Moving Base Simulation of an ASTOVL Lift-Fan Aircraft

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Nomenclature

h	altitude, ft
$\dot{h}$	vertical velocity, ft/sec
K_{fnt}	scale factor for lift from jet-induced fountain
p	roll rate, deg/sec
q	pitch rate, deg/sec
r	yaw rate, deg/sec
T_{CN}	cruise nozzle thrust, lb
T_{LF}	lift-fan thrust, lb
T_{LN}	lift-nozzle thrust, lb
T_R	rise time, sec
V	airspeed, knots
V_{ej}	equivalent jet velocity ratio
V_x	ground speed, ft/sec
V_y	lateral velocity, ft/sec
β	sideslip angle, deg
$\Delta L/T$	normalized jet-induced aerodynamic ground effect
δ_{LF_x}	longitudinal lift-fan deflection, deg
δ_{LF_y}	lateral lift-fan deflection, deg
δ_{LN}	lift-nozzle deflection, deg
δ_{lat}	lateral stick deflection, in.
δ_{lon}	longitudinal stick deflection, in.
δ_N	thrust deflection angle, deg
δ_{ped}	pedal deflection, deg
δ_{th}	power lever angle, deg
ϕ	bank angle, deg
γ	flightpath angle, deg
ψ	heading angle, deg
θ	pitch attitude angle, deg

ACAH	attitude command/attitude hold
APP	approach control mode
ASTOVL	advanced short takeoff and vertical landing
ATM	automatic transition control sub-mode
CGI	computer-generated imaging
CTO	cruise/takeoff control mode
FPC	flightpath command
FTM	full thrust command control sub-mode
HQR	handling qualities ratings
HUD	head-up display
IGV	inlet guide vane
IMC	instrument meteorological conditions
MTV	manual thrust vector control mode
RC	rate command
RCAH	rate command/attitude hold
rms	root mean square
SCAS	stability and command augmentation system
SKP	station-keeping point
SS	sea state
STOL	short takeoff and landing
STOVL	short takeoff and vertical landing
TRC	translational rate command control mode
VC	velocity command
VMC	visual meteorological conditions
VMS	Ames Vertical Motion Simulator
V/STOL	vertical or short takeoff and landing

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Summary

Using a generalized simulation model, a moving-base simulation of a lift-fan short takeoff/vertical landing fighter aircraft was conducted on the Vertical Motion Simulator at Ames Research Center. Objectives of the experiment were to (1) assess the effects of lift-fan propulsion system design features on aircraft control during transition and vertical flight including integration of lift fan/lift/cruise engine/aerodynamic controls and lift fan/lift/cruise engine dynamic response, (2) evaluate pilot-vehicle interface with the control system and head-up display including control modes for low-speed operational tasks and control mode/display integration, and (3) conduct operational evaluations of this configuration during takeoff, transition, and landing similar to those carried out previously by the Ames team for the mixed-flow, vectored thrust, and augmentor-ejector concepts. Based on results of the simulation, preliminary assessments of acceptable and borderline lift-fan and lift/cruise engine thrust response characteristics were obtained. Maximum pitch, roll, and yaw control power used during transition, hover, and vertical landing were documented. Control and display mode options were assessed for their compatibility with a range of land-based and shipboard operations from takeoff to cruise through transition back to hover and vertical landing. Flying qualities were established for candidate control modes and displays for instrument approaches and vertical landings aboard an LPH assault ship and DD-963 destroyer. Test pilot and engineer teams from the Naval Air Warfare Center, Boeing, Lockheed, McDonnell Douglas, and the British Defence Research Agency participated in the program.

Introduction

NASA Ames Research Center is participating in technology development for advanced short takeoff and vertical landing (ASTOVL) fighter aircraft as a member of the Advanced Research Projects Agency (ARPA) ASTOVL program. Integration of flight and propulsion controls is one of the critical technologies being pursued in that program. NASA's role in the program is to participate in developing design guidelines for integrated flight/propulsion controls, support ARPA technology development for ASTOVL demonstrator aircraft, and provide consultation on integrated control design to ARPA contractors. This work will be accomplished in a joint program with ARPA, Department of Defense agencies, US and UK industry, and the UK Ministry of Defence. Specifically, NASA will carry out design guideline analyses for the control system and conduct piloted simulations on the Ames Research Center Vertical Motion Simulator (VMS) to evaluate design guidelines and to assess the merits of contending design approaches.

As part of NASA's effort in support of ARPA's ASTOVL aircraft, a moving-base simulation of a lift-fan configuration was conducted to examine its flying qualities over the low-speed flight envelope, including transition from conventional to vertical flight, hover and vertical landing. Objectives of the experiment were to (1) assess the effects of lift-fan propulsion system design features on aircraft control during transition and vertical flight including integration of lift fan/lift/cruise engine/aerodynamic controls and lift fan/lift/cruise engine dynamic response, (2) evaluate pilot-vehicle interface with the control system and head-up display including control modes for low-speed operational tasks and control mode/display integration, and (3) conduct operational evaluations of this configuration during takeoff, transition, and landing similar to those carried out previously by the Ames team for the mixed-flow, vectored thrust and augmentor-ejector concepts. The flying qualities evaluation included decelerating transitions to hover and vertical landing shipboard or land-based, waveoffs to accelerating transitions, short takeoffs, and vertical takeoffs. The balance of this report provides a description of the aircraft and of the simulation experiment, followed by a discussion of results extracted from the program.

Description of the Lift-Fan ASTOVL Aircraft

The lift-fan STOVL aircraft is a single-place, single-engine fighter/attack aircraft (fig. 1) featuring a wing-canard arrangement with twin vertical tails. It is a configuration developed at Ames Research Center through analytical predictions to permit generic studies of flight characteristics of this STOVL concept. The

propulsion system concept (fig. 2) consists of a remote lift fan coupled to a lift/cruise turbofan engine to permit continuous transfer of energy from the lift/cruise engine to the lift fan. The model can generically represent response characteristics of either a gas- or shaft-coupled configuration. The lift/cruise engine exhaust is either ducted aft to a thrust-deflecting cruise nozzle in conventional flight or diverted to two deflecting lift nozzles in vertical flight. Throughout transition, flow can be continuously transferred between the cruise and lift nozzles. Lift-fan and lift-nozzle thrust can be deflected from 45 to 100 deg below the aircraft waterline. The cruise nozzle can be deflected ±20 deg vertically.

The basic flight control system consists of the canard, ailerons, and twin rudders for aerodynamic effectors during forward flight. For powered-lift operation, control is provided by differential thrust transfer between the lift fan and lift nozzles, deflection of lift-fan and lift-nozzle thrust, and deflection of cruise nozzle thrust. Pitch control is achieved by a combination of canard deflection, thrust transfer between the lift fan and lift nozzles, and deflection of the cruise nozzle. Roll control is produced by the ailerons and differential thrust transfer between the lift nozzles. Yaw control is derived from the combination of rudder deflection, differential lift-nozzle deflection, and lateral lift-fan thrust deflection. As an option, reaction control, powered by engine compressor bleed air, can provide additional control moments through nozzles located in the wing extremities and in the tail. Longitudinal acceleration is achieved through thrust transfer between the lift fan, lift nozzles, and cruise nozzle and by deflection of the lift-fan and lift-nozzle thrust.

A variety of control command modes, as shown in table 1, are available depending on the phase of flight and the pilot's task. In the cruise/takeoff (CTO) mode, the pilot has direct control of the magnitude of the lift/cruise engine thrust. The propulsive lift system is not in use, and the pilot has no direct control of thrust vector angle. Rate damping augmentation is provided for pitch and roll control along with dutch roll damping and turn coordination for the yaw axis. In transition, one control option, the manual thrust vector (MTV) mode, allows the pilot to control the magnitude of the propulsion system thrust (lift-fan plus lift/cruise engine thrust) as well as the direction of the net thrust vector for speed and flightpath control. Pitch and roll are controlled through rate command/attitude hold augmentation in transition, blending to attitude command/attitude hold at low speed. Yaw control is the same as for CTO at higher speeds during transition and blends to yaw rate command at low speed. Another control option, the approach (APP) mode, activates a longitudinal acceleration command/velocity hold system, with the net thrust vector angle as the speed

control effector. In decelerating from wing-borne to powered-lift flight, a flightpath control system is activated as the net thrust vector angle exceeds 70 deg and the commanded core engine thrust exceeds 60 percent of its maximum value. This flightpath system remains activated until the net thrust vector angle decreases below 50 deg. The portion of the APP mode that does not use a flightpath controller is called FTM (full thrust mode), as the pilot still has direct control of the lift/cruise engine thrust, while that portion that uses a flightpath controller is called ATM (automatic transition mode). For either mode, flightpath can also be controlled with pitch attitude while in semi-jet-borne flight down to airspeeds of approximately 70 knots. Pitch, roll, and yaw control are identical to that for MTV. While the pilot may opt to stay in either MTV or APP mode for hover, the translational rate command (TRC) mode operates exclusively in the low-speed powered lift and hover flight regime. Propulsion system control in this mode consists of a vertical velocity and a longitudinal velocity control system. Lateral velocity command is realized through roll control. The yaw axis control remains the same as for MTV.

Control mode availability is subject to the restrictions shown in figure 3. The philosophy behind these restrictions is to prevent the pilot from engaging or disengaging the lift fan when the sudden addition or deletion of lift-fan thrust could upset the aircraft. Details on control mode selection restrictions will be given in terms of what modes the pilot can select while the control system is already engaged in a particular mode.

From the CTO mode, the lift fan can be engaged (that is, MTV or APP mode can be selected) if the aircraft is airborne and the airspeed is between 250 and 150 knots. As the APP mode features a longitudinal speed loop, the inceptor for the longitudinal acceleration (a thumbwheel) must be in its detent for this mode to be engaged. Mode switches on the control panel can be used to engage either flight control mode; MTV can also be engaged by depressing a button on top of the thrust vector lever (the "waveoff switch"). Once the pilot successfully engages MTV or APP from CTO, a 5 sec delay occurs before any lift-fan thrust can be commanded. This delay accounts for reconfiguration of the lift-fan nozzle and inlet for powered-lift flight. TRC cannot be selected directly from CTO. When on the ground, the MTV mode can be selected for STO.

From MTV mode, APP may be entered at any time, provided the thumbwheel is in its detent position. CTO may only be entered if the lift-fan thrust is vectored fully aft or if the aircraft is on the ground; the pilot selects this mode by depressing the MTV button, thus deselecting this mode in favor of CTO. An automatic switch to CTO

occurs if the airspeed exceeds 250 knots. When changing from a lift-fan engaged mode to CTO, a 10 sec delay in lift-fan shutdown occurs after the mode is selected, simulating lift-fan spool-down, cooling, and lift-fan inlet and nozzle reconfiguration. TRC mode can only be engaged if the airspeed is below 60 knots and the thumbwheel is in its detent.

From APP mode, the MTV mode can be entered by depressing the APP mode on the control panel (deselecting the APP mode), by selecting the MTV mode button directly, or by depressing the waveoff switch. TRC can only be entered if the thumbwheel is in detent and if the airspeed is below 60 knots. As in the case with MTV, CTO can only be entered if the thrust vector angle of the aircraft is directed fully aft. Automatic switching to CTO occurs if the airspeed exceed 250 knots. Upon a landing immediately following jet-borne flight, the flight control mode automatically reverts to MTV, thereby disengaging the vertical velocity control system.

While in TRC, the pilot can use the thumbwheel to switch to APP mode and accelerate to semi-jet-borne flight. APP can also be engaged by deselecting TRC or by directly selecting the APP switch on the control panel. MTV mode can only be selected through the waveoff switch, although landing in TRC will cause an automatic switch to MTV.

A head-up display (HUD) that has been employed by NASA in several previous V/STOL simulations provided the primary flight display for this experiment. The display is described here in general terms. The reader should consult reference 1 for a complete description of symbology and drive laws. Head-up display modes are associated with the transition from conventional flight to hover and with the precision hover and vertical landing, and are tailored to the characteristics of the control mode selected by the pilot. The transition and hover modes are depicted in figure 4. For the transition phase, shown in detail in figure 4(a), the display is flightpath centered and presents the pilot with a pursuit tracking task for following the intended transition and approach guidance to a final hover point. Course and glide slope guidance are provided in the form of a lead (ghost) aircraft that flies the desired flight profile with a lead separation time of 10 sec. The pilot's task is to maneuver the flightpath vertically and laterally to track the ghost aircraft. As indicated in references 1 and 2, the flightpath symbol was quickened to compensate for lags in the airframe and propulsion system response. For the MTV or FTM control modes, the flightpath compensation included lagged pitch rate and washed out throttle commands in combination with the true flightpath. For ATM, the flightpath was complemented with its commanded value in the short term. True lateral flightpath was represented by the flightpath symbol. Deceleration

guidance is presented by an acceleration error ribbon on the left side of the flightpath symbol which the pilot nulls to achieve the deceleration required to bring the aircraft to a hover at the initial hover point. Situation information that accompanies the flightpath and ghost aircraft symbology includes aircraft attitude, altitude, sink rate, airspeed, reference angle of attack, engine rpm, thrust vector angle, longitudinal acceleration, heading, and distance to the hover point.

During the latter stages of the deceleration as the aircraft approaches the intended point of hover, selective changes are made to the approach display to provide guidance for the hover point capture. Specifically, the longitudinal velocity vector, predicted longitudinal velocity, and station-keeping cross appear referenced to the flightpath symbol as shown in figure 4(b). The pilot controls the predicted velocity toward the station-keeping cross position and adjusts velocity to bring the cross to rest at the reference hover point indicated by the cross being adjacent to the flightpath symbol. Once the aircraft is stabilized in this condition, the pilot is ready to perform the vertical landing.

For the vertical landing, including recovery to the ship, the HUD format superimposes horizontal (plan) and vertical views and provides command and situation information in a pursuit tracking presentation (fig. 4(c)). The aircraft symbol is centrally located and fixed in the display and represents the relative locations of the landing gear and nose boom in plan view. In the horizontal frame, a rectangular pad symbol represents a landing area 40 by 70 ft and is scaled in proportion to the landing gear of the aircraft symbol. The aircraft's horizontal velocity vector is represented by a line emanating from the aircraft symbol. A horizontal velocity predictor symbol indicates magnitude and direction of the pilot's velocity commands. The pilot's task is to place the predicted velocity symbol over the intended hover position, typically the landing pad, and keep it there as the aircraft and pad symbols converge. The aircraft's height above the landing pad is represented by the deck bar, which is displaced at a scaled vertical distance below the aircraft symbol. Commanded vertical velocity is displayed by a diamond, which is referenced to the right leg of the aircraft symbol and to a ribbon that represents the allowable range of sink rate. To maintain altitude, the pilot keeps the vertical velocity diamond adjacent to the right leg of the aircraft symbol, indicating zero sink. To initiate the vertical landing and to maintain the desired closure rate to the pad, the pilot commands the diamond to the desired sink rate within the allowable limits. Predicted horizontal and vertical velocity presentations were compensated for aircraft and propulsion system lags, as they were for transition. In this case, for the MTV mode, true velocities were complemented with

translational accelerations and washed out control commands. For the TRC mode, the commanded horizontal velocities were displayed directly. Vertical velocity was complemented with washed out vertical velocity command. Attitude, altitude, sink rate, airspeed and ground speed, distance to the hover point, engine rpm, thrust vector angle, heading, vertical velocity limits, and wind direction are provided as situation information.

Aerodynamic data on which the simulation was based were derived from analytical predictions for wing-borne, power-off conditions and for jet-borne conditions during transition and hover, including ground effect and hot gas ingestion. The propulsion model of the engine, the characteristics of the various nozzles, and the inlet momentum are used in defining the direct force term. A linear transfer function defined the transient response of the lift/cruise engine and lift-fan thrust. The aerodynamic model of the aircraft is described in detail in reference 3 while the propulsion system and integrated flight/propulsion controls are covered in similar detail in reference 2.

Simulation Experiment

Simulator Facility

This experiment was conducted on the Vertical Motion Simulator (fig. 5) at Ames Research Center. The simulator provides six degree-of-freedom motion that permits particularly large excursions in the vertical and longitudinal axes and bandwidths of acceleration in those axes, as well as pitch, roll, and yaw, that encompass the bandwidths of motion sensing that are expected to be of primary importance to the pilot in vertical flight tasks. Appendix A lists the simulator motion system performance as well as the motion washout filter characteristics adopted for this experiment.

An interior view of the cockpit is shown in figure 6(a). A three-window, computer-generated imaging (CGI) system provided the external view. The CGI could present an airfield scene or a ship scene, the latter of which modeled either an LPH assault class carrier or a Spruance-class destroyer (DD-963). An overhead optical combining glass projected the HUD for the pilot. A center stick and rudder pedal arrangement is seen in the figure, along with a left-hand throttle quadrant of the kind used in the Harrier. This quadrant contained both the power lever (throttle) and thrust vector deflection handle (nozzle lever). A schematic of the instrument panel is shown in figure 6(b). Control mode selection buttons on the instrument panel were arranged vertically so that the button for the most heavily augmented lift-fan mode (TRC) was on the top, and the least augmented lift-fan mode (MTV) was on the bottom.

If the control system allowed the pilot to enter the selected control mode, the mode button would be illuminated, along with any mode buttons below the one that was selected. In this way, the number of lit buttons served as a reminder of the degree of control augmentation. The mode button would not light if the pilot tried to select a mode that could not be entered. When the control system was in CTO mode, all of the mode button lights were off, which also indicated that the lift fan was not engaged. Computer frame time for the real-time digital simulation was 20 msec. Overall frame time for output of the CGI in response to the pilot's control inputs was 64 msec.

Evaluation Tasks and Procedures

The pilot's operational tasks for evaluation during the simulation were (1) curved decelerating approaches to hover, followed either by a vertical landing on the airfield or aboard the LPH or the DD-963, (2) accelerating transitions from hover to conventional flight, (3) short takeoffs, and (4) vertical takeoffs. In addition, discrete maneuvers were performed to assess control power demands; these included longitudinal and lateral quick stops from a steady translational velocity, pedal turns and heading captures, and decrab prior to touchdown during a crosswind landing. For evaluation purposes, the decelerating approaches were divided into two phases. The first phase was initiated under instrument meteorological conditions (IMC) in level flight at 1100 ft altitude at 200 knots in the landing configuration. The aircraft's initial position was on a downwind heading abeam the initial hover station-keeping position. The sequence of events for the initial phase was a 3 deg glide slope capture, commencement of a 0.1 g nominal deceleration, a left turn to base leg and then to align with the final approach course, and, on short final at a range of 1000 ft, a change in nominal deceleration rate to 0.05 g. Desired performance was defined as keeping the center of the ghost aircraft within the circular element of the flightpath symbol, with only momentary excursions permitted (analogous to 1/2 dot deflection on a standard instrument landing display). Adequate performance was achieved when tracking excursions were significant, but not divergent. The initial phase of the approach was considered complete at the change in deceleration rate corresponding to the final closure to the hover point. Meteorological conditions consisted of a ceiling of 100 ft and a visual range of 1200 ft in fog with wind varying up to a maximum of 34 knots at 30 deg to the left of the final approach course and with an rms turbulence up to 6 ft/sec.

Acquisition of the hover 43 ft above the landing surface was the final phase of the approach. For the shipboard approaches, this included an initial station-keeping hover

100 ft to port and 100 ft astern of the landing spot, followed by a constant altitude translation to a hover over the landing pad. Desired performance was defined as acquisition of the hover with minimal overshoot and altitude control within ±5 ft. Adequate performance was achieved when overshoot did not result in loss of the landing pad symbol from the display field of view and altitude control was safe.

The vertical landing was accomplished on either a 100 by 200 ft landing pad on the runway or shipboard on Spot 7 on the aft deck of the LPH or on a 40 by 70 ft landing pad on the DD-963's aft deck. Desired landing performance was defined as touchdown within a 5 ft radius of the center of the pad with a sink rate of 3 to 5 ft/sec. Adequate performance was considered to be touchdown within the confines of the pad at sink rates less than 12 ft/sec and with minimal lateral drift. Wind conditions for the runway landings were identical to those for the approach. For shipboard recovery, calm seas and sea states up to 4 (for the DD-963) and 5 (for the LPH) were represented. Wind over deck varied from 15 to 34 knots from 30 deg to port. For the DD-963 at sea state 4, peak motions of the ship's landing pad were 7 ft heave, 2 ft sway, and 4 deg roll. Ship motion and airwake were based on the model of reference 4.

Accelerating transitions were initiated from the hover under visual meteorological conditions (VMC) with full throttle and rotation of the thrust vector. The rate of thrust vector deflection was restrained to ensure a level to slightly climbing flightpath. The pilot chose the pitch attitude to achieve best acceleration. The transition was considered complete when the aircraft accelerated to 200 knots. Transitions were performed in calm air. In addition, waveoffs were executed at various points during the decelerating approach to permit the pilot to assess the transient control associated with conversion from the approach to an accelerating transition. The pilots' assessments of this task were based on the effort required to execute the transition within the constraints imposed above, and the sensitivity of their performance of the task to abuses or variations from the recommended technique.

Short takeoffs were executed either from the runway or from the deck of the LPH. Takeoff procedures involved setting the stop for the thrust vector lever in accord with the takeoff weight, setting full thrust and initiating the takeoff roll, accelerating to lift-off speed, moving the thrust vector lever to the takeoff stop, and rotating the aircraft to a pitch attitude of 12 deg. Following lift-off, the aircraft was allowed to climb and accelerate; the pilot vectored the thrust aft while maintaining a positive rate of climb.

Vertical takeoffs were also carried out from the runway or LPH, initiated with the thrust vector lever set at the hover stop of 85 deg followed by application of maximum thrust.

Five pilots with V/STOL and powered-lift aircraft experience performed as evaluation pilots in this experiment. Handling qualities ratings (HQR) and comments were obtained, based on the Cooper-Harper scale (ref. 5). Time histories of data were processed in real time or post-run to document the aircraft's behavior and pilot performance.

Experiment Configurations

The performance of the propulsion system is critical to STOVL aircraft especially in low-speed and hover flight. In this flight region, the propulsion system contributes most of the control power that is available to the pilot when the aerodynamic control effectors lose their effectiveness. The dynamic characteristics of the propulsion system, such as bandwidth, nonlinearity, rate limits, and thrust transfer rate, can directly influence flying qualities during low-speed maneuvers.

In this experiment, specific propulsion system performance characteristics were investigated to determine their effect on pitch and heave control for transition, hover, vertical landing, vertical takeoff, and short takeoff. Experimental variables for the investigation of propulsion system response were the time constant for lift-fan transient response, variable inlet guide vane authority, lift-fan thrust augmentation ratio, and core engine acceleration limit. The baseline configuration of the lift/cruise engine was defined as a second order dynamic response with a bandwidth of 10 rad/sec with a damping ratio of 0.6, a thrust rate limit of 8,000 lb/sec, and a maximum thrust of 32,500 lb. The individual nozzle thrust transfer rate was 10,000 lb/sec. The lift-fan time constant was 0.1 sec with zero inlet guide vane (IGV) authority. The maximum lift-fan thrust output was limited to 17,400 lb.

Variations of the lift-fan IGV authority and lift-fan inertia dependent time constant were conducted to examine the pitch control dynamics of the lift fan/lift/cruise propulsion configuration. A matrix of cases for time constant and guide vane authority is shown in table 2. Two values of lift-fan augmentation ratio were used, the baseline being 2.0, the alternate being 2.5. Lift/cruise engine acceleration limits of 4, 8, 10, and 25 percent of maximum thrust per second (baseline) were also explored.

One control inceptor variation was evaluated. In the APP mode, the pilot could either use pitch attitude to control the final deceleration to the initial hover point with the thrust vector at a fixed deflection angle, or directly

command longitudinal deceleration through a thumbwheel with the aircraft at a fixed pitch attitude.

For the decelerating approach to vertical landing and rolling vertical landing, experiment variables were the control system configuration and levels of wind and turbulence. Both the MTV mode and the APP:FTM mode switching to APP:ATM mode were investigated for the approach and for rolling vertical landings; MTV mode and APP:ATM mode switching to TRC mode were evaluated for the vertical landing. Three wind conditions of 0, 15, and 34 knots with turbulence of 0, 3, and 6 ft/sec rms respectively were included for the approach and runway landing. For shipboard landings, sea states of 0, 3, and 5 with wind conditions of 10, 15, and 30 knots respectively were assessed for operations to the LPH. Sea states of 0, 3, and 4, with wind conditions of 15, 27, and 34 knots respectively were used for the DD-963.

For accelerating transitions, and vertical and short takeoffs, only the MTV mode was used, since the pilots preferred to have direct control of thrust vector angle and magnitude for this task.

Results

Effects of Propulsion System

A summary of the pilot evaluations of lift-fan dynamic response is shown in figure 7 in terms of bandwidth of the lift fan and authority of the inlet guide vanes, expressed as percent of maximum pitch control authority. At low inlet guide vane control authority, precise pitch control is very sensitive to reduction in lift-fan bandwidth. However, for guide vane authorities that exceed 20 percent of total pitch control, the sensitivity to lift-fan bandwidth appears insignificant. For any combination of lift-fan character-istics, a range of marginal control capability exists between clearly acceptable and unacceptable character-istics. The range of marginal performance is dependent on the aggressiveness of the pilot's pitch or heave control inputs. The lower bound for marginal performance was obtained from nominal performance of the task of decel-eration to hover and vertical landing. The upper bound was obtained from purposely introducing large pitch and vertical velocity command inputs throughout the approach and while maintaining hover at the station-keeping point.

Increasing the lift-fan augmentation ratio from 2.0 to 2.5 did not significantly change the flying qualities of the aircraft in calm conditions. Pilots did note some degra-dation of pitch axis control in heavy turbulence. Addi-tionally, one pilot noted that the rudder pedals seemed to be more sensitive in hover. As lateral lift-fan deflection is used as a control effector in this regime, a reduction in

deflection authority may have been required to compen-sate for the increased lift-fan augmentation ratio.

Lift/cruise engine acceleration limits of 10 and 8 percent per second did not affect aircraft handling qualities ratings. Power lever inputs near the capture of the hover station-keeping point resulted in uncontrollable pitch axis oscillations when this acceleration limit was reduced to 4 percent per second.

Closed-Loop Response

The integrated flight/propulsion control was an implicit state rate feedback model-following command regulator structure combined with a nonlinear inverse portion to accommodate the aerodynamic and propulsion character-istics of the aircraft across the flight envelope. Perfor-mance of the design was tuned to produce Level 1 handling qualities as described in reference 2, based on previous work developed at Ames (refs. 6 and 7). Documentation of system performance is shown in the form of frequency responses in figures 8–17. Pitch and roll rate command/attitude hold, sideslip, and flightpath responses for transition (120 knots) are shown in figures 8–11. Responses of pitch and roll attitude command/attitude hold, yaw rate command, vertical speed control, and longitudinal and lateral translational rate command in hover are shown in figures 12–17. A summary of the frequency bandwidth of closed-loop response is shown in table 3. The bandwidth is defined as the frequency at which the amplitude is –3 dB for attitude systems or the frequency for 45 deg phase lag for rate systems. Measurements of bandwidth and phase delay extracted from the attitude frequency responses in hover are noted in table 4. In this case, bandwidth and phase delay conform to the definition of reference 8 where bandwidth is the lowest frequency that satisfies a 6 dB gain or 45 deg phase margin. Results from table 4 compared to the bandwidth criteria for hover suggested in reference 8 show that pitch, roll, and yaw performance meets Level 1 requirements. Flying qualities levels are based on the Cooper-Harper rating scale, where Level 1 applies to handling qualities ratings from 1 to 3, Level 2 to ratings from 4 to 6, and Level 3 to ratings from 7 to 9 on the scale.

