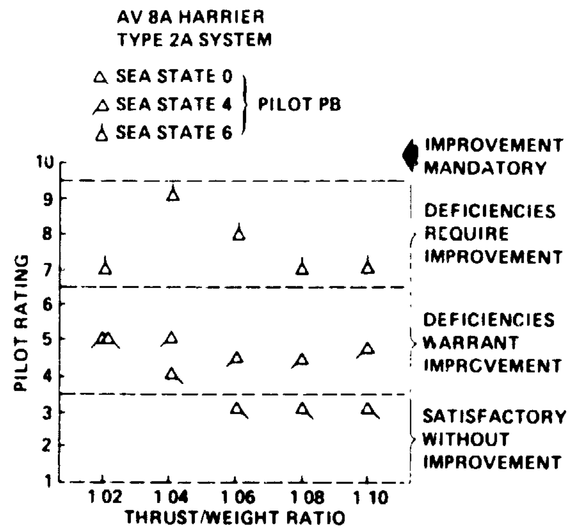


Figure 20.-Pilot ratings for landings with various thrust/weight ratios.

afforded by the HUD. This point requires further investigation by performing the same kind of landing tests visually, without a HUD.

Task Performance Parameters

Transition- Transition times for both control/display systems are shown in figure 21. In all of the tests, the transition times exceeded the 96 sec corresponding to the reference velocity schedule (termed "reference minimum" in fig. 21). The additional time was needed by the pilots to make final corrections to acquire the initial station-keeping point. A comparison of the results shown in figure 21 with those obtained in the previous simulation of the Type 1 and Type 2 systems (fig. 27 in ref. 1) reveals that the increase of transition time with turbulence level when using the Type 2 system does not occur with the Type 2A system. Furthermore, the transition times using any of the Type 1, Type 1A, and Type 2A systems are about the same, and average about 20 sec longer than the reference minimum. These results again provide good evidence that the flight-director problems noted in the Type 2 system have been largely overcome in the Type 2A system.

The maximum and rms longitudinal velocity errors are shown in figure 22. There is a systematic increase of these errors with turbulence level that was not as apparent in the tests of the Type 1 and Type 2 systems (fig. 28 in ref. 1). The maximum velocity errors occurring with the Type 1A system are less than half of those using the Type 1 system. The most probable reason for this result is that the use of flightpath-angle command with the Type 1A system permits the pilot to allocate much more time to the task of longitudinal-velocity control, with a corresponding increase of accuracy. It is also apparent that smaller velocity errors occur when using the Type 2A system than when using the Type 2 system. This improvement stems from the already noted fact (see Longitudinal (Thrust-Vector-Angle) Flight Director) that the Type 2A system's longitudinal-flight-director switching lines were reshaped to

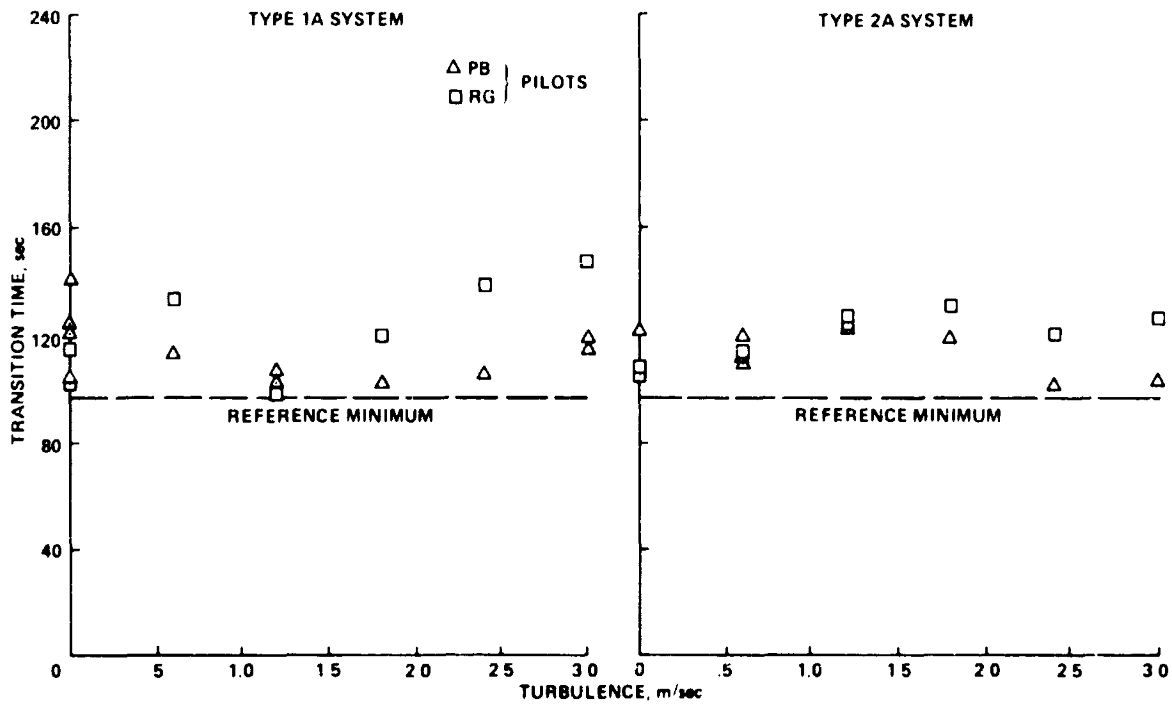


Figure 21.- Transition times.

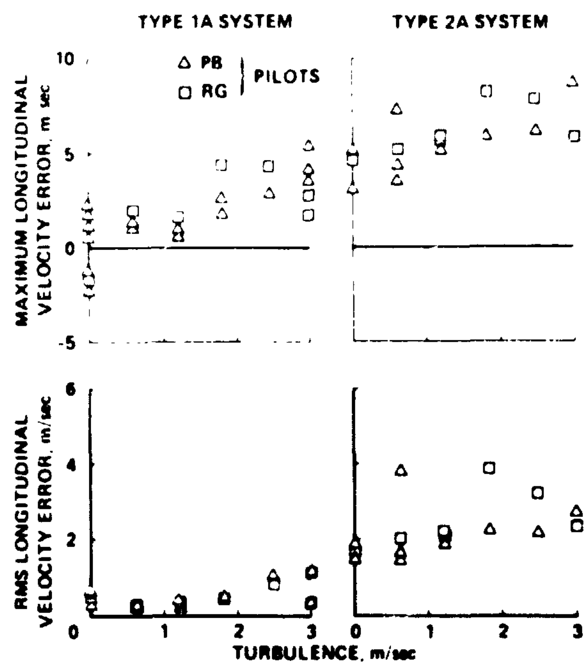


Figure 22.- Velocity errors in transition.

provide a control of velocity tighter than that for the Type 2 system. As noted in reference 1, velocity error is a critical parameter only when the aircraft is close to the initial station-keeping point, and with either the Type 1A or Type 2A system, this type of error was always less than about 1.5 m/sec (5 ft/sec).

In reference 1, maximum and rms altitude errors were given. However, the tests described in reference 1 were all started with the aircraft on the glide slope with zero altitude error. The current tests were always started with the aircraft 15 m (50 ft) below the glide slope, and, in all of the tests performed, this initial altitude error was always the largest measured. It can be seen from figure 29 of reference 1 that the altitude errors were substantially lower than those measured when using the Type 2 system (up to 30 m). The rms altitude errors from the current tests are not presented here, because the difference in initial conditions between this and the previous simulation precludes a comparison. In any case, maximum altitude error is clearly the critical parameter.

Landing- The time taken to fly from the initial station-keeping point to touchdown for both types of system is shown in figure 23. The average landing time using either system was 67 sec, although the standard deviation was slightly larger using the Type 2A system (9.5 sec compared with 7 sec for the Type 1A system). Of the 67-sec average landing time, about 47 sec were required for the horizontal maneuvers. A comparison of the results of figure 23 with those of figure 30 of reference 1 shows that landing times using either the Type 1A or Type 2A systems average 2 sec less than those obtained with the lift-fan transport and Type 1 system, 22 sec less than with the AV-8A and Type 1 system, and 49 sec less than with the AV-8A and Type 2 system. In addition, the results derived using the Type 2A system do not show the rapid increase of landing time with sea state apparent in the Type 2 system results. The primary reason for the reduced landing times is the use of translational-velocity command, both laterally and longitudinally. A secondary reason, relevant to the Type 1A system test results, is the improved coordination derived from using the stick to control both longitudinal and lateral translation in place of the Type 1 system approach of using the thumb button (left hand) for longitudinal translation and the stick (right hand) for lateral translation.

