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# Simulation Comparison of a Decoupled Longitudinal Control System and a Velocity-Vector Control Wheel Steering System During Landings in Wind Shear

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# SUMMARY

This report presents a comparison of the velocity-vector control wheel
steering (VCWS) system that currently exists on the NASA Terminal Configured
Vehicle (TCV) and a decoupled longitudinal control system. The evaluation was
conducted in the TCV aft cockpit simulator. The primary piloting task was to
capture and maintain a $3^\circ$ glide slope in the presence of wind shear using the
electronic attitude-direction indicator (EADI) and to complete the landing
using that display's perspective runway.

The decoupled longitudinal control system used constant prefilter and
feedback gains to provide steady-state decoupling of flight-path angle, pitch
angle, and forward velocity. There was essentially no difference between the
pilots' performance with the two control systems in light and moderate wind
shear. However, the decoupled control system improved the pilots' ability to
control airspeed and flight-path angle during the final stages of an approach
made in severe wind shear. The use of decoupled controls also improved the
pilots' ability to complete safe landings in severe wind shear. The pilots
preferred the decoupled control system in severe winds and, on a pilot rating
scale, rated the approach and landing task with the decoupled control system as
much as 3 to 4 increments better than use of the VCWS system.

# INTRODUCTION

Wind shear occurring during the approach and landing phase of flight has
been a significant factor in several airplane crashes (refs. 1 and 2) that have
occurred during the past few years. A fixed-base simulation study (ref. 3)
reported the beneficial effect of decoupled longitudinal controls during the
approach and landing of a Boeing 737-100 jet transport in the presence of wind
shear. The flight instrumentation used in reference 3 included a conventional
localizer and a flight director. The primary piloting task was to capture and
maintain a $3^\circ$ glide slope by using the flight director and then to complete the
landing by using visual cues provided below an altitude of 61 m by closed-
circuit television and a terrain model. The decoupled control system provided
steady-state decoupling of flight-path angle, pitch angle, and forward velocity
and demonstrated improved performance over the conventional 737 control system
during both approach and landing. Although the pilots preferred the decoupled
controls, rating the approach and landing task 1 to 3 increments better on a
pilot rating scale over use of conventional controls, they believed that their
performance with the decoupled controls was hampered by the lack of a display of
commanded flight-path angle. In addition, reference 3 compared an augmented
airplane to an unaugmented conventional airplane.

The present simulation study compared the performance of the decoupled
control system of reference 3 with the velocity-vector control wheel steering
(VCWS) mode of NASA's Terminal Configured Vehicle (TCV) during the landing
approach in the presence of wind shear. The simulation included the six-degree-

of-freedom nonlinear equations of motion that represent the Boeing 737-100 airplane. The advanced avionics display (ref. 4) of the simulated TCV included a perspective runway and track symbolism that enabled the landings to be completed without the use of simulated visual cues from outside the airplane. The display included commanded flight-path angle and was employed with both the VCWS and the decoupled control system. The simulation included the effects of light, moderate, and severe wind shears and turbulence.

Use of trade names or names of manufacturers in this report does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

## SYMBOLS

| | |
|---|---|
| A | matrix of aircraft stability coefficients |
| $a_z$ | longitudinal and normal acceleration, respectively, g units ($1g = 9.8$ m/sec$^2$) |
| B | matrix of aircraft-control coefficients |
| C | matrix relating desired output vector to state vector |
| $C_m$ | pitching-moment coefficient |
| $C_W$ | weight coefficient, $-\dfrac{2mg}{\rho v^2 S}$ |
| $C_X$ | longitudinal-force coefficient |
| $C_Z$ | normal-force coefficient |
| $\bar{c}$ | mean aerodynamic chord, m |
| DMR( ) | statistical quantity of Duncan multiple range test; parentheses designate particular factor considered |
| F | calculated test statistic, dimensionless |
| G | matrix of prefilter gains used in decoupled controller (see appendix A) |
| g | acceleration due to gravity, m/sec$^2$ |
| H | matrix of feedback gains used in decoupled controller (see appendix A) |

| | |
|---|---|
| h | altitude, m |
| I | identity matrix |
| $I_X, I_Y, I_Z$ | moments of inertia about X, Y, and Z body axes, respectively, $kg-m^2$ |
| $I_{XZ}$ | product of inertia, $kg-m^2$ |
| J | performance index used in determining optimal control (see appendix A) |
| m | mass of airplane, kg |
| n | number of flights |
| P | solution to matrix Riccati equation (see appendix A) |
| Q | state-variable weighting matrix used in performance index J |
| q | pitch rate, deg/sec or rad/sec |
| R | control-variable weighting matrix used in performance index J |
| $R_a$ | range from aircraft to threshold, measured on Earth's surface, m |
| $\vec{r}$ | vector of commanded inputs by pilot |
| S | wing area, $m^2$ |
| s | Laplace variable |
| T | total thrust, N |
| t | time, sec |
| t( ) | statistical quantity of t-test of Student's t-distribution; parentheses designate particular factor considered |
| u,w | velocity components along X and Z body axes, respectively, knots |
| $\vec{u}$ | vector of control variables |
| $\hat{u}$ | difference between instantaneous control vector and vector of pilot inputs |
| V | true airspeed, knots |
| $V_{GS}$ | ground speed, knots |

| $X,Y,Z$ | body axes |
| --- | --- |
| $\vec{x}$ | vector of state variables |
| $\vec{x}_e$ | vector of state variables at equilibrium conditions |
| $\hat{x}$ | difference between instantaneous and equilibrium state vectors |
| $Y_i$ | inertial axis located at runway threshold, positive $Y_i$ to right |
| $y$ | distance along $Y_i$-axis, m |
| $\vec{y}$ | vector of state variables to be controlled in a decoupled manner |
| $\alpha$ | angle of attack, deg |
| $\gamma$ | inertial flight-path angle, deg |
| $\Delta\gamma$ | deviation in flight-path angle from the $3^\circ$ reference condition, deg |
| $\delta_a$ | aileron deflection, deg or rad |
| $\delta_{col}$ | column deflection, m |
| $\delta_e$ | elevator deflection, positive for trailing edge down, deg or rad |
| $\delta_{sp}$ | spoiler deflection, deg or rad |
| $\delta_{th}$ | equivalent throttle deflection |
| $\delta_{wheel}$ | control wheel deflection |
| $\theta$ | pitch angle, deg or rad |
| $\rho$ | air density, $kg/m^3$ |
| $\phi$ | bank angle, deg or rad |

Aircraft stability and control coefficients:

$$C_{X_{\delta_{sp}}} = \frac{\delta C_X}{\partial \delta_{sp}} \qquad C_{Z_{\delta_{sp}}} = \frac{\partial C_Z}{\partial \delta_{sp}} \qquad C_{m_{\delta_{sp}}} = \frac{\partial C_m}{\partial \delta_{sp}}$$

$$C_{X_{\delta_e}} = \frac{\partial C_X}{\partial \delta_e} \qquad C_{Z_{\delta_e}} = \frac{\partial C_Z}{\partial \delta_e} \qquad C_{m_{\delta_e}} = \frac{\partial C_m}{\partial \delta_e}$$

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$$C_{X_{\delta_{th}}} = \frac{\partial C_X}{\partial \delta_{th}} \qquad C_{Z_{\delta_{th}}} = \frac{\partial C_Z}{\partial \delta_{th}} \qquad C_{m_{\delta_{th}}} = \frac{\partial C_m}{\partial \delta_{th}}$$

$$C_{X_u} = \frac{\partial C_X}{\partial \frac{u}{V}} \qquad C_{Z_u} = \frac{\partial C_Z}{\partial \frac{u}{V}} \qquad C_{m_u} = \frac{\partial C_m}{\partial \frac{u}{V}}$$

$$C_{X_\alpha} = \frac{\partial C_X}{\partial \alpha} \qquad C_{Z_\alpha} = \frac{\partial C_Z}{\partial \alpha} \qquad C_{m_\alpha} = \frac{\partial C_m}{\partial \alpha}$$

$$C_{X_q} = \frac{\partial C_X}{\partial \frac{q\bar{c}}{2V}} \qquad C_{Z_q} = \frac{\partial C_Z}{\partial \frac{q\bar{c}}{2V}} \qquad C_{m_q} = \frac{\partial C_m}{\partial \frac{q\bar{c}}{2V}}$$

$$C_{X_{\dot\alpha}} = \frac{\partial C_X}{\partial \frac{\dot\alpha\bar{c}}{2V}} \qquad C_{m_{\dot\alpha}} = \frac{\partial C_m}{\partial \frac{\dot\alpha\bar{c}}{2V}}$$

Superscripts:

T          matrix transpose

-1         matrix inverse

'          nondimensional perturbations from equilibrium

Subscripts:

c          commanded by pilot

0          trim condition

L          left

Abbreviations:

AFD        aft flight deck

AGCS       advanced guidance and control system

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|---|---|
| ANOV | analysis of variance |
| ATTSYNC | attitude synchronization |
| DC | Decoupled Controls |
| $\Delta$IAS | deviation in indicated airspeed from reference condition (normally 130 knots but was 122 knots for decoupled controls in light turbulence) |
| d.o.f. | degrees of freedom |
| EADI | electronic attitude-direction indicator |
| EHSI | electronic horizontal situation indicator |
| ELOC | localizer error |
| GSE | glide-slope error |
| IAS | indicated airspeed |
| ILS | instrument landing system |
| MLS | microwave landing system |
| NCDU | navigation control/display unit |
| PMCC | panel-mounted control column |
| PMCW | panel-mounted control wheel |
| RCE | roll control enable |
| RCOD | roll control out of detent |
| rms | root mean square |
| TCV | Terminal Configured Vehicle |
| VCWS | velocity-vector control wheel steering |

A dot over a symbol denotes differentiation with respect to time.


## SIMULATED AIRPLANE DESCRIPTION

The simulated TCV airplane was a Boeing 737-100 medium jet transport (fig. 1) generated by the real-time solution of the nonlinear equations of motion for six rigid-body degrees of freedom. The simulation included detailed response characteristics of the Pratt & Whitney JT8D-9 turbofan engines, non-linear actuator models, and ILS and MLS sensor models. The physical charac-

teristics of the simulated airplane are presented in table I and the initial conditions are given in table II. The two-man aft flight deck (AFD) is shown in figure 2 and includes panel-mounted controllers for pitch and roll control and conventional rudder petals.

The electronic attitude-direction indicator (EADI) was the primary display used during the approach and landing. A sketch of the EADI is presented in figure 3. The essential features of the display included (a) an artificial horizon and attitude reference, (b) a roll indicator, (c) a commanded flight-path angle or "gamma wedges," (d) an inertial flight-path angle, (e) glide-slope and localizer indicators, (f) a relative track indicator, and (g) a perspective runway. The perspective runway, drawn on a $30^\circ$ by $40^\circ$ field of view, included the outline of the runway with an extended center line beginning 1 n. mi. before the runway threshold and extending to the horizon. The runway symbol represented a 3048-m runway approximately 46 m wide. Four lines were drawn perpendicular to the runway center line at intervals of 304.8 m, beginning 304.8 m beyond the runway threshold. The inertially referenced track angle of the airplane relative to the runway heading, or relative track angle, was indicated by a tab that moved along a horizontal line parallel to the artificial horizon line of the EADI. The track scale was drawn on the EADI horizon line in $10^\circ$ increments referenced to the runway heading. The magnitudes of the inertial and commanded flight-path angle were read off the pitch scale by using the solid and dashed gamma wedges, respectively.

## Velocity-Vector Control Wheel Steering System

The TCV simulator was equipped with an advanced control system that included the velocity-vector control wheel steering (VCWS) mode used in the current study. When the VCWS mode was selected, the application of a pitch force above the detent level resulted in a commanded angular rate. The panel-mounted control column (PMCC) employed a 2.54-mm deadband and had a maximum deflection of ±7.6 mm. Inertial sensor signals were used in the control laws to maintain flight-path angle when the control force was released. In addition, the thumb controller on the left horn of the control yoke could be used to change flight-path angle in increments of 1/4 degree per click. The velocity control mode in the roll axis was designed to hold the airplane attitude constant after the roll control force was released when the bank angle was greater than $5^\circ$. When the bank angle was less than $5^\circ$ at control release, the control system attempted to hold the present ground track of the airplane by modulating bank angle. The panel-mounted control wheel (PMCW) had full-scale deflections of ±$30^\circ$. Block diagrams of the velocity control mode for the pitch and roll axes are presented in figures 4 and 5, respectively. A more detailed description of the VCWS system may be seen in reference 4.

## Decoupled Control System

The general approach taken for providing independent or decoupled control of flight-path angle, pitch angle, and forward velocity is depicted in the following sketch:
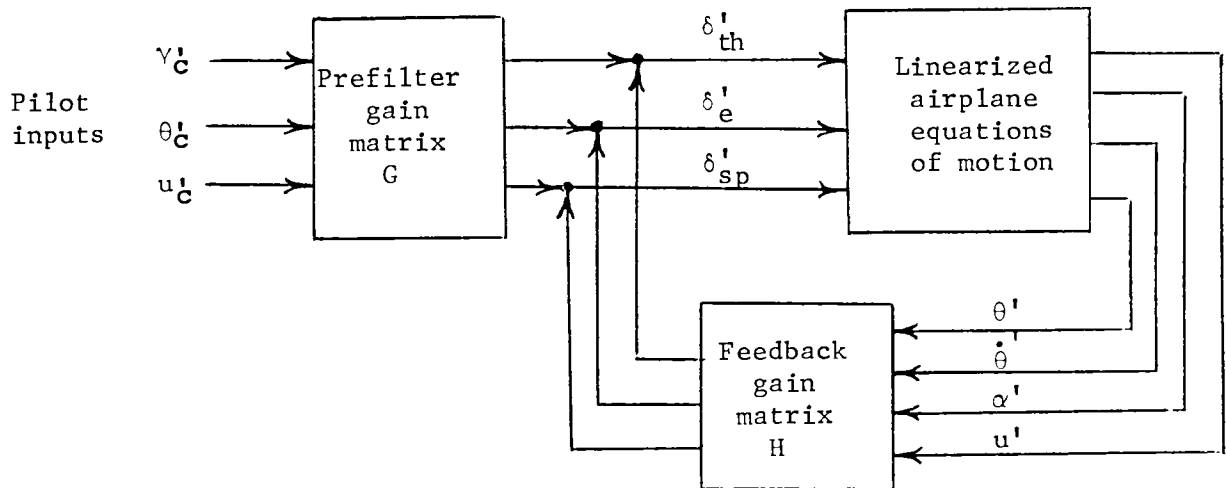
The decoupled control system was applied to the longitudinal mode and was mechanized so that the pilot commanded flight-path angle $\gamma_c'$ through inputs to the column, pitch angle $\theta_c'$ through the speed brake handle, and forward velocity $u_c'$ through the throttle. In addition, the thumb controller on the left horn of the control yoke could be used to trim flight-path angle, at a constant rate of 1 deg/sec. The decoupled controller was a closed-loop control system that required continuous measurement of pitch angle, pitch rate, angle of attack, and forward velocity.