Height control time response in hover of the closed-loop system is shown in figure 18. It shows a rise time to 50 percent of peak response of 1.4 sec and a vertical speed per vertical control input of 550 ft/min/in. From the rise time performance and the requirements suggested in reference 8, Level 2 handling qualities performance would be expected. However, results of the experiment indicate

Level 1 performance during the shipboard landing in calm and medium sea state as well as in wind and turbulence.

Operation with Control Modes and Displays

Pilots found the variety of control modes available and the mode selection restrictions to be acceptable. The thumb-wheel used to command longitudinal deceleration caused some difficulties involving the selection of APP mode. To satisfy the initial switch into APP mode and the switch from APP to TRC, the thumbwheel was required to be in its detent. The detent initially used did not give the pilots a strong tactile cue as to its location. As a result, the pilots unexpectedly could not enter the modes that they desired and were distracted from their primary tracking or station-keeping tasks. Replacing the thumbwheel with one that had a distinct detent made this mode switch acceptable.

While lit mode switches indicated that the lift fan was available to provide thrust, some pilots wanted to see a direct indication of fan rpm. The pilot in an actual lift-fan aircraft would have additional cues to indicate lift-fan operation, such as fan noise, that were not included in this simulation.

Pilots commented favorably on the HUD pursuit guidance display during transition. Tracking of the ghost aircraft with the flightpath symbol was intuitive and could be easily accomplished. Station-keeping point capture was more easily performed using the predictor ball, velocity vector, and station-keeping cross compared to using the display format that only presented the velocity vector and station-keeping point. Control of the predictor ball was easily interpreted and precise. In general, the pilots preferred to maintain constant pitch attitude and perform the capture using the thumbwheel to control rate of closure.

Flying Qualities Assessment

Transition— The pilots' assessments of flying qualities during transition in various wind and turbulence condi-tions are shown in figure 19. APP mode was considered to be Level 1 in calm air and light turbulence. While tracking the ghost aircraft and decelerating, the pilots controlled flightpath with pitch attitude until well into the semi-jet-borne regime. At that point (approximately 70 knots) flightpath or vertical velocity came under control of the throttle. Pitch response was predictable but the tracking of the ghost aircraft required more effort during the initial transition due to flightpath response in turbulence which was the result of the low wing loading of the aircraft. This led to the majority of the Level 2 ratings at the higher levels of turbulence. Additionally, pitch and flightpath perturbations occurred during initial

lift-fan spool-up. The integrated flight/propulsion control system improperly canceled the pitching moment incre-ment due to lift-fan thrust during the propulsion system reconfiguration. Once the full authority of the flightpath command was established, the task became easy to perform. The switchover of the throttle controller from thrust command to flightpath command control during the transition was transparent to the pilots.

A representative time history for the APP mode of the decelerating transition to the decision height of 100 ft in heavy turbulence is presented in figure 20. It can be seen that after establishing the descent and capturing the final approach course, workload was reduced to using the throttle to maintain the flightpath, with occasional adjustments made with the thumbwheel to maintain the constant deceleration profile. The increase in propulsion control activity after the closed-loop flightpath control engages is evident. Lateral disturbances required continu-ous adjustments with the lateral stick, but the tight yaw control kept sideslip excursions small to ease the lateral tracking task.

Ratings for the MTV mode during the approach are solidly Level 2, regardless of turbulence conditions. A representative time history with MTV mode during the approach is shown in figure 21. The primary reason for these ratings is that the pilots objected to having to work two inceptors with one hand (the power and nozzle levers) during this task. Additionally, continuous throttle manipu-lation was required in the semi-jet-borne regime, complicating the task.

Hover point acquisition— Hover point acquisition consists of changing deceleration profile from 0.1 g to 0.05 g and capturing the station-keeping point which is positioned 100 ft behind and to the left of the designated touchdown point on the deck. The pilot executes this acquisition at a 43 ft altitude. Pilot ratings for the APP mode under different weather conditions are shown in figure 19 and generally fall within Level 1. The use of a predictor ball and velocity vector allowed the pilots to accurately and aggressively capture the station-keeping point. No degradation in pilot ratings occurs with increasing turbulence since the aircraft response to winds is negligible at low dynamic pressure. Occasional trim inputs were sometimes required near the end of the approach once the control system fully blended from rate command/attitude hold to attitude command to establish the hover attitude.

A representative time history of hover point acquisition in heavy turbulence is shown in figure 22 for the APP mode. The deceleration was reduced from 0.1 g to 0.05 g by simply rolling the thumbwheel forward. Further adjust-ments of the thumbwheel were made to close to the

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station-keeping point. Height control was accomplished with minor throttle adjustments. Propulsion control activity is less than that during the approach due to the reduced sensitivity to turbulence. Lateral control was used primarily to make adjustments to counteract drift due to winds.

For the MTV mode, capturing the station-keeping point with the pilot controlling speed via pitch attitude was not considered difficult; the major issue in this case was maintaining altitude with manual thrust. This led to Level 2 ratings with some degradation in turbulence, as shown in figure 19. At least one pilot thought the predictor ball symbology was somewhat confusing when used in conjunction with the MTV mode because it did not directly match the control inceptor inputs as it did with the thumbwheel in APP mode. A representative time history is shown in figure 23.

Airfield landing– Although no specific pilot ratings were obtained for this task, the pilots found the flightpath symbology useful in providing guidance to the hover point over the STOL runway touchdown zone. The task was easy to repeat in crosswinds and turbulence, despite the effect of these disturbances on the HUD flightpath symbol.

Shipboard landing– In general, vertical landings were easy to perform in calm air and less so in sea state with deck motion and air disturbance. Difficulties arose when pilots were trying to maintain the relative touchdown position while keeping a desirable sink rate. Pilot ratings for a range of sea states are shown in figure 19 for the APP and MTV modes for landings on the LPH and DD-963.

LPH: Landings at sea state 0 and sea state 3 generally received Level 1 ratings and comments for the TRC mode. This mode allowed pilots to aggressively capture the landing pad, and the vertical velocity command system allowed them to easily capture the desired sink rate. The ratings began to scatter from Level 1 to Level 2 once the weather condition degraded to sea state 5. Level 2 ratings were mainly a consequence of exceeding desired sink rates of 5 ft/sec at touchdown due to the heave motion of the deck. A representative time history of landing on an LPH in sea state 5 is shown in figure 24. Control activity in all axes is modest until the latter stage of the descent to touchdown when control of longitudinal and lateral position relative to the touchdown spot becomes quite active.

A representative time history of the same landing task with MTV mode is shown in figure 25. Using MTV alone, pilot ratings were Level 2 because of the lack of a vertical velocity command system and the pilot effort to maintain

position over the hover pad with the attitude command system. Poorer height control precision can be noted in the figure in comparison to that shown for the TRC mode in figure 24. Also evident are the pitch attitude excursions associated with control of longitudinal position relative to the landing spot.

DD-963: The pilots generally found it more difficult to judge sink rates and to time the aircraft touchdown with the DD-963 than with the LPH. Consequently, touchdown sink rates were not consistently less than 5 ft/sec for landing in sea states 3 and 4 and were the basis for Level 2 ratings for the TRC mode. Otherwise, control of longitudinal and lateral position was not any more difficult than it was for the LPH for this mode. For the MTV mode, the ratings for the DD-963 landings are nearly identical to those for the MTV landings on the LPH, despite the differences in the motion of the two ships. The lack of the vertical velocity command system and difficulty with sink rate control for this mode are the factors that led to these Level 2 ratings.

Accelerating transition/waveoff– Qualitative evaluations were made for accelerating transitions which required switching from TRC to MTV, ATM to MTV, and FTM to MTV modes. The pilot made these mode changes via the waveoff switch on the thrust vector lever. The pilots followed Harrier transition technique by maintaining a level or slightly climbing flightpath while moving the thrust vector to the aft position. None of the pilots encountered any difficulty in executing missed approaches. Switching the throttle lever from flightpath command to manual thrust control was transparent to the pilot. No pitch disturbances were encountered at 250 knots during automatic lift-fan shutdown.

Short takeoff– The pilots found MTV mode acceptable for short takeoff. The use of the thrust vector lever led to a predictable, intuitive aircraft response when coupled with a short takeoff procedure that was similar to that of the Harrier. Transition to fully wing-borne flight was executed without difficulty.

Vertical takeoff– The manual thrust mode posed no difficulty for the pilots in executing vertical takeoffs. Once stabilized at the desired hover altitude, the pilots could easily switch to APP or TRC without thrust transients.

Control Power

Total pitch, roll, and yaw control available across the low-speed flight envelope from hover to 200 knots in steady level flight is shown in figures 26–28. Contributions to total control authority come from the aerodynamic control surfaces and from the propulsion control effectors. The

authority of the latter are dependent on the steady-state level of thrust associated with the particular flight condition. Maximum control power required for maneuvering during specific phases of a decelerating approach to landing is shown in figures 29-31. Data points represent pitch, roll, and yaw control power maxima for individual approaches with the control power required to trim subtracted. Phases of the approach include deceleration to the 100 ft decision height, capture of the station-keeping point, and vertical landing aboard either the LPH or DD-963. The influences of wind, turbulence, and sea condition are represented in these data. Control power usage includes the contributions of both the aerodynamic and propulsion effectors.

Pitch control usage for the various flight phases is shown in figure 29. For the decelerating approach, the maximum pitch control usage shows only a modest variation from 0.21 rad/sec^2 in calm air to 0.26 rad/sec^2 in heavy turbulence. There is also only a slight influence of turbulence on control during capture of the station-keeping point. In this case, the maximum pitch control power is 0.23 rad/sec^2 in heavy turbulence. This falls within a control power of 0.29 rad/sec^2 derived from the Level 1 requirement of MIL-F-83300 (ref. 9) for an attitude command system having a natural frequency of 2 rad/sec. Conversion between the requirements of reference 9, specified in terms of attitude change in 1 sec, and the related angular acceleration is described in reference 10. Pitch control used in the vertical landing is influenced very little by sea state. Maximum pitch control power usage is 0.25 rad/sec^2 while landing on the LPH in the heaviest sea conditions and is nearly the same for recovery to the DD-963.

Maximum roll control for the same flight phases is presented in figure 30. For the decelerating transition, peak roll control use shows a substantial increase from 0.4 rad/sec^2 in calm air to 0.7 rad/sec^2 in heavy turbulence. This assessment disregards the single point at 0.82 rad/sec^2 for the calm air case. Otherwise, the trend presents a consistent increase with level of turbulence. At the station-keeping point, a similar sensitivity to turbulence is evident, with a maximum in heavy turbulence of 0.56 rad/sec^2. This exceeds the applicable Level 1 requirement from MIL-F-83300 of 0.45 rad/sec^2 for a 2.4 rad/sec attitude command system. For shipboard landing, the sensitivity to sea state is also pronounced, with peak levels of roll control power bordering on 1 rad/sec^2 for either the LPH or DD-963.

During transition to decision height, maximum yaw control power increases substantially from calm air levels of 0.04 rad/sec^2 to 0.14 rad/sec^2 in heavy turbulence (fig. 31). The sensitivity to turbulence is somewhat less

pronounced at the station-keeping point, where maximum control power increases from 0.06 to 0.11 rad/sec^2. These results are substantially less than the MIL-F-83300 requirement for Level 1 yaw response which translates to 0.37 rad/sec^2 for a rate command system with a time constant of 0.5 sec. Shipboard landings show peak levels of control use to be about 0.1 rad/sec^2 for the LPH and 0.13 rad/sec^2 for the DD-963.

Control authority required to trim in limiting crosswinds is an important consideration in sizing the lateral and directional controls. Roll and yaw control trim requirements in a 30 knot crosswind are presented in figure 32 over the speed range from hover to 200 knots. Roll control to trim represents an increasingly significant fraction of total roll control up to speeds in the range of 120 knots. This trend is characteristic of jet V/STOL aircraft and was particularly pronounced in the early versions of the Harrier. It is attributed to the jet-induced rolling moment that arises from the same flow phenomenon that produces suckdown in free air in forward flight. Yaw control to trim shows a decreasing fraction with forward speed, although the trim requirement in hover is a significant fraction of the total available. Peak yaw control power of 0.1 rad/sec^2 was required to decrab prior to touchdown from a slow approach in the 30 knot crosswind.

Several discrete maneuvers were performed in hover to assess the representative control authorities for their execution. These maneuvers included longitudinal and lateral quick stops and pedal turns. Longitudinal quick stops were performed starting from an initial trimmed speed of 30 knots. A peak transient pitch attitude of 10 deg was reached during arrestment of the forward speed; the associated pitch control authority used was 0.2 to 0.3 rad/sec^2. Lateral quick stops from an initial lateral translational rate of 20 to 25 knots produced peak bank angle excursions of 20 deg and a maximum roll control power of 0.7 to 0.8 rad/sec^2. In executing the maneuver, the pilot established the aircraft off to the side of the runway and performed a brisk lateral translation to align with the runway centerline. Pedal turns to acquire a new heading were performed at steady rates up to 20 deg/sec and produced peak yaw control excursions of 0.2 rad/sec^2 as the pilot stopped the aircraft at the desired heading.

In conducting vertical takeoffs and landings, significant effects of ambient wind were observed on thrust margin for control of vertical velocity. In particular, it was observed that for as little as 10 knots steady wind, vertical takeoff could not be accomplished. The ground effect model documented in reference 3 was reviewed to determine the dominant speed sensitive influence on jet-induced lift. It should first be noted that the fountain

component for jet-induced lift was adjusted through a scale factor K_{fnt} to produce qualitatively a similar jet-induced lift characteristic to the AV-8B. In this case, the scale factor was set to 2.5. This produced an overall variation of jet-induced lift in ground effect shown in figure 33 with a mean ground effect and ingestion value as described in reference 10 equal to –0.006. With increasing equivalent airspeed as produced by an ambient wind, jet-induced lift displays increasing suckdown in ground proximity (fig. 33). A cross plot of the jet-induced lift variable $\Delta L/T$ with equivalent jet velocity ratio V_{ej} at wheel contact height (fig. 34) shows the aggravated suckdown to be most pronounced over the speed range of 0 to 10 knots (V_{ej} from 0 to 0.015). A review of the prediction method of reference 3 reveals the prominent contribution to this increased suckdown arises from the component associated with the ground vortex rollup. The variation in mean ground effect with increasing forward speed is –0.017 at $V_{ej} = 0.015$ (10 knots) and –0.035 at $V_{ej} = 0.042$ (30 knots). Based on the criteria of reference 10, this additional suckdown would require a commensurate increase in thrust margin of 6 percent to cater for the vertical landing in 30 knots of wind.

Conclusions

An evaluation of a generalized STOL fighter aircraft with an advanced integrated flight/propulsion control system and a lift/cruise engine was conducted in a moving base simulator. The objectives of this simulation experiment were to (1) assess the effects of lift-fan propulsion system design features on aircraft control during transition and vertical flight, including integration of lift fan/lift/cruise engine/aerodynamic controls and lift fan/lift/cruise engine dynamic response, (2) evaluate pilot-vehicle interface with the control system and head-up display including control modes for low-speed operational tasks and control mode/display integration, and (3) conduct operational evaluations of this configuration during takeoff, transition, and landing similar to those carried out previously at Ames for the mixed-flow, vectored thrust, and augmentor-ejector concepts. The evaluation tasks were decelerating transitions to recovery on either a ship or an airfield, vertical landing, accelerating transition, short takeoff, and vertical takeoff. These tasks were developed to evaluate flying qualities for the integrated flight control modes, HUD display symbology, and the control utilization.

With the baseline propulsive configuration, most pilots rated the flying qualities for the initial decelerating

transition adequate but not satisfactory. This was due to a combination of objectionable flightpath response to turbulence due to light wing loading characteristics of the aircraft and pitch attitude transients due to thrust distribution characteristics during the initial lift-fan startup. However, once the aircraft decelerated to slower speeds, the flightpath tracking task became easy and precise when using the flightpath command control mode. The HUD symbology coupled with good speed and flightpath control led to satisfactory flying qualities for the decelerating approach down to station-keeping point acquisition. A longitudinal velocity predictor on the HUD aided the capture of the station-keeping point. After switching to a translational rate command system, hover position and height control during the vertical landing was determined to be excellent. Difficulties with control of sink rate at touchdown in heavy sea state conditions, however, led to adequate (rather than satisfactory) ratings for vertical landing.

Regions of acceptable and unacceptable lift-fan characteristics (lift-fan time constant and inlet guide vane authority) were established for the transition and vertical landing. The range of marginal performance between the two regions was a reflection of levels of pilots' aggressiveness in performing the task. Lift-fan bandwidth became insignificant in pitch control response when IGV authority was above 20 percent.

Control power usage for trimming and maneuvering in crosswinds was documented. Maximum pitch control power usage of 0.23 rad/sec^2 for an attitude system was within MIL-F-83300 requirements. Maximum roll control power usage of 0.57 rad/sec^2 for an attitude system substantially exceeded the MIL-F-83300 requirement. Maximum yaw control power usage of 0.11 rad/sec^2 for a rate command system was considerably less than the MIL-F-83300 requirement. Both the roll and yaw results are consistent with the findings of reference 10 and reflect a need to reconsider the requirements of MIL-F-83300 as applied to this class of STOVL aircraft.

Pitch, roll, and yaw attitude response bandwidths met recommended criteria. In hover, the vertical velocity control rise time of 1.4 sec only met the suggested Level 2 (adequate) guideline. However, the pilots' assessments were Level 1 (satisfactory) except during transition under heavy turbulence and shipboard landing in heavy sea state.

Appendix A

Vertical Motion Simulator Motion Characteristics

The Vertical Motion Simulator used in this experiment is capable of producing large translational and rotational motion cues over frequency ranges that encompass the bandwidths of control of the tasks associated with transition and vertical flight. Longitudinal, lateral, and vertical motion limits were ±20, ±4, and ±30 ft, respec- tively. Motion system bandwidth (frequency for 45 deg phase lag) is 8 rad/sec for the vertical axis. The rotational limits in pitch, roll, and yaw are 18, 18, and 24 deg. Bandwidths are 10 rad/sec for pitch and roll and 6 rad/sec for yaw. Motion drive logic for each axis commands accelerations through second order high pass (washout) filters that are characterized by their gain, natural frequency, and damping ratio. In all cases, damping ratios of 0.7 were used. Filter gains and natural frequencies are presented in table A1 for the low- and high-speed regions of the transition envelope. These parameters were varied linearly between the low- and high-speed values over the speed range from 20 to 60 knots.

Table A1. Motion system gains and natural frequencies

Motion axis	Low speed		High speed	
	Gain	Frequency, rad/sec	Gain	Frequency, rad/sec
Pitch	0.5	0.7	0.5	0.6
Roll	0.3	0.2	0.35	0.75
Yaw	0.5	0.2	0.5	2.0
Longitudinal	0.7	0.7	0.4	0.8
Lateral	1.0	1.2	0.5	2.0
Vertical	0.8	0.2	0.6	0.5

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10. Franklin, J. A.: Criteria for Design of Integrated Flight/Propulsion Control Systems for STOVL Fighter Aircraft. NASA TP-3356, Apr. 1993.

Table 1. Flight control modes

Control axis	Control mode designations (applicable flight phases)				
	CTO (wing-borne flight)	MTV (transition, hover)	APP: FTM (transition)	APP: ATM (transition, hover)	TRC (hover)
Pitch/roll	Rate command/ attitude hold	Rate command/ attitude hold, blend to attitude command	Rate command/ attitude hold, blend to attitude command/ attitude hold	Rate command/ attitude hold, blend to attitude command/ attitude hold	
Yaw	Sideslip command	Sideslip command, blend to yaw rate command	Sideslip command, blend to yaw rate command	Sideslip command, blend to yaw rate command	Yaw rate command
Vertical	Aerodynamic lift	Thrust magnitude	Thrust magnitude	Flightpath command, blend to velocity command	Velocity command
Longitudinal	Thrust magnitude	Thrust vector angle	Acceleration command/ velocity hold	Acceleration command/ velocity hold	Velocity command
Lateral					Velocity command

Table 2. Propulsion system characteristic matrix

Bandwidth, rad/sec	Inlet guide vane authority, percent maximum pitch control				
	0	7	18	35	70
10	X				
8	X		X	X	
6	X			X	X
4	X	X	X	X	X
2	X	X	X	X	X
1	X	X	X	X	X
0.5		X	X	X	X

Table 3. Bandwidth summary of the closed-loop response

Flight Mode	Axis	Control mode	Bandwidth, rad/sec
Transition, APP:ATM	Pitch	RCAH	2.0
(120 knots, level flight)	Roll	RCAH	3.6
	Flightpath	FPC	1.0
Hover, APP:ATM	Pitch	ACAH	2.0
	Roll	ACAH	2.4
	Yaw	RC	2.0
	Vertical velocity	VC	1.1
Hover, TRC	Longitudinal velocity	VC	0.9
	Lateral velocity	VC	1.1

Table 4. Phase bandwidth and delay in hover

Axis	Control mode	Bandwidth, rad/sec	Phase delay, sec
Pitch	ACAH	3	0.069
Roll	ACAH	5.5	0.017
Yaw	RC	2	0.076
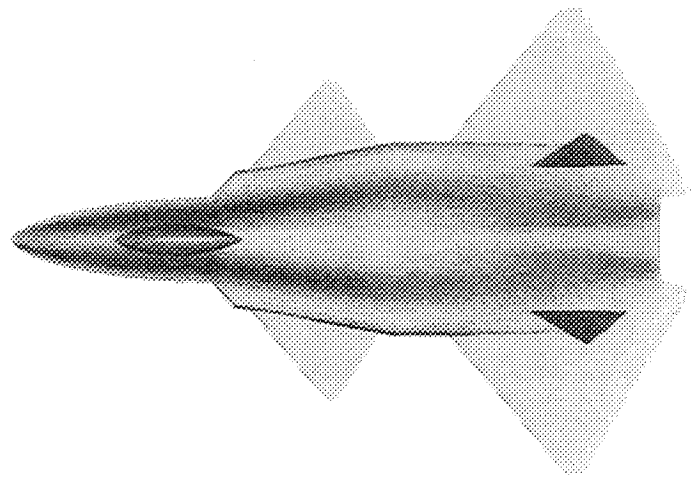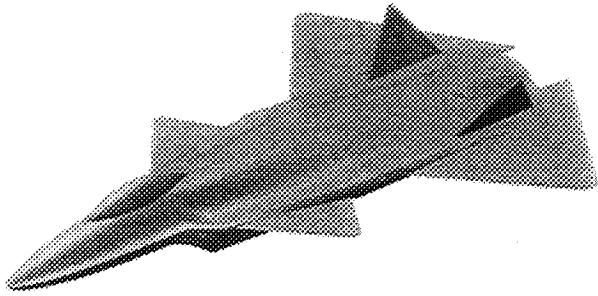
Figure 1. Views of the ASTOVL lift-fan aircraft.
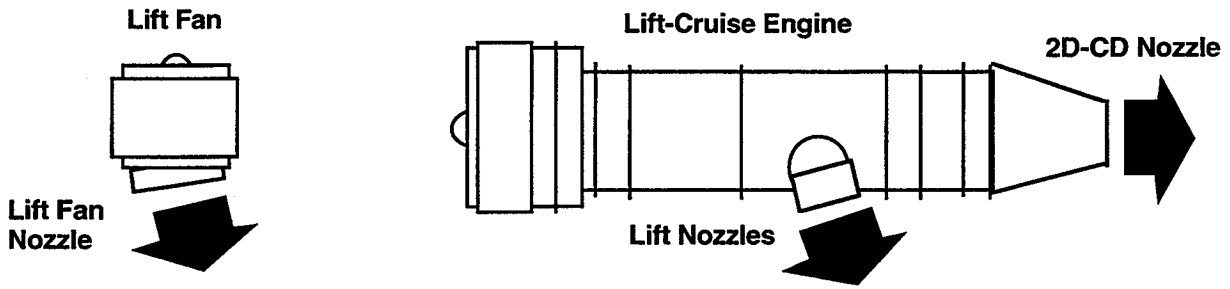
Figure 2. Propulsion system configuration.

Airspeed:	> 250 kts	≤ 250 kts, > 150 kts	≤ 150 kts, > 60 kts	Wingborne/Jetborne < 60 kts	WOW Any Airspeed
Lift Fan Off	CTO	CTO	CTO	CTO	CTO
Allowable Mode Switching					
Lift Fan On		MTV ◄──► APP	MTV ◄──► APP	MTV, TRC, APP	MTV
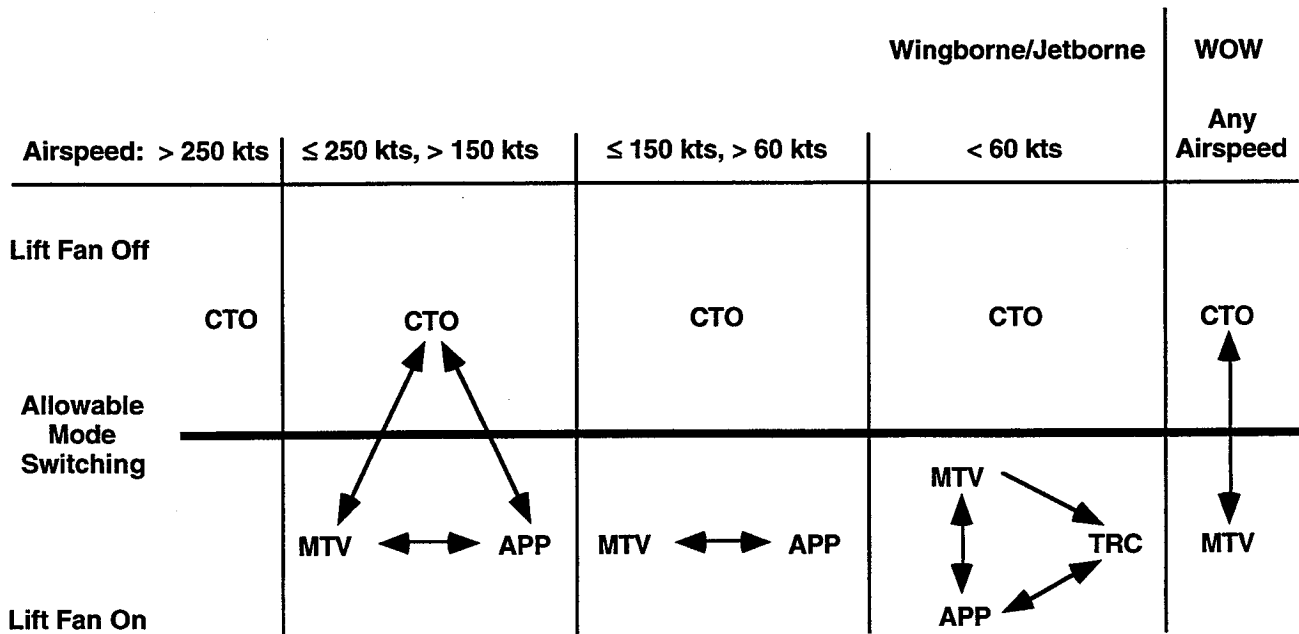
- When airborne/jetborne, the pilot cannot manually disengage the lift fan until the total thrust vector is deflected fully aft

- Disengagement of the nozzle lever clutch in APP or TRC mode causes reversion to the MTV mode

- Switching between FTM and ATM submodes within APP not shown as this change does not depend on airspeed

Figure 3. Control mode selection logic.