The horizontal-position errors and maximum wheel vertical velocities for both systems are shown in figures 24 and 25, respectively. These results may be compared with those for the Type 1 and Type 2 systems shown in figures 31 and 32 of reference 1. Considering first the position errors, it is clear from figure 24 that these are roughly the same for both systems, and are always less than 2.5 m (8.2 ft). A comparison of the results for the Type 1A and Type 1 systems shows that, although the Type 1A system has a self-trimming lateral-velocity command mode, the position errors occurring using this system (fig. 24) are about 1 m (3 ft) greater than those occurring using the Type 1 system (fig. 31 in ref. 1), which has only a roll-attitude command mode (and lateral f[illegible] director). This result is less surprising when one remembers that the ship model in the current tests had six degrees of freedom compared with only three degrees of freedom in the previous tests. The additional degrees of freedom increased the lateral motion of the landing point by up to 1 m (3 ft), from which it may be inferred that the differences in position errors between the Type 1A and Type 1 systems are largely due to the additional deck motion in the

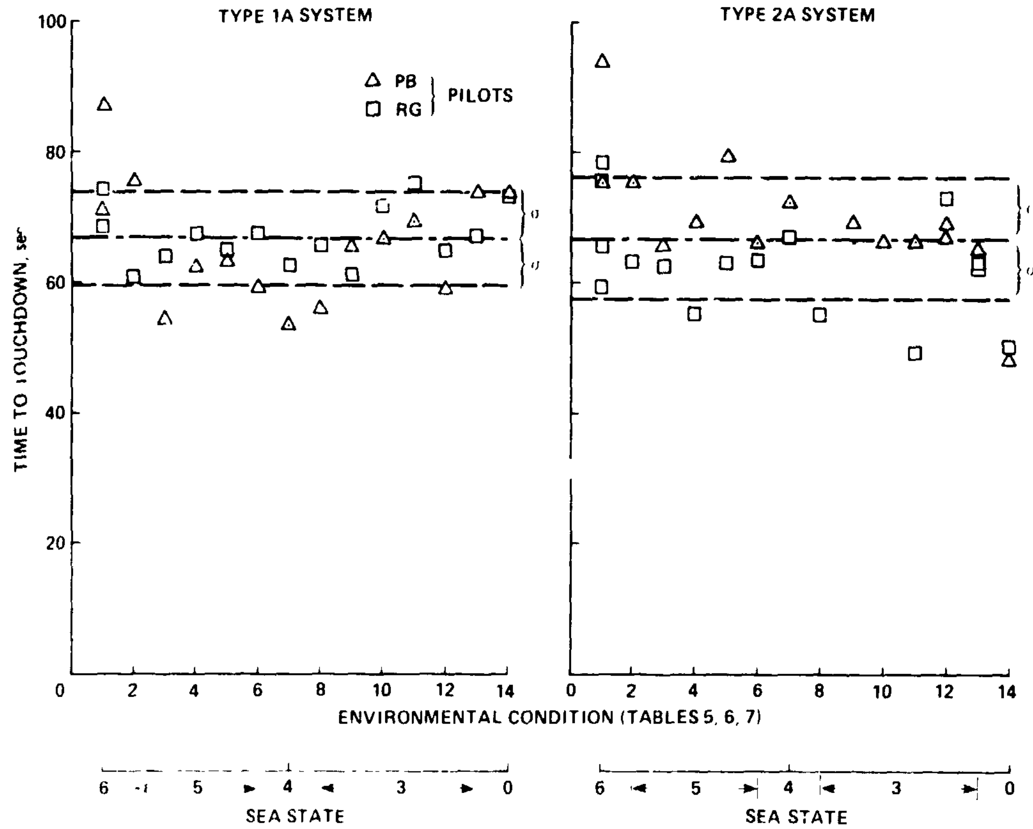


Figure 23.- Time from initial station-keeping point to touchdown.

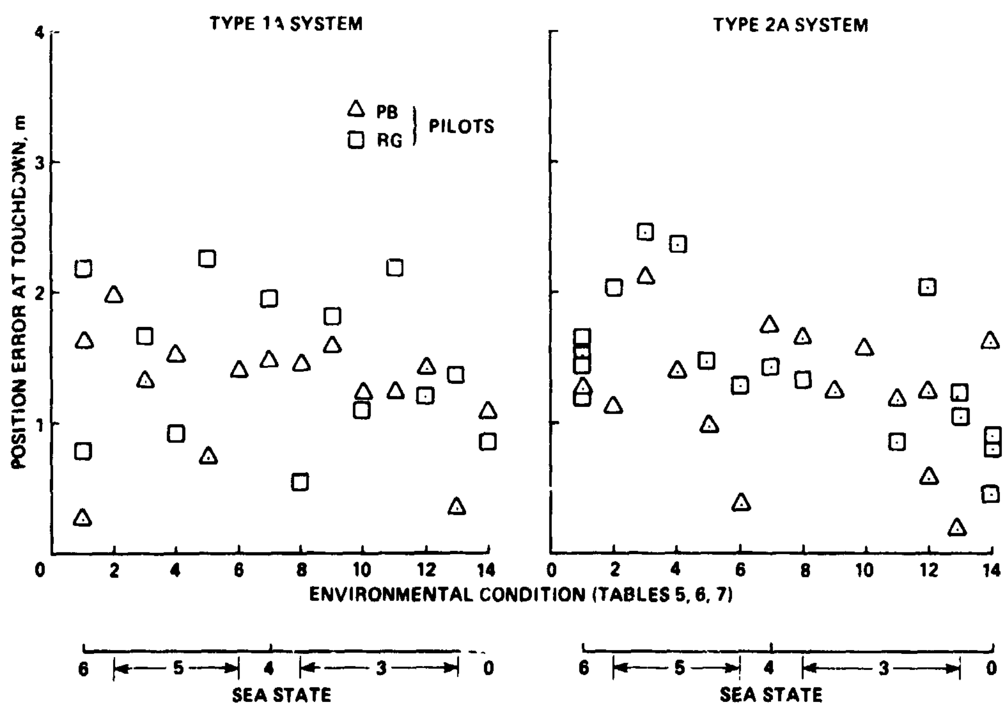


Figure 24.- Position errors at touchdown.

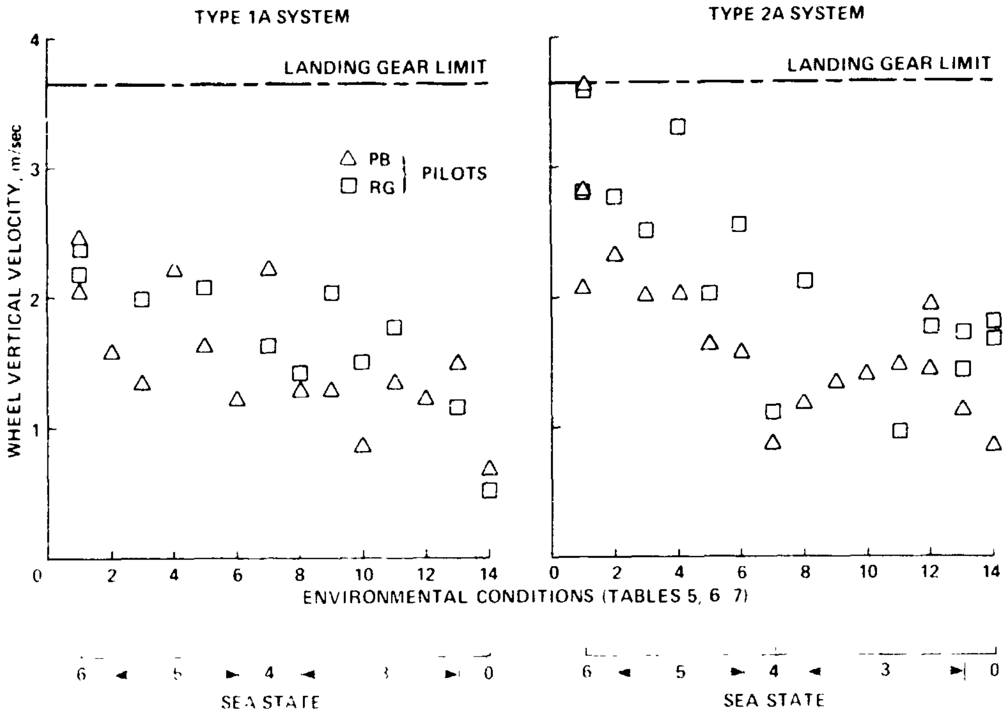


Figure 25.- Highest wheel vertical velocities at touchdown.

current tests. Another reason that the Type 1A system does not appear to reduce the position errors significantly below those for the Type 1 system is to be found in the piloting technique used in the final descent. Rather than chase the desired landing point, the pilot simply maintains the aircraft as close as possible to the mean position of the landing point as indicated by the appropriate HUD symbol (station-keeping point on fig. 2(c)). Although the workload is low using this technique, the standard deviation of position error for any given sea state cannot be less than the standard deviation of the horizontal position of deck, which is independent of the type of control system. Total error, then, is the sum of the deck displacements and errors in positioning the aircraft over the mean position of the landing point, these latter errors being indicated to the pilot on the HUD by the distance between the aircraft symbol and the station-keeping point. The pilots were prepared to accept aircraft positioning errors up to about 1 m (3 ft), and were able to achieve this error range with either the Type 1A or Type 1 systems, although more easily with the former. Thus, although the pilots had the capability of reducing position errors using the Type 1A system by something less than 1 m, they regarded the effort as unnecessary. The comments relative to the Type 1A system are also valid for the Type 2A system, since both have self-trimming translational-velocity command modes for both longitudinal and lateral positioning. With the Type 2 system (fig. 31 of ref. 1) the situation differed considerably. Because the Type 2 system has pitch- and roll-attitude command modes, the pilot had to cope with low damping in all translational axes, and was less and less able to achieve acceptable aircraft positioning as the ship-wake turbulence level increased. This, then, is the reason for the large increase in position error with increasing sea state shown in figure 31 of reference 1.

Considering now the maximum wheel vertical velocities, it is apparent from figure 25 that, at low sea states, both systems give similar results, but at high sea states the use of the Type 2A system results in considerably higher vertical velocities. This is a significant result, since the pilot ratings for the two systems during landing (figs. 17 and 19) in high sea states differ by only about 1 unit, yet it would appear that using the Type 2A system could be considerably more dangerous. A possible reason for this result is that the simulator motion base was unable to adequately represent the severe vertical accelerations associated with heavy landings, and so the pilots may not have fully accounted for these heavy landings in their pilot ratings. A comparison of figure 25 with figure 32 of reference 1 shows that the vertical touchdown velocities occurring using the Type 2A system were less than those that occurred using the Type 2 system. This result is to be expected, since the much higher workload involved in horizontally positioning the aircraft using the Type 2 system reduces the attention the pilot can give to the vertical-descent task. As might be expected, the results for the Type 1A system were about the same as for the Type 1 system, with all wheel vertical velocities less than 2.5 m/sec (8.2 ft/sec), and well within the landing-gear limit of 3.66 m/sec (12 ft/sec).