The feedback gain matrix H and prefilter gain matrix G resulted in the throttle $\delta_{th}'$, elevator $\delta_e'$, and spoilers $\delta_{sp}'$ moving to produce steady-state decoupled control of flight-path angle, pitch angle, and forward velocity as commanded by the pilot. Spoiler panels 2, 3, 6, and 7 (fig. 1) were deployed asymmetrically for roll control and symmetrically for longitudinal control when the decoupled controls were used. The most versatile means for obtaining G and H is the use of an onboard computer to find the time-varying adaptive gains. However, the simplified approach used in reference 3 was also used in the present investigation where the use of the controller was restricted to the approach and landing phase of operations. Consequently, constant prefilter and feedback gains (calculated for the conditions in table II) could be used so that in an actual airplane no onboard computation would be necessary. The decoupled longitudinal control law is developed in appendix A. The lateral control law is the velocity control system shown in figure 5.

TEST PROGRAM

The wind-hazard data used in this study and in the study described in reference 3 were produced for the Federal Aviation Administration (FAA) (ref. 5). The wind profiles are modeled in the TCV simulator in terms of three-axis mean wind specifications and Dryden turbulence specifications. All specifications are modeled in the simulator by means of a table lookup given as a function of both altitude and range from runway threshold. Six wind-shear profiles (denoted B2, B3, B6, B7, D3, and D10) were chosen to be used in the simulation study.

Profiles B2 and B3 (figs. 6 and 7) were representative of low-intensity wind shears and had little turbulence, as indicated in table III. Profiles B6 and B7 (figs. 8 and 9) were representative of moderate wind shear. Profile B7 included turbulence (table IV) with rms gust intensities up to 8 knots. Two very severe wind shears (figs. 10 and 11) which also included table IV turbulence were also simulated and are denoted D3 and D10, respectively. Profile D10 was a reconstruction of the wind shear present during the Eastern Airlines crash at the John F. Kennedy International Airport in 1975.

Three research pilots were required to perform six flights in each wind condition (light, moderate, and severe) with each control system. All three pilots were rated for the B-737 airplane, and the combinations of wind shear and control configuration were randomized (ref. 6) through the use of a Latin square. The pilots' task was to assume command of the airplane in level flight and use the glide-slope deviation and flight-path angle indicators to capture and maintain the desired $3^{\circ}$ glide slope. When the decoupled control system was used, the pitch attitude was nominally set at $3^{\circ}$ to keep the nose wheel off the ground at touchdown. The commanded airspeed was set at the desired touchdown value of 122 knots shortly after flight initiation in light and moderate wind shear. When the turbulence level was high, as was the case in severe wind shear, the pilots generally maintained 130 knots until just before touchdown. The decoupled control system attempted to maintain the commanded pitch attitude and airspeed as the flight progressed without further pilot attention. When the MLS beam was intercepted, the pilots trimmed the airplane onto the desired $3^{\circ}$ descent path using the trim button on the control yoke. The pilots then used either the trim button or the column to make any necessary changes in flight-path angle. The pilots used the perspective runway to complete the landings nominally 304.8 m down the runway from the threshold. The VCWS system was employed in the same manner as the decoupled control system except that the initial 130-knot airspeed was normally maintained until just prior to touchdown regardless of the wind condition. The decoupled control system is compared with the VCWS on a statistical basis during three different segments of the approach. The statistical analysis is discussed in detail in appendix B. In addition, the touchdown performance is measured against standards presented in reference 7. Pilot ratings are also used to compare the two control systems.

RESULTS AND DISCUSSION

Successful approaches were made with either control system in the presence of both light and moderate wind shear. As shown in figure 12, however, severe wind shear such as D10 often precluded success when the VCWS was employed. Approximately 115 sec into the flight at an altitude of about 130 m, the airplane encountered winds that reduced the airspeed to the point of stalling, even though the VCWS system sharply increased thrust. The airplane descended below the desired glide slope and although the control system pitched the nose up in excess of $25^{\circ}$, the airplane impacted approximately 840 m short of the runway. This large pitch angle may have actually contributed to the stall because it resulted in the airplane operating in a very high drag condition on the backside of the lift curve, where it would be very difficult to counteract the airspeed reduction caused by a head wind shearing to a tail wind.

When landings were attempted in the same wind condition with the decoupled control system, the pilots could consistently attain the runway. A typical flight is presented in figure 13. On this flight, the decoupled control system kept the airspeed from falling below 115 knots and although not shown in the figure, the airplane landed 472 m down from threshold with a sink rate of 1.5 m/sec. The decoupled control system also maintained pitch attitude at very nearly the desired $3°$ (fig. 13) even in the presence of severe wind shear. The penalty paid for the improved performance in severe winds with the decoupled control system was a more active throttle (compare figs. 12 and 13) than was the case with the VCWS system. If this level of throttle activity is undesirable, a preliminary investigation indicated that filtering u-feedback with a first-order linear filter having a 1-sec time constant reduced the rms throttle response to severe turbulence by approximately one-half without a detectable effect on approach and landing performance. Further reduction in rms throttle activity could be achieved by increasing the time constant; however, the ability of the decoupled control system to maintain the desired airspeed in the presence of severe winds was adversely affected. Although the VCWS system had less throttle activity in severe winds, the apparently high gains in the pitch loop resulted in pitch acceleration and normal acceleration levels that were much higher than the decoupled control system (compare figs. 12 and 13). For example, the VCWS system had several normal acceleration spikes that approached 1g, whereas the decoupled control system was generally less than $\frac{1}{2}$g. In addition, the pitch acceleration with the VCWS system was approximately 3 times that of the decoupled control system. The pilots, however, could not evaluate these differences in ride qualities with the fixed-base simulator used in this study.

## Approach Performance

The performance data for the approach phase of the study are presented for an early portion of the approach and two later portions of the approach. The first portion includes rms values from data taken every 31.25 msec between altitudes of 457 m and 228 m. The performance parameters considered (fig. 14) were flight-path angle error, glide-slope error, indicated airspeed error, localizer error, and the control inputs to the panel-mounted control wheel and control column. The trim airspeed was 130 knots when the VCWS system was used and when the decoupled control system was used in severe winds. When the decoupled control system was used in light and moderate shears, the trim speed was 122 knots, the desired touchdown value for the simulated aircraft weight. Each symbol shown in figure 14 denotes the mean value of six flights performed by each pilot, with each control system, under each wind condition. There was very little difference due to control systems in any of the six mean approach performance parameters. Flight-path angle and glide-slope errors tended to be larger with decoupled controls, but the difference generally was not statistically significant. (See appendix B for a detailed statistical analysis of the various pilot, control, and wind interactions.) The error in indicated airspeed was normally smaller with decoupled controls, but again, the difference generally was not statistically significant. However, two of three pilots had standard deviations about the mean airspeed with the VCWS system that were significantly larger in each wind condition than was the case with decoupled

controls. Increased wind severity degraded all the performance parameters except localizer error, but the degradation was generally not statistically significant. There was no effect of pilots except for control wheel inputs, where pilot B consistently made larger inputs than the other pilots. In summary, there was little effect of controls, winds, or pilots during the initial portion of the approach.

The approach performance parameters for the intermediate portion of the approach, between altitudes of 76.2 m and 30.4 m, are shown in figure 15. Of the six approach performance parameters only two, indicated airspeed error and localizer error, showed a statistically significant effect of control system. The mean indicated airspeed error was smaller when the decoupled control system was used at each wind condition for all three pilots. The improvement due to the use of decoupled controls was not, however, statistically significant at the 95-percent confidence level for all pilot and wind shear combinations. In addition, the standard deviation about the mean (appendix B) was smaller when decoupled controls were used. The localizer error, a lateral control parameter, was also reduced when decoupled controls were used. However, the improvement was generally not statistically significant. The degradation due to increased wind severity affected all the approach performance parameters at the 99-percent confidence level except control column activity. The significant degradations generally occurred in severe winds. There was no effect of pilots on performance with the exception of pilot B, who again made significantly larger control wheel inputs with either control system.

The approach performance parameters for the final portion of the approach, between altitudes of 30.4 m and 15.1 m, are shown in figure 16. The mean error in indicated airspeed with decoupled controls was less than that with the VCWS system for all pilots under all wind conditions. In addition, the standard deviation about the mean was generally smaller by an amount that was significant at the 99-percent confidence level. The mean flight-path angle error was smaller in severe winds for all three pilots when the decoupled control system was used. Although the difference between the means due to control systems was not statistically significant, the lack of significance was probably due to the large standard deviations about the mean that occurred when the VCWS system was used. Controls had no significant effect on the other approach performance parameters. The degradation due to increased wind shear affected all the approach performance parameters at the 99-percent level except control wheel activity. Pilot B again made significantly larger control wheel inputs with either control system than the other two pilots. There were no other significant pilot effects.

Touchdown Performance

The mean touchdown performance data are summarized in figure 17. The touchdown performance parameters examined during this investigation were longitudinal and lateral position, pitch angle, bank angle, sink rate, and forward velocity. The limits shown in figure 17 reflect Category II requirements discussed in reference 7. The mean values of all six performance parameters were generally within these limits for all pilots under all wind conditions when decoupled controls were used. The exception was the range from threshold, where

pilots A and B landed approximately 120 m long with decoupled controls in severe winds. This was still an improvement over the VCWS system, because the data plotted in figure 7 are the mean values of all flights that did not crash. Of the 18 landings attempted in severe winds with the VCWS system, 8 sustained loss of control with resulting crashes. Although none of the flights made with decoupled controls resulted in loss of control, performance was marginal in shears as severe as those present during the Eastern Airlines crash at the John F. Kennedy International Airport in 1975. In addition, one flight made with decoupled controls in moderate wind shear touched down 15 m short of the runway.

The mean sink rate at touchdown with the VCWS system was generally outside the limit. The error in indicated airspeed was within the limits with either control system in light and moderate shears (fig. 17), but in severe winds two of the three pilots had values outside the limits when the VCWS system was used. The pitch attitude at touchdown with the VCWS system was outside the limits for all three pilots in moderate and severe wind shears. In fact, it was less than zero in each case which corresponds to landing on the nose wheel. In addition, the standard deviation about the mean with the VCWS system was generally larger for sink rate, indicated airspeed, pitch angle, and range from threshold (appendix B) than was the case with the decoupled control system. The lateral performance parameters, bank angle and lateral displacement, were well within the limits with either control system. The variation between pilots was statistically significant only for indicated airspeed.

Pilot Opinion

The pilots were asked to rate the landing task with each control system in light, moderate, and severe wind shear using the pilot rating system shown in table V. The pilot rating results are summarized in table VI. The three research pilots did not differentiate between the two control systems in light wind shears and gave the task a pilot rating of 2 to 3. For moderate winds pilots B and C indicated that the task was somewhat easier with decoupled controls, as denoted by pilot ratings that were 1 to 3 increments better than with the VCWS system. However, there was a major difference between control systems in severe winds. Typical pilot ratings with decoupled controls were 4 to 6, indicating that adequate performance was possible but that moderate to extensive pilot compensation would be required. When the VCWS system was used, all the pilots felt that adequate performance was not attainable and two of the pilots gave the task a rating approaching 10, indicating that control would be lost at some point. This rating of 10 was not merely a reflection of the fact that the airplane occasionally stalled and crashed, but was also associated with the large pitch angles that occurred in Kennedy-type (wind shear D10) conditions. When the pitch attitude exceeded 15°, the usefulness of the EADI was severely compromised because the horizon and the perspective runway were lost from the field of view, sometimes for fairly long periods of time.

The length of time that the pitch angle $\theta$ exceeded 15° during each of the nine flights made by the three pilots in wind shear D10 is shown in table VII. Also shown is the time that the airspeed was less than $V_{min}$. The pitch attitude exceeded the limit for as long as 18 sec and averaged 6.3 sec when the VCWS system was used; the limit was never exceeded when the decoupled control system

was used. Similar behavior is noted for the airspeed, where the average time spent at speeds less than $V_{min}$ was almost 12 sec with the VCWS system compared with zero with decoupled controls. It should be noted that the pilot ratings do not reflect the violation of the velocity boundary because the simulator employed did not attempt to simulate buffet or to model the stickshaker.

## CONCLUDING REMARKS

A fixed-base simulation study has been conducted to evaluate the use of decoupled longitudinal controls as a means for improving pilot performance during approach and landing of the NASA Terminal Configured Vehicle (TCV) aircraft in the presence of wind shear. The decoupled longitudinal control system employed the throttle, the elevators, and the symmetric spoilers as active control elements to provide steady-state decoupling of flight-path angle, pitch angle, and forward velocity. Restricting the controller to the approach and landing phase of operations permitted the use of constant prefilter and feedback gains in the mechanization of the decoupled control system. The piloting task was to use the electronic attitude-direction indicator (EADI) to capture and maintain a $3^\circ$ glide slope and then use the perspective runway included on that display to complete the landing. The task was also performed using the velocity-vector control wheel steering (VCWS) system currently in use on the TCV.

The following results are indicated from this study:

1. During the early portion of the approach there was essentially no difference between the decoupled control system and the VCWS system. During the final portion of the approach, the decoupled control system showed an improvement over the VCWS system in either the mean error or the standard deviation about the mean for indicated airspeed and flight-path angle. The performance degraded with either control system as wind severity increased but generally showed no statistically significant variability between pilots.

2. The use of decoupled controls increased the pilots' ability to complete landings successfully in the presence of severe wind shear. Of the 18 landings attempted in severe winds with the VCWS system, 8 sustained loss of control with resultant crashes. Although none of the flights made with decoupled controls resulted in loss of control, performance was marginal in shears as severe as those during the Eastern Airlines crash at the John F. Kennedy International Airport in 1975.

3. The pilots reported no differences between the two control systems in light wind shear. Two of the pilots indicated that the task was somewhat more difficult with the VCWS in moderate wind shear. However, there were major deficiencies with the VCWS system in severe wind shear, whereas the decoupled control system resulted in pilot ratings that were as much as 3 or 4 increments better.