15
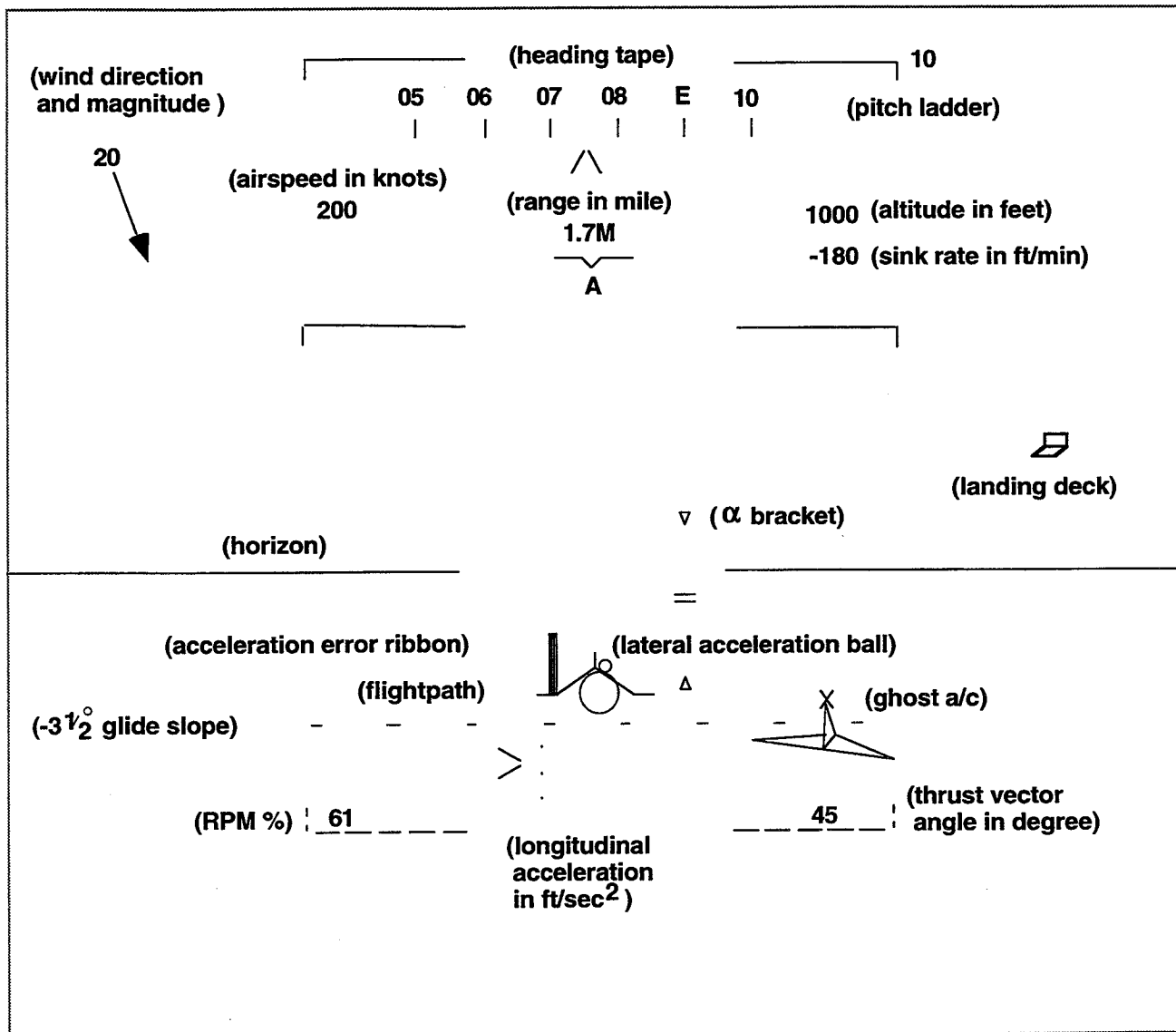
Figure 4(a). Head-up display approach mode.

05   06   07   08   E   10

20

50

(station keeping point, SKP)

(range in feet)
900

200

-120

A

(longitudinal velocity
predictor ball)

(longitudinal velocity vector)

(vertical and
lateral velocity)

73   85
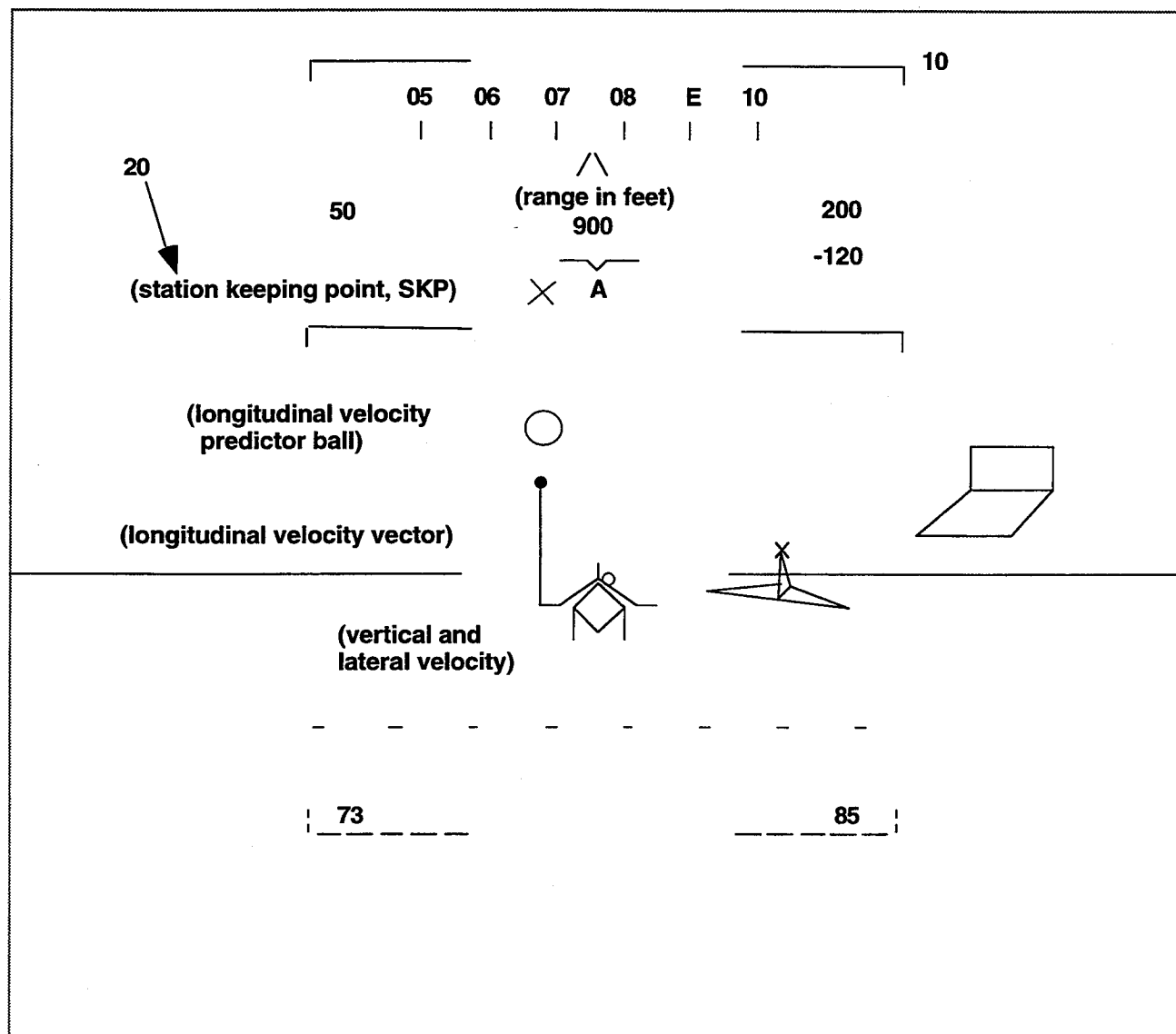
Figure 4(b). Head-up display approach mode for station-keeping point capture.

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05 06 07 08 E 10 10

20   150   100

(ground velocity   18   -120
in kts)

H

(velocity predictor ball)

(velocity vector)   (a/c trident)

(wind direction)

(SKP moves to the
TD point on the deck
when a/c is closing   (vertical velocity)
in to the deck)

81   (deck and allowable sink   88
rate ribbon are displayed
when a/c is over the deck)
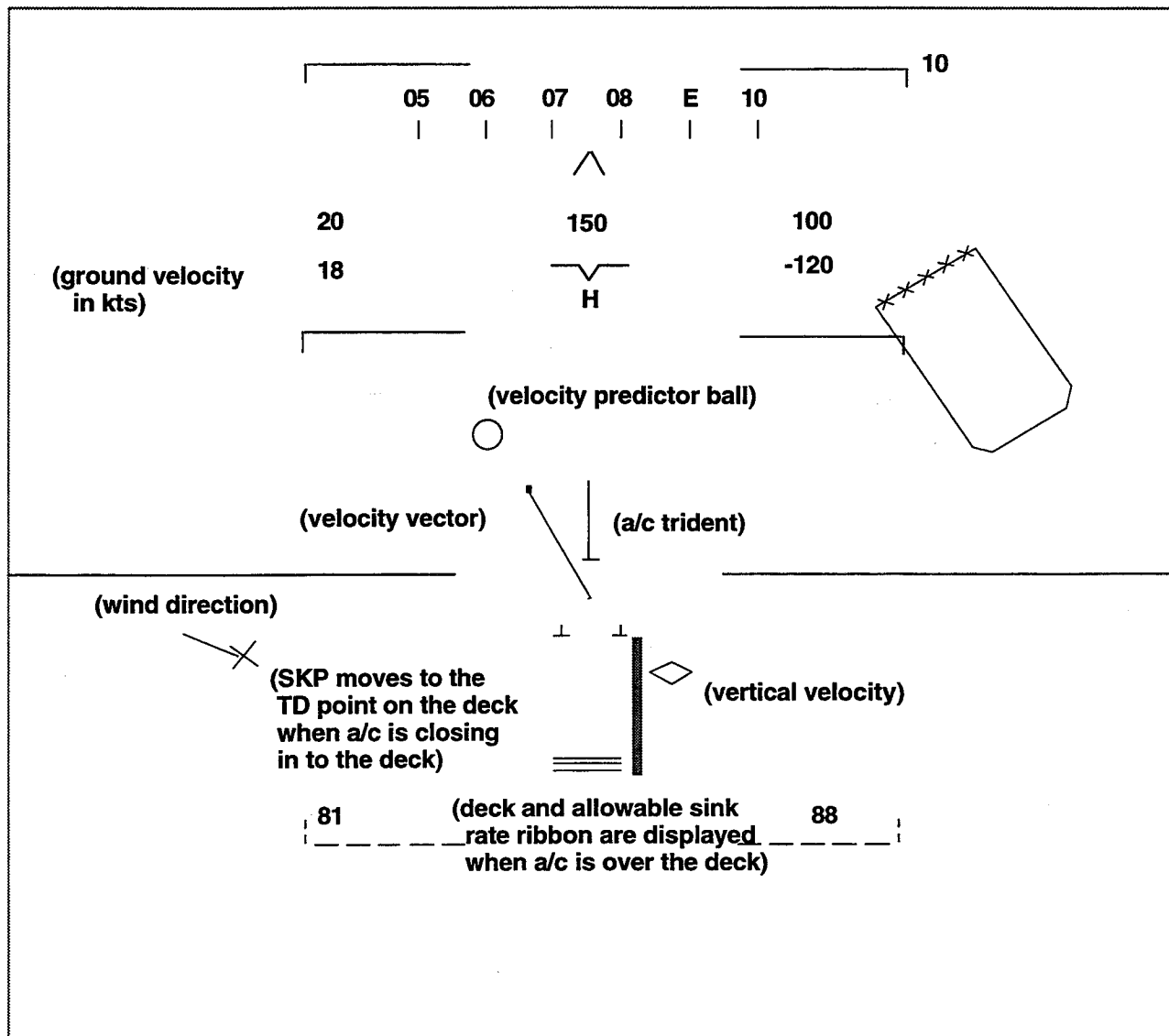
Figure 4(c). Head-up display hover mode.

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VMS NOMINAL OPERATIONAL MOTION LIMITS			
Axis	Displ	Velocity	Accel
Vertical	±30	16	24
Longitudinal	±20	8	16
Lateral	±4	4	10
Roll	±18	40	115
Pitch	±18	40	115
Yaw	±24	46	115

All numbers, units in ft, deg, sec
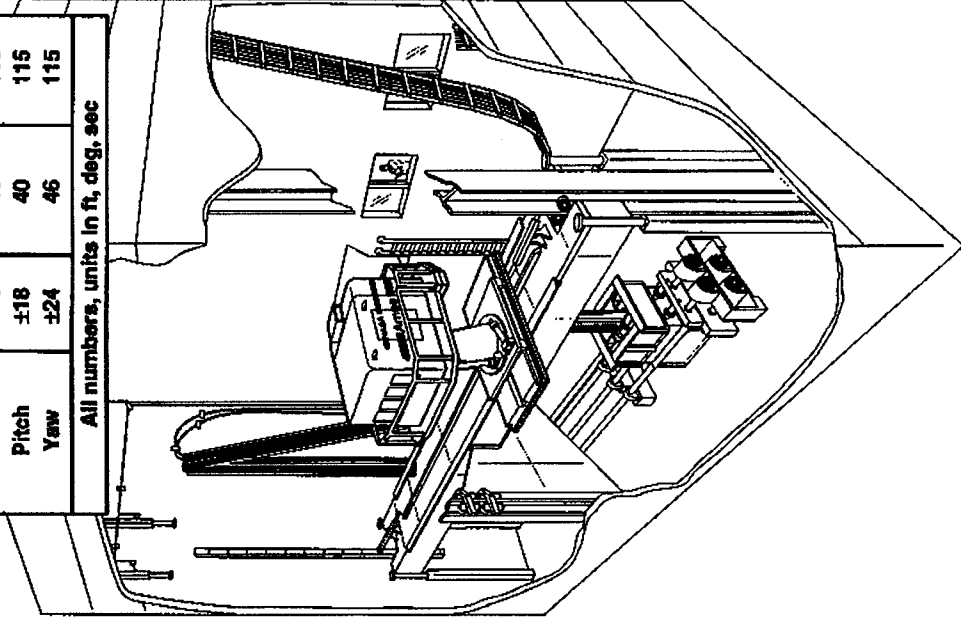
Figure 5. Vertical Motion Simulator.
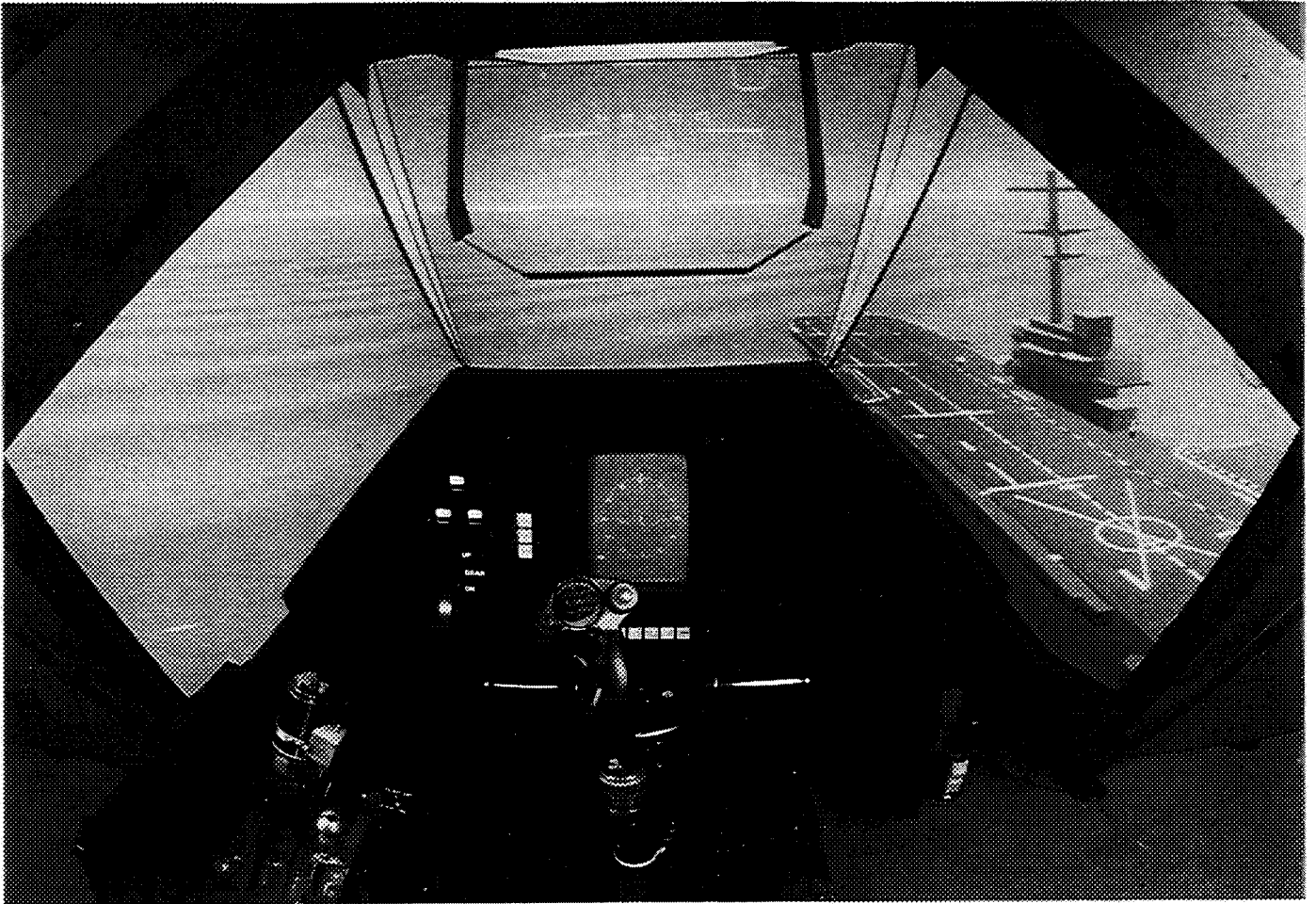
Figure 6(a). Simulator cockpit arrangement.
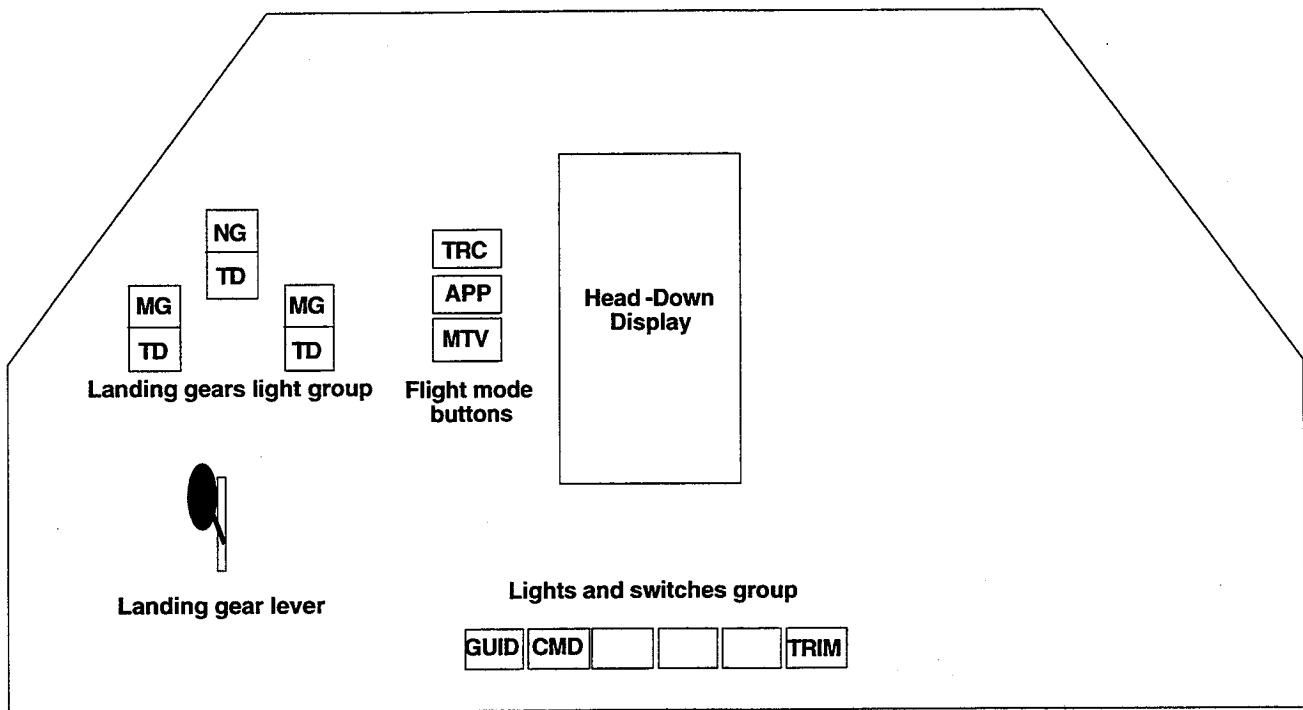
Figure 6(b). Instrument panel detail.
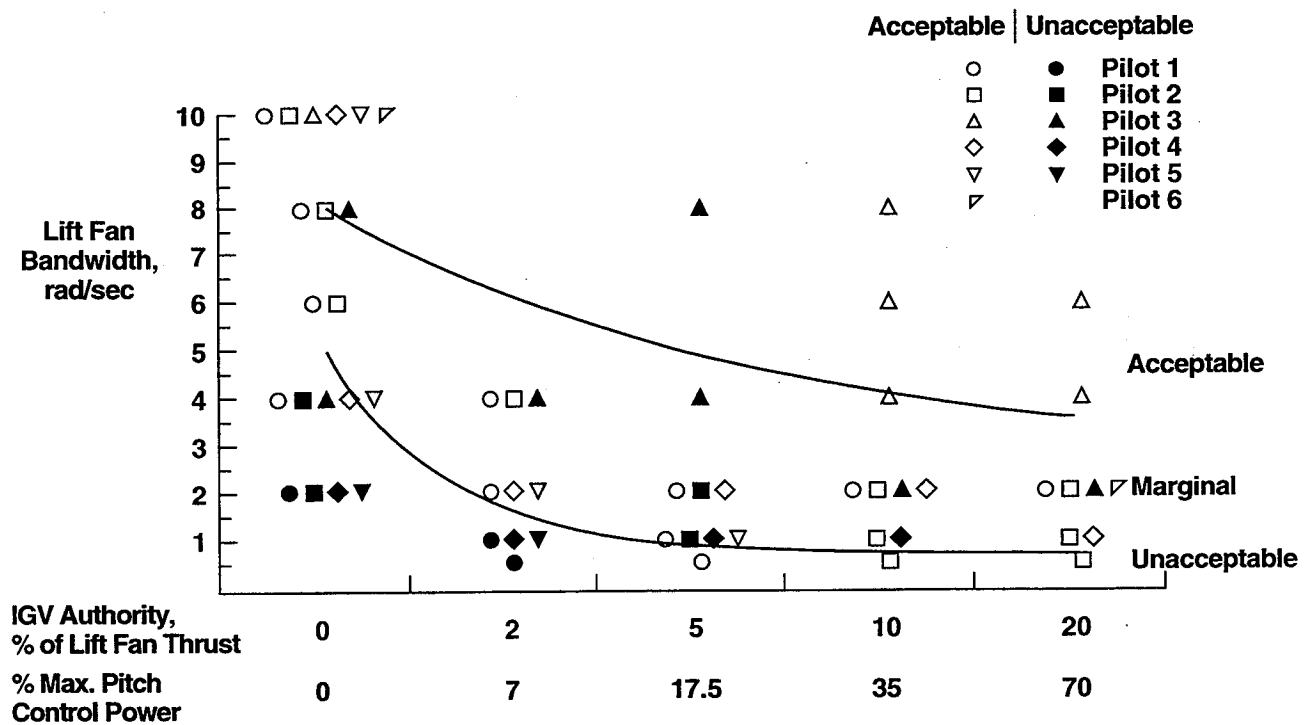
Figure 7. Effect of dynamic lift-fan response on pitch control.
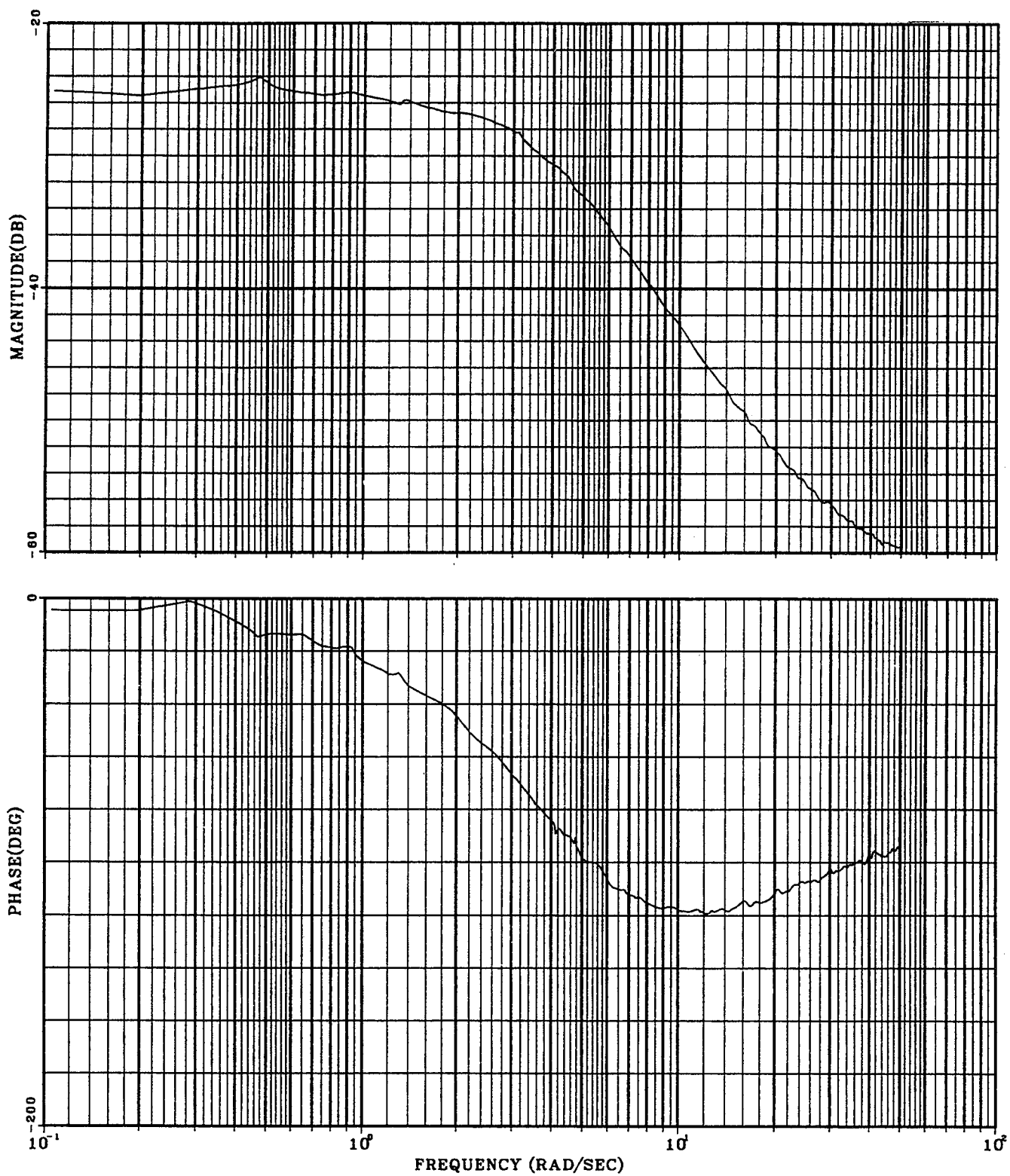
Figure 8. Pitch rate frequency response in transition, q/δ_{lon}.
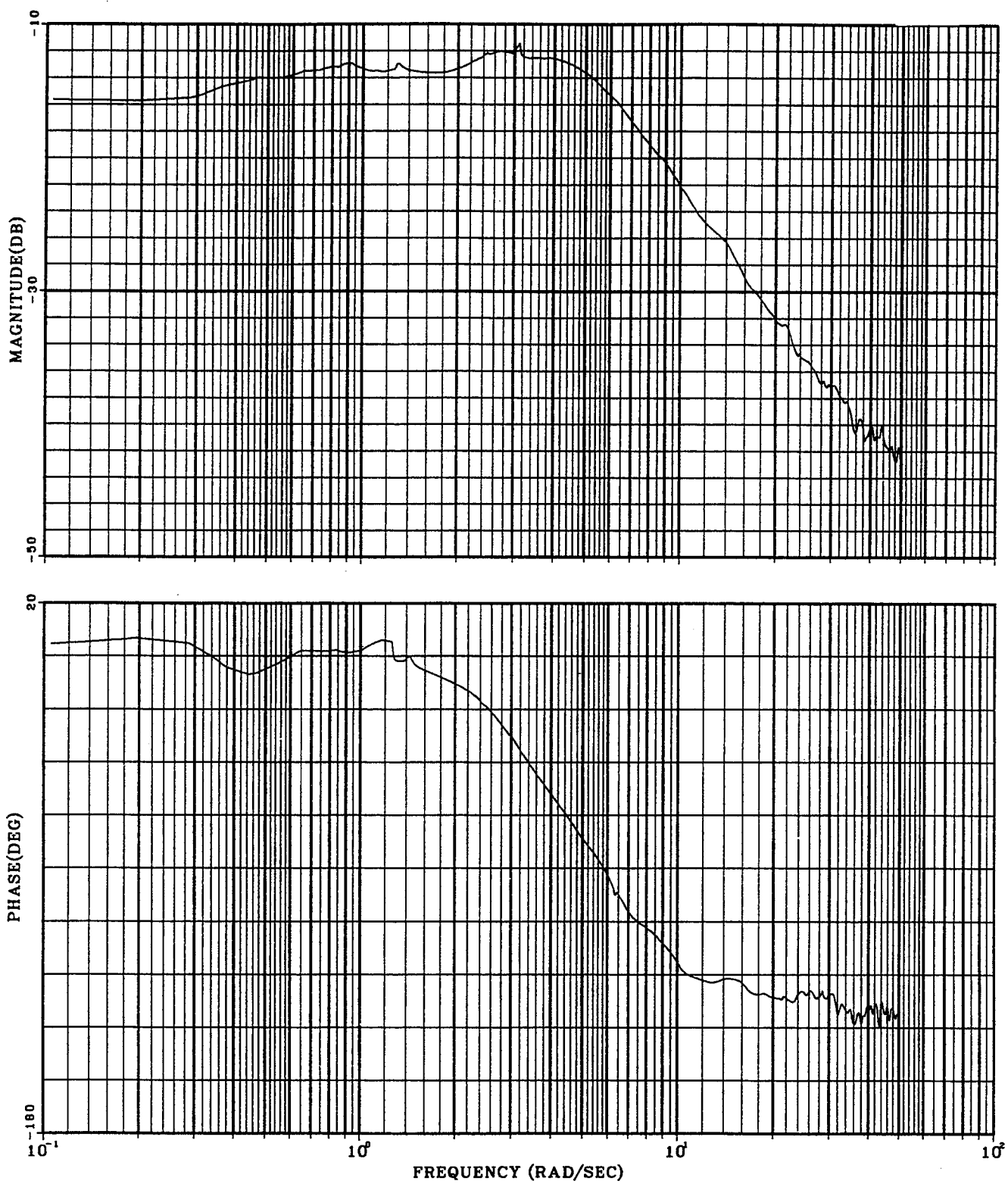
Figure 9. Roll rate frequency response in transition, p/δ_{lat}.
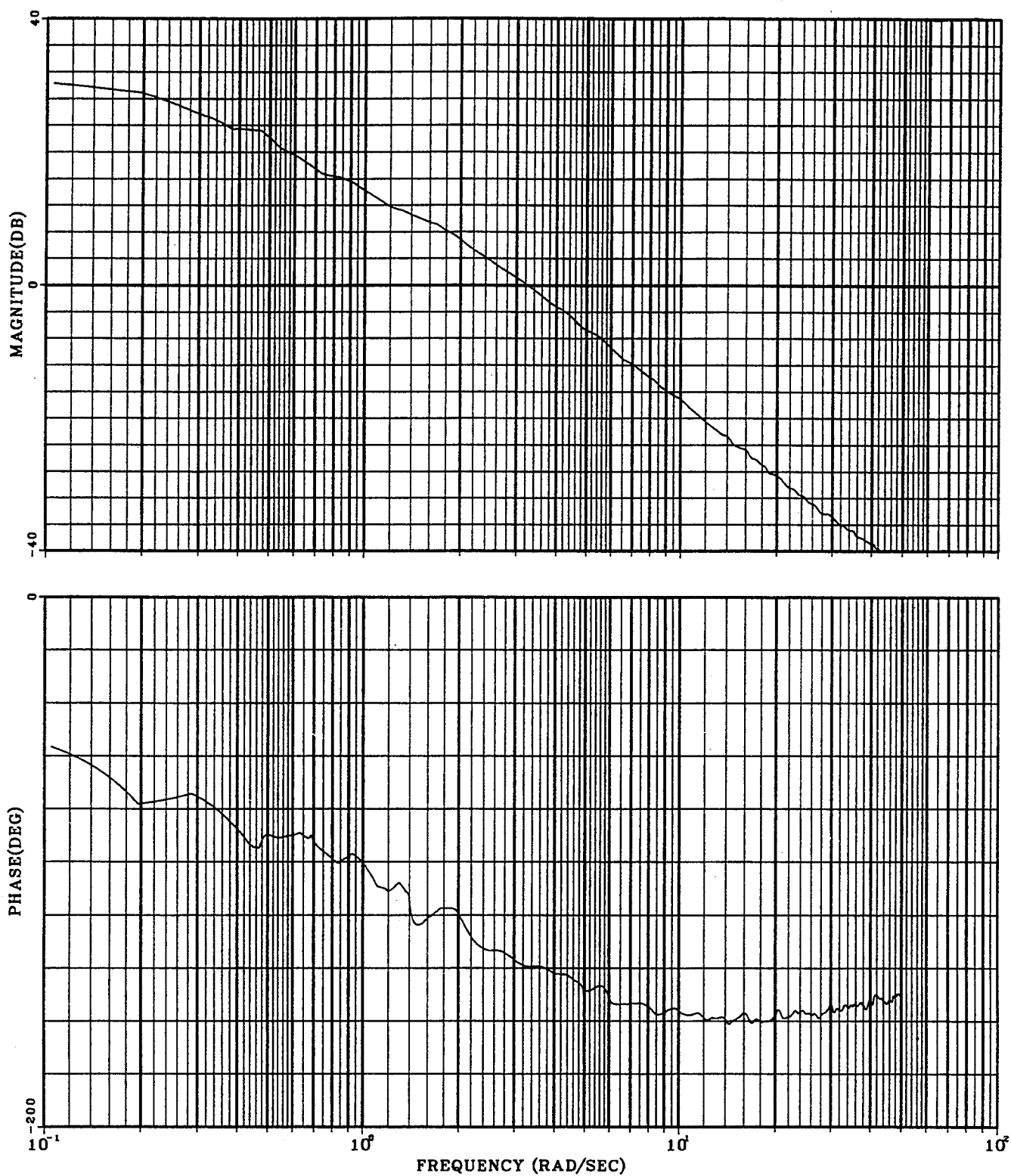
Figure 10. Sideslip frequency response in transition, β/δ_{ped}.
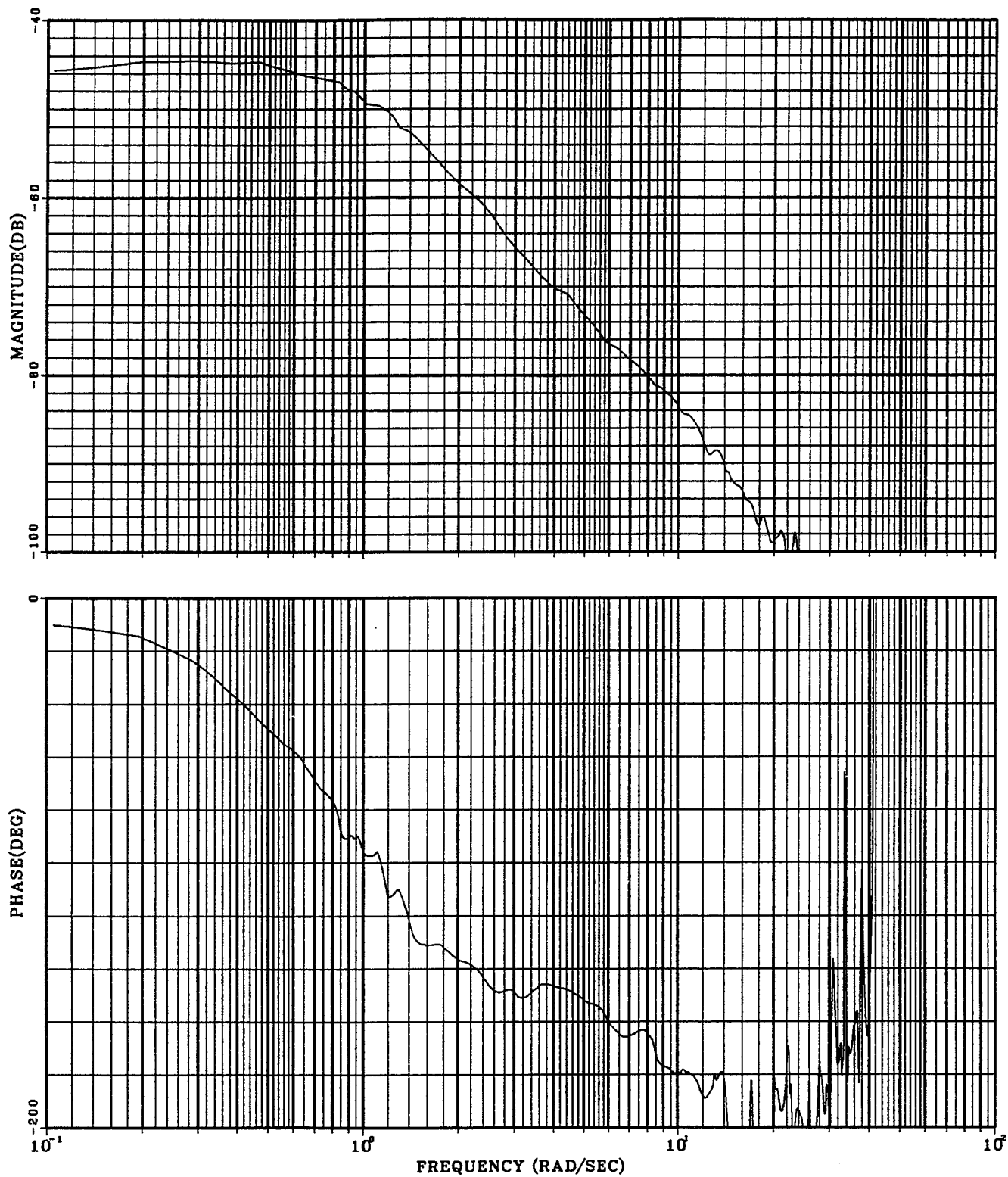
Figure 11. Flightpath frequency response in transition, γ/δ_{th}.