The variation of extremes of altitude with WOD during the horizontal-maneuvers part of the landing is shown in figure 26. When using the Type 1A system, the pilot does not move the vertical-velocity-command lever out of its detent during the horizontal maneuvers. With the lever in the detent, the altitude-hold feature of the vertical flight controller is engaged, as is clear from figure 26, which shows very small deviations from the reference hover altitude of 25 m (82 ft) above sea level. The situation is quite different with the Type 2A system, which requires the pilot to maintain altitude with uncompensated power, using a flight director displayed on the

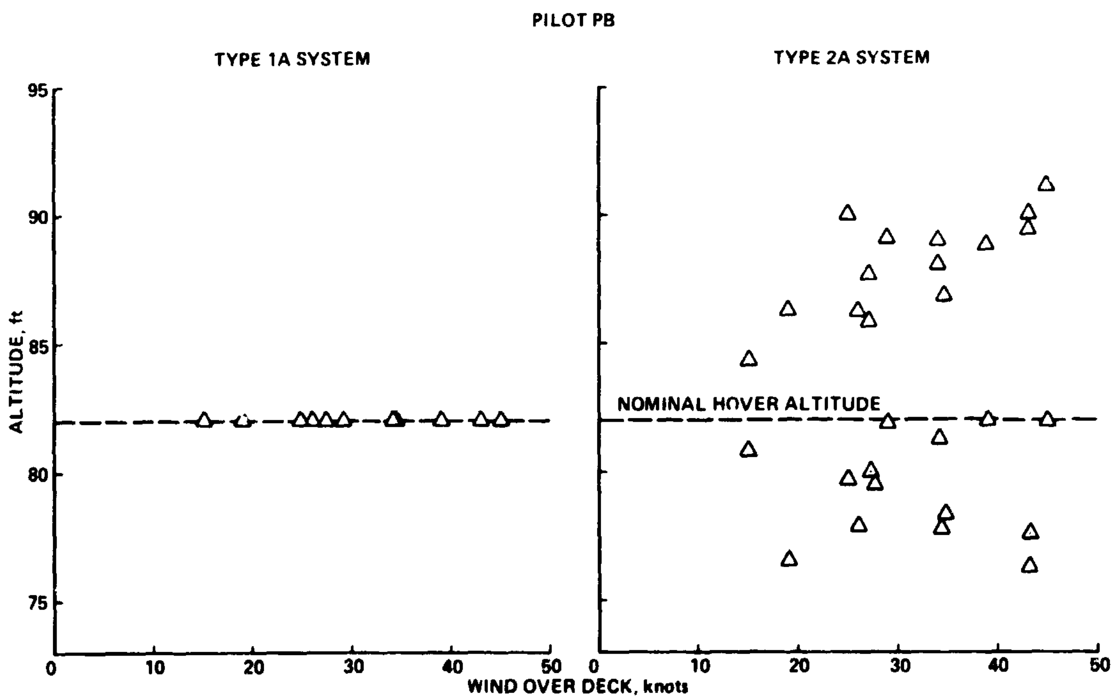


Figure 26.- Extremes of altitude during horizontal maneuvers in hover.

HUD (fig. 5(c)). The pilot had to operate the power level continuously and did not control altitude precisely, allowing deviations up to 2.75 m (9 ft) above and 1.85 m (6 ft) below the reference altitude. However, deviations of this magnitude did not cause the pilots any concern, and there appears to be no special virtue in the improved altitude-holding performance afforded by the Type 1A system, although the reduced workload when using the Type 1A vertical control was appreciated.

Control Use

Transition- Extreme values of aileron angle, rudder angle, and stabilizer angle for various free-air turbulence levels are shown in figures 27, 28, and 29, respectively. Since the attitude controllers are the same for both systems, there should be little difference in control use between the two, and this expectation is confirmed by the results. The amount of control required to maneuver the aircraft laterally and directionally (zero turbulence results) is quite small, amounting to no more than 2°-3° of aileron and rudder, with the requirements being dictated at high transition speed (165 knots) in the turn entry (fig. 10). Increasing turbulence gradually increases the required aileron and rudder angles, but this result is due largely to the turbulence-compensating action of the roll and yaw controllers rather than to additional pilot inputs. In fact, pilots did not need to move the rudder pedals during transition, so that all of the rudder use shown in figure 27 was due to the yaw-controller action in countering sideslip.

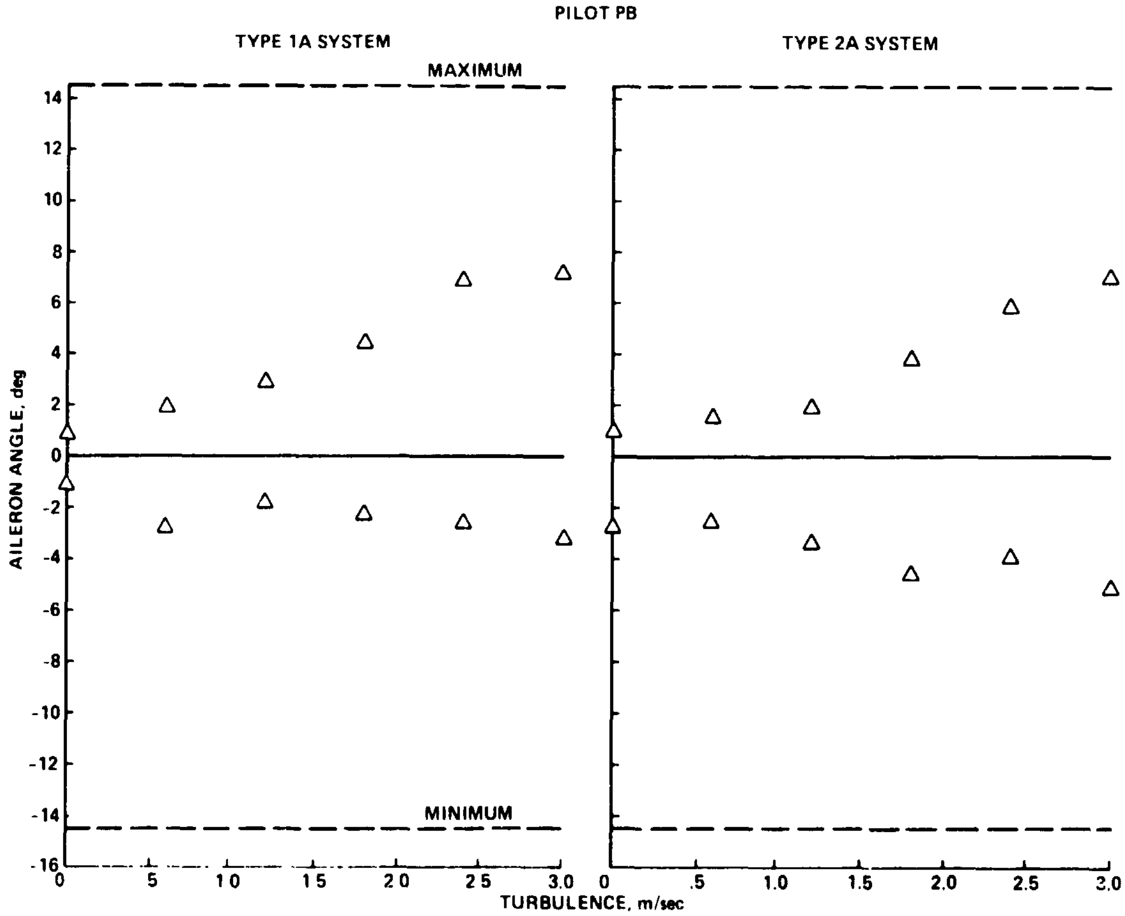


Figure 27.- Extreme aileron angles during transition.

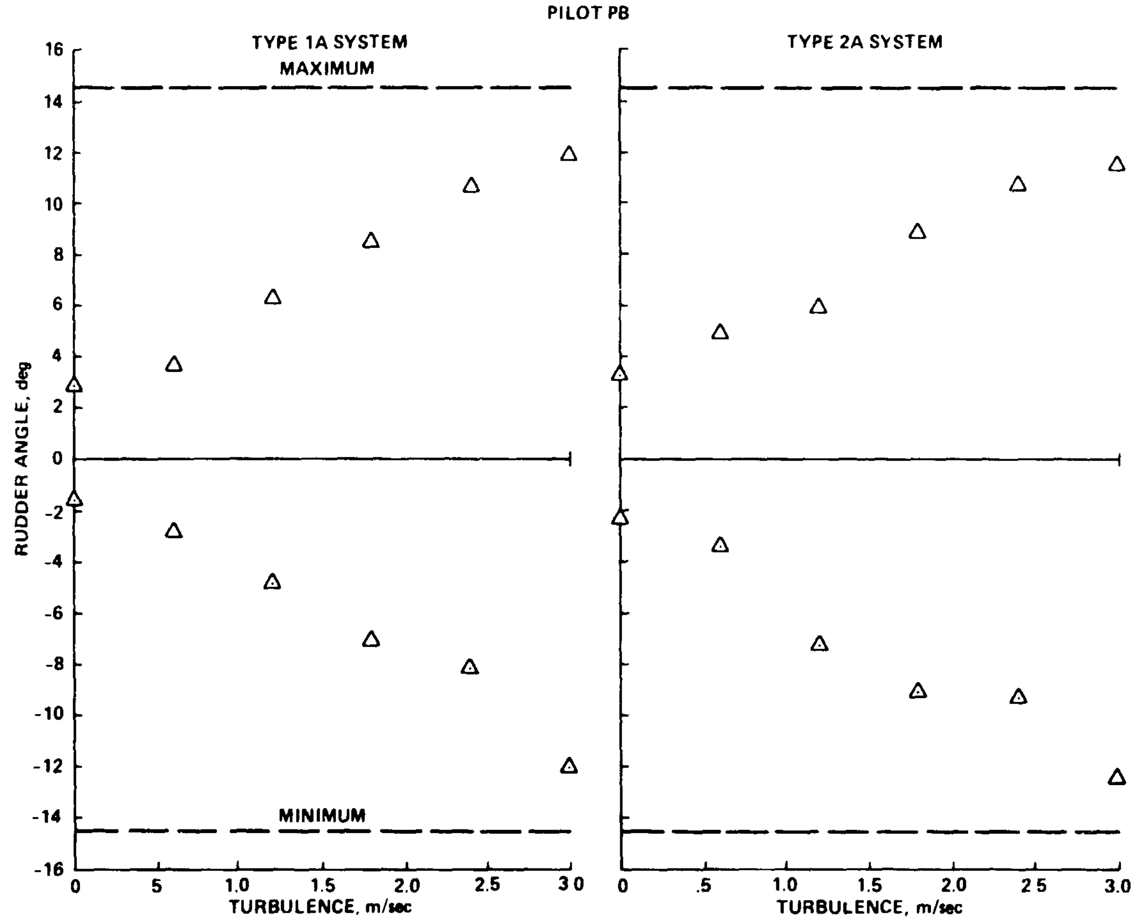


Figure 28.- Extreme rudder angles during transition.