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## DECOUPLED LONGITUDINAL CONTROLS

The three longitudinal equations of motion were linearized as perturbations about an equilibrium condition in equation (1-59) of reference 8. These three equations can be nondimensionalized with respect to time using

$$t' = \frac{V_0}{\bar{c}} t \qquad (A1)$$

and, neglecting $C_{z_{\dot{\alpha}}}$ and $C_{z_q}$, solved simultaneously to give

$$\frac{d^2\theta'}{dt'^2} = \frac{1}{2\mu K_y{}^2}\left[\left(\frac{C_{m_q} + C_{m_{\dot{\alpha}}}}{2}\right)\frac{d\theta'}{dt'} + \left(C_{m_{\alpha}} + \frac{C_{m_{\dot{\alpha}}}C_{z_{\alpha}}}{4\mu}\right)\alpha'\right.$$

$$+ \left(C_{m_u} + \frac{C_{m_{\dot{\alpha}}}C_{z_u}}{4\mu}\right)u' + \left(C_{m_{\delta_{th}}} + \frac{C_{m_{\dot{\alpha}}}C_{z_{\delta_{th}}}}{4\mu}\right)\delta'_{th}$$

$$\left. + \left(C_{m_{\delta_e}} + \frac{C_{m_{\dot{\alpha}}}C_{z_{\delta_e}}}{4\mu}\right)\delta'_e + \left(C_{m_{\delta_{sp}}} + \frac{C_{m_{\dot{\alpha}}}C_{z_{\delta_{sp}}}}{4\mu}\right)\delta'_{sp}\right] \qquad (A2)$$

$$\frac{d\alpha'}{dt'} = \frac{1}{2\mu}\left(2\mu\frac{d\theta'}{dt'} + C_{z_{\alpha}}\alpha' + C_{z_u}u' + C_{z_{\delta_{th}}}\delta'_{th} + C_{z_{\delta_e}}\delta'_e + C_{z_{\delta_{sp}}}\delta'_{sp}\right) \qquad (A3)$$

$$\frac{du'}{dt'} = \frac{1}{2\mu}\left[C_W\theta' + \left(\frac{C_{x_q} + C_{x_{\dot{\alpha}}}}{2}\right)\frac{d\theta'}{dt'} + \left(C_{x_{\alpha}} + \frac{C_{x_{\dot{\alpha}}}C_{z_{\alpha}}}{4\mu}\right)\alpha' + \left(C_{x_u} + \frac{C_{x_{\dot{\alpha}}}C_{z_u}}{4\mu}\right)u'\right.$$

$$+ \left(C_{x_{\delta_{th}}} + \frac{C_{x_{\dot{\alpha}}}C_{z_{\delta_{th}}}}{4\mu}\right)\delta'_{th} + \left(C_{x_{\delta_e}} + \frac{C_{x_{\dot{\alpha}}}C_{z_{\delta_e}}}{4\mu}\right)\delta'_e$$

$$\left. + \left(C_{x_{\delta_{sp}}} + \frac{C_{x_{\dot{\alpha}}}C_{z_{\delta_{sp}}}}{4\mu}\right)\delta_{sp}\right] \qquad (A4)$$

The terms $C_{z_{\dot{\alpha}}}$ and $C_{z_q}$ given in reference 8 were neglected. Also, $\sin \Theta$ was assumed to equal 0 and $\cos \Theta$ to equal 1 ($\Theta$ is the angle between the horizon and X equilibrium axis).

The primed parameters are perturbations from the equilibrium or trim conditions of the airplane in nondimensional form; that is,

$$\theta' = \theta - \theta_0 \tag{A5}$$

$$\alpha' = \alpha - \alpha_0 = \frac{w - w_0}{u_0} \tag{A6}$$

$$u' = \frac{u - u_0}{u_0} \tag{A7}$$

and where

$$\mu = \frac{m}{\rho S \bar{c}} \tag{A8}$$

$$K_y^2 = \frac{I_Y}{m\bar{c}^2} \tag{A9}$$

The mass and dimensional characteristics of the simulated airplane are presented in tables I and II. Constant coefficients were employed in the linearized longitudinal equations of motion corresponding to an angle of attack of 4°, a forward velocity of 125 knots, and a thrust coefficient of 0.1735.

The linearized longitudinal equations of motion can be written in state vector notation as

$$\dot{\vec{x}} = A\vec{x} + B\vec{u} \tag{A10}$$

where the state vector is

$$\vec{x} = \begin{bmatrix} \theta' \\ \dot{\theta}' \\ \alpha' \\ u' \end{bmatrix} \tag{A11}$$

and the control vector is

$$\vec{u} = \begin{bmatrix} \delta'_{th} \\ \delta'_{e} \\ \delta'_{sp} \end{bmatrix}$$

(A12)

The general control law is given as

$$\vec{u} = -H\vec{x} + G\vec{r}$$

(A13)

where $\vec{r}$ is the vector of commanded pilot inputs $\gamma'_c$, $u'_c$, and $\theta'_c$ that are to be controlled in a decoupled manner. The output equation is

$$\vec{y} = C\vec{x}$$

(A14)

When equation (A13) is substituted into equation (A10), the Laplace transform of the result can be written as

$$\vec{x}(s) = (sI - A + BH)^{-1} BG\vec{r}(s)$$

(A15)

Substituting the Laplace transform of equation (A14) into equation (A15) and requiring that the output $\vec{y}(s)$ be equal to the commanded pilot input $\vec{r}(s)$ under steady-state conditions results in the prefilter gain

$$G = -\left[C(A - BH)^{-1}B\right]^{-1}$$

(A16)

Having obtained the prefilter gain matrix G required for decoupled steady-state control, it is desirable to obtain the control that will reach that condition as efficiently as possible. Consequently, modern control theory was employed to obtain the feedback gain matrix H.

For a given constant-pilot input $\vec{r}$, there is an associated equilibrium state $\vec{x}_e$ that is reached in the steady-state case; that is,

$$0 = (A - BH)\vec{x}_e + BG\vec{r}$$

(A17)

which, since it is zero, can be subtracted from the closed-loop equations of motion,

$$\dot{\hat{x}} = (A - BH)\vec{x} + BG\vec{r} - \left[(A - BH)\vec{x}_e + BG\vec{r}\right] \tag{A18}$$

where $\hat{x}$ is the difference between the instantaneous state $\vec{x}$ and the new equilibrium state $\vec{x}_e$. Equation (A18) is, therefore,

$$\dot{\hat{x}} = (A - BH)\hat{x} \tag{A19}$$

which can be written as

$$\dot{\hat{x}} = A\hat{x} + B\hat{u} \tag{A20}$$

where

$$\hat{u} = -H\hat{x} \tag{A21}$$

which is the difference between the instantaneous control vector $\vec{u}$ and the control input associated with the new equilibrium state. The performance index

$$J = \int_0^\infty \left(\hat{x}^T Q \hat{x} + \hat{u}^T R \hat{u}\right) dt \tag{A22}$$

and equation (A20) constitute the familiar state-regulator problem with quadric performance index for which the optimal control $\hat{u}*$ (ref. 9) is

$$\hat{u}* = -R^{-1}B^T P\hat{x} \tag{A23}$$

where P is the solution to the time invariant matrix Riccati equation

$$PA + A^T P - PBR^{-1}B^T P + Q = 0 \tag{A24}$$

The particular solution for the Riccati equation is based on the iterative approach taken in reference 10.

Equating the general control $\hat{u}$ to the optimal control $\hat{u}*$ permits the solution for the remaining unknown gain matrix

$$H = R^{-1}B^T P \tag{A25}$$

The feedback gain $H$ is optimal for a given set of weighting matrices $Q$ and $R$ in the performance index (eq. (A22)). The off-diagonal terms in these weighting matrices were zero, whereas the diagonal terms were varied as a function of pilot opinion early in the simulation. The final values which were used in this study were

$$Q = \begin{bmatrix} 1.0 & 0 & 0 & 0 \\ 0 & 0.01 & 0 & 0 \\ 0 & 0 & 0.02 & 0 \\ 0 & 0 & 0 & 0.5 \end{bmatrix} \tag{A26}$$

and

$$R = \begin{bmatrix} 0.005 & 0 & 0 & 0 \\ 0 & 0.1 & 0 & 0 \\ 0 & 0 & 0.01 & 0 \\ 0 & 0 & 0 & 0.01 \end{bmatrix} \tag{A27}$$

The resulting prefilter and feedback gain matrices were

$$G = \begin{bmatrix} 3.9304 & 9.6802 & 8.0530 \\ -0.8772 & 1.5967 & -1.8829 \\ -8.0800 & 3.8552 & 11.6078 \end{bmatrix} \tag{A28}$$

and

$$H = \begin{bmatrix} 1.1336 & 16.9936 & 0.0606 & 5.4089 \\ -3.1518 & -31.1558 & 0.6122 & 0.6983 \\ 3.3400 & 42.7517 & 0.8662 & -0.6189 \end{bmatrix} \tag{A29}$$

These matrices were converted to the appropriate dimensions and implemented through the general control law $\vec{u} = -H\vec{x} + G\vec{r}$ using the six-degree-of-freedom nonlinear equations simulating the B-737.

APPENDIX B


STATISTICAL ANALYSIS OF APPROACH AND TOUCHDOWN PERFORMANCE

An analysis of variance (ANOV) (refs. 6 and 11) was performed on each approach performance parameter to determine whether any of the experimental factors (pilots, wind shears, or control systems) or their interactions were statistically significant at the 95-percent confidence (5-percent signifi- cance) level or greater. That is, the analysis was to determine whether the probability of identifying two sample means as being from different popula- tions when they were actually from the same population was less than 5 percent. In this experiment there were two or more levels of each experimental factor. The two levels of controls were VCWS and decoupled controls; the three pilot levels were pilots A, B, and C; and the three wind levels were light, moderate, and severe. The resulting experiment employed 6 replicates for each condition for a total of 108 flights or 107 degrees of freedom. When the ANOV showed a given factor to be significant, further testing was performed to determine at which levels of that factor the means were significantly different. It should be noted that the standard error used in testing the pilot and wind levels included only those data associated with the particular control system being considered rather than data pooled for both control systems. The Student's t-test was used for level testing for winds and controls, and the Duncan mul- tiple range (DMR) test was used to test the pilots' performance. Not only were the differences between the mean values of the approach performance parameters examined, their variability from run to run was also reviewed. Consequently, the results of the homogeneity-of-variance test have been included.

The approach performance was examined in three segments: an early segment of altitudes between 457 m and 228 m; an intermediate segment at altitudes between 76 m and 31 m; and a final segment at altitudes between 31 m and 15 m.


Initial Approach Segment

The ANOV (table VIII) for the initial segment, between altitudes of 457 m and 228 m, showed that the type of control was statistically signficant at the 95-percent confidence level or better for flight-path angle error, glide-slope error, and error in indicated airspeed. Wind conditions were a statistically significant factor at the 95-percent confidence level or better for flight-path angle error and glide-slope error in the longitudinal mode and localizer error and control wheel activity in the lateral mode. The effect of pilots was a sta- tistically significant factor only for control wheel activity and error in indi- cated airspeed. Interaction effects were statistically significant only for control column activity where controls and pilots interacted and flight-path angle error where controls and winds interacted. In the lateral mode, the con- trol wheel activity showed significant interactions between pilots and winds.

The results of level testing for the initial approach segment are pre- sented in tables IX and X, along with the mean and standard deviation, for VCWS and decoupled controls, respectively. When the t-test was applied to winds, the light shear condition was the reference against which the other winds were

tested, as is indicated in tables IX and X. In addition, the VCWS system was chosen as the reference (table IX) when the t-test was applied to controls. The Duncan multiple range (DMR) test was used to measure each pilot's performance in relation to the others. For example, error in indicated airspeed with VCWS controls (table IX) had a significant pilot effect in moderate wind shears. The DMR test indicated that the errors of pilot A were significantly larger, at the 95-percent confidence level, than those of either pilot B or C. Furthermore, the difference between the performances of pilot B and pilot C was not statistically significant. The six approach performance parameters are discussed in detail in the following paragraphs.

Flight-path angle error.- The VCWS system (table IX) produced closer adherence to the desired $3^O$ flight-path angle in five of nine possible pilot and wind combinations. However, in only one of nine cases was the difference in means statistically significant: with pilot A in severe winds. In addition, the standard deviation about the mean was significantly less with the VCWS system only for pilot A in severe winds and also for pilot A in light winds. Thus, there do not appear to be any difference between control system mean performance whose statistical significance was suppressed because of large deviations. Flight-path angle performance with the decoupled control system (table X) degraded as wind severity increased, but the degradation was significant only for one case: pilot A in severe winds. However, the standard deviations of pilots B and C were both significantly larger in severe winds (table X) than in light winds, and the statistical significance of the difference in means due to winds for both pilots may have been suppressed. With the VCWS system (table IX), the flight-path angle error was actually greater in light shears than in the higher shears. The difference was significant at the 95-percent level or better for pilot A. Although the differences in means due to winds and control systems were significant only for pilot A, the effects were not general enough for pilots to be a significant factor as indicated by the ANOV (see table VIII).

Glide-slope error.- Glide-slope error showed a significant effect of controls on mean performance only for pilot B in severe winds (table X), where the error with the decoupled control system was larger than that with the VCWS system. In addition, differences in the standard deviation, although significantly larger with decoupled controls in four of nine cases, do not appear to have suppressed the significance of any differences in the means. Winds did degrade performance and the degradation was statistically significant for two of three pilots in severe winds for both control systems. (See tables IX and X.) Pilots were not a statistically significant factor (table VIII) as far as the difference in means was concerned; however, pilot C had standard deviations or variances that were significantly larger, at the 99-percent confidence level, in all three wind conditions when the VCWS system was used.

Localizer error.- The localizer error was essentially statistically unaffected by pilots, winds, or controls. There was a wind shear effect, but it was statistically significant only when pilot A used decoupled controls in moderate wind shear.

Error in indicated airspeed.- Decoupled controls gave smaller mean errors in indicated airspeed than did the VCWS system in seven of nine possible pilot

and wind combinations (compare tables IX and X). However, the differences were significant at the 95-percent confidence level only when pilot C made significantly larger errors in both light and severe wind shears. However, two of three pilots had deviations from the mean that were significantly larger at the 99-percent confidence level when the VCWS system was used in all three wind conditions. In the case of pilot A, the large deviations appear to have suppressed the significance of the difference in means in both moderate and severe winds. As far as mean performance was concerned, winds were not statistically significant (table VIII). In addition, pilots were a significant factor only because pilot A made larger errors than the other pilots with the VCWS system in moderate winds (table IX). Also, pilot C had significantly smaller standard deviations than pilots A or B in all winds when the VCWS system was used.

Control wheel activity.- Control wheel inputs showed no statistically significant effects (table VIII) of the type of control system being used in the longitudinal mode. Larger control inputs were used with either control system (tables IX and X) as the wind severity increased, but the difference in means was statistically significant for one of three pilots in each case. The effect of pilots was statistically significant because pilot B made larger inputs than either pilot A or pilot C in moderate and severe wind shears with either control system.

Control column activity.- Control column activity showed no statistically significant effects of controls, winds, or pilots as far as the means were concerned. However, the variances about the mean were significantly smaller when the VCWS system was used (table X) in seven of nine cases.


Intermediate Approach Segment

The ANOV (table XI) for the intermediate segment, between altitudes of approximately 76 m and 31 m showed that the type of controls used was statistically significant at the 95-percent confidence level or better for localizer error and indicated airspeed error. Winds were a significant factor at the 99-percent confidence level for all of the approach parameters except control column activity, while none of the parameters except control wheel activity showed statistically significant effects of pilots. In addition, none of the interaction effects were statistically significant. The results of level testing of each approach performance parameter are discussed in the following paragraphs.

Flight-path angle error.- The type of controls did not have a statistically significant effect (table XI) on flight-path angle error nor did pilots. Winds were a statistically significant factor, but the difference in means was only significant for one of three pilots (tables XII and XIII) when either control system was used. However, the deviations about the mean were significantly larger at the 99-percent level in severe winds with either control system than in light winds in five of six possible cases. Consequently, the significance of the difference in means was apparently suppressed in severe winds for pilots B

and C when the VCWS system (table XII) was used and for pilot C when the decoupled controls (table XIII) were used. Pilots were not a statistically significant factor.

Glide-slope error.- Glide-slope error did not show a statistically significant effect (table XI) of either controls or pilots. The effect of winds was to degrade performance when either control system was used. When the VCWS system was used (table XII), the degradation was statistically significant at the 95-percent confidence level for all three pilots in severe shear and for one of three pilots in moderate shears. When the decoupled control system was used (table XIII), the degradation was statistically significant for two of three pilots in severe shears. In addition, the degradation of four of six deviations about the mean was statistically significant for either control system in moderate and severe shears.