Figure 12. Pitch attitude frequency response in hover, θ/δlon.

FREQUENCY (RAD/SEC)

PHASE(DEG)

MAGNITUDE(DB)
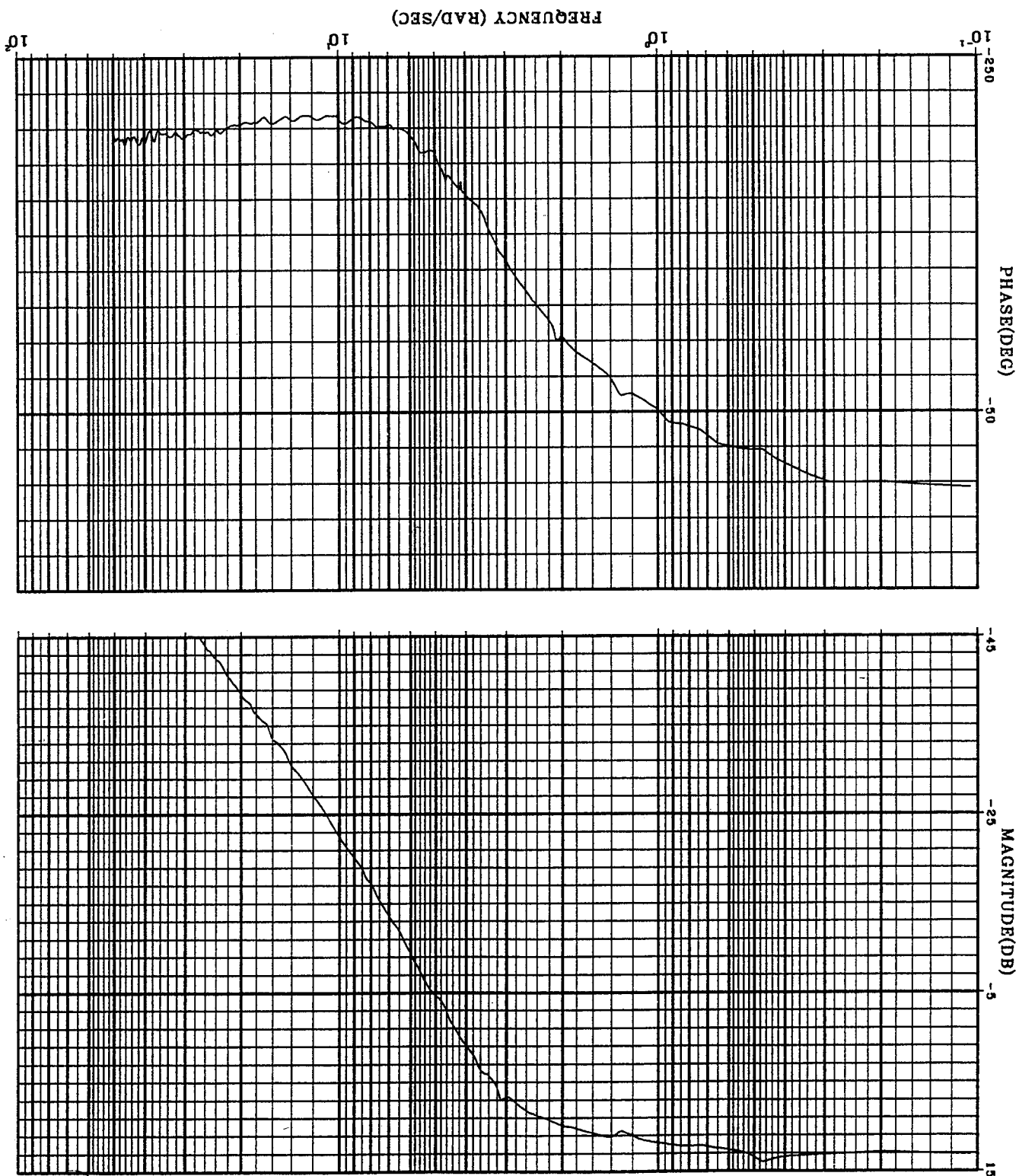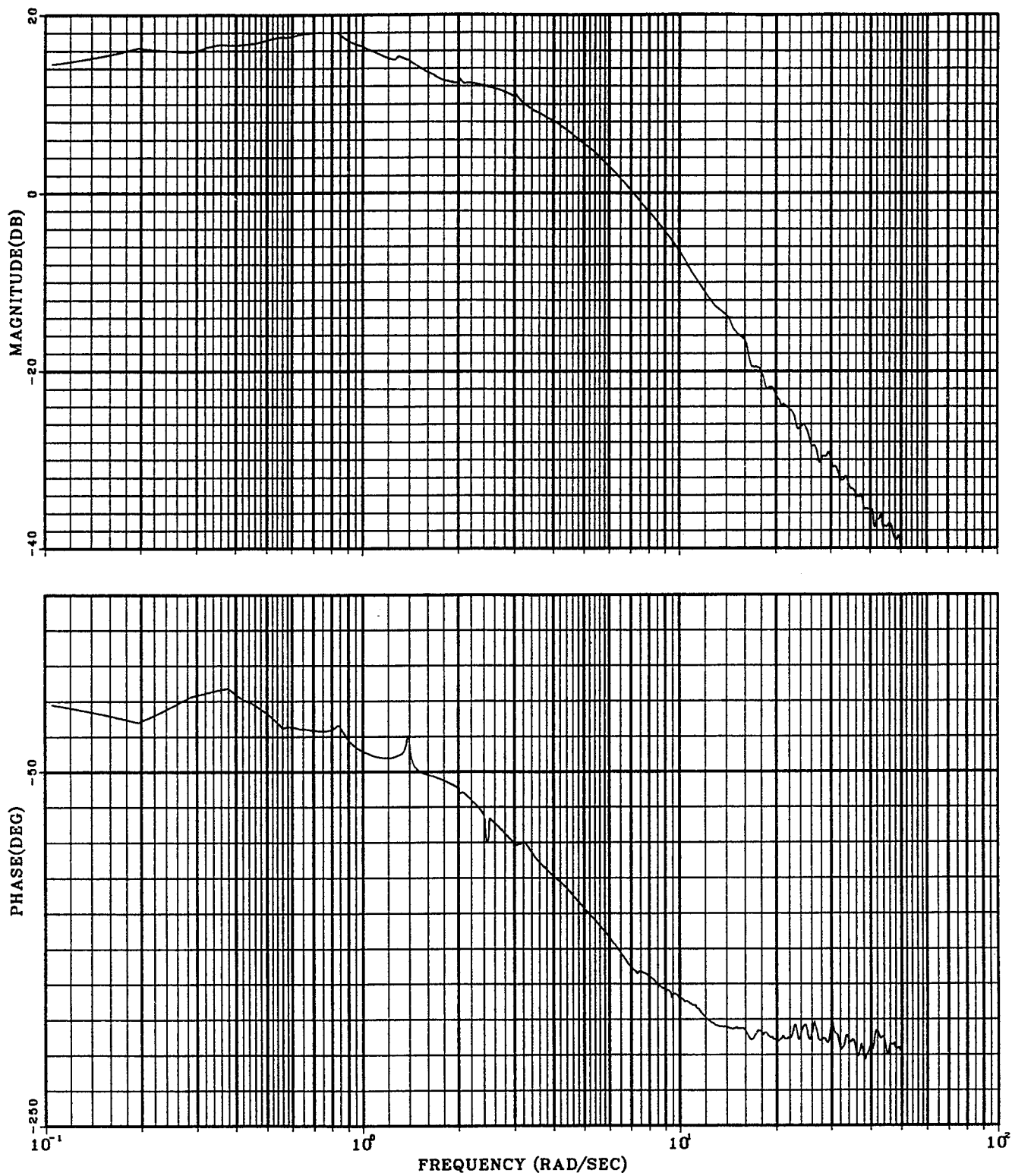
Figure 13. Roll attitude frequency response in hover, ϕ/δ_{lat}.

PHASE(DEG)

MAGNITUDE(DB)

FREQUENCY (RAD/SEC)
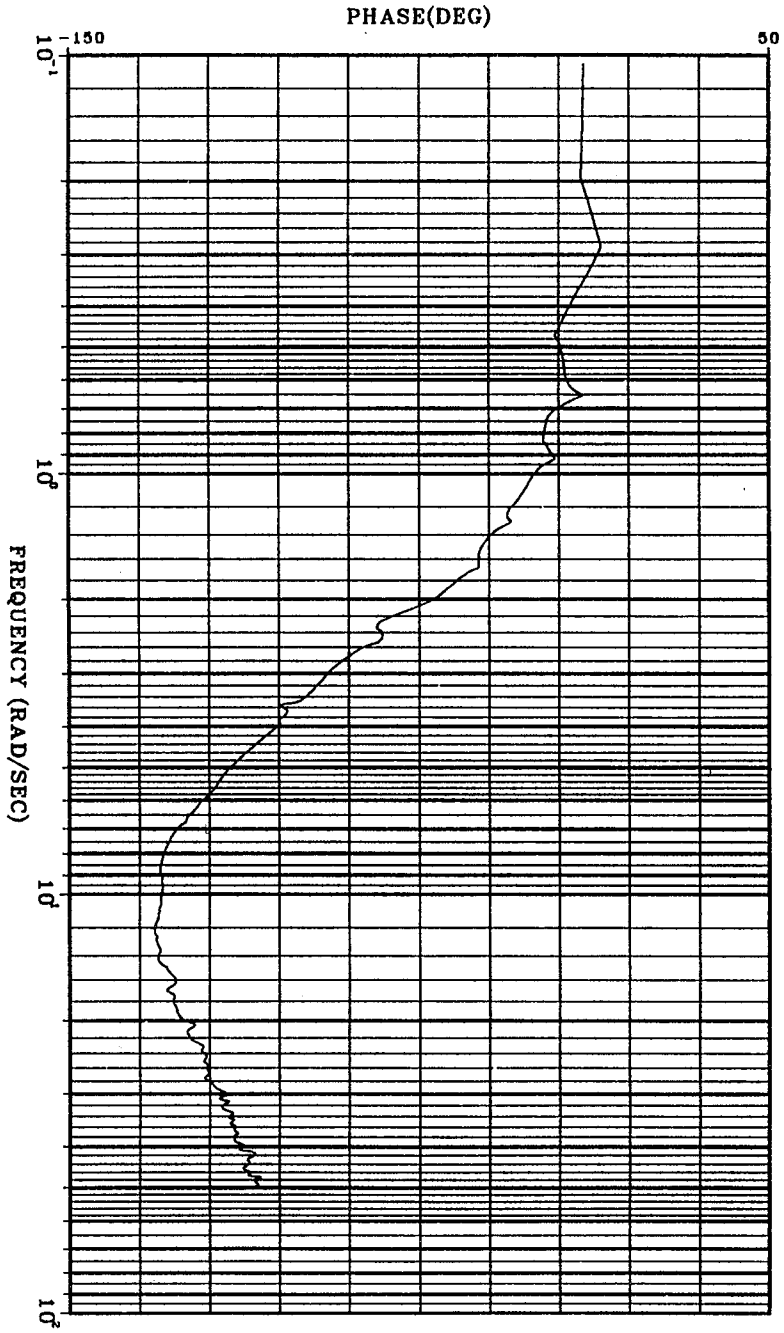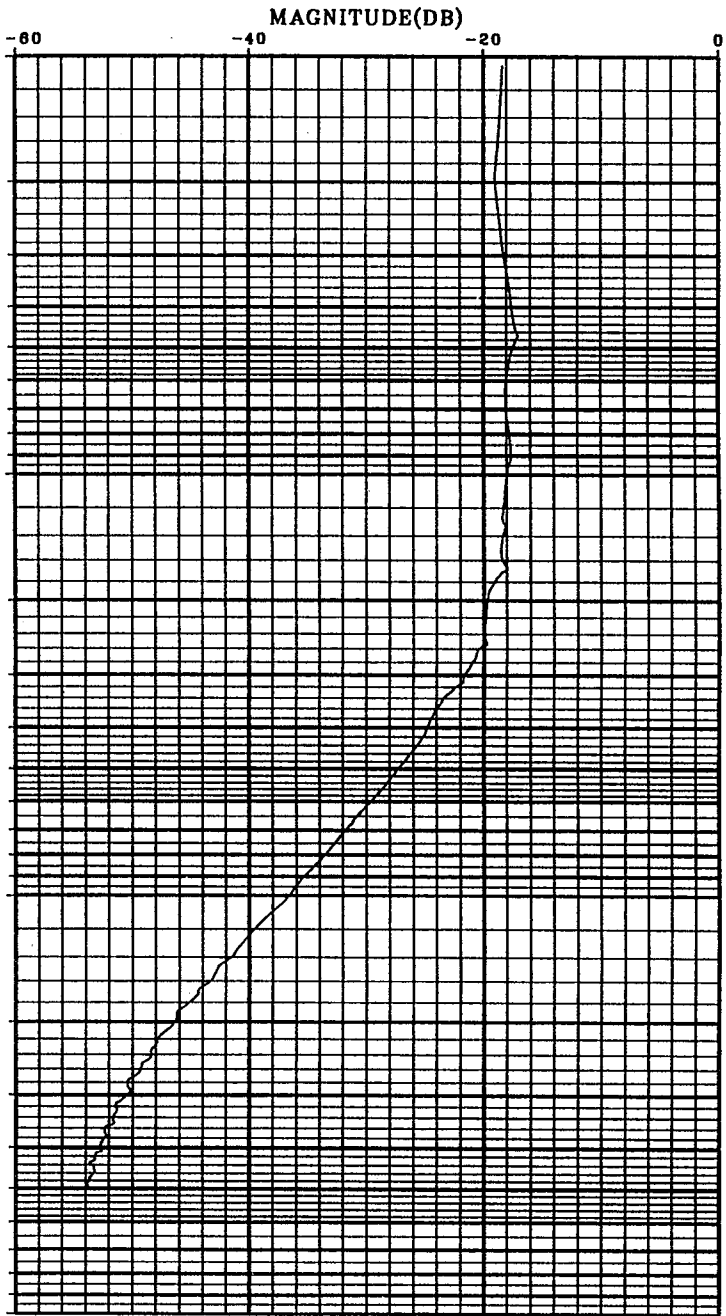
Figure 14. Yaw rate frequency response in hover, r/δped.
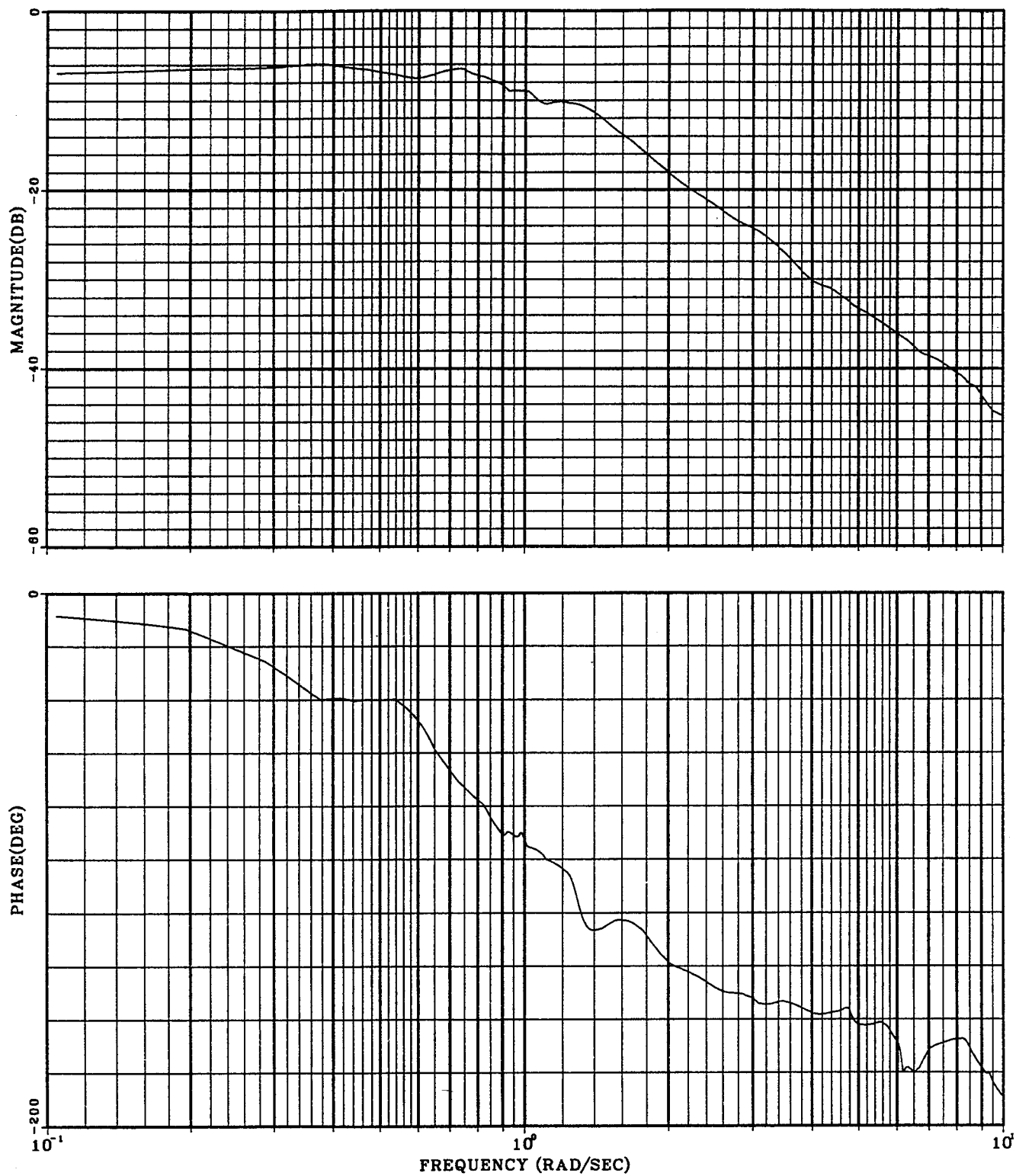
Figure 15. Vertical velocity frequency response in hover, $\dot{h}/\delta_{th}$.