Since the pitch attitude is maintained at a nominal 6.5° during transition, and since the stabilizer angle required to maintain this attitude is established automatically by the self-trimming pitch controller, the pilot is not required to make any stick inputs. Therefore, the stabilizer use shown in figure 29 is due solely to the pitch controller. In calm air (zero turbulence), the range of stabilizer angles shown in figure 29 (1.2°-7.1°) shows the trim change necessary to maintain the 6.5° pitch attitude as power and thrust-vector (engine nozzle) angle change during deceleration. The maximum stabilizer angle is required to trim at the start of transition with an airspeed of 165 knots, and the minimum at hover. The effect of turbulence on stabilizer use is considerably less than it is for the aileron and rudder (fig. 29) because, with this aircraft, the pitch accelerations due to turbulence are much less than those in roll or yaw.

Even at the 3 m/sec (9.84 ft/sec) rms turbulence level, the control-surface use was well below the maximum available. However, even if this had not been the case, it is possible that a considerable amount of control saturation due to turbulence could be tolerated without producing an unacceptable degradation of controller performance. Further tests should be carried out with reduced control authority to investigate this point.

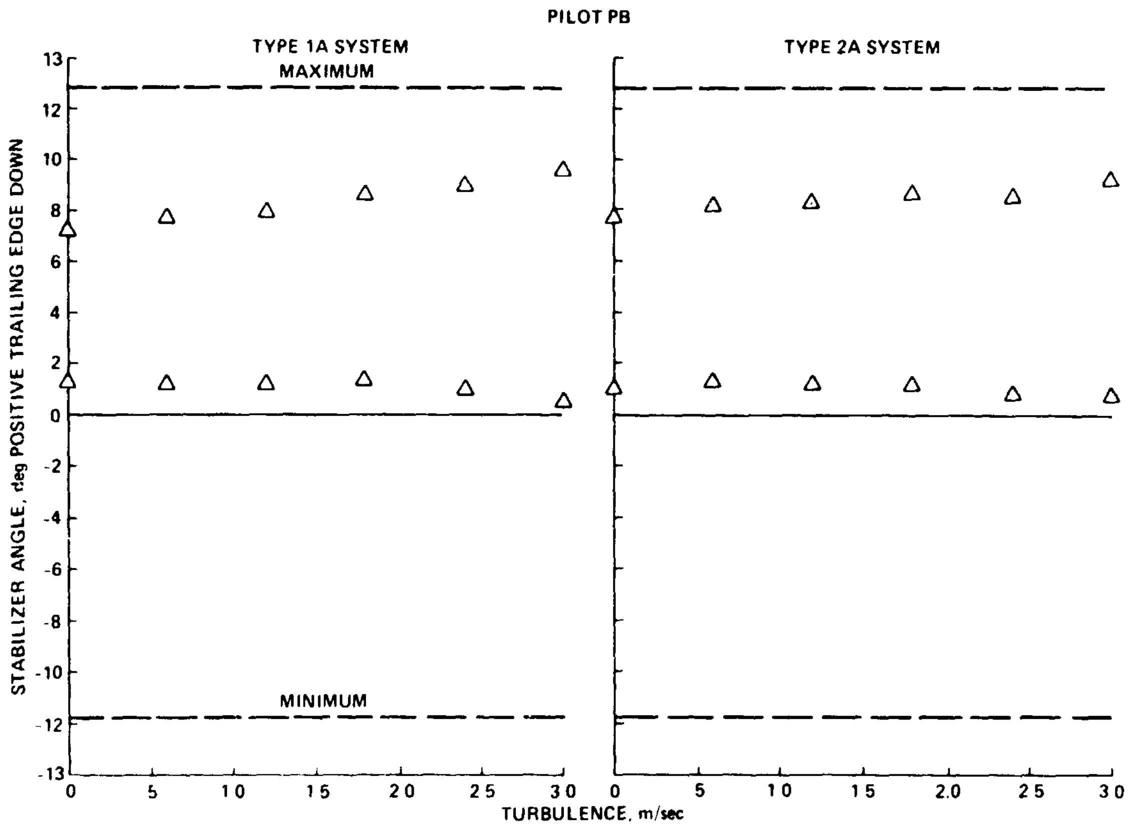


Figure 29.- Extreme stabilizer angles during transition.

Extreme values of engine speed are shown in figure 30. Although engine power is controlled differently in the two systems (vertical-velocity command in the Type 1A system and power command in the Type 2A system), the extremes of engine speed are comparable. The minimum values of rpm shown in figure 30 occur at the start of transition, and the maximum values occur at the end. Turbulence tends to affect only the minimum values because, in hover, turbulence induces only small accelerations because of the low airspeed and high aircraft wing loading (4070 N/m^2 or 85 lb/ft^2). It is clear from figure 30 that the more precise control afforded by the Type 1A vertical-velocity command results in a smaller maximum thrust/weight use (1.02 compared with 1.06).

Landing- The parameters that influence control-system use during landing are deck motion and ship-air-wake turbulence. The former is strongly dependent on sea state, and the latter on WOD. Since the station-keeping point is inertially stabilized in the horizontal plane, it follows that attitude-control use is dictated by air-wake turbulence. On the other hand, control use for vertical translation (engine speed) is dictated in the horizontal maneuvers by air-wake turbulence and in the vertical descent by both air-wake turbulence and deck motion.

Extreme aileron and rudder angles during landing are shown in figures 31 and 32 as functions of WOD. In low WOD conditions, both aileron and rudder use was only about ±1° or about 10% of the available control power. Aileron and rudder-control use increases markedly with WOD because of the flight-controller action in countering the ship-air-wake turbulence, and at a WOD of 45 knots reaches ±4° of aileron and ±5° of rudder. There is very little, if any, increase in pilot-control use as WOD

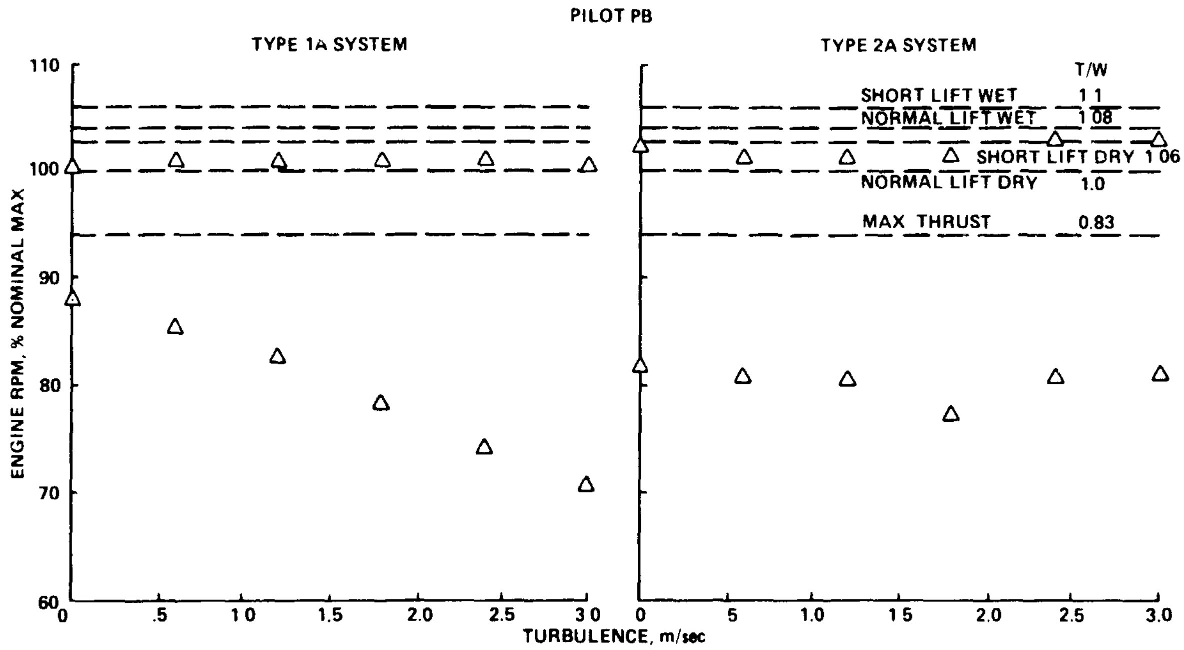


Figure 30.- Extremes of engine speed during transition.

increases, and in fact the pilots usually did not make any pedal inputs during landings. Roll-angle extremes during landings were always less than ±4° and were not correlated with WOD (fig. 33). This result is to be expected because the aircraft has relatively low translational aerodynamic force derivatives (ref. 5), and, as noted earlier, pilot-control use did not increase significantly with WOD.