Localizer error.- Localizer error was reduced when decoupled controls were used in eight of nine combinations of pilot and wind. However, the reduction was statistically significant at the 95-percent confidence level only in the case of pilot C in light winds. The standard deviation about the mean was significantly smaller, however, with the decoupled control system at the 95-percent level in four of nine cases. The mean degradation due to wind shear was statistically significant in only 3 of 12 possible combinations of pilot and control. As indicated by the ANOV (table XI), pilot was not a significant factor.

Error in indicated airspeed.- The error in indicated airspeed was less when decoupled controls were used for all pilots and all wind shears than was the case with the VCWS system. The improvement was statistically significant at the 95-percent confidence level or better (table XIII) for five out of nine pilot and wind combinations. However, two more cases, pilot A in light and moderate shears, probably had the significance of the difference in mean performance suppressed because the standard deviations with the VCWS system were so large (see table XII). In fact, the standard deviations were larger when the VCWS system was used in eight of nine pilot and wind combinations and were significantly larger at the 99-percent confidence level in five of those cases. The degradation due to wind shear was statistically significant for all three pilots in severe winds regardless of the control system used. The use of decoupled controls (table XIII) actually resulted in a statistically significant improvement in performance for two of three pilots in moderate winds when compared with their performance on light winds. There were no statistically significant effects of pilots on indicated airspeed.

Control wheel activity.- The effect of type of control on control wheel inputs was not statistically significant. The wind effect was significant only when the VCWS system was used in severe winds. Pilot effects were statistically significant because pilot B made consistently larger inputs than either pilot A or pilot C regardless of control system or wind condition.

Control column activity.- Control column inputs were essentially unaffected statistically by pilots, winds, or controls. There was a pilot effect, but it

was statistically significant only when pilot B made larger inputs than pilots A or C in severe wind shear using decoupled controls. He also made larger inputs than pilot C in moderate winds.


Final Approach Segment

The ANOV (table XIV) for the final segment, at altitudes between 31 m and 15 m, showed that the type of control was statistically significant at the 95-percent confidence level or better only for the error in indicated airspeed. Winds were statistically significant for all performance parameters except control wheel activity. Pilots were a statistically significant factor for only one longitudinal performance parameter, control column activity, but were significant for both lateral performance parameters. The pilot-control interaction effects were not statistically significant, and the control-wind interactions were significant only for flight-path angle error. Pilot-wind interaction effects were statistically significant for both wheel and column inputs and also for glide-slope error. The results of level testing are discussed separately in the following paragraphs.

Flight-path angle error.- Although the ANOV (table XIV) indicated that there was no significant difference of controls on the mean error in flight-path angle, the standard deviations about the mean were larger with the VCWS system for all three pilots in severe wind shear and the difference in control systems was statistically significant at the 99-percent confidence level (tables XV and XVI) for pilots B and C. However, pilot A had significantly larger standard deviations with the decoupled control system in light and moderate shears. Increasing wind severity degraded performance with either control system, but the degradation was statistically significant in only one case: use of the VCWS system in severe winds by pilot A. However, the degradation in the standard deviation due to winds was statistically significant (table XV) in four of six possible cases when the VCWS system was used, but was not significant (table XVI) when decoupled controls were used. Pilots were not a statistically significant factor.

Glide-slope error.- The ANOV (table XIV) indicated that there was no significant difference of the mean glide-slope error due to controls. Although the standard deviation about the mean was significantly different (table XVI) in four of nine cases, the difference was not consistent in that the standard deviation was smaller with the VCWS system in two of those cases but was smaller with the decoupled control system in the other two cases. The degradation of the mean errors due to wind shear was statistically significant in three of six cases with either the VCWS system (table XV) or the decoupled control (table XVI) system. In addition, the standard deviation about the mean showed a significant degradation due to winds in five of six cases (table XV) with the VCWS system and in two of six cases (table XVI) with the decoupled control system. These large standard deviations probably suppressed the statistical significance of the difference in means of three additional cases: pilot B in severe wind shear with both control systems and pilot C in moderate wind shear with the VCWS system. Pilots were not a statistically significant factor.

Localizer error.- There was no statistically significant effect of control system on the mean localizer error. However, the standard deviation about the mean was larger with the VCWS system in three of four cases where the difference was statistically significant at the 99-percent confidence level. Winds were a statistically significant factor, and degraded performance in two of six cases with either control system. Pilots were also a statistically significant factor, but the effects were not consistent. When the decoupled controls were used (table XVI), pilot A made larger errors than pilot C in light winds, smaller errors than pilot C in moderate winds, and larger errors than pilot B in severe winds, while pilot B made smaller errors than pilot A or pilot C in moderate winds (table XV) when the VCWS system was used.

Error in indicated airspeed.- The mean error in indicated airspeed was smaller with the decoupled control system for all pilots and at all wind conditions, but the difference was statistically significant (table XVI) in only four of nine cases. However, the statistical significance was generally suppressed by the large standard deviations that occurred with the VCWS system. The degradation that occurred with the VCWS system was statistically significant at the 95-percent confidence level in eight of nine cases. Winds degraded performance with either control system and the degradation was statistically significant (table XVI) in severe winds when decoupled controls were used. The degradation in mean performance in severe winds would have been significant with the VCWS system also had not the standard deviations been so large in severe winds (see table XV). Pilots were not a statistically significant factor.

Control wheel activity.- There was no statistically significant effect of either controls or winds on control wheel activity. Pilot effects were statistically significant but occurred because pilot B made larger wheel inputs than either pilots A or pilot C in five of six combinations of winds and controls (see tables XV and XVI).

Control column activity.- Although the mean column input with the decoupled control system was smaller than mean column input with the VCWS system in seven of nine cases (see tables XV and XVI), the differences were not large enough for controls to be a statistically significant factor. Increasing winds required larger column inputs with either control system, but the increase was statistically significant only when the VCWS system was used and then only for two of six cases. Pilot effects were statistically significant, but only because pilot B made larger inputs than pilot A in severe winds using the VCWS system.

## Touchdown Performance

The ANOV (table XVII) for the touchdown performance parameters showed that the type of control was statistically significant at the 95-percent confidence level or better for sink rate $\dot{h}$ and pitch angle $\theta$. Wind condition was a statistically significant factor for the range from threshold $R_a$, indicated airspeed IAS, and pitch angle. The effect of pilots was statistically significant only for indicated airspeed. Pilot and control interactions were not statistically significant for any of the approach performance parameters. Control and wind interactions were statistically signficiant for indicated airspeed and

pitch angle, while pilots and winds did not interact at a significant level for any of the approach parameters. The results of level testing are discussed in the following paragraphs.

Sink rate.- The sink rate at touchdown was smaller (table XIX) when decoupled controls were used than when the VCWS system (table XVIII) was used for all pilots and at all wind conditions. The ANOV (table XVII) showed a significant control effect for sink rate. The level testing using the Student's t-test, however, failed to detect a statistically significant difference. The reason for this was that the standard error used in the ANOV was based on all the data, while the standard error used in the t-test was based on only the data for the particular pilot-wind combination for which the comparison between controls was being made. Consequently, the statistical significance of the difference in mean performance between the two control systems with pilot B in severe winds was suppressed by the large standard deviation that occurred with the VCWS system. In fact, the standard deviation with the VCWS system was larger for all pilot-wind combinations than was the case with the decoupled system, and the difference was statistically significant (table XIX) in five of nine cases. Neither winds nor pilots had statistically significant effects on sink rate.

Range from threshold.- There was no statistically significant effect of controls on the mean range from threshold. The standard deviation about the mean was significantly smaller with decoupled controls in severe wind shear (table XIX) in two of three cases but significantly larger in one of three cases in moderate wind shear than with the VCWS system. Winds degraded performance with either control system but the degradation was statistically significant in only 3 of 12 cases. Pilots were not a statistically significant factor.

Indicated airspeed.- There was no statistically significant effect of controls on the mean indicated airspeed. However, the standard deviation about the mean was larger with the VCWS system in seven of nine cases (and was significantly larger in six of those cases) than when the decoupled control system was used (compare tables XVIII and XIX). Winds degraded mean performance, and the degradation was statistically significant in 3 of 12 cases: pilot A in severe winds with the decoupled controls and pilots B and C in severe winds with the VCWS system. Pilots were a statistically significant factor primarily because pilot A landed with higher speeds than either pilot B or pilot C when the VCWS system (table XVIII) was used.

Pitch angle.- The type of control used had a statistically significant effect on the mean pitch angle (table XIX) in seven of nine cases. In moderate and severe wind shear, the mean pitch angle with the VCWS system was actually negative. In addition, the standard deviation about the mean was significantly larger with the VCWS system in seven of nine cases. Winds were a statistically significant factor, but the difference due to winds was significant only in two of six cases with the decoupled control system and one of six cases with the VCWS system. Pilots were not a statistically significant factor.

Lateral displacement.- The lateral displacement from the runway center line showed no statistically significant effect of controls, winds, or pilots.

Bank angle.- The bank angle at touchdown showed no statistically significant effect of controls, winds, or pilots.

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## TABLE I.- B-737 AIRPLANE DIMENSION AND DESIGN DATA

General:
Overall length, m . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 28.65
Height to top of vertical fin, m . . . . . . . . . . . . . . . . . . . . . . 11.28

Wing:
Area, $m^2$ . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 91.04
Span, m . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 28.35
Mean aerodynamic chord, m . . . . . . . . . . . . . . . . . . . . . . . . . 3.41
Incidence angle, deg . . . . . . . . . . . . . . . . . . . . . . . . . . . . 1
Aspect ratio . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 8.83
Taper ratio . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 0.279
Dihedral, deg . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 6
Sweep (quarter-chord), deg . . . . . . . . . . . . . . . . . . . . . . . . . 25
Flap deflection (maximum), deg . . . . . . . . . . . . . . . . . . . . . . . 40
Aileron deflection (maximum), deg . . . . . . . . . . . . . . . . . . . . . ±20

Spoilers deflection (maximum):
Inboard ground spoilers (maximum), deg . . . . . . . . . . . . . . . . . . . 60
All other spoilers (maximum), deg . . . . . . . . . . . . . . . . . . . . . 40

Horizontal tail:
Total area, $m^2$ . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 28.99
Span, m . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 10.97
Stabilizer deflection (maximum), deg . . . . . . . . . . . . . . . . . . . . -14, +3
Elevator deflection (maximum), deg . . . . . . . . . . . . . . . . . . . . . ±21

Vertical tail:
Total area, $m^2$ . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 20.8
Rudder deflection, deg . . . . . . . . . . . . . . . . . . . . . . . . . . . ±24

Weight:
Maximum take-off gross weight, kN . . . . . . . . . . . . . . . . . . . . . 431
Design landing weight, kN . . . . . . . . . . . . . . . . . . . . . . . . . 399
Operational empty weight, kN . . . . . . . . . . . . . . . . . . . . . . . . 297

Propulsion system (two Pratt & Whitney JT8D-9 engines):
Maximum uninstalled thrust per engine at sea level static, kN . . . 62.3
Effective engine moment arms about center of gravity:
Lateral arm, m . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 4.94
Vertical arm, m . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 1.52

TABLE II.- INITIAL CONDITIONS FOR SIMULATION

Weight, kN . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 408

Moments of inertia:
  $I_X$, kg-m$^2$ . . . . . . . . . . . . . . . . . . . . . . . . . . . 602 000
  $I_Y$, kg-m$^2$ . . . . . . . . . . . . . . . . . . . . . . . . . 1 090 000
  $I_Z$, kg-m$^2$ . . . . . . . . . . . . . . . . . . . . . . . . . 1 780 000
  $I_{XZ}$, kg-m$^2$ . . . . . . . . . . . . . . . . . . . . . . . . . . 71 600

Center of gravity, percent of mean aerodynamic chord . . . . . . . . . . 30

Altitude, m . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 457

Field elevation, m . . . . . . . . . . . . . . . . . . . . . . . . . . . 2

Indicated airspeed, knots . . . . . . . . . . . . . . . . . . . . . . 130

Flight-path angle, deg . . . . . . . . . . . . . . . . . . . . . . . . . 0

Trailing-edge flap position, deg . . . . . . . . . . . . . . . . . . . . 40

Flight spoiler initial position (decoupled controls), deg . . . . . . . . 9

Landing-gear position . . . . . . . . . . . . . . . . . . . . . . . . Down

# TABLE III.- TURBULENCE SPECIFICATIONS FOR LIGHT WIND SHEARS

## (a) Wind shear B2

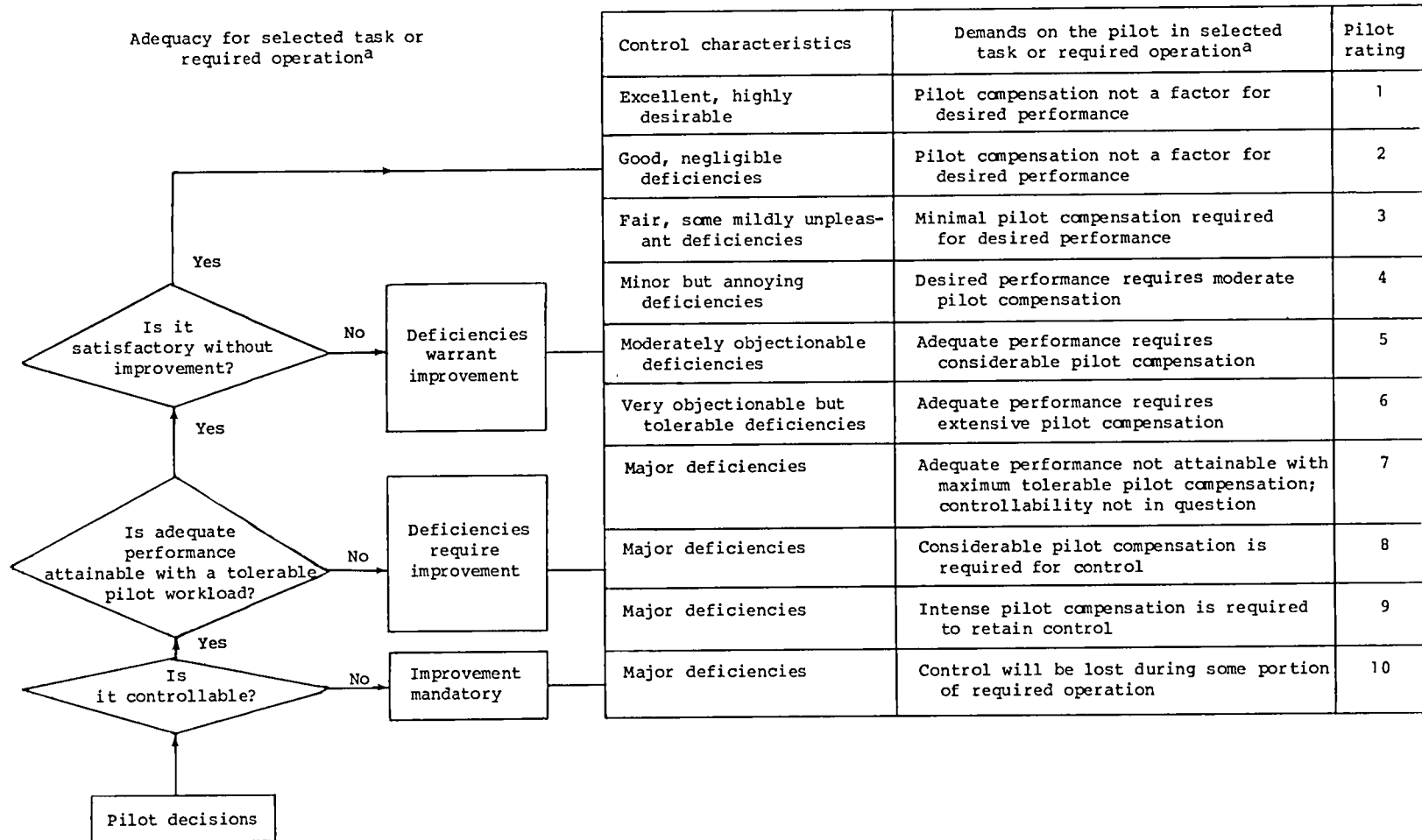| Altitude, m | rms longitudinal velocity, knots | rms lateral velocity, knots | rms vertical velocity, knots | Longitudinal scale length, m | Lateral scale length, m | Vertical scale length, m |
|---|---|---|---|---|---|---|
| 6.10 | 0.65 | 0.65 | 0.09 | 32.22 | 15.15 | 3.17 |
| 22.86 | 1.63 | 1.63 | .15 | 55.47 | 32.89 | 12.10 |
| 45.72 | 3.61 | 3.61 | .25 | 79.74 | 53.00 | 24.23 |
| 91.44 | 4.76 | 4.76 | .31 | 112.78 | 84.28 | 48.46 |
| 137.16 | .50 | .50 | .09 | 139.57 | 111.59 | 72.69 |
| 182.88 | .25 | .25 | .06 | 161.82 | 135.82 | 96.93 |
| 228.60 | .00 | .00 | .00 | 161.82 | 135.82 | 96.93 |
| 457.20 | .00 | .00 | .00 | 161.82 | 135.82 | 96.93 |