29
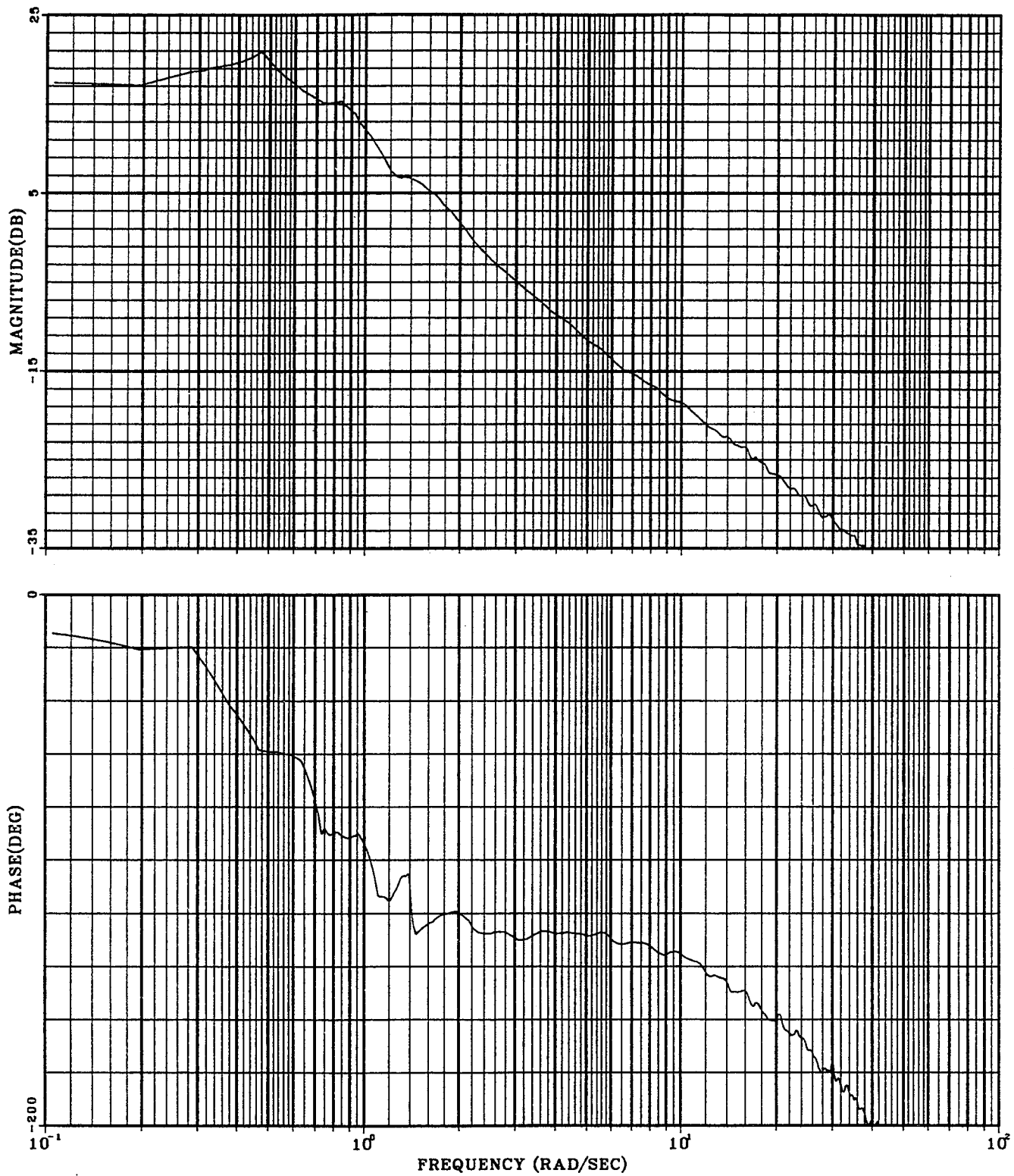
Figure 16. Longitudinal velocity frequency response in TRC, V_x/δ_{lon}.
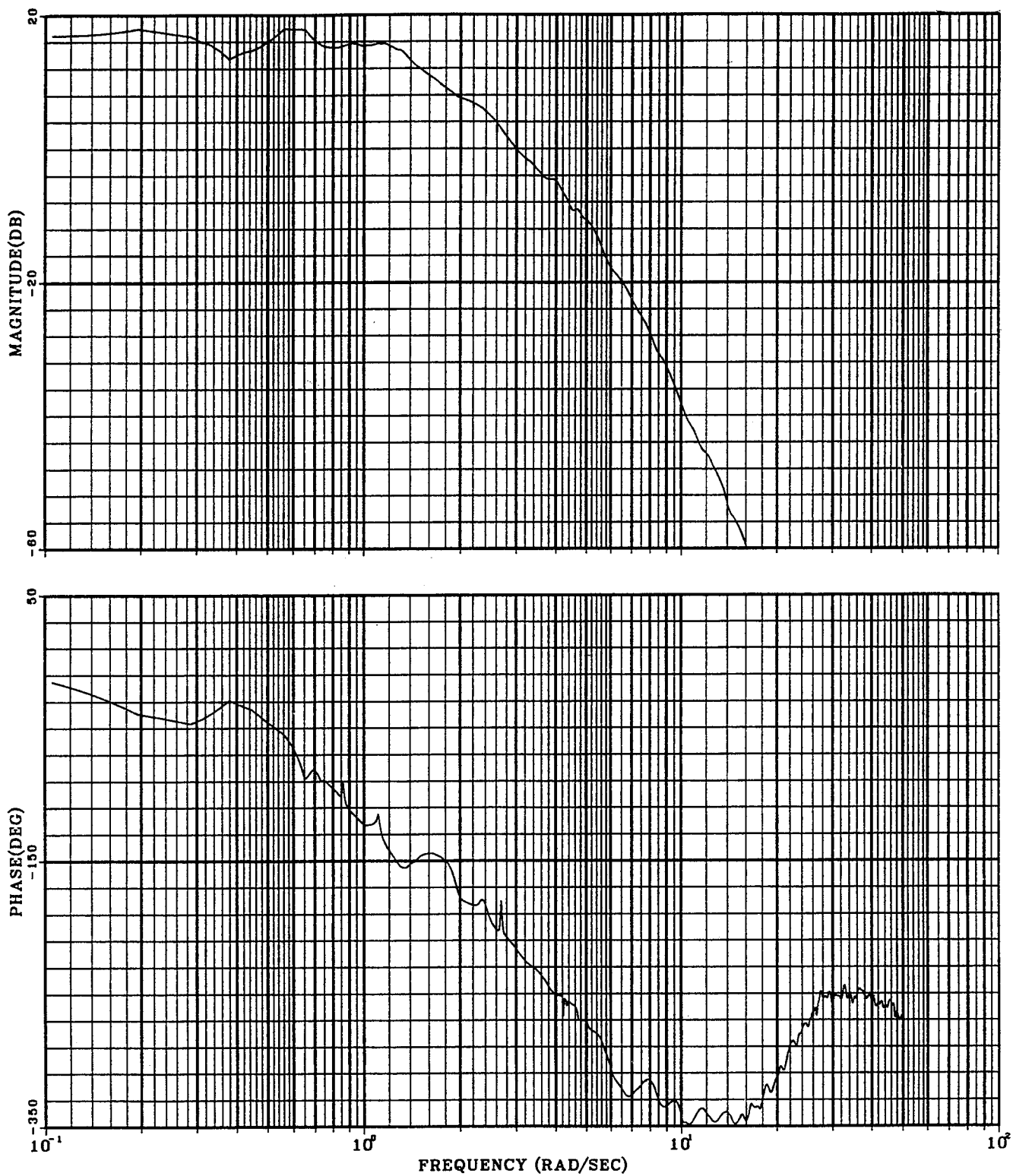
Figure 17. Lateral velocity frequency response in TRC, V_y/δ_{lat}.
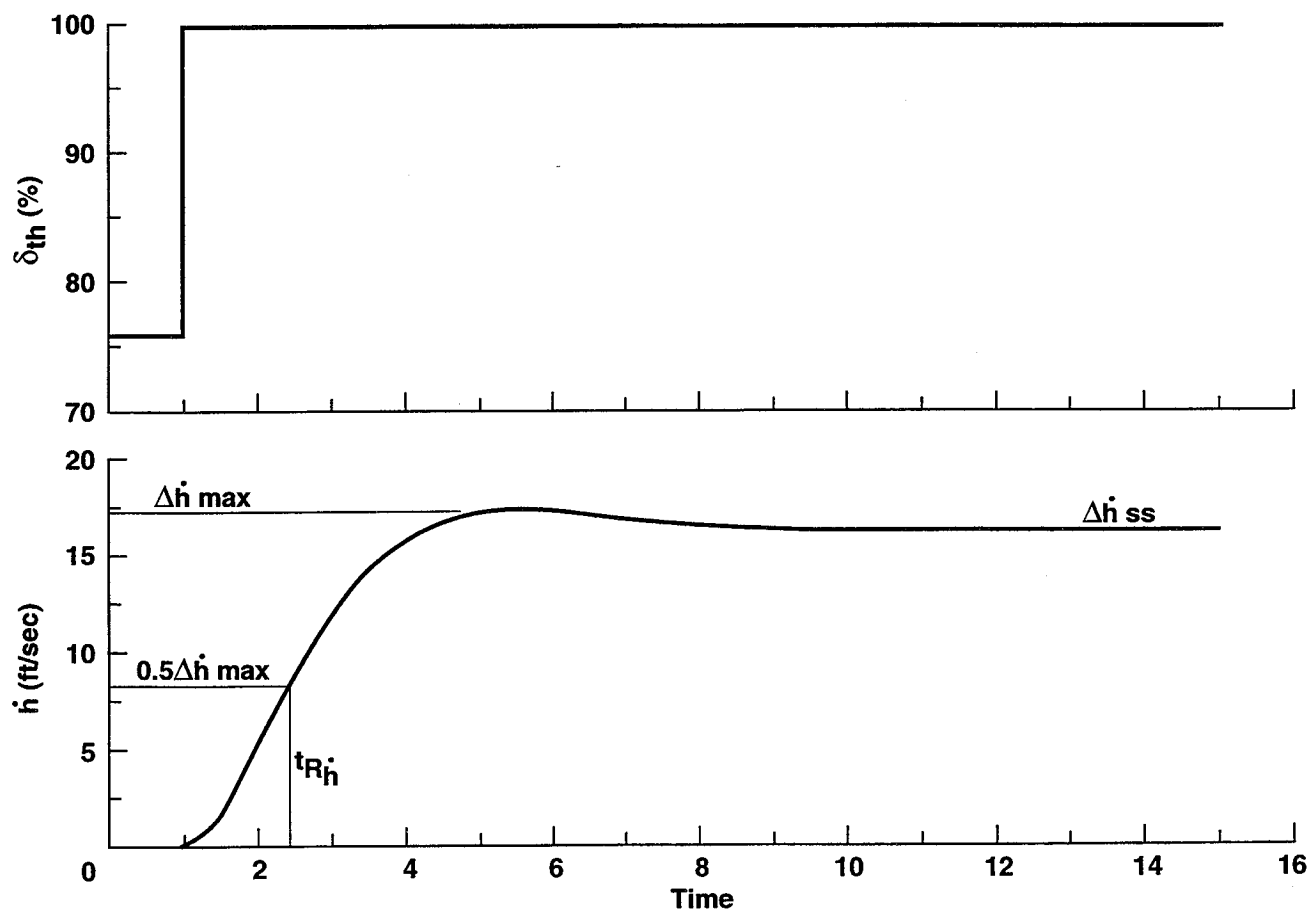
Figure 18. Vertical velocity time response due to throttle.
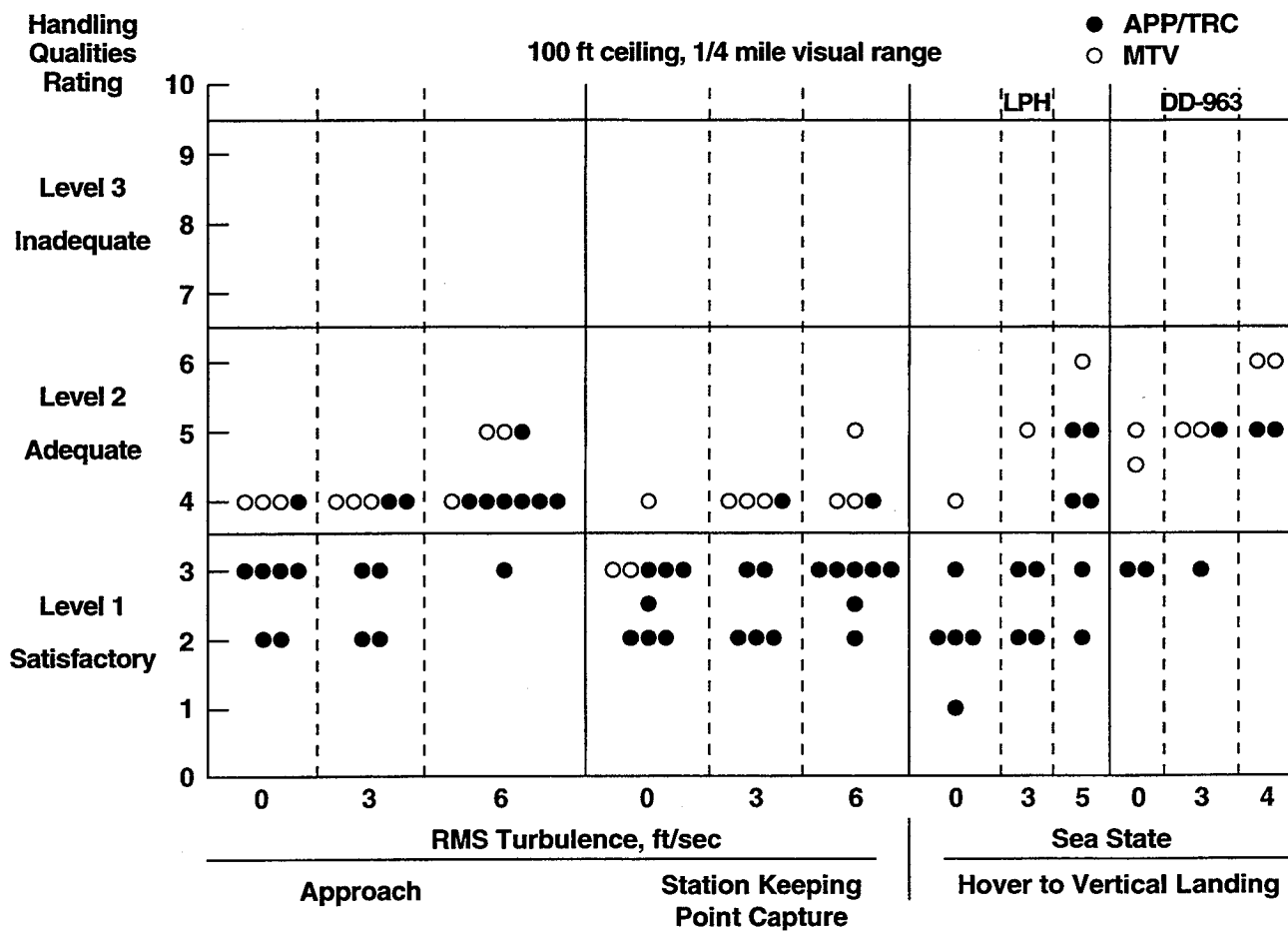
Figure 19. Pilot evaluations of APP/TRC and MTV modes for shipboard approach and landing.