Extreme stabilizer angles and pitch angles during landing are shown in figures 34 and 35. The range of stabilizer angles used was always less than 10% of the total available range for the Type 1A system, and less than 35% for the Type 2A system. Stabilizer use differs between the two systems because, with the Type 1A system, thrust-vector angles are used for longitudinal translation, and pitch angle is maintained nominally constant at 6.5° by the pitch controller; whereas, with the Type 2A system, the pitch angle is used for longitudinal translation and the thrust-vector angle is maintained constant. It is noticeable (figs. 31, 32, and 34) that air-wake turbulence has a much smaller effect on stabilizer use than on either aileron or rudder use. A similar result has been noted in transition. The small variation (±0.5°) of pitch angle about the nominal value of 6.5° when using the Type 1A system merely reflects the ability of the pitch controller to hold a constant pitch angle when the aircraft is subjected to pitching-moment disturbances due to thrust-vector angle changes and air-wake turbulence. Pitch-angle changes when using the Type 2A system (fig. 35) were about the same as the roll-angle changes (fig. 33), as might be expected, because the longitudinal- and lateral-translational-control characteristics are similar, and the longitudinal and lateral distances travelled during the hover maneuvers were equal (30.5 m or 100 ft).

Extremes of engine rpm (and T/W) during the horizontal maneuvers in various WOD conditions are shown in figure 36. The corresponding altitude changes are shown in figure 26, and are discussed under "Task Performance Parameters." Because the altitude-hold features of the Type 1A system make pilot inputs unnecessary during the

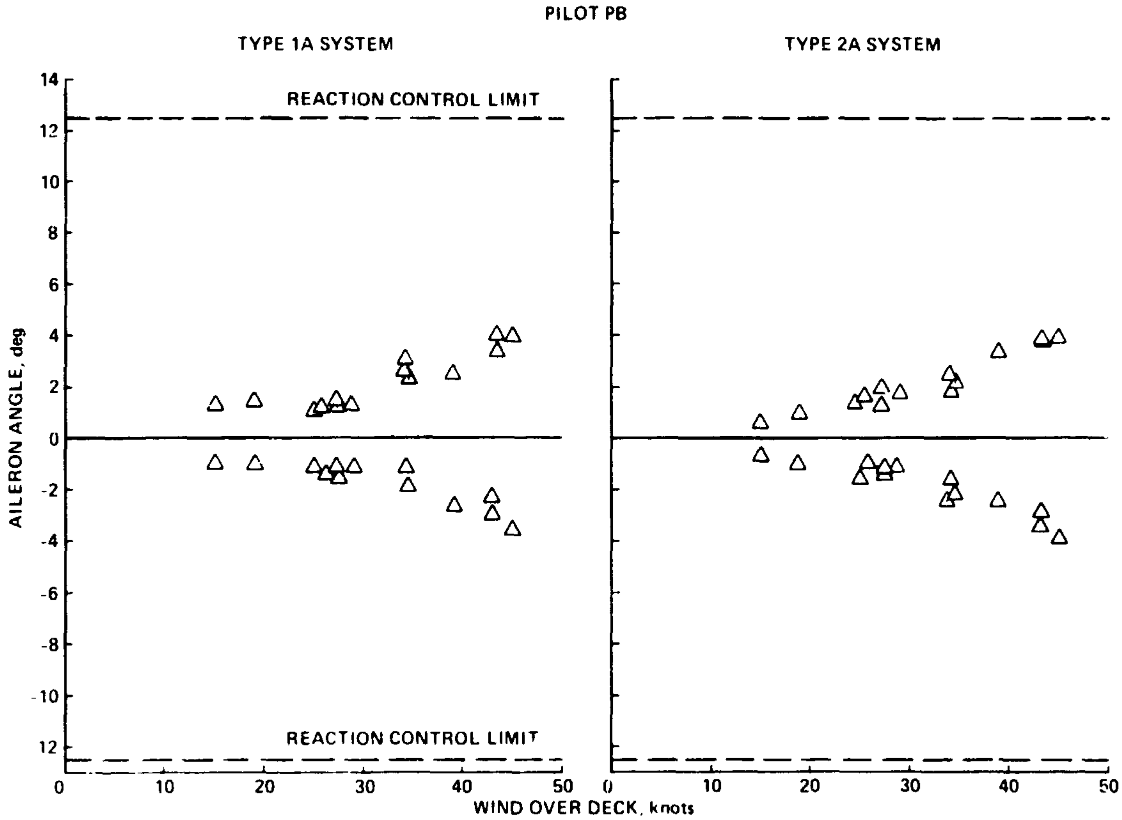


Figure 31.- Extreme aileron angles during landing.

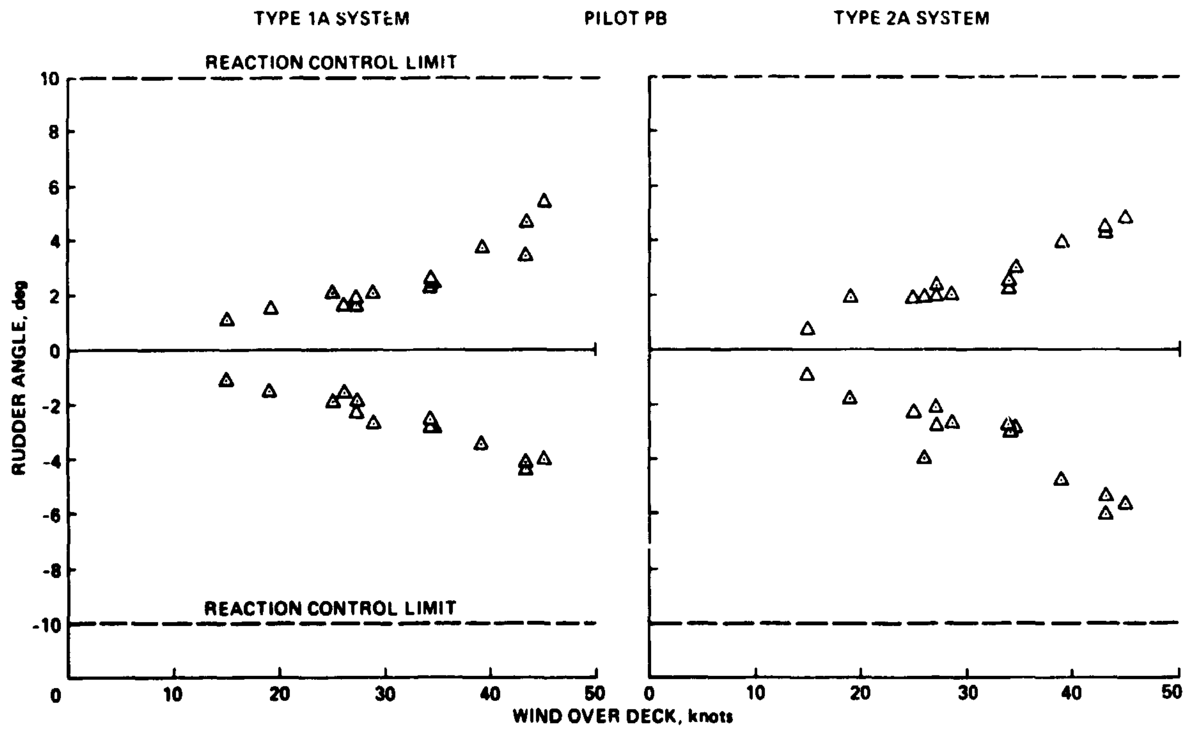


Figure 32.- Extreme rudder angles during landing.

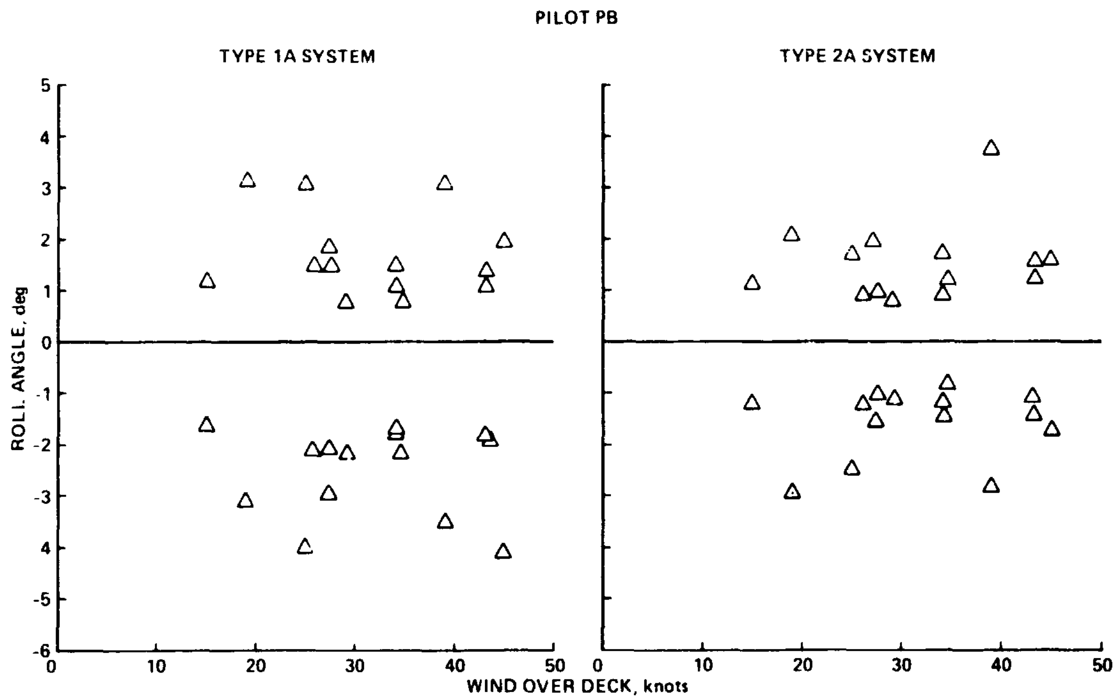


Figure 33.- Extreme roll angles during landing.