## (b) Wind shear B3

| Altitude, m | rms longitudinal velocity, knots | rms lateral velocity, knots | rms vertical velocity, knots | Longitudinal scale length, m | Lateral scale length, m | Vertical scale length, m |
|---|---|---|---|---|---|---|
| 6.10 | 0.65 | 0.65 | 0.09 | 79.49 | 79.49 | 1.52 |
| 22.86 | 1.63 | 1.63 | .15 | 674.85 | 674.85 | 5.72 |
| 45.72 | 3.61 | 3.61 | .25 | 2383.31 | 2383.31 | 11.43 |
| 91.44 | 4.76 | 4.76 | .31 | 5389.73 | 5389.73 | 22.86 |
| 137.16 | .50 | .50 | .09 | 1058.33 | 1058.33 | 34.29 |
| 182.88 | .25 | .25 | .06 | 793.75 | 793.75 | 45.72 |
| 228.60 | .00 | .00 | .00 | 793.75 | 793.75 | 45.72 |
| 457.20 | .00 | .00 | .00 | 793.75 | 793.75 | 45.72 |

TABLE IV.- TURBULENCE SPECIFICATIONS FOR WIND SHEARS B7, D3, and D10

| Altitude, m | rms longitudinal velocity, knots | rms lateral velocity, knots | rms vertical velocity, knots | Longitudinal scale length, m | Lateral scale length, m | Vertical scale length, m |
|---|---|---|---|---|---|---|
| 6.10 | 3.40 | 2.70 | 2.34 | 32.23 | 15.15 | 3.17 |
| 30.49 | 4.05 | 3.46 | 3.53 | 66.07 | 40.91 | 16.16 |
| 60.98 | 4.43 | 3.95 | 4.35 | 93.45 | 65.09 | 32.32 |
| 121.95 | 4.85 | 4.50 | 5.36 | 132.16 | 103.54 | 64.63 |
| 182.93 | 5.11 | 4.86 | 6.05 | 161.86 | 135.85 | 96.95 |
| 457.32 | 5.74 | 5.78 | 7.94 | 256.37 | 251.37 | 242.47 |

TABLE V.- PILOT RATING SYSTEM

Adequacy for selected task or
required operation[a]

| Control characteristics | Demands on the pilot in selected task or required operation[a] | Pilot rating |
|---|---|---|
| Excellent, highly desirable | Pilot compensation not a factor for desired performance | 1 |
| Good, negligible deficiencies | Pilot compensation not a factor for desired performance | 2 |
| Fair, some mildly unpleasant deficiencies | Minimal pilot compensation required for desired performance | 3 |
| Minor but annoying deficiencies | Desired performance requires moderate pilot compensation | 4 |
| Moderately objectionable deficiencies | Adequate performance requires considerable pilot compensation | 5 |
| Very objectionable but tolerable deficiencies | Adequate performance requires extensive pilot compensation | 6 |
| Major deficiencies | Adequate performance not attainable with maximum tolerable pilot compensation; controllability not in question | 7 |
| Major deficiencies | Considerable pilot compensation is required for control | 8 |
| Major deficiencies | Intense pilot compensation is required to retain control | 9 |
| Major deficiencies | Control will be lost during some portion of required operation | 10 |

Flowchart (left side):

Yes

Is it satisfactory without improvement? — No → Deficiencies warrant improvement

Yes

Is adequate performance attainable with a tolerable pilot workload? — No → Deficiencies require improvement

Yes

Is it controllable? — No → Improvement mandatory

Pilot decisions

[a]Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions.

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TABLE VI.- PILOT RATINGS

| Wind shear | Rating for control system – | | | | | |
| | VCWS | | | Decoupled controls | | |
| | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C |
|---|---|---|---|---|---|---|
| Light | 2 | 3 | 2 → 3 | 2 | 3 | 2 → 3 |
| Moderate | 3 → 4 | 4 | 4 → 8 | 3 → 4 | 3 | 4 → 5 |
| Severe | [a]5 → 6 [c]9 → 10 | [b]7 → 8 | [b]9 → 10 | [b]4 → 5 | [b]6 | [b]6 |

[a]Wind shear D3.
[b]Pilots did not differentiate between winds D3 and D10.
[c]Wind shear D10.


TABLE VII.- CONTROL SYSTEM PERFORMANCE IN SEVERE WIND PROFILE D10

| Pilot | Time that $\theta > 15°$, sec | | Time that $V < V_{min}$, sec | |
| | VCWS | DC | VCWS | DC |
|---|---|---|---|---|
| A | 7 | 0 | 17 | 0 |
| A | 5 | 0 | 13 | 0 |
| A | 10 | 0 | 16 | 0 |
| B | 2 | 0 | 4 | 0 |
| B | 8 | 0 | 5 | 0 |
| B | 3 | 0 | 7 | 0 |
| C | 18 | 0 | 21 | 0 |
| C | 6 | 0 | 15 | 0 |
| C | 0 | 0 | 7 | 0 |
| Mean | 6.3 | 0 | 11.7 | 0 |
| Standard deviation | 5.3 | 0 | 6.1 | 0 |

TABLE VIII.- ANALYSIS OF VARIANCE FOR rms APPROACH PARAMETERS WITH

PILOTS, CONTROLS, AND WINDS AS EXPERIMENTAL FACTORS

[Between altitudes of 457.2 m and 228.0 m]

| Experimental factor | $\Delta\gamma$ | | GSE | | ELOC | | $\Delta$IAS | | $\delta_{wheel}$ | | $\delta_{col}$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | d.o.f. | F | d.o.f. | F | d.o.f. | F | d.o.f. | F | d.o.f. | F | d.o.f. | F |
| Pilot | 2 | 0.80 | 2 | 2.66 | 2 | 0.25 | 2 | [a]3.62 | 2 | [b]34.40 | 2 | 1.83 |
| Wind | 2 | [a]4.90 | 2 | [b]17.48 | 2 | [b]11.87 | 2 | 1.04 | 2 | [b]13.17 | 2 | 2.33 |
| Control | 1 | [a]6.20 | 1 | [a]6.22 | 1 | 2.16 | 1 | [a]6.09 | 1 | .02 | 1 | 1.33 |
| Pilot-control interaction | 2 | .30 | 2 | 1.03 | 2 | .75 | 2 | 3.07 | 2 | 1.13 | 2 | [b]6.17 |
| Control-wind interaction | 2 | [b]10.80 | 2 | 2.44 | 2 | .45 | 2 | .99 | 2 | .47 | 2 | 1.17 |
| Pilot-wind interaction | 4 | .95 | 4 | .55 | 4 | .48 | 4 | .55 | 4 | [b]4.38 | 4 | .33 |
| Pilot-control-wind interaction | 4 | .60 | 4 | .26 | 4 | .05 | 4 | .86 | 4 | .36 | 4 | .33 |
| Error | 90 | ---- | 90 | ----- | 90 | ----- | 90 | ---- | 90 | ----- | 90 | ---- |

[a]Statistical significance at the 5-percent level ($F_{critical}$ = 3.96, 3.11, and 2.49 for 1, 2, and 4 d.o.f., respectively).

[b]Statistical significance at the 1-percent level ($F_{critical}$ = 6.97, 4.89, and 3.56 for 1, 2, and 4 d.o.f., respectively).

TABLE IX.- rms APPROACH DATA FOR VCWS CONTROLS

[Between altitudes of 457.2 m and 228.0 m]

| Experimental factor | Statistical parameter | Light shears | | | Moderate shears | | | Severe shears | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C |
| $\Delta Y$, deg | Mean | 0.39 | 0.25 | 0.36 | 0.19 | 0.15 | 0.22 | 0.13 | 0.16 | 0.31 |
| | Standard deviation | 0.05 | 0.10 | 0.10 | [d]0.18 | 0.14 | 0.14 | [c]0.05 | [c]0.10 | [d]0.35 |
| | t (controls) | Reference | Reference | Reference | Reference | Reference | Reference | Reference | Reference | Reference |
| | t (winds) | Reference | Reference | Reference | [a]2.75 | 2.00 | 0.85 | [b]8.67 | 1.29 | 0.26 |
| | DMR (pilots) | Not statistically significant (ANOV) | | | | | | | | |
| GSE, m | Mean | 14.99 | 9.83 | 21.07 | 11.56 | 11.41 | 18.26 | 22.23 | 19.91 | 27.33 |
| | Standard deviation | 2.96 | 2.26 | [c]8.27 | 2.92 | 2.25 | [c]9.12 | 4.24 | [d]7.37 | [c]14.51 |
| | t (controls) | Reference | Reference | Reference | Reference | Reference | Reference | Reference | Reference | Reference |
| | t (winds) | Reference | Reference | Reference | 2.02 | 1.22 | 0.56 | [b]3.43 | [b]3.20 | 0.92 |
| | DMR (pilots) | Not statistically significant (ANOV) | | | | | | | | |
| ELOC, m | Mean | 20.95 | 26.47 | 50.19 | 53.00 | 56.39 | 60.70 | 18.13 | 16.79 | 17.35 |
| | Standard deviation | 21.07 | 29.37 | [c]74.93 | 37.11 | 43.80 | 34.66 | 14.63 | [d]12.65 | [d]15.13 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Reference | Reference | Reference | 1.84 | 1.39 | 0.31 | 0.27 | 0.74 | 1.05 |
| | DMR (pilots) | Not statistically significant (ANOV) | | | | | | | | |

[a]Statistical significance at the 5-percent level.
[b]Statistical significance at the 1-percent level.
[c]Variances for the pilots differ at the 1-percent level of significance.
[d]Variances for the winds differ at the 1-percent level of significance.

TABLE IX.- Concluded

| Experimental factor | Statistical parameter | Light shears | | | Moderate shears | | | Severe shears | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C |
| $\Delta$ IAS, knots | Mean | 2.16 | 3.25 | 0.63 | 4.99 | 1.70 | 0.78 | 4.01 | 2.75 | 1.23 |
| | Standard deviation | 3.18 | 3.43 | [c]0.06 | 5.74 | 3.03 | [c,d]0.57 | 5.79 | 3.03 | [c,d]0.87 |
| | t (controls) | Reference | Reference | Reference | Reference | Reference | Reference | Reference | Reference | Reference |
| | t (winds) | Not statistically significant (ANOV) | | | | | | | | |
| | DMR (pilots) | (B-A), (A-C), (B-C) | | | [a](A-B), (B-C), [a](A-C) | | | (A-B), (B-C), (A-C) | | |
| $\delta_{wheel}$, deg | Mean | 2.01 | 3.92 | 2.62 | 3.18 | 6.49 | 5.06 | 1.96 | 8.09 | 4.00 |
| | Standard deviation | 2.10 | 1.19 | 1.30 | [c]0.67 | 2.67 | 1.24 | 1.90 | [c,d]0.34 | 2.17 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Reference | Reference | Reference | 1.30 | 2.16 | [b]3.34 | 0.04 | [b]8.18 | 1.03 |
| | DMR (pilots) | (B-C), (C-A), (B-A) | | | (B-C), (C-A), [b](B-A) | | | [b](B-C), (C-A), [b](B-A) | | |
| $\delta_{col}$, percent | Mean | 3.33 | 3.33 | 4.33 | 2.67 | 6.00 | 5.33 | 4.00 | 4.67 | 6.33 |
| | Standard deviation | 0.33 | 0.33 | 1.00 | [d]1.67 | [d]2.67 | [d]3.33 | [c]0.67 | [d]2.00 | [d]4.33 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Not statistically significant (ANOV) | | | | | | | | |
| | DMR (pilots) | Not statistically significant (ANOV) | | | | | | | | |

[a]Statistical significance at the 5-percent level.
[b]Statistical significance at the 1-percent level.
[c]Variances for the pilots differ at the 1-percent level of significance.
[d]Variances for the winds differ at the 1-percent level of significance.

TABLE X.- rms APPROACH DATA FOR DECOUPLED CONTROLS

[Between altitudes of 457.2 m and 228.0 m]

| Experimental factor | Statistical parameter | Light shears | | | Moderate shears | | | Severe shears | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C |
| $\Delta\gamma$, deg | Mean | 0.29 | 0.20 | 0.12 | 0.19 | 0.30 | 0.33 | 0.60 | 0.47 | 0.56 |
| | Standard deviation | [e]0.20 | 0.10 | 0.07 | 0.14 | 0.14 | [d]0.28 | [e]0.24 | [d]0.31 | [d]0.50 |
| | t (controls) | 2.17 | 0.83 | 2.18 | 0.92 | 0.43 | 0.50 | [b]4.70 | 1.11 | 1.07 |
| | t (winds) | Reference | Reference | Reference | 0.17 | 0.54 | 1.40 | [a]2.89 | 0.89 | 2.04 |
| | DMR (pilots) | Not statistically significant (ANOV) | | | | | | | | |
| GSE, m | Mean | 18.05 | 9.95 | 14.94 | 19.73 | 19.16 | 21.05 | 28.89 | 34.08 | 33.59 |
| | Standard deviation | [e]11.77 | [c]1.73 | 8.00 | [d,e]8.86 | [d,e]14.19 | 16.90 | [e]11.00 | [d]12.36 | 15.37 |
| | t (controls) | 0.62 | 0.10 | 1.30 | 2.14 | 1.26 | 0.36 | 1.38 | [a]2.41 | 0.73 |
| | t (winds) | Reference | Reference | Reference | 0.28 | 1.50 | 0.80 | 1.65 | [b]4.73 | [a]2.64 |
| | DMR (pilots) | Not statistically significant (ANOV) | | | | | | | | |
| ELOC, m | Mean | 16.35 | 15.21 | 21.81 | 56.34 | 43.00 | 38.54 | 18.78 | 15.43 | 14.68 |
| | Standard deviation | 13.41 | 14.43 | [e]23.78 | 39.86 | 43.78 | 24.79 | 15.38 | 7.22 | 15.03 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Reference | Reference | Reference | [a]2.33 | 1.48 | 1.19 | 0.29 | 0.03 | 0.62 |
| | DMR (pilots) | Not statistically significant (ANOV) | | | | | | | | |

[a]Statistical significance at the 5-percent level.
[b]Statistical significance at the 1-percent level.
[c]Variances for the pilots differ at the 1-percent level of significance.
[d]Variances for the winds differ at the 1-percent level of significance.
[e]Variances for the controls differ at the 5-percent level of significance.