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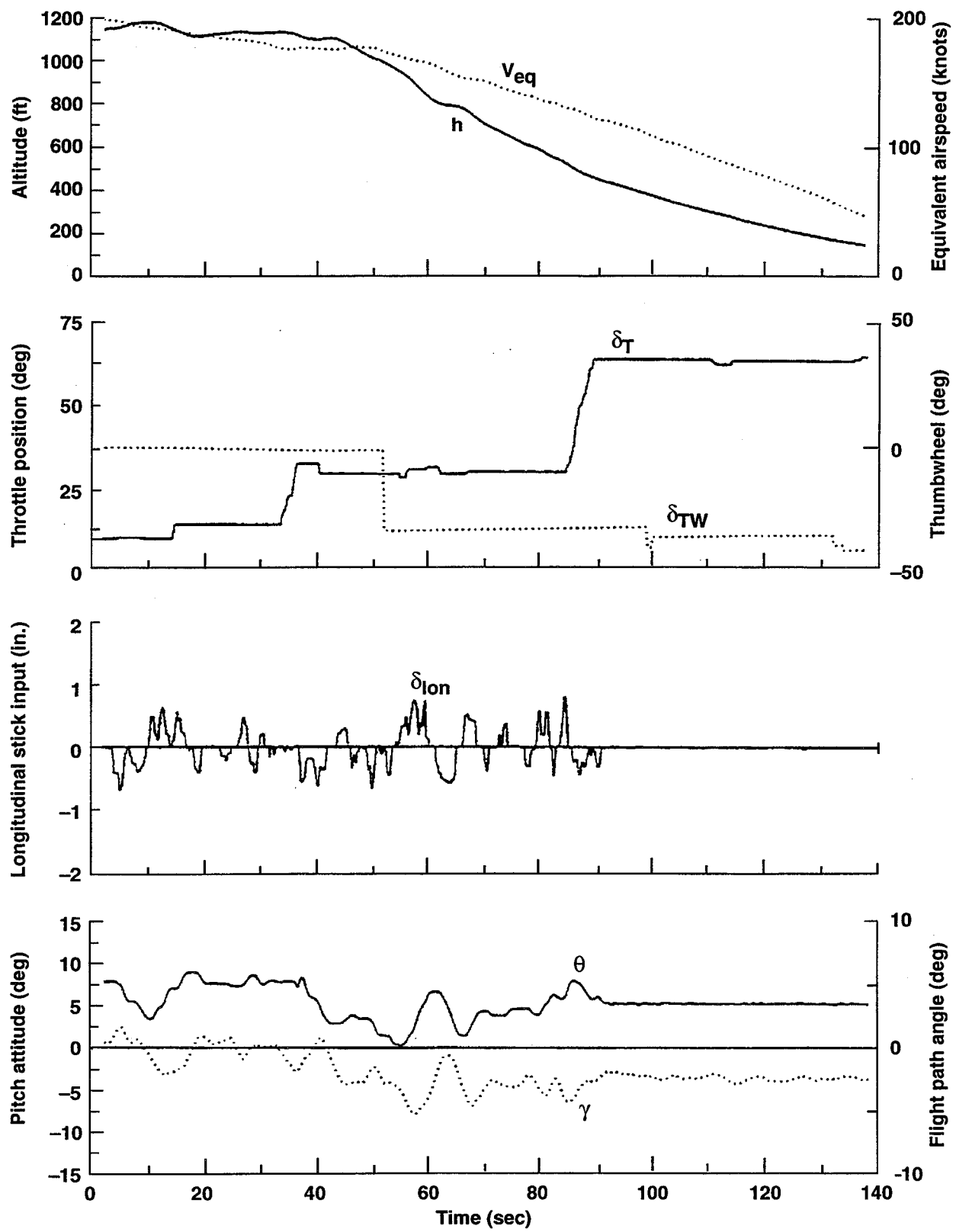
Figure 20. Time histories of decelerating transition in 6 ft/sec rms turbulence, APP mode.
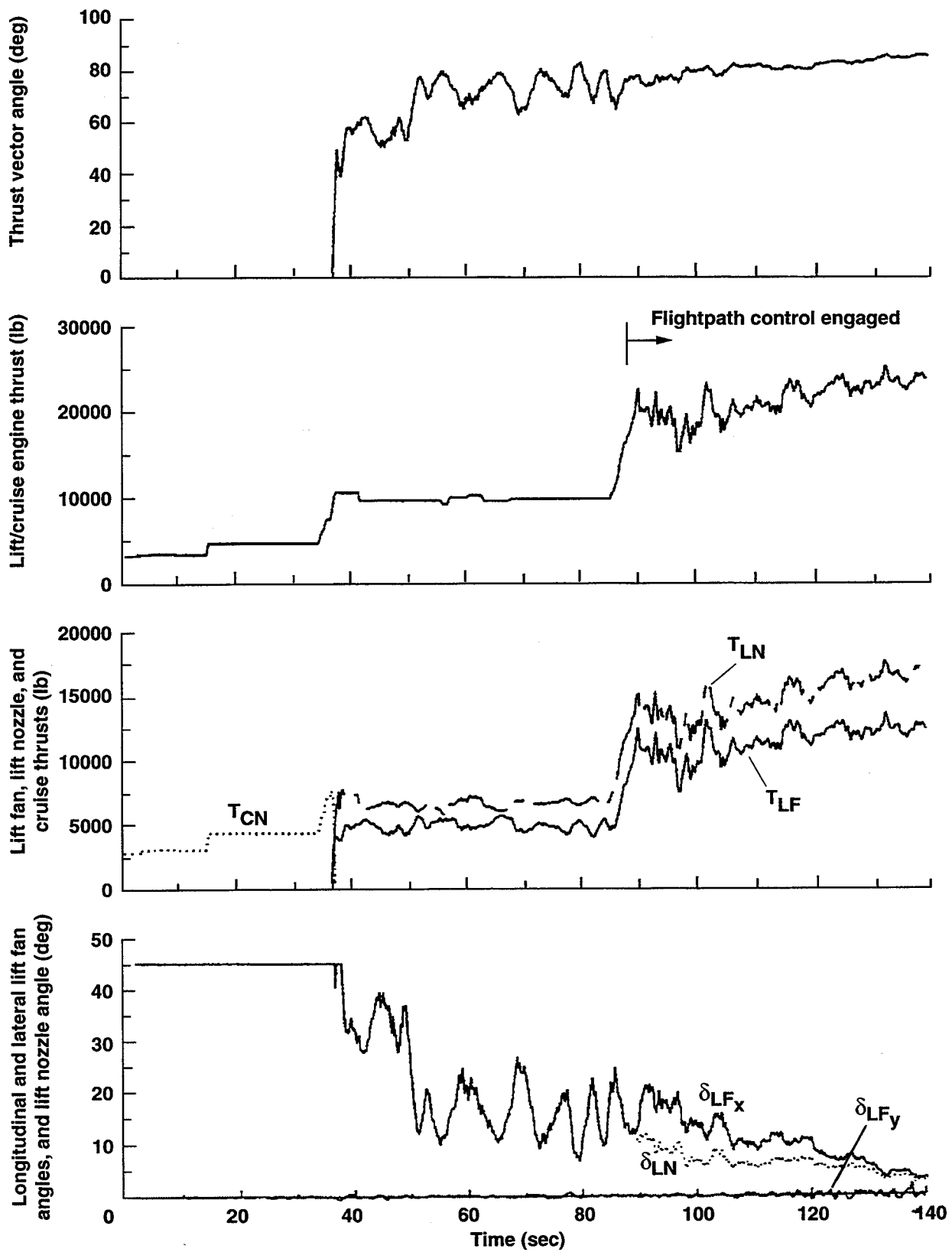
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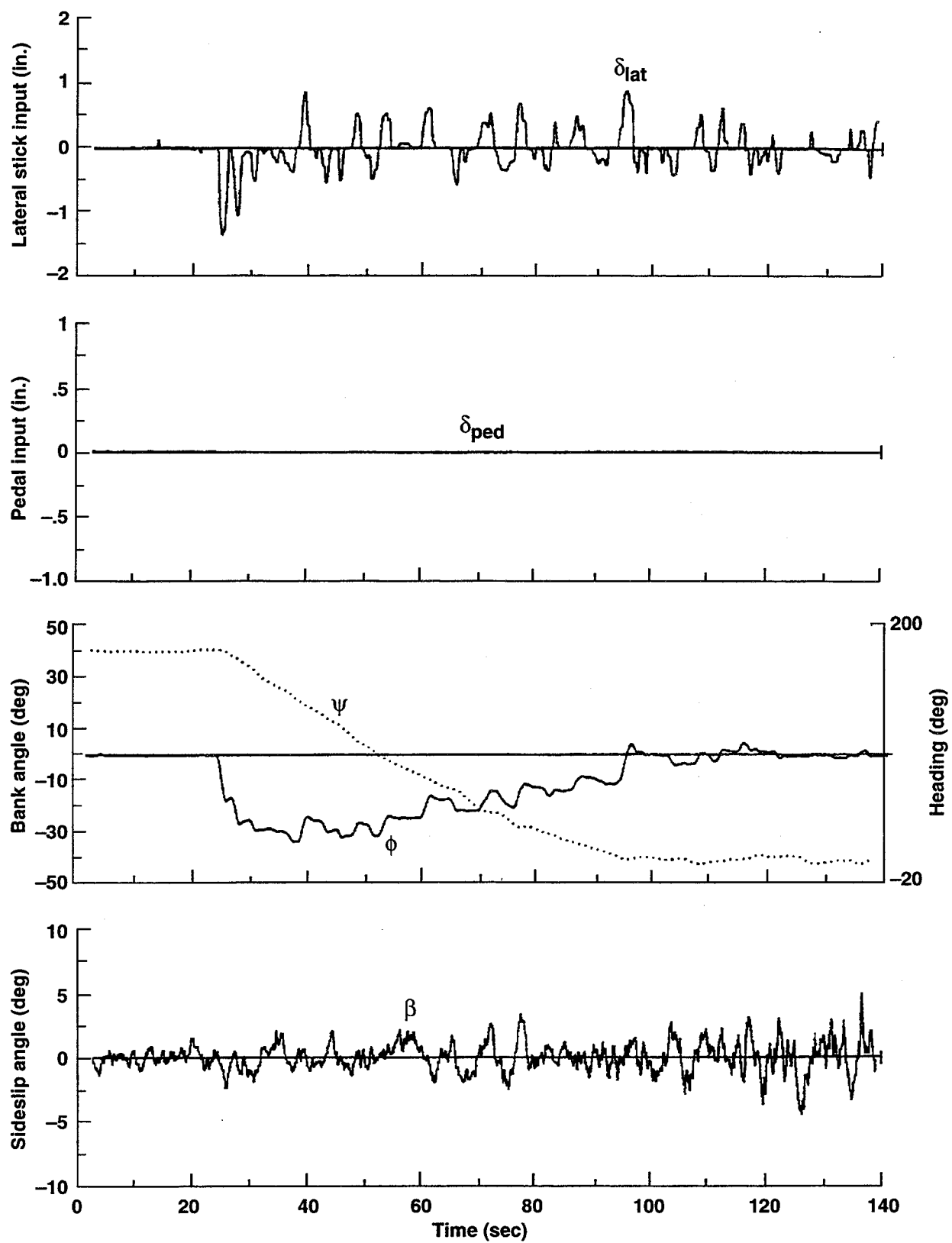
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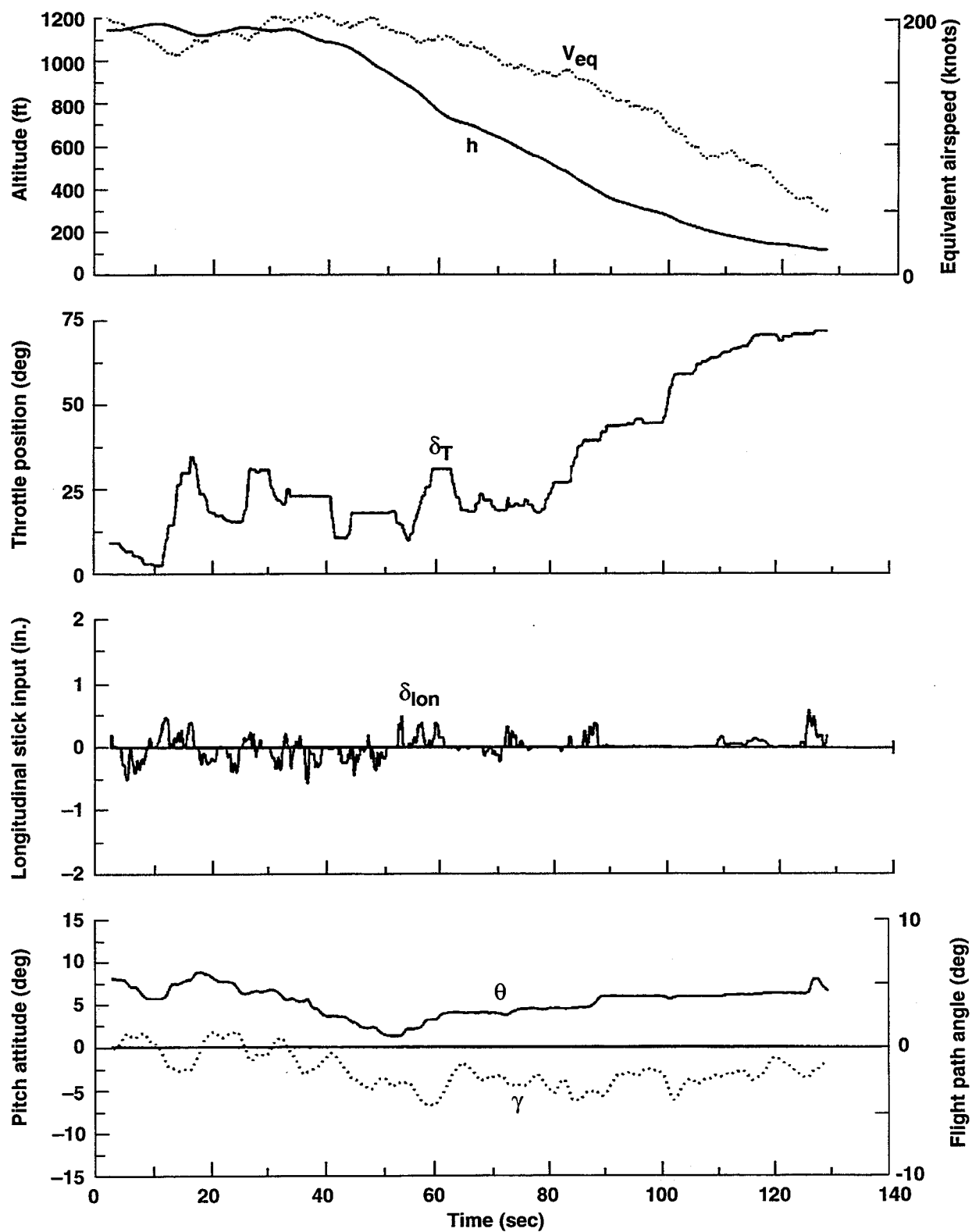
Figure 21. Time histories of decelerating transition in 6 ft/sec rms turbulence, MTV mode.
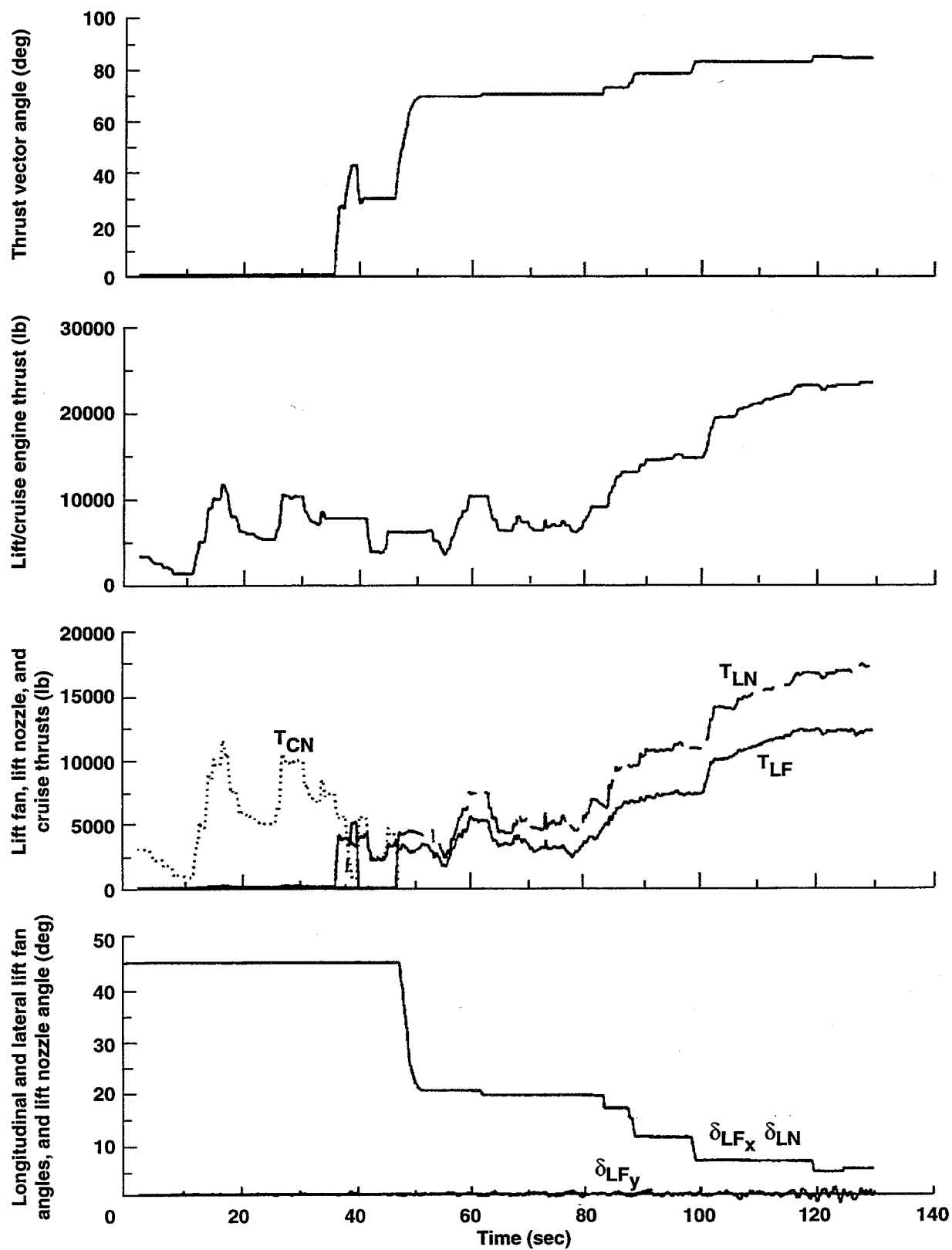
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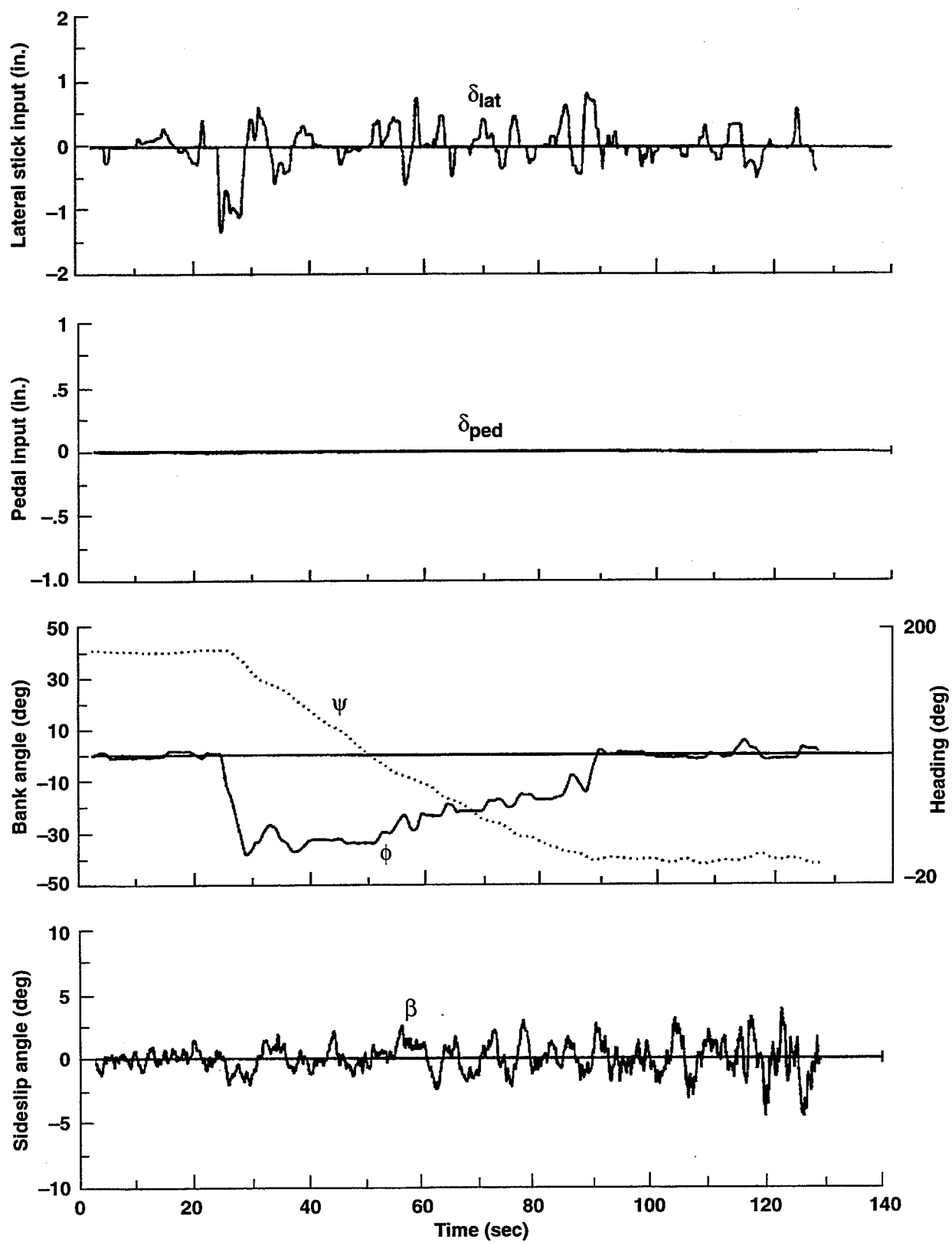
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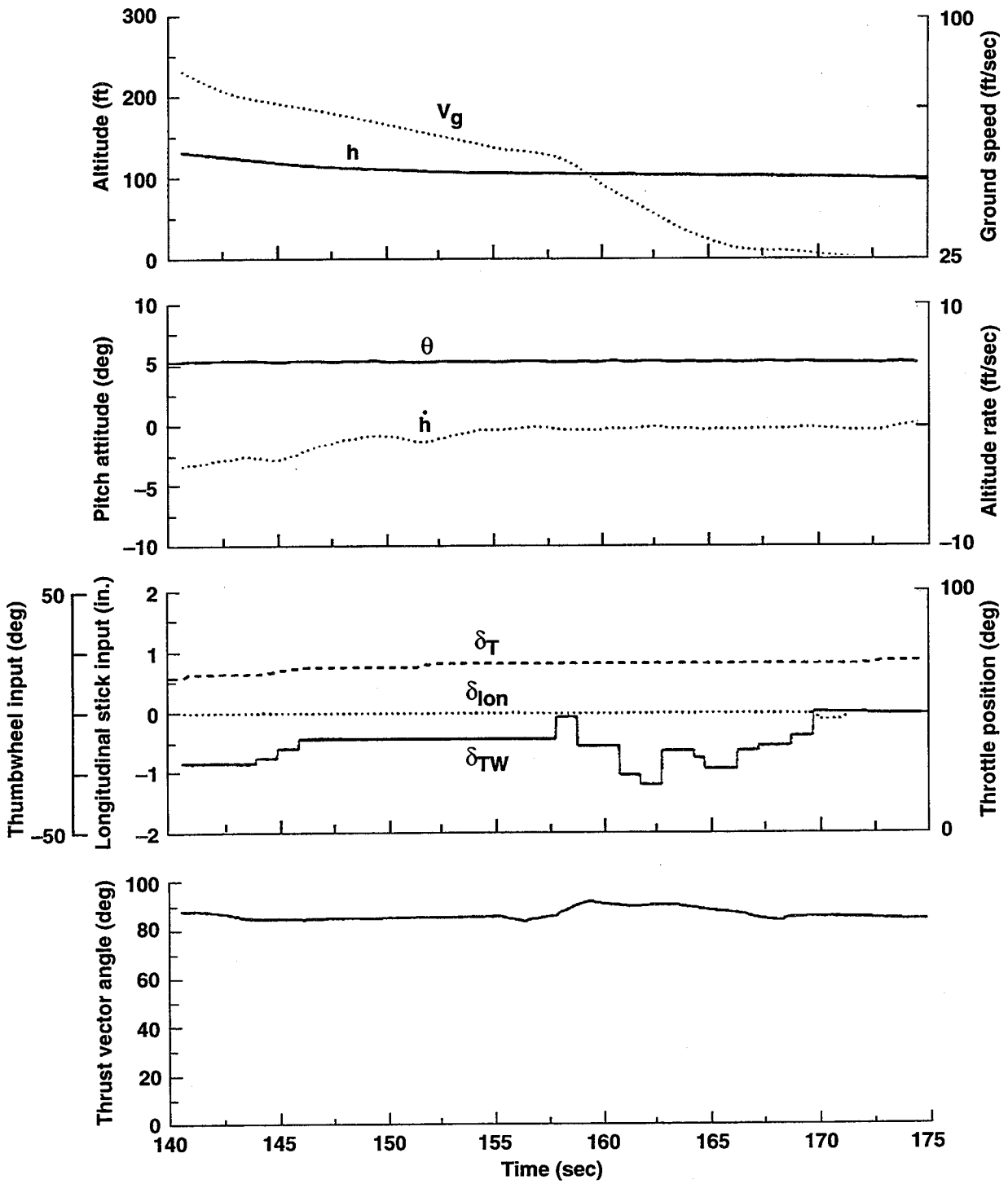
Figure 22. Time histories of hover point acquisition in 6 ft/sec rms turbulence, APP mode.
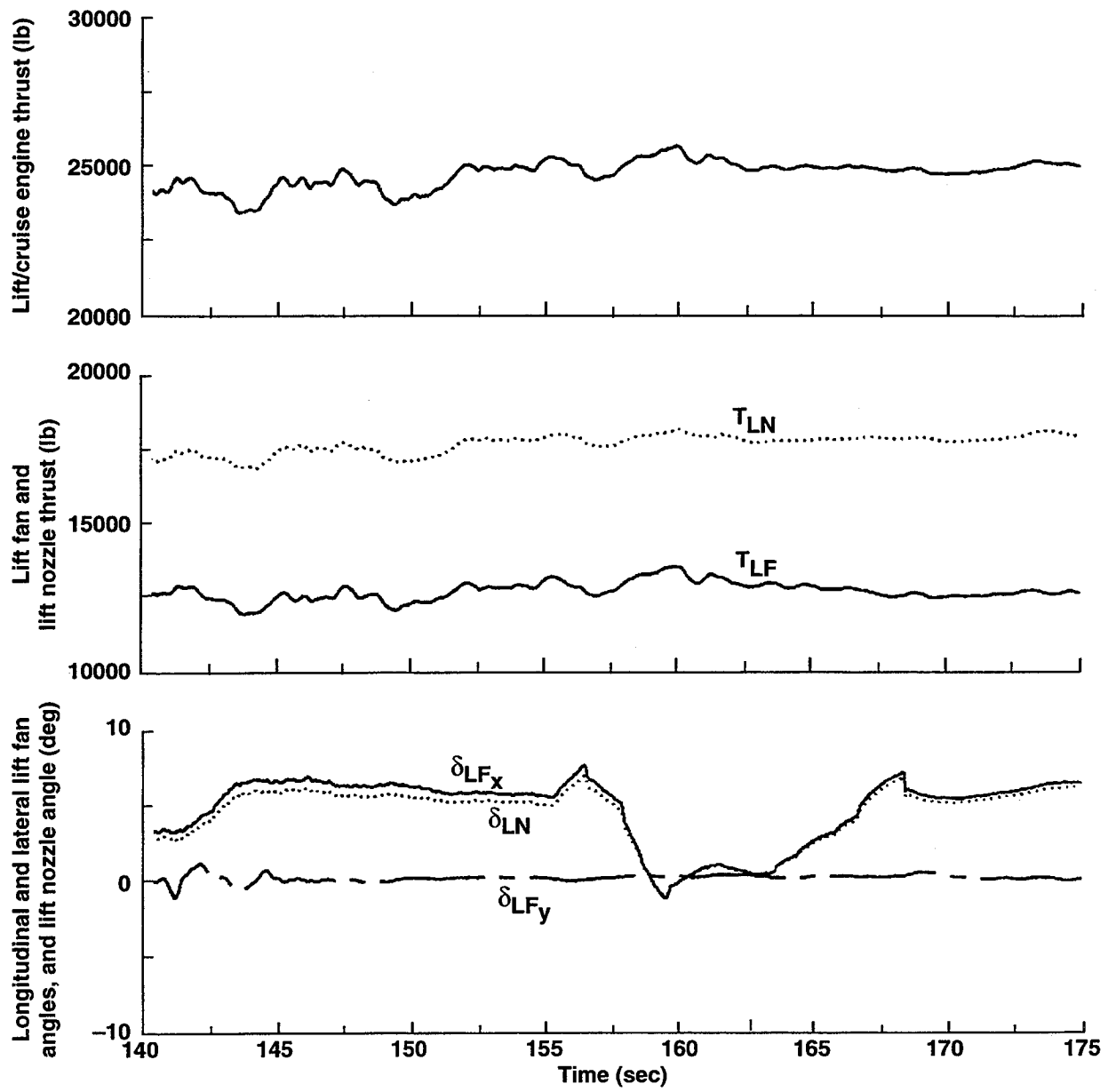
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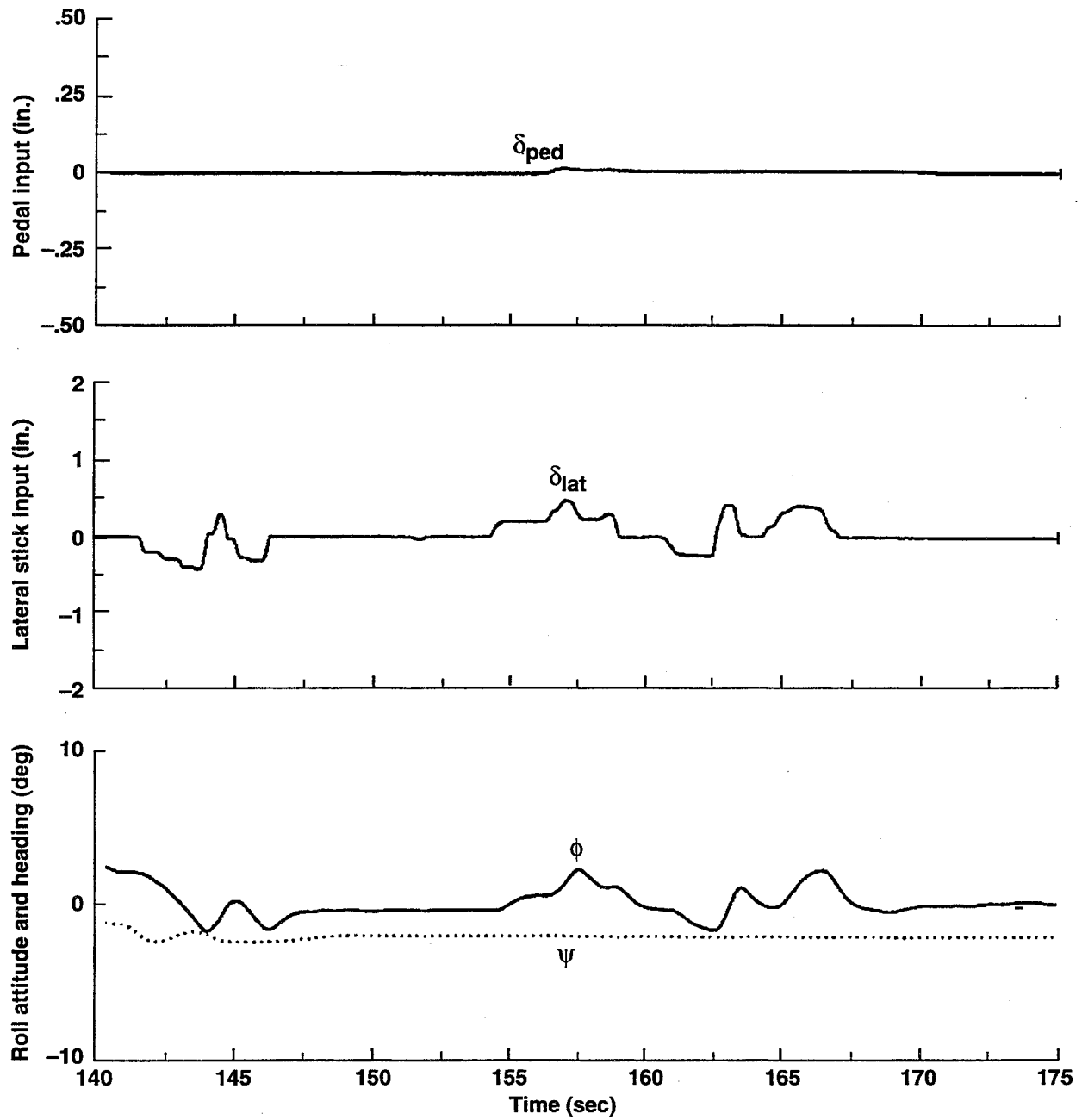
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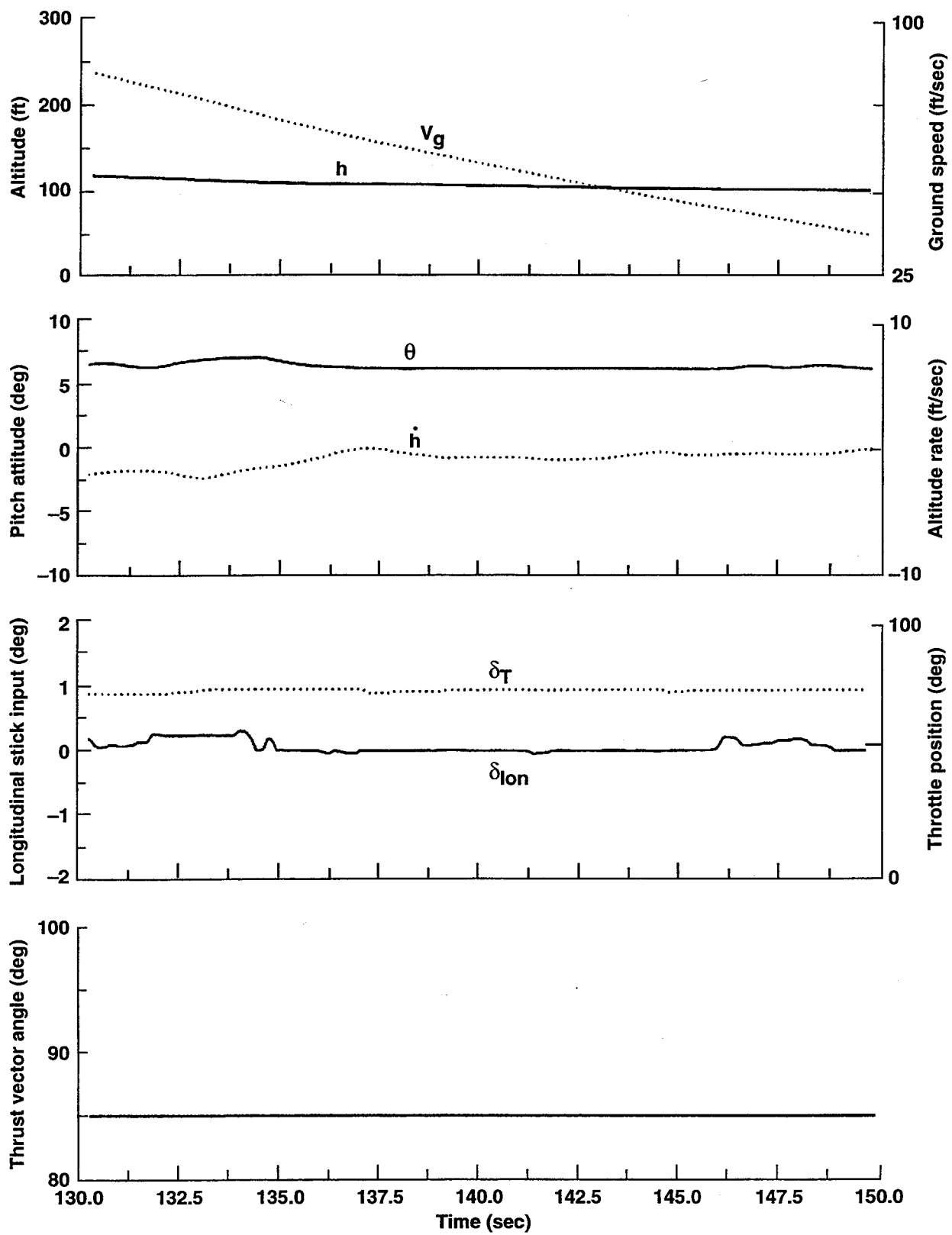
Figure 23. Time histories of hover point acquisition in 6 ft/sec rms turbulence, MTV mode.
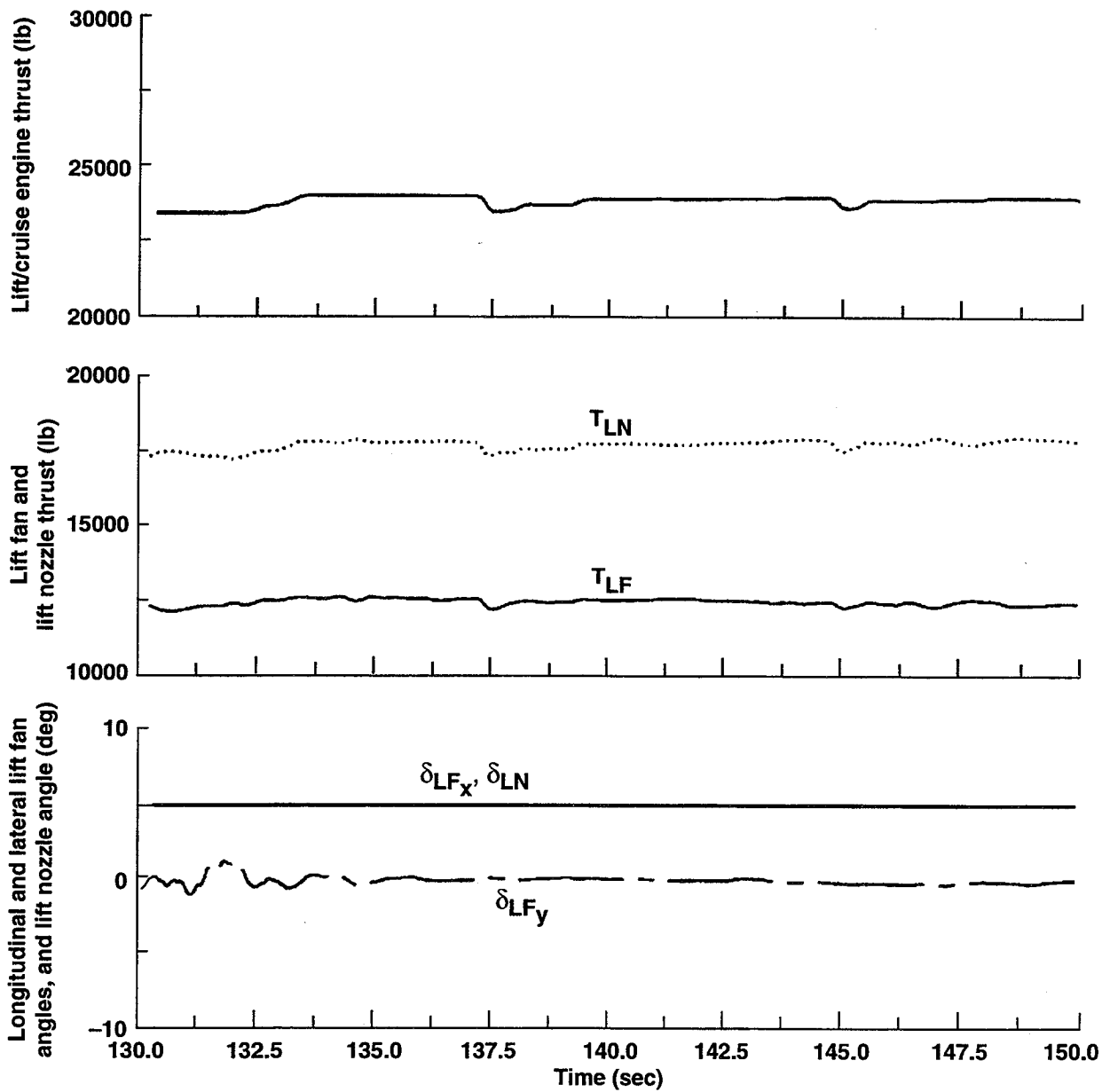
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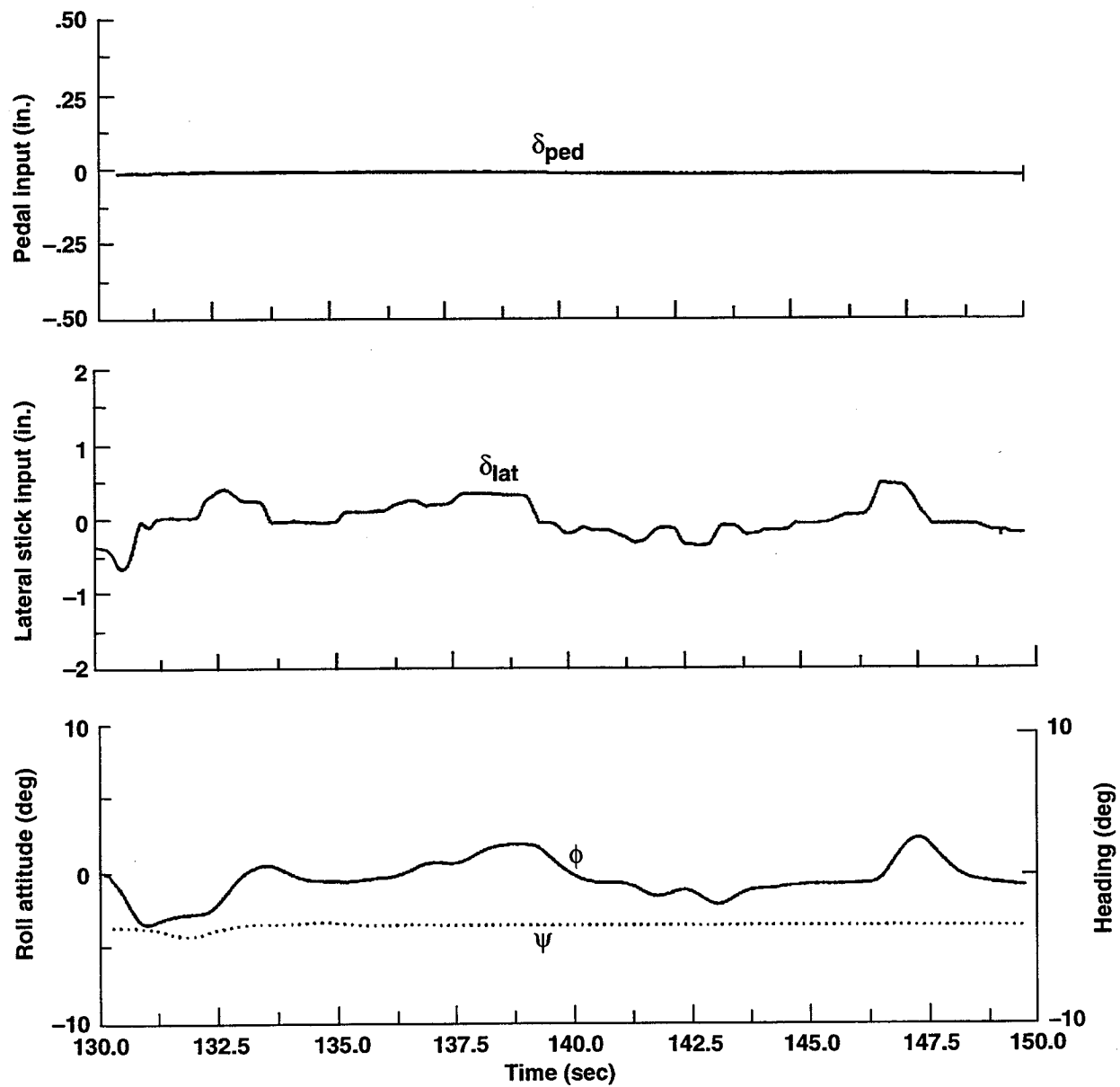
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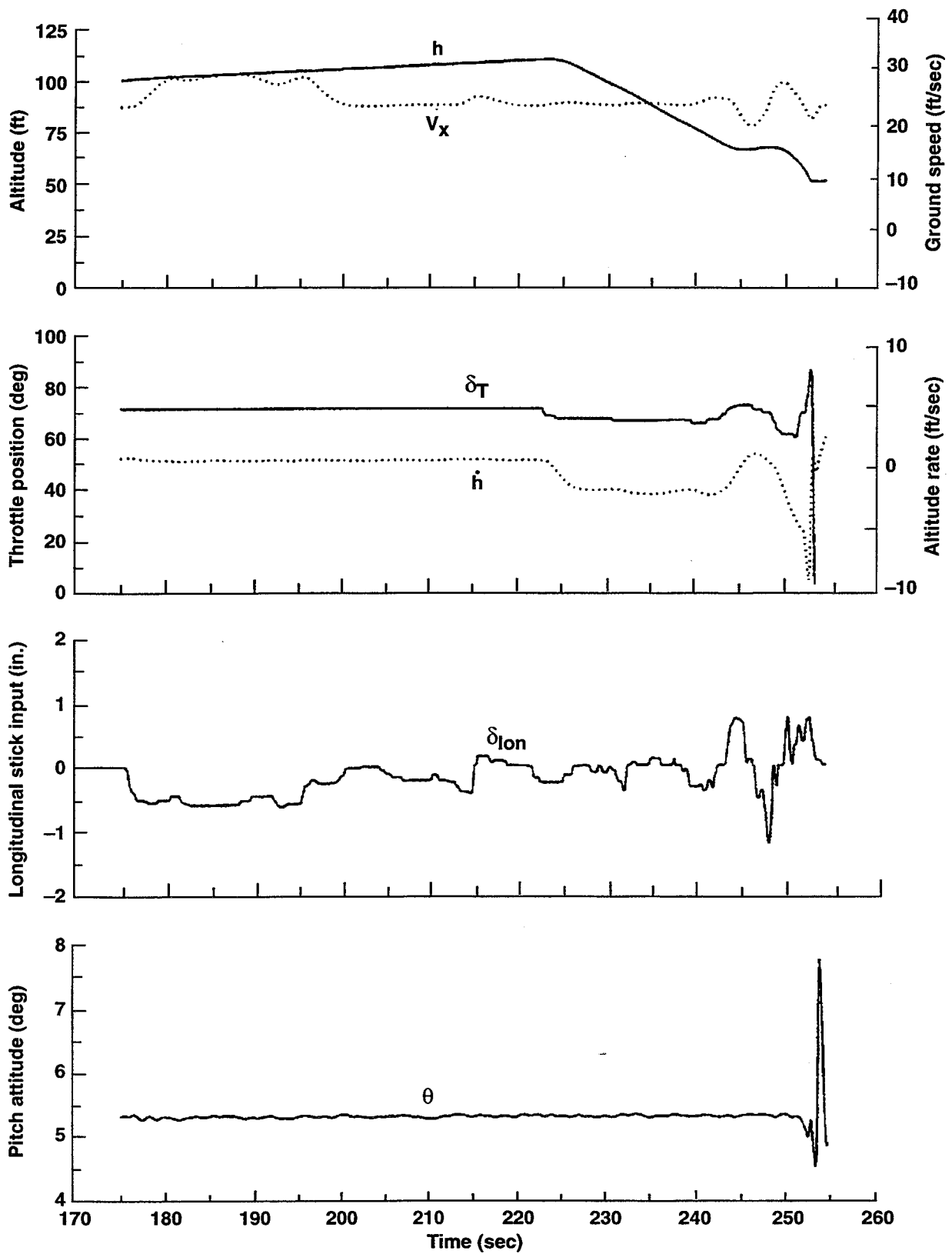
Figure 24. Time histories of landing on LPH in SS5, TRC mode.
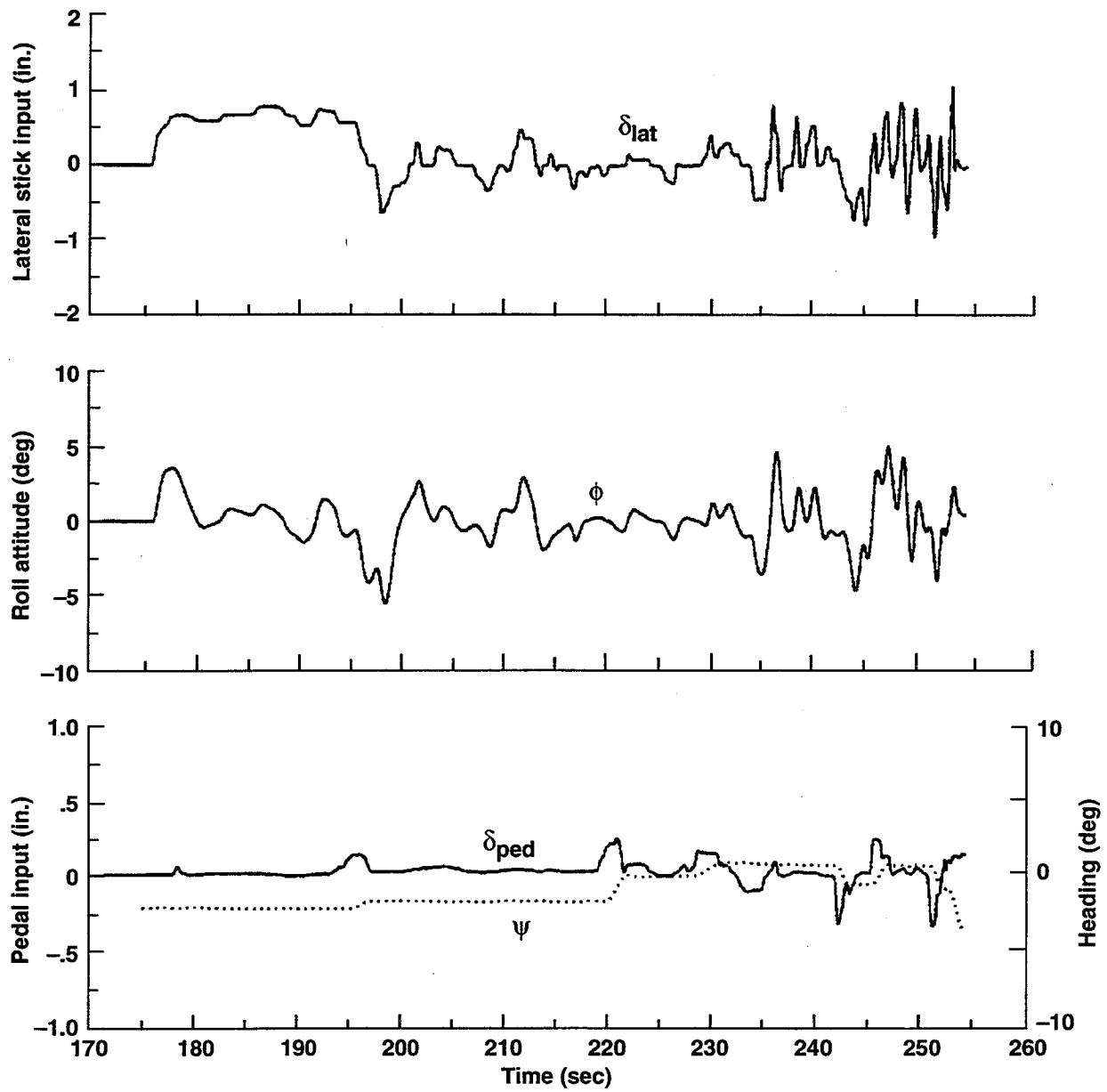
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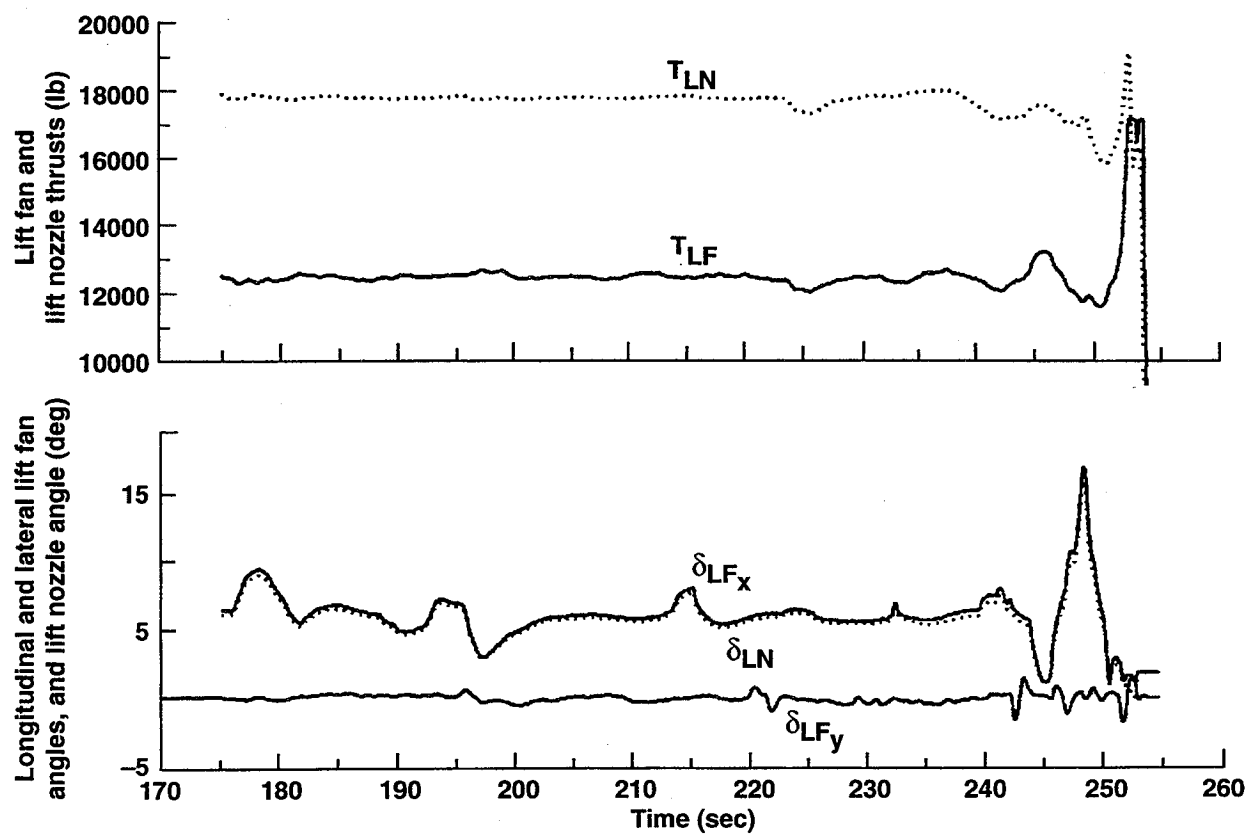
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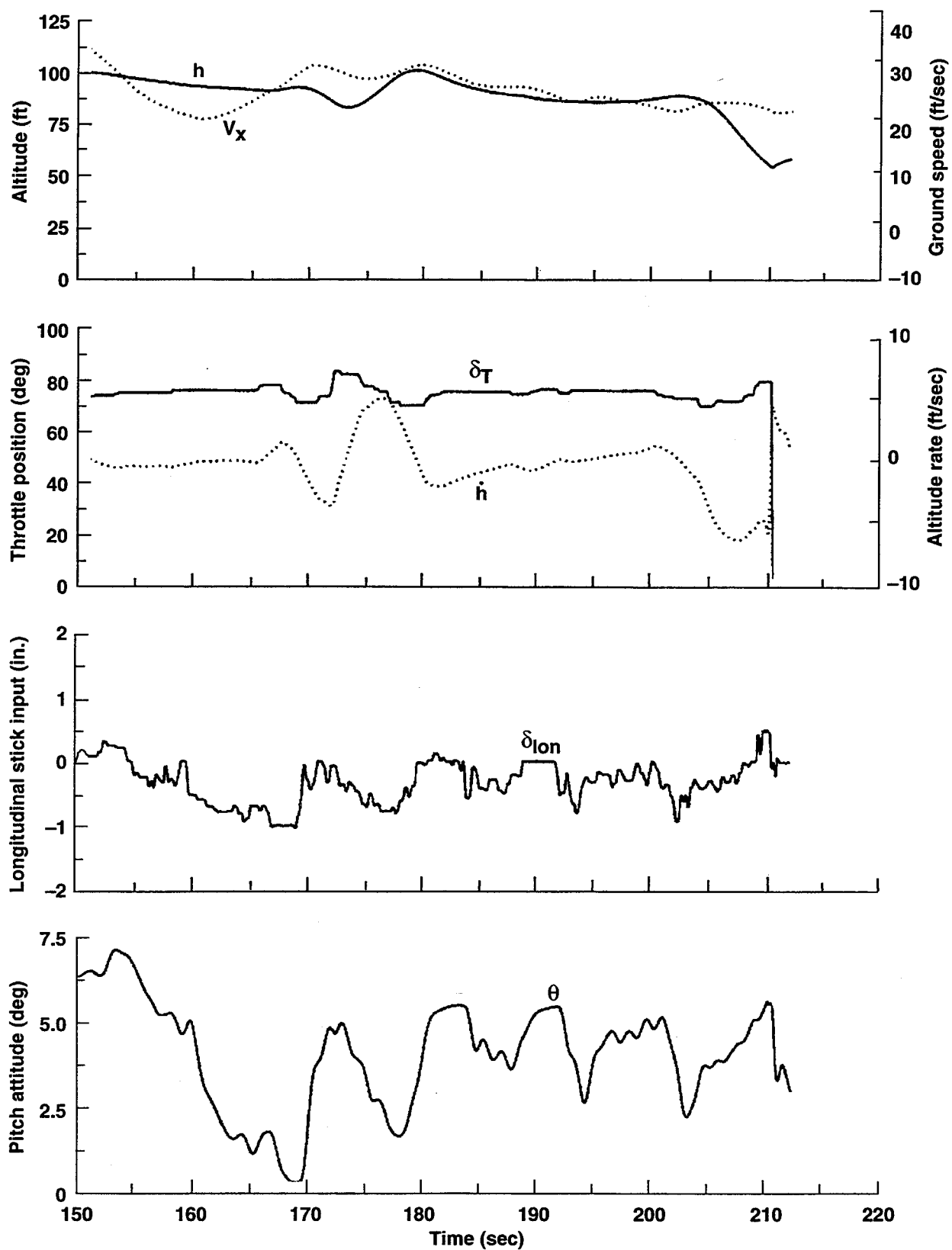
Figure 25. Time histories of landing on LPH in SS5, MTV mode.
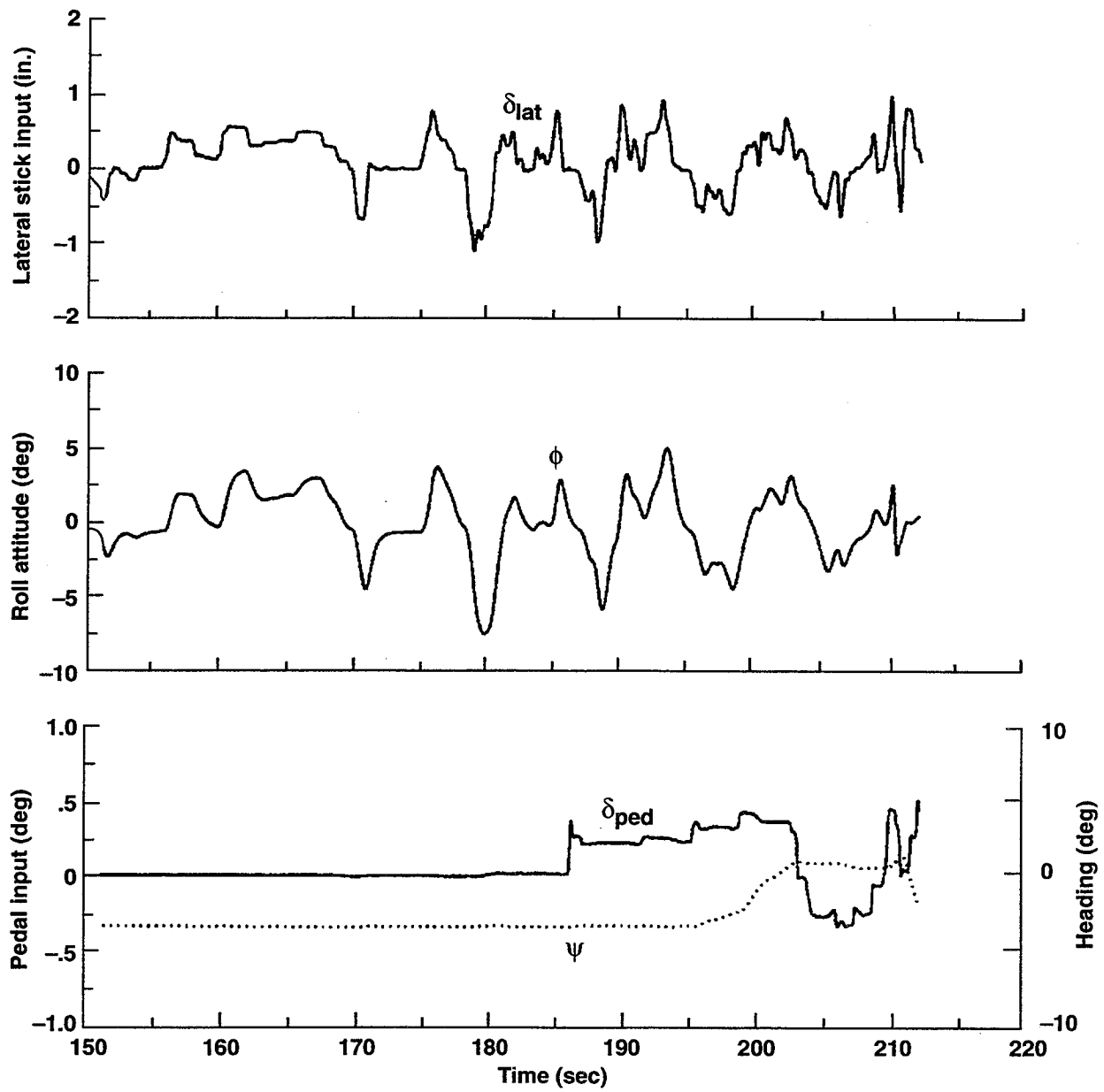
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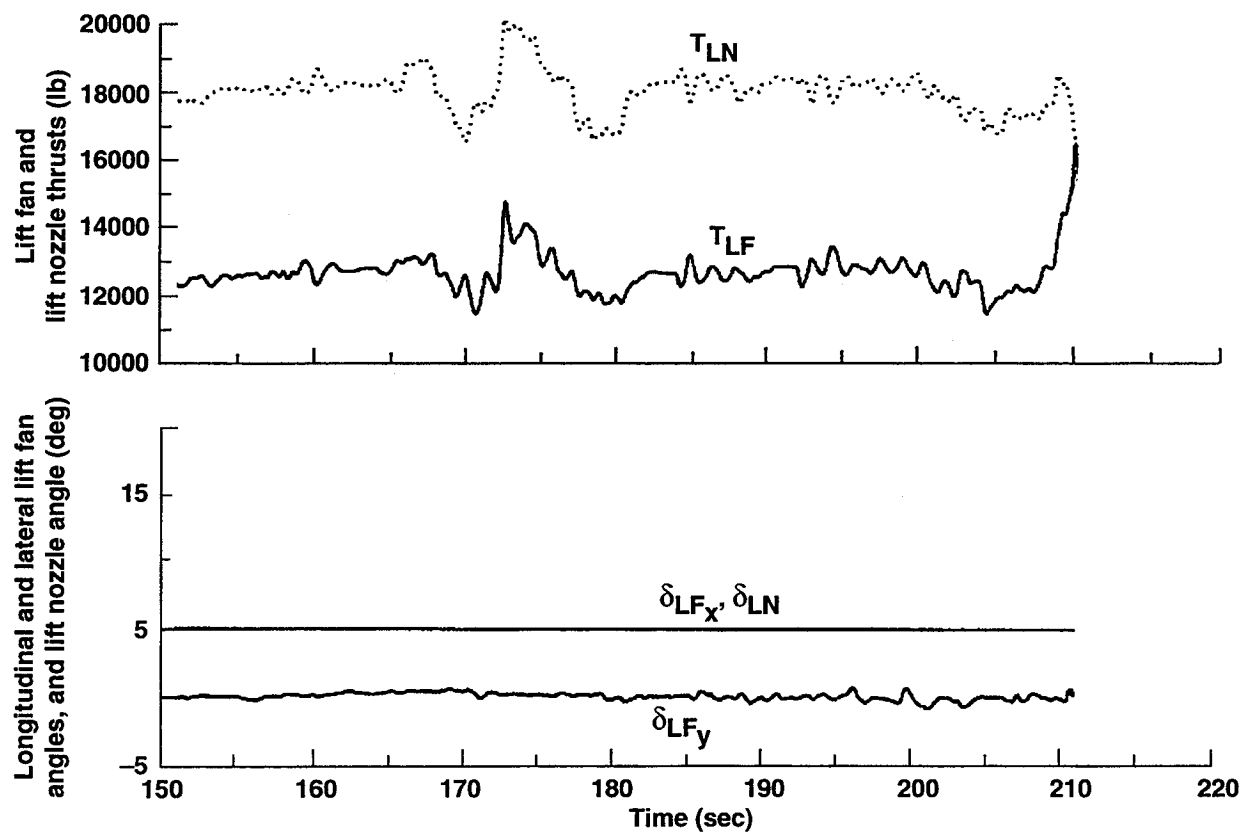
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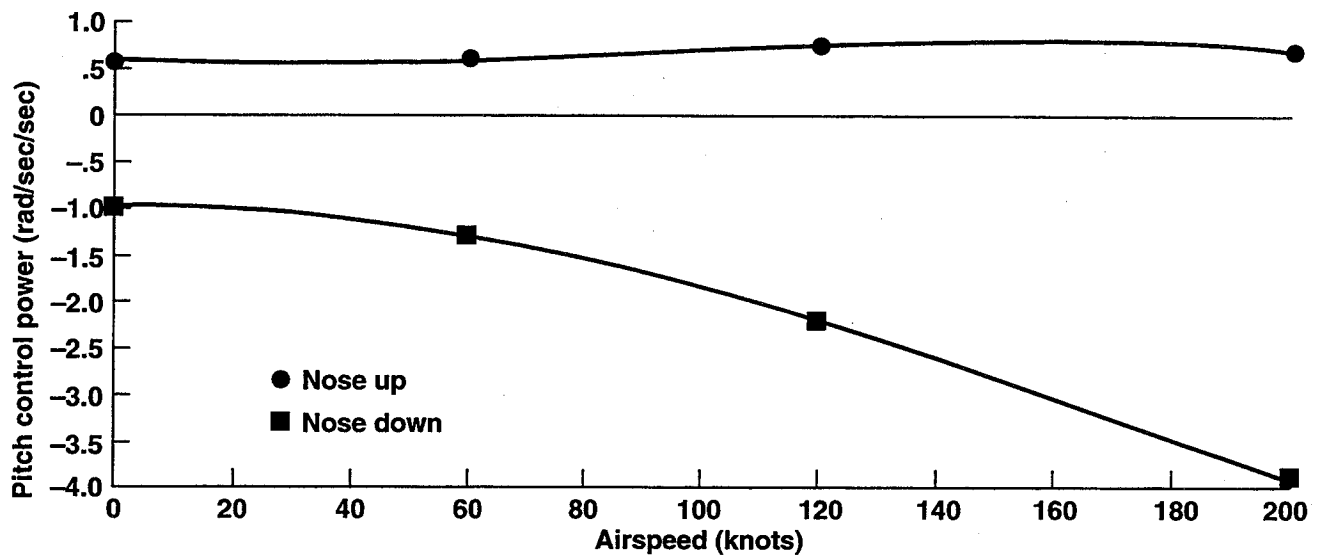
Figure 26. Total pitch control power available from hover to 200 knots.
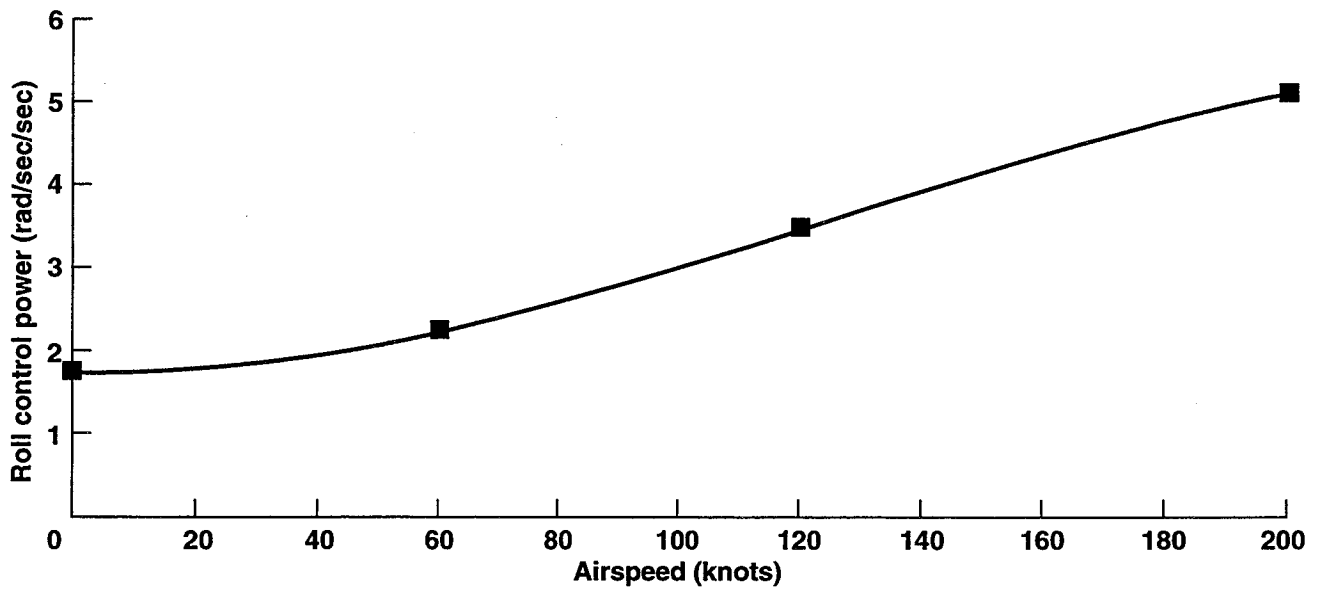
Figure 27. Total roll control power available from hover to 200 knots.
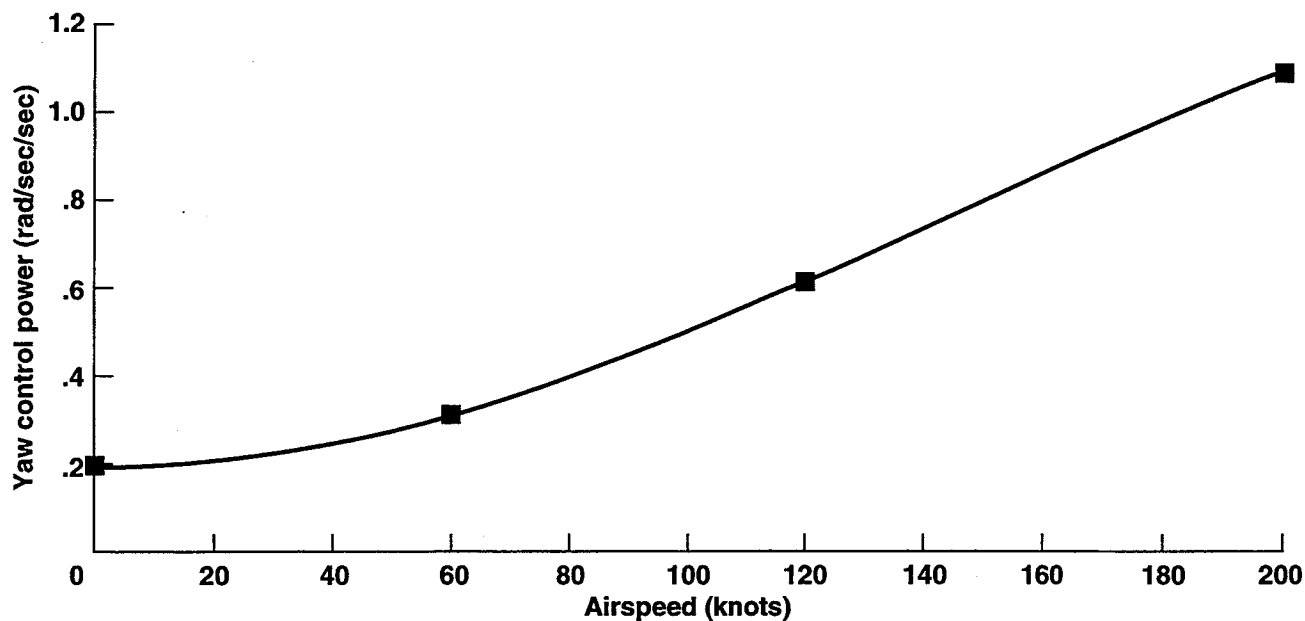
Figure 28. Total yaw control power available from hover to 200 knots.