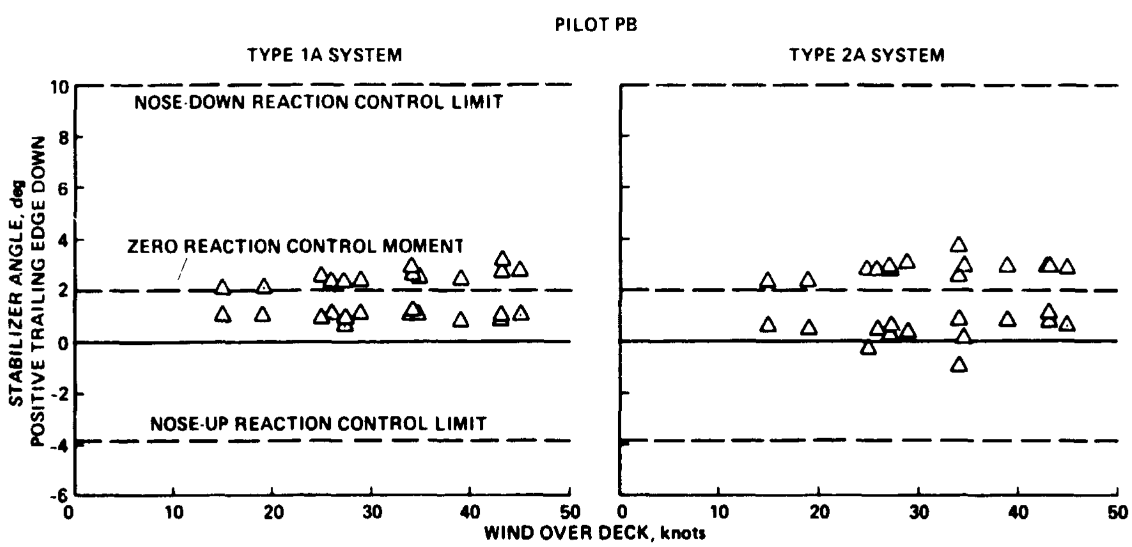


Figure 34.- Extreme stabilizer angles during landing.

hover maneuvers, the variation of extremes of engine rpm with WOD is due largely to the vertical flight controller action in countering disturbances caused by air-wake turbulence. This exclusive flight-controller action explains the well-defined variation of extreme engine rpm with WOD. When using the Type 2A system, the pilot provides all the corrective action to maintain altitude, and because this task is shared with that of translating the aircraft horizontally, control about the vertical axis

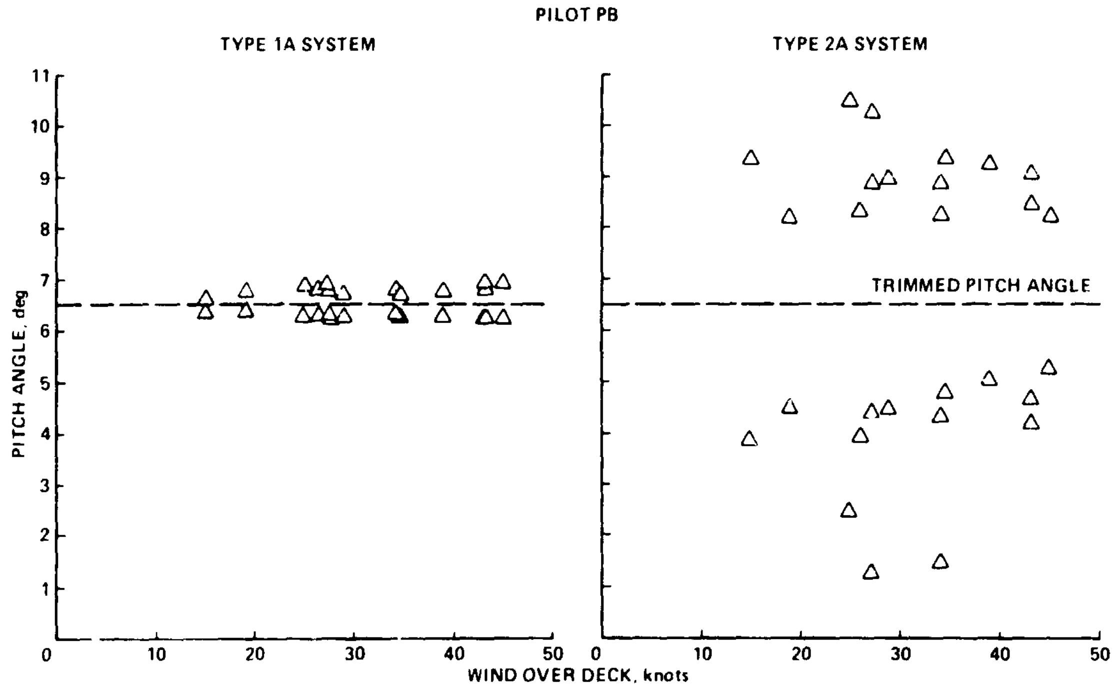


Figure 35.- Extreme pitch angles during landing.

is much looser (lower disturbance rejection bandwidth) than it is for the Type 1A system (fig. 26). It follows that the pilot is unresponsive to the high-frequency air-wake turbulence, and that power use is insensitive to WOD (fig. 36).

Shown in figure 37 are extremes of engine rpm (and T/W) during the vertical descent in various sea states. More power is used with the Type 1A system than with the Type 2A system, and the maximum available rpm of 106% is reached more often. Furthermore, power use is far less dependent on sea state with the Type 2A system than with the Type 1A system (fig. 37). Once again, these results are explained by the larger disturbance rejection bandwidth of the Type 1A vertical control.

Evaluation of HUD Formats

The pilots agreed that all the HUD format changes incorporated into the current simulation (ref. 1 and previous sections entitled "HUD Format") were improvements. No further HUD format improvements were suggested, indicating that the basic HUD format concept adopted for this simulation and that of reference 1 has reached a mature stage of development. It should be recognized that the lack of further suggestions from the pilots does not necessarily mean that the HUD format is now entirely satisfactory, but rather that further improvements should be sought in entirely different HUD format concepts stemming from a re-evaluation of the fundamental piloting tasks.

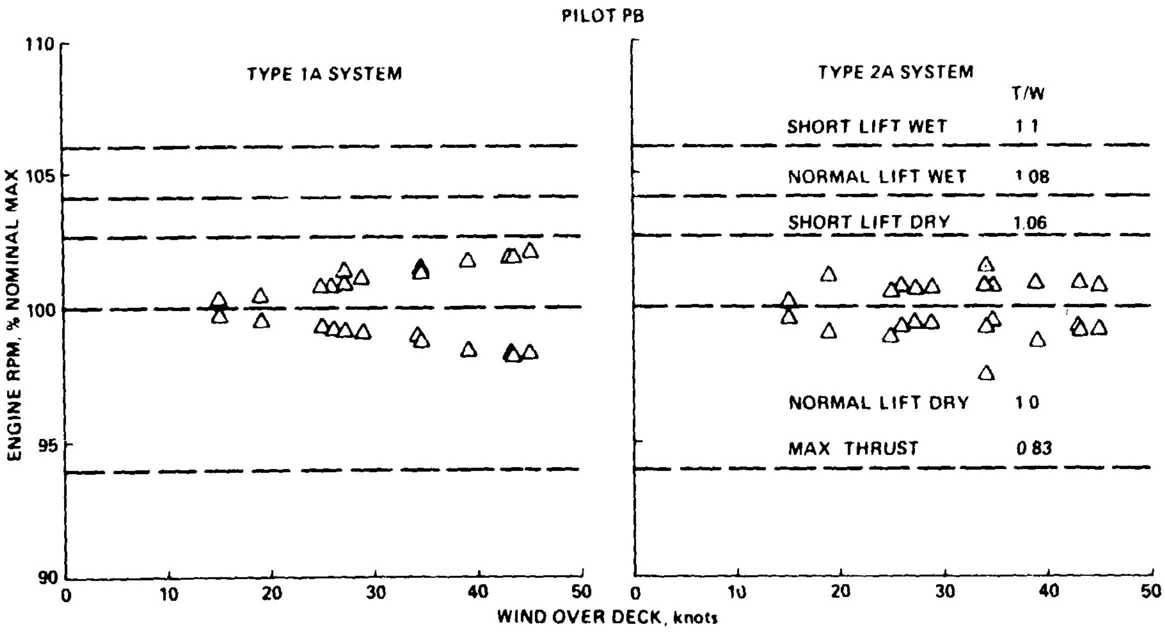


Figure 36.- Extreme engine speeds during horizontal maneuvers in hover.

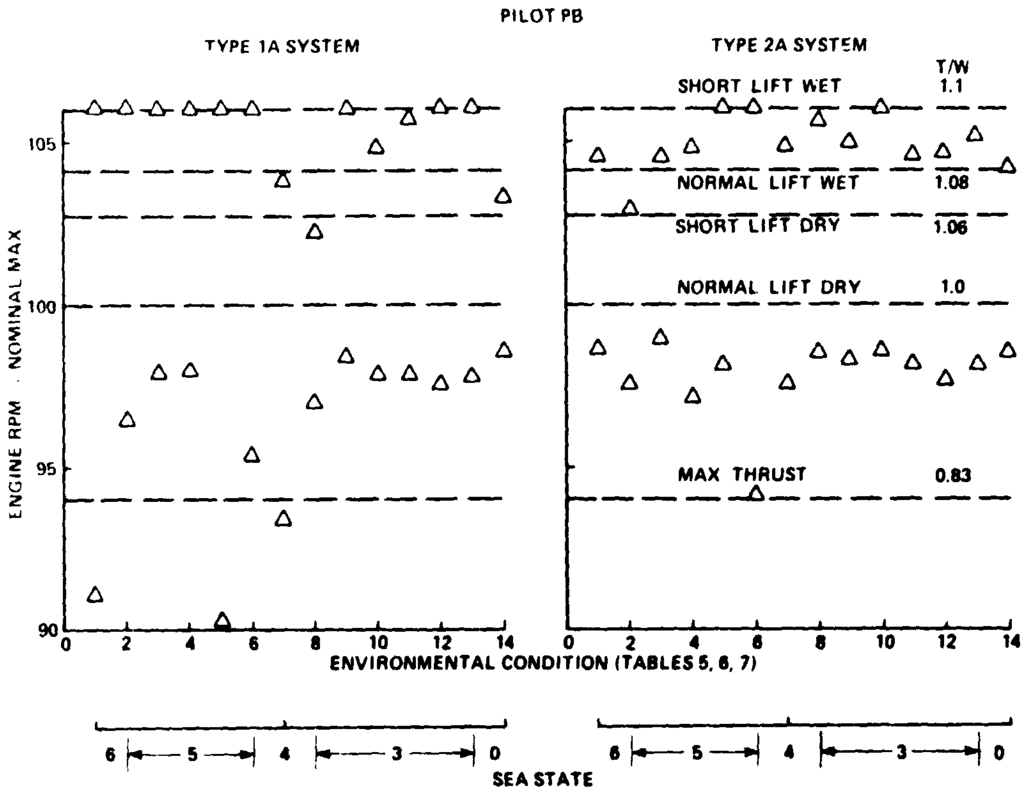


Figure 37.- Extreme engine speeds during vertical descent.