TABLE X.- Concluded

| Experimental factor | Statistical parameter | Light shears | | | Moderate shears | | | Severe shears | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C |
| ΔIAS, knots | Mean | 1.88 | 1.13 | 1.27 | 0.63 | 0.49 | 0.34 | 1.70 | 1.82 | 2.13 |
| | Standard deviation | [c]1.60 | [e]0.04 | [c,e]0.30 | [d,e]0.32 | [d,e]0.34 | 0.53 | [e]0.89 | [d,e]0.34 | 0.40 |
| | t (controls) | 0.19 | 1.21 | [b]4.92 | 1.86 | 0.11 | 1.38 | 0.90 | 0.24 | [a]2.31 |
| | t (winds) | Not statistically significant (ANOV) | | | | | | | | |
| | DMR (pilots) | (A-C), (C-B), (A-B) | | | (A-B), (B-C), (A-C) | | | (C-A), (A-B), (C-B) | | |
| δ$_{wheel}$, deg | Mean | 2.09 | 3.33 | 2.00 | 3.37 | 8.35 | 4.54 | 1.98 | 8.70 | 2.49 |
| | Standard deviation | 1.36 | 1.63 | 2.03 | 1.03 | [c]5.03 | 0.73 | 1.97 | [e]3.57 | 2.49 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Reference | Reference | Reference | 1.83 | [a]2.32 | 1.38 | 0.11 | [b]3.36 | 0.37 |
| | DMR (pilots) | (B-A), (A-C), (B-C) | | | [a](B-C), (C-A), [b](B-A) | | | [b](B-C), (C-A), [b](B-A) | | |
| δ$_{col}$, percent | Mean | 7.00 | 4.00 | 3.67 | 8.00 | 3.33 | 0.00 | 13.67 | 8.33 | 3.00 |
| | Standard deviation | [e]8.00 | [e]3.33 | [e]7.33 | [e]6.00 | 5.33 | [c,d,e]0.00 | [e]9.00 | [d,e]14.00 | 6.33 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Not statistically significant (ANOV) | | | | | | | | |
| | DMR (pilots) | Not statistically significant (ANOV) | | | | | | | | |

[a]Statistical significance at the 5-percent level.
[b]Statistical significance at the 1-percent level.
[c]Variances for the pilots differ at the 1-percent level of significance.
[d]Variances for the winds differ at the 1-percent level of significance.
[e]Variances for the controls differ at the 5-percent level of significance.

TABLE XI.- ANALYSIS OF VARIANCE FOR rms APPROACH PARAMETERS WITH

PILOTS, CONTROLS, AND WINDS AS EXPERIMENTAL FACTORS

[Between altitudes of 76.2 m and 30.5 m]

| Experimental factor | $\Delta\gamma$ | | GSE | | ELOC | | $\Delta$IAS | | $\delta_{wheel}$ | | $\delta_{col}$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | d.o.f. | F | d.o.f. | F | d.o.f. | F | d.o.f. | F | d.o.f. | F | d.o.f. | F |
| Pilot | 2 | 0.91 | 2 | 0.13 | 2 | 2.70 | 2 | 1.97 | 2 | [b]50.86 | 2 | [b]5.70 |
| Wind | 2 | [b]9.40 | 2 | [b]25.90 | 2 | [b]6.00 | 2 | [b]24.77 | 2 | [b]7.03 | 2 | 1.29 |
| Control | 1 | .45 | 1 | .44 | 1 | [a]6.86 | 1 | [b]23.06 | 1 | .05 | 1 | .60 |
| Pilot-control interaction | 2 | .62 | 2 | .03 | 2 | 1.82 | 2 | 2.00 | 2 | 2.31 | 2 | 1.40 |
| Control-wind interaction | 2 | .02 | 2 | .12 | 2 | .59 | 2 | 1.82 | 2 | 1.57 | 2 | .30 |
| Pilot-wind interaction | 4 | 1.41 | 4 | .35 | 4 | 1.44 | 4 | .16 | 4 | 1.18 | 4 | 1.10 |
| Pilot-control-wind interaction | 4 | 1.00 | 4 | .23 | 4 | 1.14 | 4 | .10 | 4 | 1.35 | 4 | .90 |
| Error | 90 | ---- | 90 | ------ | 90 | ---- | 90 | ------ | 90 | ------ | 90 | ---- |

[a]Statistical significance at the 5-percent level ($F_{critical}$ = 3.96, 3.11, and 2.49 for 1, 2, and 4 d.o.f., respectively).

[b]Statistical significance at the 1-percent level ($F_{critical}$ = 6.97, 4.89, and 3.56 for 1, 2, and 4 d.o.f., respectively).

TABLE XII.- rms APPROACH DATA FOR VCWS CONTROLS

[Between altitudes of 76.2 m and 30.5 m]

| Experimental factor | Statistical parameter | Light shears | | | Moderate shears | | | Severe shears | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C |
| $\Delta\gamma$, deg | Mean | 0.08 | 0.20 | 0.18 | 0.43 | 0.24 | 0.17 | 0.40 | 1.11 | 0.56 |
| | Standard deviation | 0.06 | 0.10 | 0.10 | [d]0.46 | 0.13 | 0.14 | [d]0.25 | [c,d]1.51 | [c,d]0.78 |
| | t (controls) | | Not statistically significant (ANOV) | | | | | | | |
| | t (winds) | Reference | Reference | Reference | 1.75 | 0.57 | 0.14 | [b]3.20 | 1.45 | 1.19 |
| | DMR (pilots) | | Not statistically significant (ANOV) | | | | | | | |
| GSE, m | Mean | 1.82 | 1.86 | 1.53 | 4.37 | 2.83 | 6.69 | 16.41 | 16.36 | 12.24 |
| | Standard deviation | 1.18 | 1.30 | 0.65 | 2.38 | 2.53 | [d]8.33 | [d]15.03 | [d]13.84 | [d]10.30 |
| | t (controls) | | Not statistically signficant (ANOV) | | | | | | | |
| | t (winds) | Reference | Reference | Reference | [a]2.34 | 0.84 | 1.51 | [a]2.39 | [a]2.55 | [a]2.54 |
| | DMR (pilots) | | Not statistically significant (ANOV) | | | | | | | |
| ELOC, m | Mean | 4.83 | 8.21 | 9.36 | 12.59 | 6.54 | 10.90 | 15.55 | 8.09 | 21.12 |
| | Standard deviation | 3.72 | 8.30 | 6.28 | 7.07 | 4.10 | 6.20 | 11.66 | [c]4.50 | 16.32 |
| | t (controls) | Reference | Reference | Reference | Reference | Reference | Reference | Reference | Reference | Reference |
| | t (winds) | Reference | Reference | Reference | [a]2.38 | 0.44 | 0.43 | 2.14 | 0.03 | 1.65 |
| | DMR (pilots) | | Not statistically significant (ANOV) | | | | | | | |

[a]Statistical significance at the 5-percent level.
[b]Statistical significance at the 1-percent level.
[c]Variances for the pilots differ at the 1-percent level of significance.
[d]Variances for the winds differ at the 1-percent level of significance.

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TABLE XII.- Concluded

| Experimental factor | Statistical parameter | Light shears | | | Moderate shears | | | Severe shears | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C |
| ΔIAS, knots | Mean | 5.31 | 4.17 | 2.09 | 8.48 | 4.21 | 1.76 | 16.57 | 14.17 | 11.41 |
| | Standard deviation | 6.96 | [c]2.76 | [c]1.70 | 10.92 | [c]3.58 | [c]0.77 | 5.10 | [d]6.60 | [c]2.82 |
| | t (controls) | Reference | Reference | Reference | Reference | Reference | Reference | Reference | Reference | Reference |
| | t (winds) | Reference | Reference | Reference | 0.60 | 0.02 | 0.43 | [b]3.20 | [b]3.42 | [b]6.90 |
| | DMR (pilots) | Not statistically significant (ANOV) | | | | | | | | |
| δ_wheel, deg | Mean | 0.54 | 7.30 | 3.24 | 2.63 | 6.86 | 2.12 | 4.57 | 9.94 | 3.95 |
| | Standard deviation | 0.60 | 1.19 | 1.82 | [d]3.47 | 2.24 | 2.26 | [d]2.35 | 1.48 | 2.79 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Reference | Reference | Reference | 1.45 | 0.42 | 0.94 | [b]4.07 | [b]3.43 | 0.52 |
| | DMR (pilots) | [b](B-C), [b](C-A), [b](B-A) | | | (B-A), (A-C), (B-C) | | | [a](B-A), (A-C), [a](B-C) | | |
| δ_col, percent | Mean | 0.33 | 2.00 | 0.00 | 2.67 | 4.67 | 0.00 | 9.33 | 12.00 | 10.00 |
| | Standard deviation | 1.00 | [c]3.33 | [c]0.00 | [d]5.00 | 7.00 | [c]0.00 | [d]7.00 | 7.33 | [d]18.00 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Not statistically significant (ANOV) | | | | | | | | |
| | DMR (pilots) | (B-A), (A-C), (B-C) | | | (B-C), (A-C), (B-C) | | | (B-C), (C-A), (B-A) | | |

[a]Statistical significance at the 5-percent level.
[b]Statistical significance at the 1-percent level.
[c]Variances for the pilots differ at the 1-percent level of significance.
[d]Variances for the winds differ at the 1-percent level of significance.

TABLE XIII.- rms APPROACH DATA FOR DECOUPLED CONTROLS

[Between altitudes of 76.2 m and 30.5 m]

| Experimental factor | Statistical parameter | Light shears | | | Moderate shears | | | Severe shears | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C |
| $\Delta\gamma$, deg | Mean | 0.20 | 0.14 | 0.27 | 0.40 | 0.53 | 0.22 | 0.41 | 0.72 | 1.09 |
| | Standard deviation | 0.12 | 0.09 | 0.21 | [c,d]0.53 | [c,d,e]0.55 | 0.22 | 0.29 | [d,e]0.52 | [c,d]0.94 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Reference | Reference | Reference | 0.91 | 1.70 | 0.42 | 1.62 | [a]2.76 | 2.10 |
| | DMR (pilots) | Not statistically significant (ANOV) | | | | | | | | |
| GSE, m | Mean | 5.55 | 1.98 | 2.40 | 4.37 | 5.12 | 4.31 | 16.16 | 18.45 | 15.49 |
| | Standard deviation | [e]3.50 | [c]0.91 | [e]2.19 | 2.27 | [d]3.92 | 3.95 | [d]15.20 | [d]17.27 | [d]9.64 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Reference | Reference | Reference | 0.69 | 1.91 | 1.04 | 1.67 | [a]2.33 | [b]3.24 |
| | DMR (pilots) | Not statistically significant (ANOV) | | | | | | | | |
| ELOC, m | Mean | 8.63 | 5.74 | 2.25 | 6.21 | 6.00 | 8.11 | 12.72 | 6.15 | 9.36 |
| | Standard deviation | [e]6.72 | [e]2.63 | [e]2.33 | 3.64 | 3.28 | 6.02 | 8.81 | 3.45 | 6.36 |
| | t (controls) | 1.21 | 0.70 | [a]2.59 | 1.96 | 0.23 | 0.79 | 0.47 | 0.84 | 1.64 |
| | t (winds) | Reference | Reference | Reference | 0.78 | 0.09 | [a]2.23 | 0.90 | 0.23 | [a]2.58 |
| | DMR (pilots) | Not statistically significant (ANOV) | | | | | | | | |

[a]Statistical significance at the 5-percent level.
[b]Statistical significance at the 1-percent level.
[c]Variances for the pilots differ at the 1-percent level of significance.
[d]Variances for the winds differ at the 1-percent level of significance.
[e]Variances for the controls differ at the 5-percent level of significance.

TABLE XIII.- Concluded

| Experimental factor | Statistical parameter | Light shears | | | Moderate shears | | | Severe shears | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C |
| ΔIAS, knots | Mean | 1.01 | 0.76 | 1.16 | 0.57 | 0.30 | 0.29 | 5.86 | 7.42 | 6.01 |
| | Standard deviation | [e]0.55 | [e]0.31 | [e]0.43 | [e]0.52 | [c,e]0.82 | 0.37 | [d]2.79 | [d]4.59 | [d]4.75 |
| | t (controls) | 1.51 | [a]2.99 | 1.29 | 1.77 | [a]2.68 | [b]4.20 | [b]4.52 | 2.06 | [a]2.39 |
| | t (winds) | Reference | Reference | Reference | 1.42 | [b]3.29 | [b]3.78 | [b]4.18 | [b]3.54 | [a]2.49 |
| | DMR (pilots) | Not statistically significant (ANOV) | | | | | | | | |
| δwheel, deg | Mean | 1.74 | 7.15 | 0.59 | 3.40 | 11.07 | 1.50 | 5.90 | 8.10 | 2.76 |
| | Standard deviation | [e]2.32 | 0.92 | 0.96 | 2.74 | [d,e]6.35 | [c]1.59 | 4.32 | 2.31 | [d]3.71 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Reference | Reference | Reference | 1.14 | 1.50 | 1.20 | 2.08 | 0.94 | 1.39 |
| | DMR (pilots) | [b](B-A), (A-C), [b](B-C) | | | [b](B-A), (A-C), [b](B-C) | | | (A-C), (C-B), (A-B) | | |
| δcol, percent | Mean | 6.00 | 3.67 | 0.00 | 3.00 | 8.33 | 0.00 | 5.33 | 19.33 | 5.33 |
| | Standard deviation | [e]8.00 | 3.67 | 0.00 | 3.00 | [c]10.33 | 0.00 | 4.33 | [c,d]16.33 | [d]8.67 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Not statistically significant (ANOV) | | | | | | | | |
| | DMR (pilots) | (A-B), (B-C), (A-C) | | | (B-A), (A-C), [a](A-C) | | | [a](B-A), (A-C), [a](B-C) | | |

[a]Statistical significance at the 5-percent level.
[b]Statistical significance at the 1-percent level.
[c]Variances for the pilots differ at the 1-percent level of significance.
[d]Variances for the winds differ at the 1-percent level of significance.
[e]Variances for the controls differ at the 5-percent level of significance.