100 ft ceiling and 1/4 mile visual range
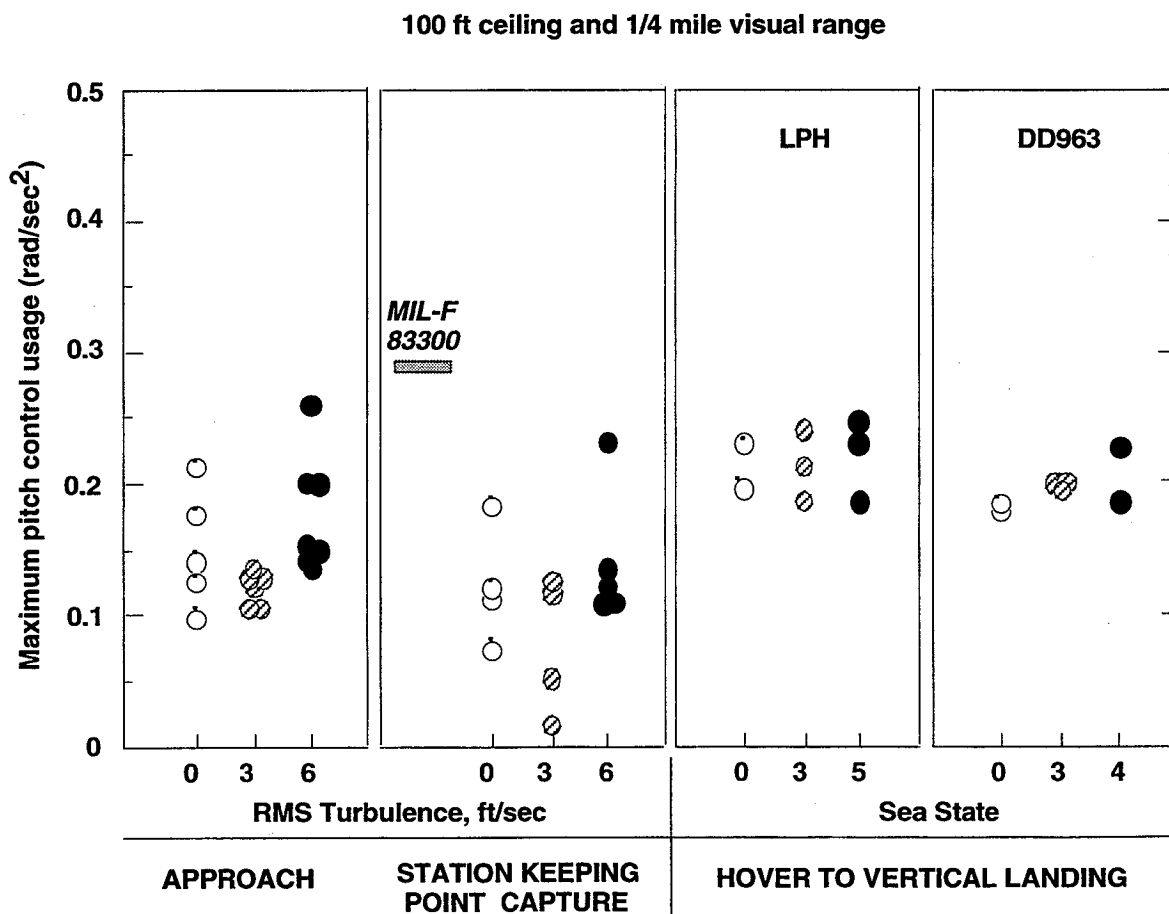
Figure 29. Pitch control power usage.