Listed below are three broad areas in which the present HUD format has been criticized:

1. Altitude, velocity vector, horizon, and guidance are not sufficiently highlighted. Moreover, the form in which information on these parameters is presented is not sufficiently compelling to excite spontaneous pilot reactions.

2. The display focuses pilot attention on the fixed aircraft symbol, whereas, in good piloting technique and training, attention is centered on the aircraft's velocity vector in accordance with the aphorism that where the aircraft is going is more important than where it is pointing.

3. Many elements are not conformal with the visual scene and could be presented just as effectively "head-down."

The HUD display format introduced in reference 9 (designated HUD 55) for CTOL approach and landing seems to approach the ideal, and has obtained a significant level of approval from pilots. Certainly HUD 55 largely overcomes the above three major deficiencies of the current HUD format. A fruitful approach to future HUD format development for VTOL applications may be to adapt and augment HUD 55 to handle the special problems associated with precision hover and hover maneuvers.

Evaluation of Pilot Control Modes

Differences between the pilot control modes of the Type 1A and Type 1 systems may be seen in tables 1 and 2; and between the Type 2A and Type 2 systems, in tables 3 and 4.

Considering first the Type 1A system, the substitution of flightpath-angle command for transition in place of the Type 1 system of vertical-velocity command was regarded by the pilots as a significant improvement (see the section "Pilot's Evaluations of Transitions and Landings"). It was conjectured prior to the simulation that some difficulties might be encountered toward the end of transition, when the effective height-control authority available to the pilot through the flightpath-angle command mode is small (because the forward velocity is small). However, the height deviations from the desired flightpath were always so small during this low-speed phase that the low height-control authority passed without comment. Later in the simulation, when alternative arrangements of pilot controls were evaluated, a need arose to perform a series of constant-altitude visual approach transitions (see "Evaluation of Pilot Controls"). During these approaches, the low height-control authority became apparent to the pilots, and was regarded as a possible source of difficulty under some conditions. There are at least two ways to overcome the problem. One is to blend the flightpath-angle command mode into a vertical-velocity command mode at low speed (e.g., a ground speed of less than 40 knots). The disadvantage of this approach is that it forces the pilot back into the position of having to adjust the vertical speed continuously toward the end of transition, resulting in a workload identical to that of the Type 1 system. A second technique, and one which minimizes the additional workload, is to keep the lever used to command vertical velocity in hover active in the same mode during transition, but make it command a vertical velocity additional to that commanded by the flightpath-angle-command mode (thumb wheel). Then, if the aircraft's altitude deviates significantly from that of the desired approach path, the lever can be used to command a vertical velocity to reacquire the approach path.

A flightpath-angle rate-command mode was briefly tested. This mode was implemented by integrating the pilot input to the flightpath-angle command mode. This rate-command mode proved to be acceptable to pilot PB, but was not superior to the flightpath-angle command mode. The choice between the two modes may depend on the type of pilot control used. If, for some reason, the vertical control had a self-centering spring action which required the pilot to hold a force, then the rate-command mode would probably be preferred.

In hover, the altitude-hold feature of the Type 1A system proved to be satisfactory, and relieved the pilots of having to make any vertical control inputs during the hover maneuvers, even in the highest wake turbulence used in the tests (see ref. 1, "Evaluation of Pilot Control Modes").

The translational-velocity command mode used for the Type 1A lateral control and for the Type 2A lateral and longitudinal controls proved to be much more satisfactory than the attitude-command modes used in the Type 1 and Type 2 systems. The dynamic characteristics selected for the translational-velocity command mode (see "Lateral Control in Hover") were satisfactory. It is clear that the primary advantage of this command mode is that it provides a high degree of translational damping--a characteristic lacking in all fixed-wing VTOL aircraft. It is reasonable to expect that an attitude-command mode would provide satisfactory translational control if the translational damping of the aircraft could be independently augmented in some way, perhaps through the engine nozzles. Indeed, such a scheme presents a possible alternative to translational-velocity command, and may be advantageous in avoiding a mode change for hover.

The yaw-control mode for both types of system is a combination of turn coordination through bank-angle feedback when the pedals are centered, and side-acceleration command when the pedals are moved (see "Yaw Control in Transition"). During the transition tests, the pedals were rarely used and the sideslip behavior of the aircraft in the turn was satisfactory, indicating that the bank-angle feedback turn coordination was satisfactory. Only a small amount of flying was done by pilot PB to test the side-acceleration command mode, and this mode was judged to be satisfactory both statically and dynamically. During a period of testing not specifically associated with the yaw-control evaluation, the pilot yawed the aircraft at an airspeed of about 60 knots and the lateral control saturated--a phenomenon well understood with the AV-8A. This incident, although isolated, points to the need for a sideslip limiter in the yaw controller, because the pilot is unaware of how much lateral control is being used by the roll controller to keep the wings level.

Evaluation of Flight Directors

The flight directors for the Type 1A system are identical to those of the Type 1 system, and had already been accepted as satisfactory by the pilots in the previous simulation (ref. 1).

Both the vertical and longitudinal flight directors of the Type 2 system were rated unsatisfactory in the previous simulation (ref. 1), and were modified for the Type 2A system (see "Type 2A Control/Display System"). These modifications resulted in considerable improvement. Both pilots rated the vertical flight director satisfactory for both transition and hover. Pilot RG rated the longitudinal flight director satisfactory, but pilot PB considered the number of times required to press the TVRS to be excessive (an average of 10 times per transition). However, the terminal switching scheme worked well and the pilots were able to bring the aircraft to a hover very close (within 2 m) to the initial station-keeping point. The potential of the longitudinal flight director scheme adopted was not fully exploited in the design process, and it is conceivable that the number of times required to press the TVRS could be reduced without compromising the director's performance.

It may be possible to reduce the workload for the transition task by adopting a different approach to the longitudinal guidance. In all of the transition tests, starting from those reported in reference 2, the longitudinal guidance has been based on the concept of following a reference longitudinal velocity that is a predefined function of range or "distance to go." It was pointed out in reference 1 that such a reference velocity schedule is largely arbitrary. An alternative approach is to provide the pilot with a continuous indication of the constant level of deceleration required to reach zero speed at the initial station-keeping point. The pilot is then required to fly the aircraft so that the actual acceleration is equal to the desired one. With such a guidance technique there is no velocity error, because there is no reference velocity--only a reference deceleration. The advantage of this technique is that the reference deceleration is a very slowly varying quantity, and therefore easy to follow. Furthermore, the pilot is no longer constrained to start the deceleration at a specific range, and can adopt any level of deceleration he desires. Not only does the pilot gain increased operational flexibility, but the idea of nulling an acceleration error for VTOL approaches is appealing as a natural extension of the idea of nulling a speed error for CTOL approaches. It seems certain that this proposed guidance technique will simplify or possibly even eliminate the longitudinal flight directors and reduce the workload for both control/display systems.

Evaluation of Pilot Controls (Inceptors)

A summary of the results of the pilot-control tests is given in table 9. All of the 12 combinations of controls were acceptable. This result is not too surprising because the Type 1A control modes provide the aircraft with static and dynamic characteristics that require no additional compensation from the pilot. Therefore, the entire approach and landing task requires only steering action from the pilot, and this type of control input can be performed acceptably with any combination of the controls provided.

The preferred senses of the various controls throughout the entire approach and landing was back displacement to climb and back displacement to decelerate. Pilot PB had some difficulty reconciling this preference with his Harrier experience in which the power lever is moved forward to climb; however, pilot PH with his helicopter experience had no difficulty since he viewed the vertical control as analogous to a helicopter collective control.

The pilots were satisfied with the thumb wheels as primary controls, while stressing the need for good mechanical characteristics (detent and friction). The thumb wheel on the lever had poorer mechanical characteristics than the one on the stick, and this defect was responsible for the poor rating in transition given to case 7 of table 9. Pilot PB felt that single-handed control of two primary functions (thumb wheel with either the stick of the lever) was less satisfactory than two-handed control.

Use of the center stick for either vertical (flightpath) or longitudinal (acceleration) control involved additional workload over the other three controls, because the stick forces required continuous trimming as the speed changed. However, this was not a difficult operation.

Pilot PB considered control cases 3, 4, and 8 to be the easiest and most natural for transition. It should be noted that case 11 of table 9 appears to be that of the Type 1A system, which therefore should be satisfactory. However, case 11 was unsatisfactory because of the difficulty of positioning both thumb wheels in their respective detents at just the right time to switch to the hover mode. This difficulty does not occur with the Type 1A system, since the controls change on switching to hover, and the thumb wheels are electrically disconnected. The new set of controls for use in hover--namely, the lever and stick--are already centered so that the problem noted with case 11 is avoided.