TABLE XIV.- ANALYSIS OF VARIANCE FOR rms APPROACH PARAMETERS WITH

PILOTS, CONTROLS, AND WINDS AS EXPERIMENTAL FACTORS

[Between altitudes of 30.5 m and 15.1 m]

| Experimental factor | $\Delta\gamma$ | | GSE | | ELOC | | $\Delta$IAS | | $\delta_{wheel}$ | | $\delta_{col}$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | d.o.f. | F | d.o.f. | F | d.o.f. | F | d.o.f. | F | d.o.f. | F | d.o.f. | F |
| Pilot | 2 | 0.90 | 2 | 0.68 | 2 | [b]8.44 | 2 | 0.94 | 2 | [b]25.47 | 2 | [a]4.45 |
| Wind | 2 | [b]9.82 | 2 | [b]18.85 | 2 | [a]3.33 | 2 | [b]14.19 | 2 | 2.21 | 2 | [b]11.36 |
| Control | 1 | 3.43 | 1 | .59 | 1 | 2.21 | 1 | [b]27.04 | 1 | 1.17 | 1 | 2.52 |
| Pilot-control interaction | 2 | 1.06 | 2 | 1.60 | 2 | .79 | 2 | .52 | 2 | 2.34 | 2 | 1.24 |
| Control-wind interaction | 2 | [b]5.39 | 2 | .21 | 2 | 1.67 | 2 | 1.88 | 2 | 1.16 | 2 | 1.18 |
| Pilot-wind interaction | 4 | .53 | 4 | [a]2.91 | 4 | 1.96 | 4 | .30 | 4 | [a]3.29 | 4 | [a]3.09 |
| Pilot-control-wind interaction | 4 | .38 | 4 | 1.43 | 4 | 1.83 | 4 | .13 | 4 | 1.73 | 4 | 2.17 |
| Error | 90 | ---- | 90 | ----- | 90 | ---- | 90 | ----- | 90 | ----- | 90 | ----- |

[a]Statistical significance at the 5-percent level ($F_{critical}$ = 3.96, 3.11, and 2.49 for 1, 2, and 4 d.o.f., respectively).

[b]Statistical significance at the 1-percent level ($F_{critical}$ = 6.97, 4.89, and 3.56 for 1, 2, and 4 d.o.f., respectively).

# TABLE XV.- rms APPROACH DATA FOR VCWS CONTROLS

[Between altitudes of 30.5 m and 15.1 m]

| Experimental factor | Statistical parameter | Light shears | | | Moderate shears | | | Severe shears | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C |
| $\Delta\gamma$, deg | Mean | 0.15 | 0.22 | 0.29 | 0.33 | 1.00 | 0.61 | 1.65 | 3.20 | 1.94 |
| | Standard deviation | 0.11 | 0.13 | 0.25 | 0.25 | [c,d]0.91 | 0.64 | [d]1.09 | [c,d,e]3.48 | [c,d,e]2.69 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Reference | Reference | Reference | 1.64 | 2.11 | 1.14 | [b]3.33 | 1.42 | 1.50 |
| | DMR (pilots) | Not statistically significant (ANOV) | | | | | | | | |
| GSE, m | Mean | 0.83 | 1.60 | 1.07 | 3.91 | 1.99 | 5.07 | 4.86 | 15.32 | 12.03 |
| | Standard deviation | 0.80 | 0.80 | 0.92 | [d]3.01 | 1.33 | [c,d]8.09 | [d]2.84 | [c,d]19.15 | [d]4.73 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Reference | Reference | Reference | [a]2.43 | 0.62 | 1.20 | [b]3.36 | 1.75 | [b]5.59 |
| | DMR (pilots) | Not statistically significant (ANOV) | | | | | | | | |
| ELOC, m | Mean | 5.06 | 3.67 | 5.32 | 11.97 | 4.02 | 11.81 | 7.41 | 3.49 | 10.96 |
| | Standard deviation | 3.09 | 3.77 | 3.22 | 6.45 | 2.26 | 4.26 | 3.26 | 2.85 | [c,d]11.45 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Reference | Reference | Reference | [a]2.37 | 0.19 | [a]2.98 | 1.28 | 0.09 | 1.16 |
| | DMR (pilots) | (C-A), (A-B), (C-A) | | | (A-C), [a](C-B), [a](A-B) | | | (C-A), (A-B), (C-B) | | |

[a]Statistical significance at the 5-percent level.
[b]Statistical significance at the 1-percent level.
[c]Variances for the pilots differ at the 1-percent level of significance.
[d]Variances for the winds differ at the 1-percent level of significance.

TABLE XV.- Concluded

| Experimental factor | Statistical parameter | Light shears | | | Moderate shears | | | Severe shears | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C |
| $\Delta$IAS, knots | Mean | 5.96 | 7.86 | 4.20 | 8.88 | 5.73 | 4.80 | 16.44 | 17.99 | 12.94 |
| | Standard deviation | [c]3.61 | [c]3.53 | 1.24 | [d]8.92 | 5.13 | [c]2.67 | [d]12.31 | [d]14.43 | [d]12.89 |
| | t (controls) | Reference | Reference | Reference | Reference | Reference | Reference | Reference | Reference | Reference |
| | t (winds) | Reference | Reference | Reference | 0.74 | 0.84 | 0.50 | 2.00 | 1.67 | 1.65 |
| | DMR (pilots) | Not statistically significant (ANOV) | | | | | | | | |
| $\delta_{wheel}$, deg | Mean | 2.40 | 6.29 | 2.02 | 4.18 | 6.60 | 2.53 | 4.49 | 3.34 | 4.25 |
| | Standard deviation | [c]3.68 | 1.58 | [c]0.89 | 4.18 | 1.73 | 1.99 | 3.22 | 2.38 | [d]3.17 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Not statistically significant (ANOV) | | | | | | | | |
| | DMR (pilots) | [a](B-A), (A-C), [b](B-C) | | | (B-A), (A-C), [a](B-C) | | | (A-C), (C-B), (A-B) | | |
| $\delta_{col}$, percent | Mean | 4.67 | 6.00 | 1.67 | 6.33 | 9.00 | 9.33 | 9.33 | 62.67 | 23.67 |
| | Standard deviation | 3.00 | 4.67 | 3.33 | 4.00 | 6.00 | [c,d]15.33 | [c]6.00 | [c,d]61.00 | [c,d]30.67 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Reference | Reference | Reference | 0.83 | 1.00 | [c]1.21 | 1.75 | [a]2.27 | 1.74 |
| | DMR (pilots) | (B-A), (A-C), (B-C) | | | (C-B), (B-A), (C-A) | | | (B-C), (C-A), [a](B-A) | | |

[a]Statistical significance at the 5-percent level.
[b]Statistical significance at the 1-percent level.
[c]Variances for the pilots differ at the 1-percent level of significance.
[d]Variances for the winds differ at the 1-percent level of significance.

TABLE XVI.- rms APPROACH DATA FOR DECOUPLED CONTROLS

[Between altitudes of 30.5 m and 15.1 m]

| Experimental factor | Statistical parameter | Light shears | | | Moderate shears | | | Severe shears | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C |
| $\Delta\gamma$, deg | Mean | 0.42 | 0.28 | 0.49 | 0.66 | 0.66 | 0.81 | 0.79 | 0.84 | 0.66 |
| | Standard deviation | [e]0.29 | 0.29 | 0.30 | [e]0.69 | 0.59 | 0.86 | 0.68 | [e]0.58 | [e]0.81 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Reference | Reference | Reference | 1.47 | 1.41 | 0.86 | 1.23 | 2.15 | 0.49 |
| | DMR (pilots) | Not statistically significant (ANOV) | | | | | | | | |
| GSE, m | Mean | 3.43 | 1.46 | 2.55 | 6.75 | 6.25 | 2.88 | 10.50 | 13.18 | 8.02 |
| | Standard deviation | [e]2.40 | 0.80 | 2.12 | 2.83 | [d,e]4.89 | [e]1.54 | [c]5.65 | [c,d]12.31 | [c,e]1.18 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Reference | Reference | Reference | 2.20 | [a]2.37 | 0.31 | [a]2.82 | 1.99 | [b]5.53 |
| | DMR (pilots) | Not statistically significant (ANOV) | | | | | | | | |
| ELOC, m | Mean | 7.51 | 4.22 | 2.66 | 3.31 | 4.35 | 9.02 | 9.48 | 2.77 | 8.10 |
| | Standard deviation | 4.55 | 2.68 | 2.98 | [e]2.04 | 2.53 | 6.20 | [c,e]7.57 | [e]1.09 | [c,e]3.78 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Reference | Reference | Reference | 2.07 | 0.09 | [a]2.26 | 0.55 | 1.23 | [a]2.78 |
| | DMR (pilots) | (A-B), (B-C), [a](A-C) | | | (C-B), (B-A), [a](C-A) | | | (A-C), (C-B), [a](A-B) | | |

[a]Statistical significance at the 5-percent level.
[b]Statistical significance at the 1-percent level.
[c]Variances for the pilots differ at the 1-percent level of significance.
[d]Variances for the winds differ at the 1-percent level of significance.
[e]Variances for the controls differ at the 5-percent level of significance.

TABLE XVI.- Concluded

| Experimental factor | Statistical parameter | Light shears | | | Moderate shears | | | Severe shears | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C |
| $\Delta$IAS, knots | Mean | 0.91 | 0.61 | 0.88 | 2.89 | 1.69 | 1.71 | 5.70 | 6.76 | 5.40 |
| | Standard deviation | [e]0.31 | [e]0.33 | 0.63 | [d,e]3.24 | [d,e]1.84 | [c,e]1.16 | [d,e]4.82 | [d,e]5.49 | [d,e]4.60 |
| | t (controls) | [b]3.41 | [b]5.00 | [b]5.82 | 1.54 | 1.82 | [a]2.60 | 1.99 | 1.78 | 1.35 |
| | t (winds) | Reference | Reference | Reference | 1.49 | 1.42 | 1.54 | [a]2.43 | [a]2.73 | [a]2.39 |
| | DMR (pilots) | Not statistically significant (ANOV) | | | | | | | | |
| $\delta_{wheel}$, deg | Mean | 1.35 | 6.97 | 0.69 | 1.67 | 12.21 | 1.98 | 5.51 | 6.58 | 1.76 |
| | Standard deviation | [e]1.14 | 2.28 | 1.05 | 2.01 | [c,e]6.31 | 1.03 | [d]4.52 | 5.27 | 2.08 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Not statistically significant (ANOV) | | | | | | | | |
| | DMR (pilots) | [b](B-A), (A-C), [b](B-C) | | | [b](B-C), (C-A), [b](B-A) | | | (B-A), (A-C), (B-C) | | |
| $\delta_{col}$, percent | Mean | 4.33 | 4.00 | 1.00 | 11.00 | 11.00 | 0.33 | 9.33 | 24.67 | 14.33 |
| | Standard deviation | 4.00 | 4.00 | 2.67 | [d,e]14.33 | 13.00 | [c,d,e]0.67 | 9.67 | [d,e]24.00 | [d]26.67 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Reference | Reference | Reference | 1.11 | 1.24 | 0.40 | 1.15 | 2.07 | 1.21 |
| | DMR (pilots) | (A-B), (B-C), (A-C) | | | (A-B), (B-C), (A-C) | | | (B-C), (C-A), (B-A) | | |

[a]Statistical significance at the 5-percent level.
[b]Statistical significance at the 1-percent level.
[c]Variances for the pilots differ at the 1-percent level of significance.
[d]Variances for the winds differ at the 1-percent level of significance.
[e]Variances for the controls differ at the 5-percent level of significance.

TABLE XVII.- ANALYSIS OF VARIANCE FOR TOUCHDOWN PARAMETERS WITH

PILOTS, CONTROLS, AND WINDS AS EXPERIMENTAL FACTORS

| Experimental factors | $R_a$ | | $y$ | | $\dot{h}$ | | IAS | | $\theta$ | | $\phi$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | d.o.f. | F | d.o.f. | F | d.o.f. | F | d.o.f. | F | d.o.f. | F | d.o.f. | F |
| Pilot | 2 | 1.92 | 2 | 0.36 | 2 | 0.33 | 2 | [b]10.13 | 2 | 0.06 | 2 | 0.14 |
| Wind | 2 | [b]7.41 | 2 | .87 | 2 | 1.52 | 2 | [b]34.78 | 2 | [a]4.79 | 2 | .52 |
| Control | 1 | .16 | 1 | .08 | 1 | [b]17.61 | 1 | 1.01 | 1 | [b]104.54 | 1 | .26 |
| Pilot-control interaction | 2 | 2.56 | 2 | .01 | 2 | .66 | 2 | 3.09 | 2 | 1.02 | 2 | .02 |
| Control-wind interaction | 2 | .73 | 2 | .41 | 2 | 1.39 | 2 | [b]5.32 | 2 | [b]4.97 | 2 | .13 |
| Pilot-wind interaction | 4 | 1.08 | 4 | .31 | 4 | .43 | 4 | .39 | 4 | .66 | 4 | .13 |
| Pilot-control-wind interaction | 4 | [b]7.17 | 4 | .36 | 4 | .04 | 4 | 1.86 | 4 | .19 | 4 | .42 |
| Error | [c]82 | ---- | [c]82 | ---- | [c]82 | ----- | [c]82 | ----- | [c]82 | ------ | [c]82 | ---- |

[a]Statistical significance at the 5-percent level ($F_{critical}$ = 3.97, 3.12, and 2.50 for 1, 2, and 4 d.o.f., respectively).

[b]Statistical significance at the 1-percent level ($F_{critical}$ = 7.00, 4.92, and 3.59 for 1, 2, and 4 d.o.f., respectively).

[c]Data for 8 runs with VCWS were lost due to crashes to reduce d.o.f. by 8.

# TABLE XVIII.- TOUCHDOWN DATA FOR VCWS CONTROLS

| Experimental factor | Statistical parameter | Light shears | | | Moderate shears | | | Severe shears | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C |
| $\dot{h}$, m/sec | Mean | -1.48 | -2.13 | -1.44 | -2.23 | -2.00 | -2.19 | -2.39 | -2.67 | -2.59 |
| | Standard deviation | 0.35 | [c]1.34 | 0.65 | 0.81 | 2.06 | 1.29 | [d]1.18 | 2.22 | 1.94 |
| | t (controls) | Reference | Reference | Reference | Reference | Reference | Reference | Reference | Reference | Reference |
| | t (winds) | Not statistically significant (ANOV) | | | | | | | | |
| | DMR (pilots) | Not statistically significant (ANOV) | | | | | | | | |
| $R_a$, m | Mean | 427.3 | 390.4 | 402.9 | 375.6 | 331.6 | 496.8 | 469.3 | 425.6 | 1643.9 |
| | Standard deviation | 89.9 | 146.9 | 162.2 | 100.1 | 156.6 | 193.3 | [d]460.6 | [c,d]784.4 | 170.1 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Reference | Reference | Reference | 0.94 | 0.67 | 0.91 | 0.19 | 0.10 | [b]8.02 |
| | DMR (pilots) | Not statistically significant (ANOV) | | | | | | | | |
| IAS, knots | Mean | 125.95 | 118.80 | 117.25 | 131.09 | 120.20 | 119.41 | 140.35 | 133.48 | 138.22 |
| | Standard deviation | 7.32 | 4.01 | 3.50 | 10.41 | 8.13 | 6.48 | 8.77 | 5.15 | [c]1.58 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Reference | Reference | Reference | 0.99 | 0.38 | 0.72 | 2.29 | [b]4.81 | [b]7.10 |
| | DMR (pilots) | [a](A-B), (B-C), [a](A-C) | | | [a](A-B), (B-C), [a](A-C) | | | (A-C), (C-B), (A-B) | | |

[a]Statistical significance at the 5-percent level.
[b]Statistical significance at the 1-percent level.
[c]Variances for the pilots differ at the 1-percent level of significance.
[d]Variances for the winds differ at the 1-percent level of significance.