100 ft ceiling and 1/4 mile visual range
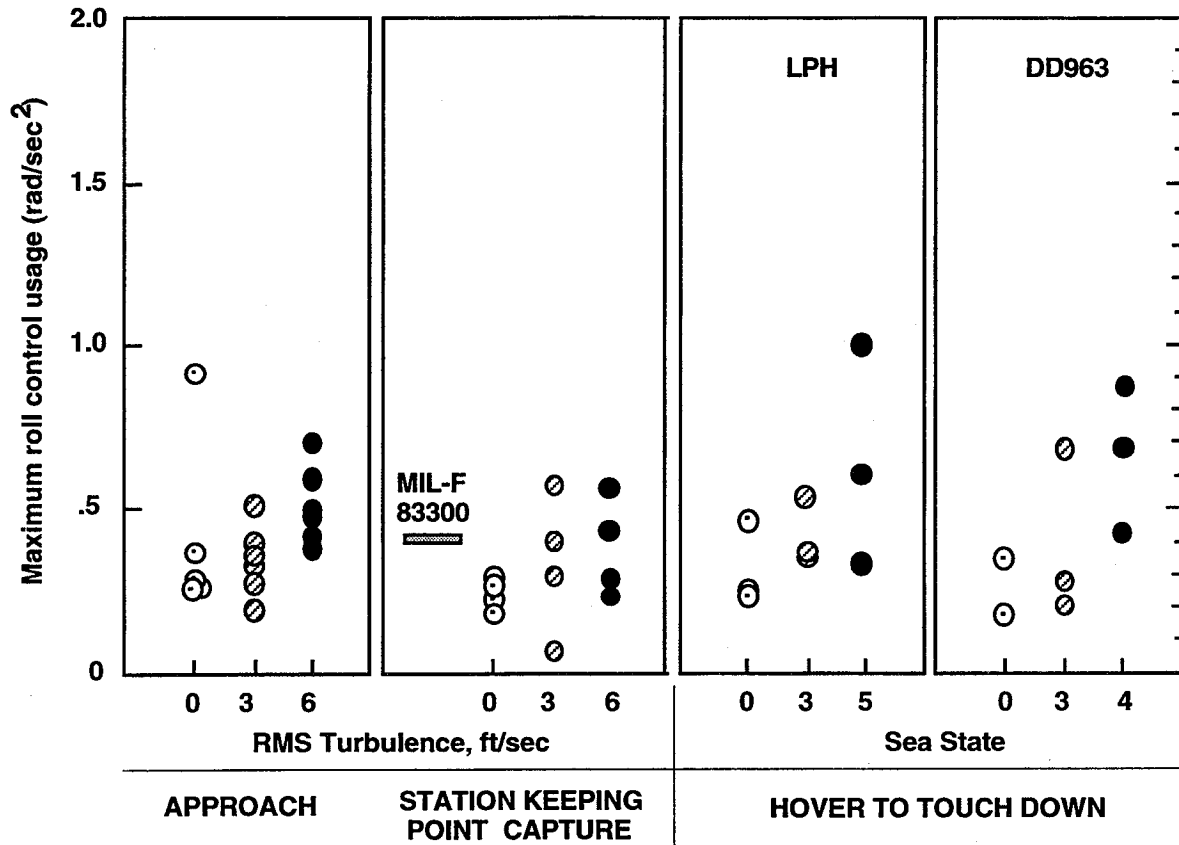
Figure 30. Roll control power usage.

100 ft ceiling and 1/4 mile visual range
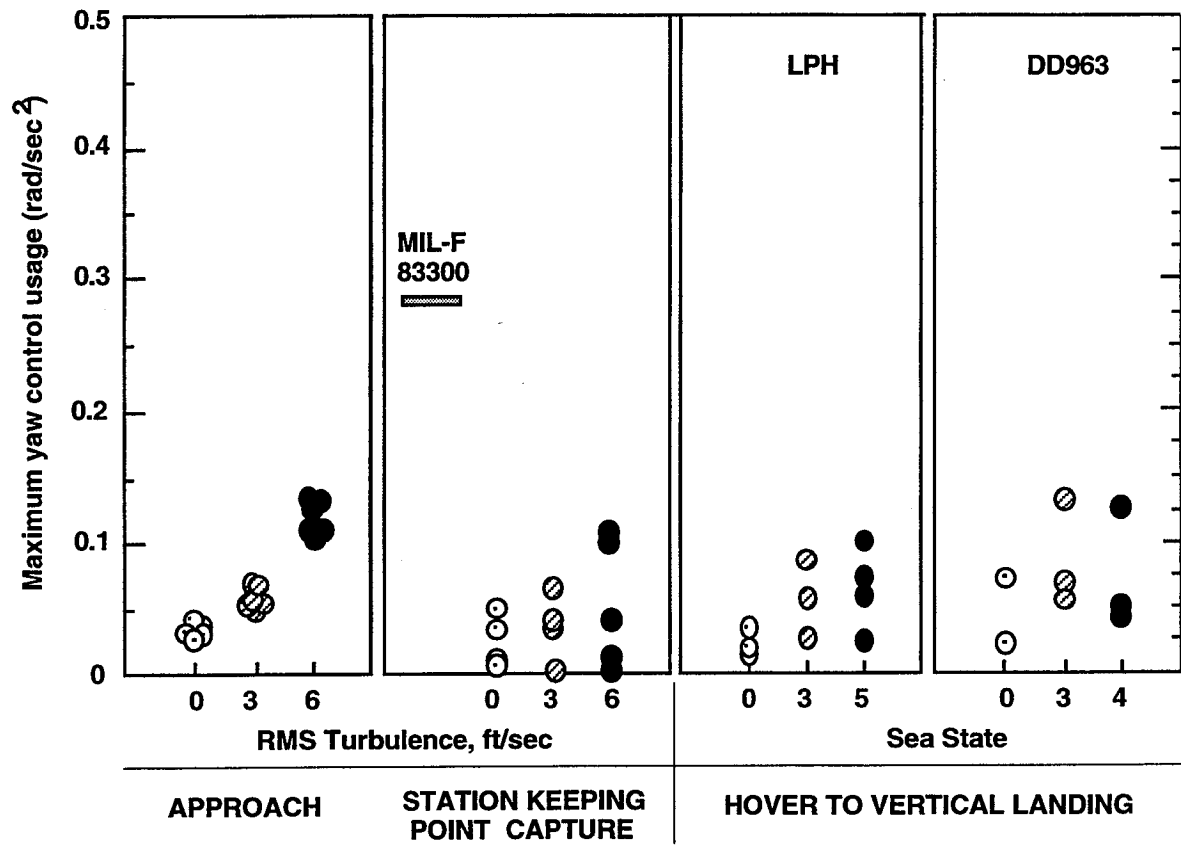
Figure 31. Yaw control power usage.
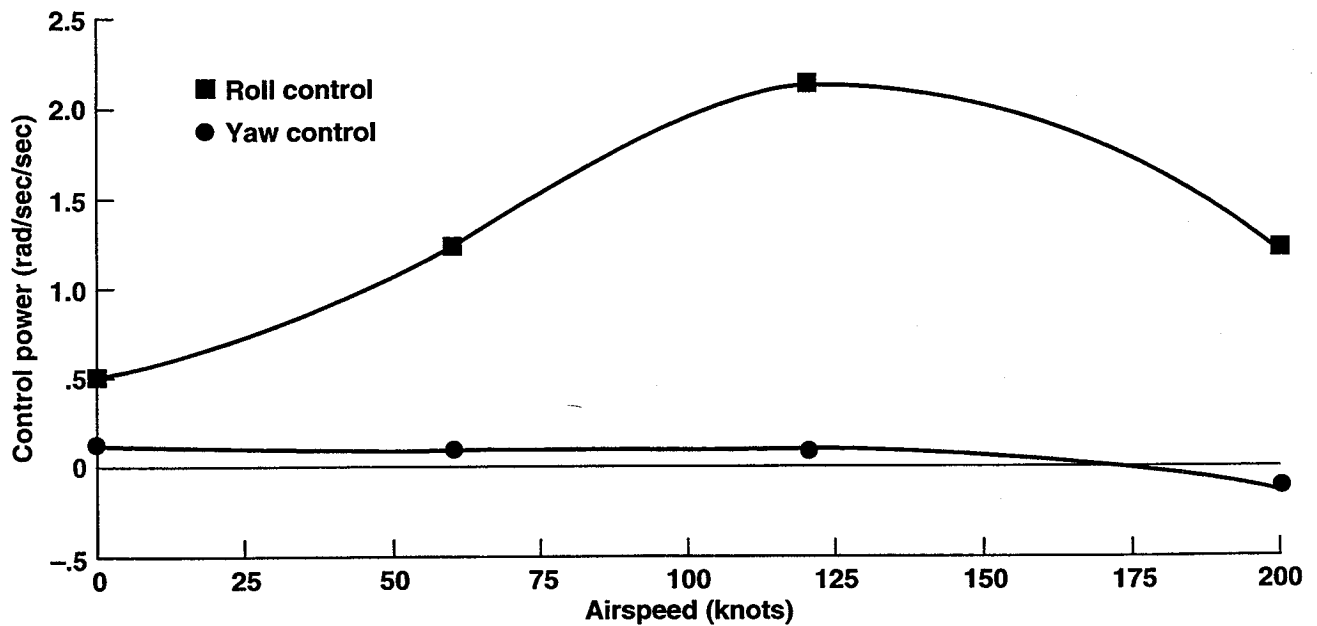
Figure 32. Control power to trim in 30 knot crosswind.
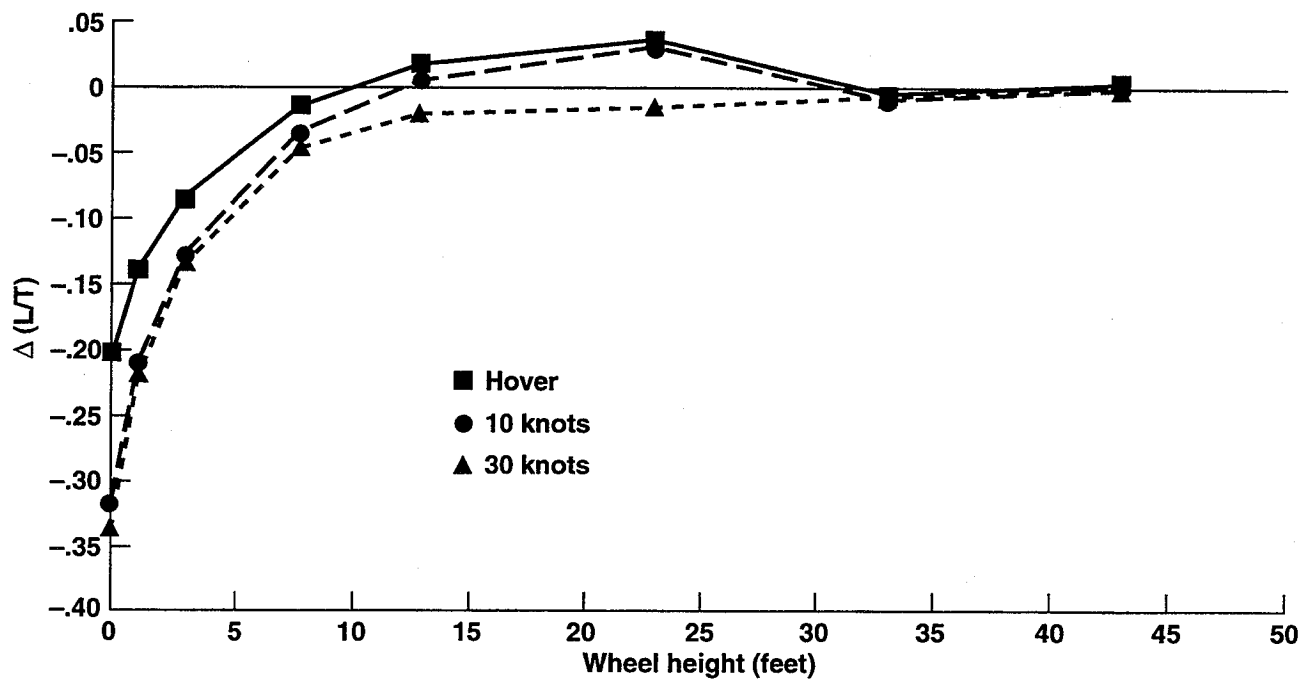
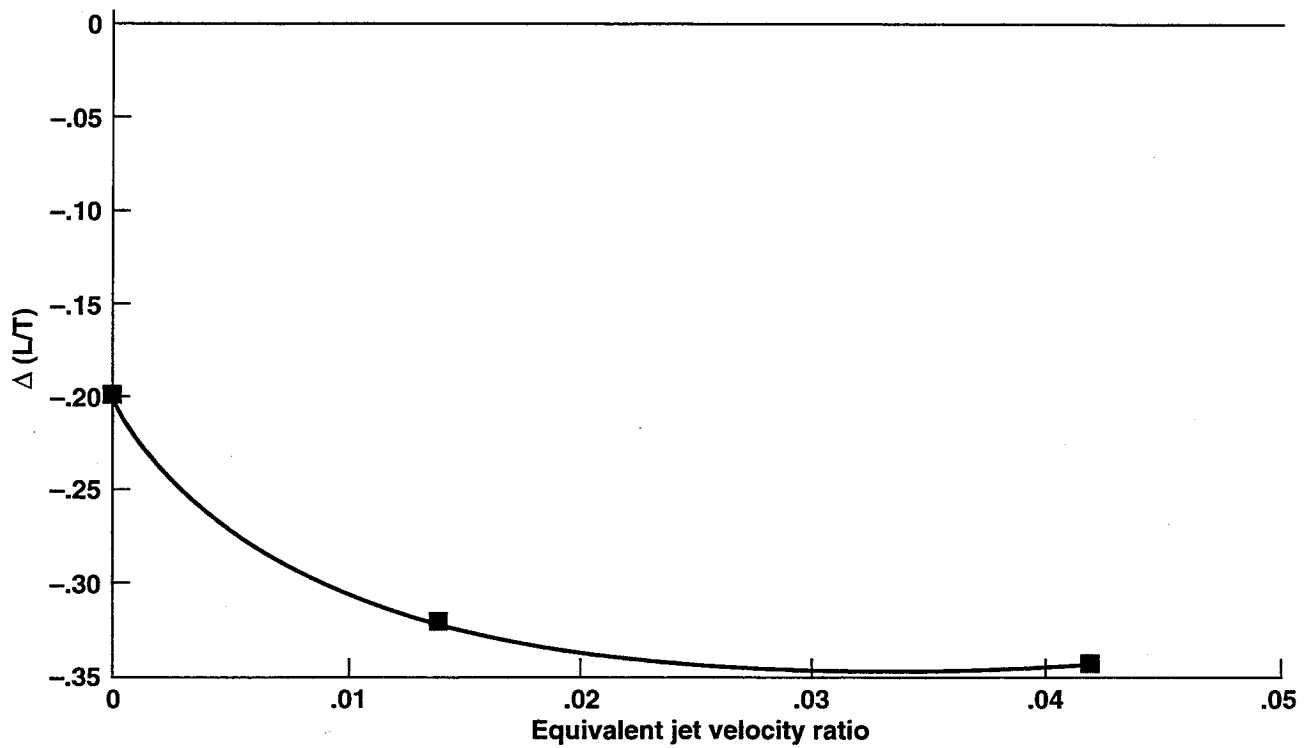Figure 33. Variation of jet-induced lift in ground effect.

Figure 34. Variation of jet-induced lift with aircraft at wheel height.

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13. ABSTRACT *(Maximum 200 words)*

Using a generalized simulation model, a moving-base simulation of a lift-fan short takeoff/vertical landing fighter aircraft was conducted on the Vertical Motion Simulator at Ames Research Center. Objectives of the experiment were to (1) assess the effects of lift-fan propulsion system design features on aircraft control during transition and vertical flight including integration of lift fan/lift/cruise engine/aerodynamic controls and lift fan/lift/cruise engine dynamic response, (2) evaluate pilot-vehicle interface with the control system and head-up display including control modes for low-speed operational tasks and control mode/display integration, and (3) conduct operational evaluations of this configuration during takeoff, transition, and landing similar to those carried out previously by the Ames team for the mixed-flow, vectored thrust, and augmentor-ejector concepts. Based on results of the simulation, preliminary assessments of acceptable and borderline lift-fan and lift/cruise engine thrust response characteristics were obtained. Maximum pitch, roll, and yaw control power used during transition, hover, and vertical landing were documented. Control and display mode options were assessed for their compatibility with a range of land-based and shipboard operations from takeoff to cruise through transition back to hover and vertical landing. Flying qualities were established for candidate control modes and displays for instrument approaches and vertical landings aboard an LPH assault ship and DD-963 destroyer. Test pilot and engineer teams from the Naval Air Warfare Center, Boeing, Lockheed, McDonnell Douglas, and the British Defence Research Agency participated in the program.

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