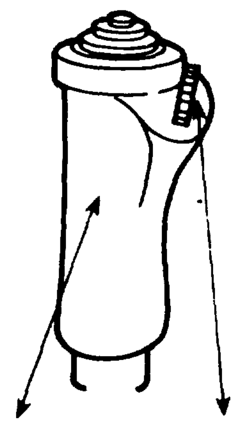
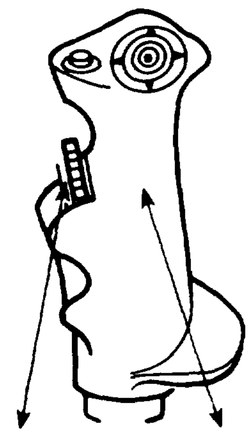
All of the pilots considered control cases 9 and 10 to be the easiest and most natural for the hover maneuvers. These cases use the stick for both longitudinal and lateral translation in helicopter fashion. Case 9 is used in the Type 1A system.

For vertical descent, the task was one of controlling only the rate of descent relative to the deck, since the self-trimming lateral and longitudinal flight controllers provide adequate station-keeping without pilot intervention. Such a single-axis task could be performed equally well with any of the four controls; and the workload, and therefore the pilot rating (4-1/2), was dictated entirely by the ship motion.

An additional test was performed to evaluate a newly developed, thumb-actuated, two-axis proportional control (ref. 10). This device, shown in figure 38, had much more compliance than the one used in previous simulations (refs. 1 and 2). The new thumb button was located on the lever (fig. 1); it was tested in the hover-maneuvers task. The thumb button was used to control longitudinal and lateral velocities, and

TABLE 9.– SUMMARY OF PILOT-CONTROL TESTS

TYPE 1A CONTROL MODES (SEE TABLE 1)
SEA STATE 4   1.22 m/sec TURBULENCE

TEST CASE					PILOT RATING TRANSITION (T)	PILOT RATING HOVER (H)	PILOT RATING DESCENT (D)	SYSTEM
1	LONG.	VERT.			3¼	4	4½	
2	LONG.		VERT.		3	2¼	4½	
3	LONG.			VERT.	3	3¼	4½	
4		LONG.		VERT.	3	3¾	4½	
5		LONG.	VERT.		3	2¼	4½	
6			LONG.	VERT.	3	3¼–6	4½	
7	VERT.	LONG.			5	3¾	4½	
8	VERT.		LONG.		3	3¼–6	4½	
9	VERT.			LONG.	3	1½	4½	TYPE 1A (H&D)
10		VERT.		LONG.	3¾	1½	4½	
11		VERT.	LONG.		3¾	3¼–6	4½	TYPE 1A (T)
12			VERT.	LONG.	3	1½	4½	

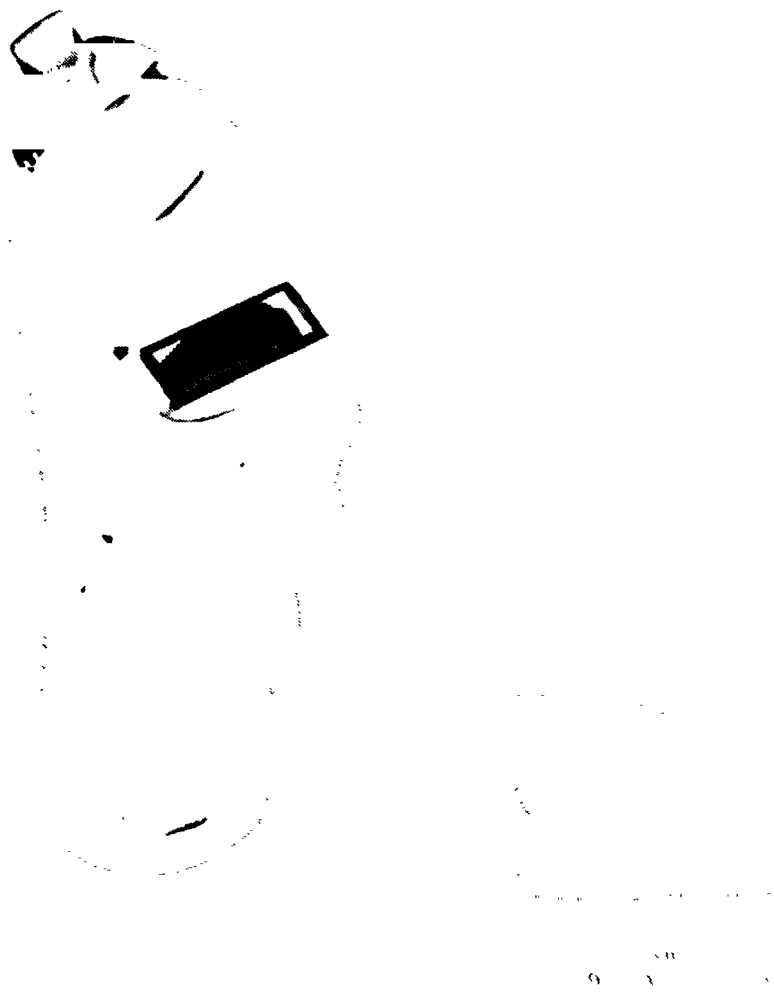


Figure 38.- Photograph of two axis proportional control.

the lever was used to control vertical velocity. The system was therefore identical to the Type 1 system of reference 1. Pilot PB gave a satisfactory rating to the self-centering, breakout force and compliance of the new thumb button. The characteristics of the device are given in table 10. A minor objection was a slight granularity that interfers with smooth operation, but this is not a fundamental problem with the device. The pilot rating for the hover maneuvering task was 1-1/2, which is the same as when using the stick for the same controller inputs. However, pilot PB was of the opinion that it would be better to mount the thumb button on the stick for use with the right hand to equalize the workload between the two hands.

TABLE 10.- CHARACTERISTICS OF TWO-AXIS PROPORTIONAL THUMB CONTROL

Breakout force	1.1 N (0.25 lb)
Maximum X or Y deflection from center at thumb position	$\pm 0.89 \times 10^{-2}$ m (±0.35 in.)
Force at full deflection	5.56 N (1.25 lb)

The evaluation of pilot controls involves many subtleties which are discussed in reference 8.

Simulation Equipment Limitations

With the exception of the ship-model drive system, the equipment and aircraft model used in this simulation were the same as those used in the previous simulation (ref. 1).

As in the previous simulation, the restricted field of view was the most significant equipment limitation. During some of the visual approaches that preceded the evaluation of each combination of pilot controls, the problem of exceeding the maximum speed of the visual attachment was noted. However, since all of the actual evaluation tests used a reference deceleration of only 0.91 m/sec^2 (3 ft/sec^2), the visual attachment always had time to catch up with the aircraft before breaking out of the fog.

The inclusion of all six degrees of freedom in the motion of the ship model added significantly to the realism of the landing task. The effect of sway and yaw was to increase the workload during the final descent, because the position of the aircraft's outrigger wheels relative to the edge of the landing pad had to be monitored more frequently. The severity of this additional workload was minimized by the use of the scaled horizontal view of the deck and aircraft presented on the HUD.

CONCLUSIONS

Two control/display systems, differing in overall complexity, but designed expressly for VTOL approaches and landings on ships in instrument meteorological conditions (IMC), were evaluated in a piloted, moving-base simulation using the Ames Research Center's Flight Simulator for Advanced Aircraft (FSAA). The basic aircraft assumed in the mathematical modeling was an AV-8A, and landings were made on a moving model of a DD 963 destroyer.

The two control/display systems, designated Type 1A and Type 2A, were derived from the Type 1 and Type 2 systems described in reference 1. For transition, the Type 1A system has attitude command in pitch, rate command with attitude hold in roll, lateral-acceleration command in yaw, acceleration command with velocity hold longitudinally, and flightpath-angle command vertically. For hover, the Type 1A system has longitudinal-velocity command through engine nozzle angle, lateral-velocity command through roll angle, vertical-velocity command with altitude hold through engine thrust, and constant pitch-rate command with pitch-attitude hold. For transition, the Type 2A system has the same attitude command modes as the Type 1A system, together with engine-thrust command and constant-rate engine-nozzle-angle command. In hover, the Type 2A system has longitudinal-velocity command through pitch, lateral-velocity command through roll, yaw-rate command, and constant-rate engine-nozzle-angle command. Because of the longitudinal-velocity command mode, the constant-rate-engine-nozzle angle command appears to the pilot as a constant-pitch-rate command.

An important overall distinction between the two system is that in the Type 1A system, engine power and nozzle angle are operated indirectly through flight controllers, whereas in the Type 2A system, they are operated directly by the pilot.

The principal conclusions from the simulation are as follows:

1. Acceptable transitions can be performed using either control/display system in free-air turbulence up to at least 3.0 m/sec (9.84 ft/sec) rms. The Type 2A system received pilot ratings averaging 1-1/2 units worse than the Type 1A system for the same turbulence level.

2. Acceptable landings can be performed using the Type 1A system up to sea state 6, and using the Type 2A system up to sea state 5. The Type 2A system received pilot ratings averaging 1-1/2 units worse than the Type 1A system for the same environmental condition.

3. For both transitions and landings, the Type 1A system received better pilot ratings than the Type 1 system, and the Type 2A system received better pilot ratings than the Type 2 system.

4. Flightpath angle or flightpath-angle rate command provides lower workload than vertical-velocity command in transition.

5. Altitude hold is a desirable feature in hover.

6. Translational-velocity command through either attitude or thrust deflection is markedly superior to attitude command for hover maneuvers and final descent.

7. Lateral-acceleration command is a satisfactory yaw-controller mode in transition.

8. The dynamic characteristics of the flight directors provided for both systems were acceptable.

9. The HUD formats provided for both systems were acceptable.

10. For all the environmental conditions assumed in the approach and landing tests, the control power used was always substantially less than the maximum available.

11. With the Type 1A system pilot-control modes, the type of pilot controls (stick, lever, thumb wheel) used was not a major factor in the ability to perform the approach and landing task.

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