TABLE XVIII.- Concluded

| Experimental factor | Statistical parameter | Light shears | | | Moderate shears | | | Severe shears | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C |
| $\theta$, deg | Mean | 0.70 | 1.21 | 0.39 | -0.90 | -0.81 | -0.17 | -1.00 | -0.31 | -1.56 |
| | Standard deviation | 1.57 | 2.09 | 2.21 | 0.89 | 1.91 | 1.52 | 0.49 | 1.60 | [d]0.57 |
| | t (controls) | Reference | Reference | Reference | Reference | Reference | Reference | Reference | Reference | Reference |
| | t (winds) | Reference | Reference | Reference | 2.19 | 1.74 | 0.51 | [a]2.62 | 1.48 | 2.14 |
| | DMR (pilots) | Not statistically significant (ANOV) | | | | | | | | |
| $y$, m | Mean | 0.81 | -0.29 | 3.67 | 1.85 | 0.07 | 2.64 | 1.10 | -3.46 | -2.86 |
| | Standard deviation | 6.23 | 9.92 | 4.69 | 9.04 | 6.72 | 14.56 | [c]8.36 | [c]5.41 | [d]0.49 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Not statistically significant (ANOV) | | | | | | | | |
| | DMR (pilots) | Not statistically significant (ANOV) | | | | | | | | |
| $\phi$, deg | Mean | -0.48 | -0.50 | -0.19 | -0.40 | -0.34 | -0.77 | -0.46 | -0.64 | 0.13 |
| | Standard deviation | 0.77 | 1.16 | 0.46 | 1.17 | [c]0.68 | [d]3.14 | 1.62 | 1.73 | 1.47 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Not statistically significant (ANOV) | | | | | | | | |
| | DMR (pilots) | Not statistically significant (ANOV) | | | | | | | | |

[a]Statistical significance at the 5-percent level.
[b]Statistical significance at the 1-percent level.
[c]Variances for the pilots differ at the 1-percent level of significance.
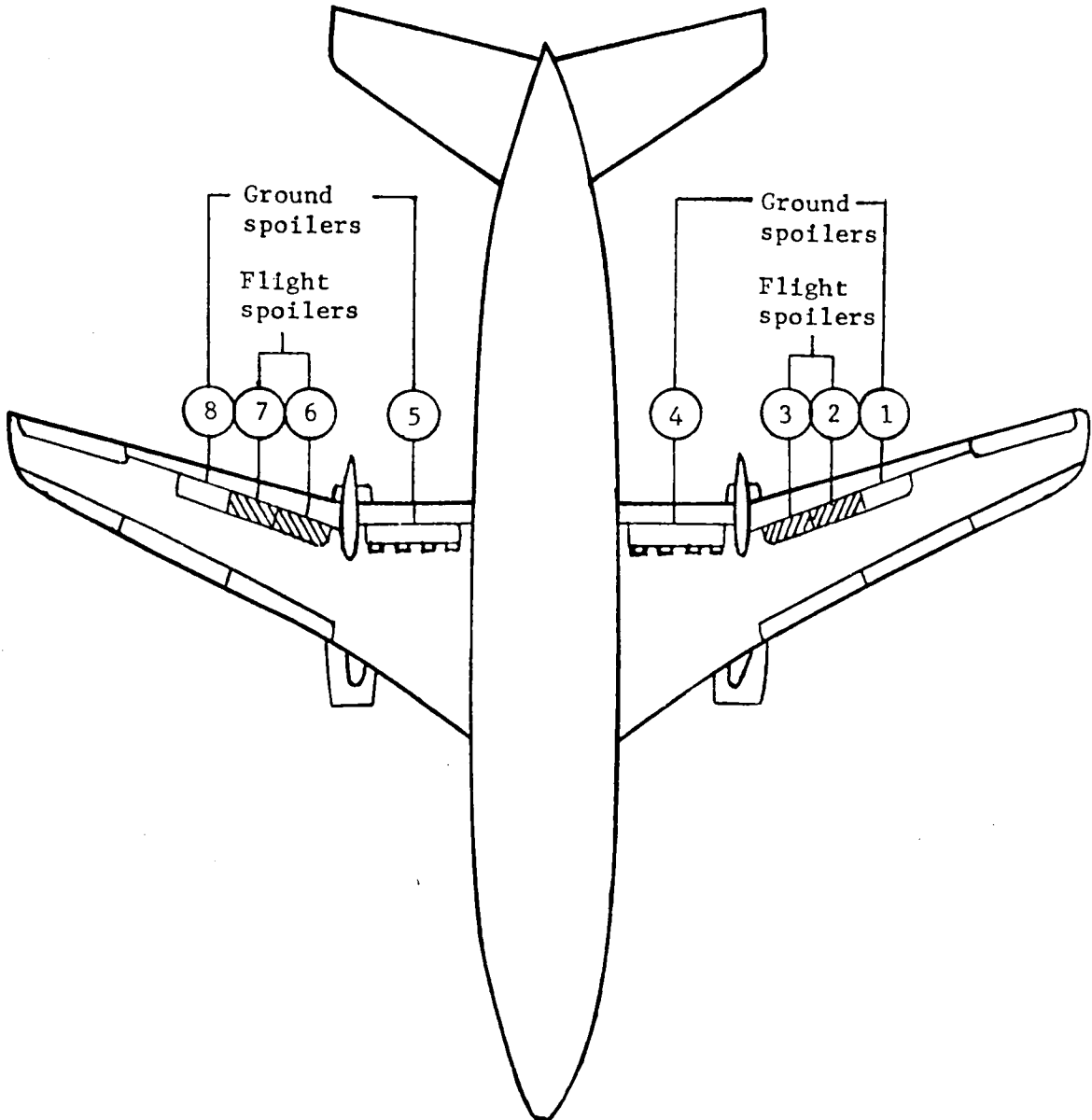[d]Variances for the winds differ at the 1-percent level of significance.

TABLE XIX.- TOUCHDOWN DATA FOR DECOUPLED CONTROLS

| Experimental factor | Statistical parameter | Light shears | | | Moderate shears | | | Severe shears | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C |
| $\dot{h}$, m/sec | Mean | -1.13 | -1.13 | -0.76 | -1.35 | -0.92 | -1.14 | -1.65 | -1.08 | -1.35 |
| | Standard deviation | 0.43 | [e]0.52 | 0.47 | 0.89 | [e]0.88 | [e]0.52 | [e]0.34 | [e]0.40 | 0.97 |
| | t (controls) | 1.52 | 1.69 | 2.06 | 1.80 | 1.19 | 1.84 | 0.35 | 1.59 | 1.02 |
| | t (winds) | Not statistically significant (ANOV) | | | | | | | | |
| | DMR (pilots) | Not statistically significant (ANOV) | | | | | | | | |
| $R_a$, m | Mean | 463.7 | 433.4 | 549.2 | 506.6 | 280.8 | 334.5 | 629.6 | 630.8 | 527.1 |
| | Standard deviation | 129.4 | 76.4 | 149.6 | [e]284.7 | 188.6 | 145.4 | [e]113.7 | [d,e]340.2 | 148.2 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Reference | Reference | Reference | 0.34 | 1.84 | [a]2.50 | [a]2.37 | 1.39 | 0.26 |
| | DMR (pilots) | Not statistically significant (ANOV) | | | | | | | | |
| IAS, knots | Mean | 124.65 | 124.56 | 124.28 | 124.42 | 121.73 | 124.17 | 134.86 | 130.10 | 127.56 |
| | Standard deviation | [e]1.27 | [e]1.58 | [e]1.11 | [e]2.24 | [c]4.48 | [e]1.35 | [e]2.77 | [d]6.98 | [d,e]3.87 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Reference | Reference | Reference | 0.22 | 1.46 | 0.15 | [b]8.23 | 1.90 | 2.00 |
| | DMR (pilots) | (A-B), (B-C), (A-C) | | | (A-C), (C-B), (A-B) | | | (A-B), (B-C), [a](A-C) | | |

[a]Statistical significance at the 5-percent level.
[b]Statistical significance at the 1-percent level.
[c]Variances for the pilots differ at the 1-percent level of significance.
[d]Variances for the winds differ at the 1-percent level of significance.
[e]Variances for the controls differ at the 5-percent level of significance.

TABLE XIX.- Concluded

| Experimental factor | Statistical parameter | Light shears | | | Moderate shears | | | Severe shears | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C | Pilot A | Pilot B | Pilot C |
| $\theta$, deg | Mean | 2.37 | 2.63 | 2.32 | 2.13 | 2.30 | 2.06 | 2.32 | 1.97 | 2.17 |
| | Standard deviation | [e]0.26 | [e]0.11 | [e]0.20 | [e]0.36 | [d,e]0.37 | [e]0.18 | 0.27 | [d,e]0.48 | 0.39 |
| | t (controls) | [a]3.15 | 1.67 | 2.14 | [b]7.77 | [b]3.94 | [b]3.54 | [b]11.50 | [a]2.99 | [b]8.95 |
| | t (winds) | Reference | Reference | Reference | 1.33 | 2.06 | [a]2.36 | 0.33 | [b]3.3 | 0.83 |
| | DMR (pilots) | Not statistically significant (ANOV) | | | | | | | | |
| $y$, m | Mean | 0.81 | 1.24 | 3.27 | 1.90 | −3.33 | −0.90 | 2.94 | −3.28 | −2.57 |
| | Standard deviation | 8.04 | 5.71 | 5.28 | [d,e]3.38 | 5.22 | 9.86 | 7.66 | 2.52 | [e]4.06 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Not statistically significant (ANOV) | | | | | | | | |
| | DMR (pilots) | Not statistically significant (ANOV) | | | | | | | | |
| $\phi$, deg | Mean | −0.32 | −0.13 | −0.34 | −0.30 | −0.87 | −0.53 | −0.65 | −0.13 | −0.26 |
| | Standard deviation | 0.72 | 0.53 | 0.80 | [e]0.43 | [c]1.47 | [c]1.42 | 1.52 | 0.98 | 0.91 |
| | t (controls) | Not statistically significant (ANOV) | | | | | | | | |
| | t (winds) | Not statistically significant (ANOV) | | | | | | | | |
| | DMR (pilots) | Not statistically significant (ANOV) | | | | | | | | |

[a]Statistical significance at the 5-percent level.
[b]Statistical significance at the 1-percent level.
[c]Variances for the winds differ at the 1-percent level of significance.
[d]Variances for the controls differ at the 5-percent level of significance.

Figure 1.- Simulated TCV airplane.
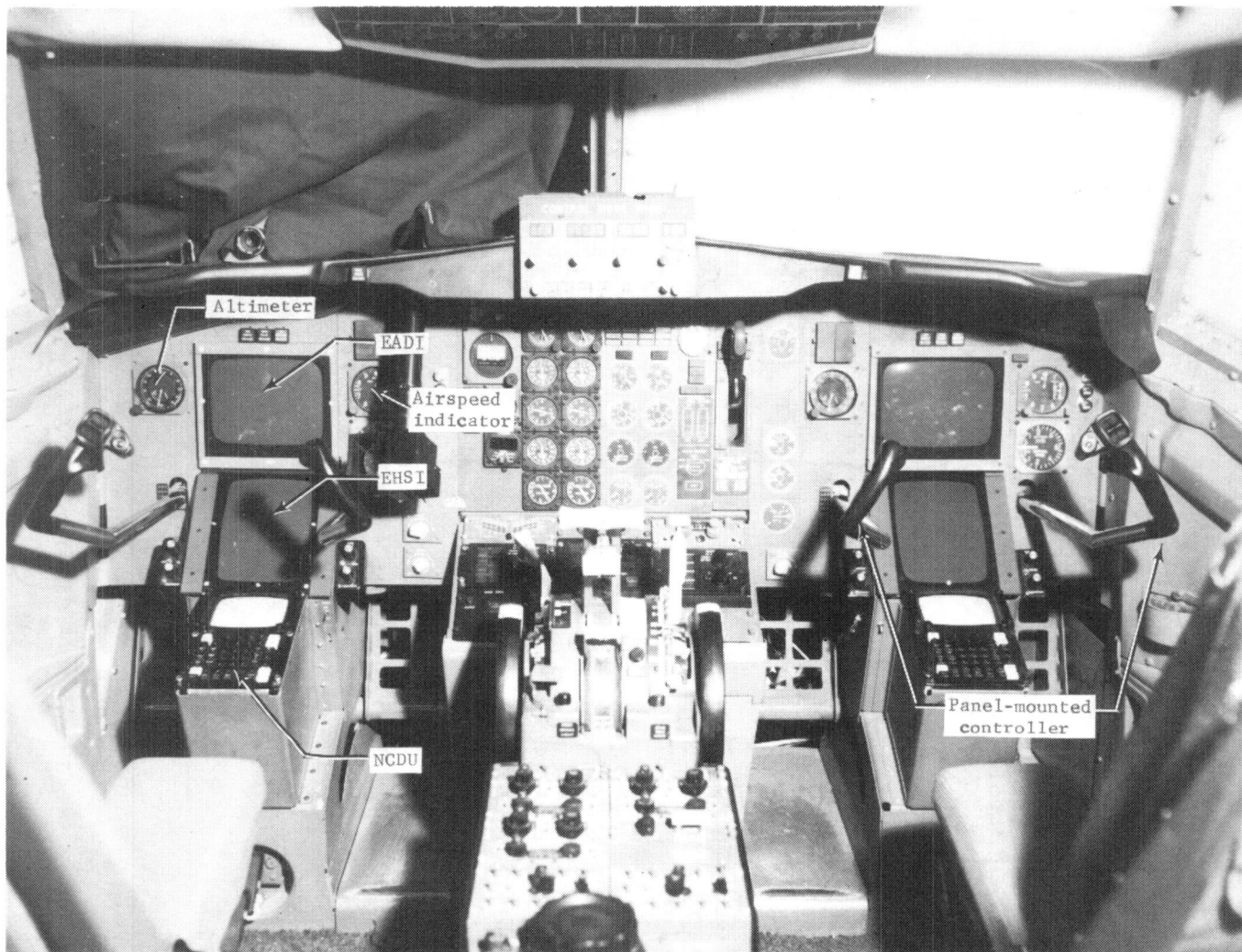
L-79-640

Figure 2.- AFD cockpit control and display layout.

1. Roll pointer
2. Roll scale
3. Pitch grid
4. Radar altitude
5. Airplane reference symbol
6. Speed error indicator
7. Glide-slope error indicator
8. Localizer error indicator
9. Runway symbol
10. Track pointer
11. Pitch reference line
12. Flight-path acceleration
13. Flight-path angle
14. Reference flight-path angle
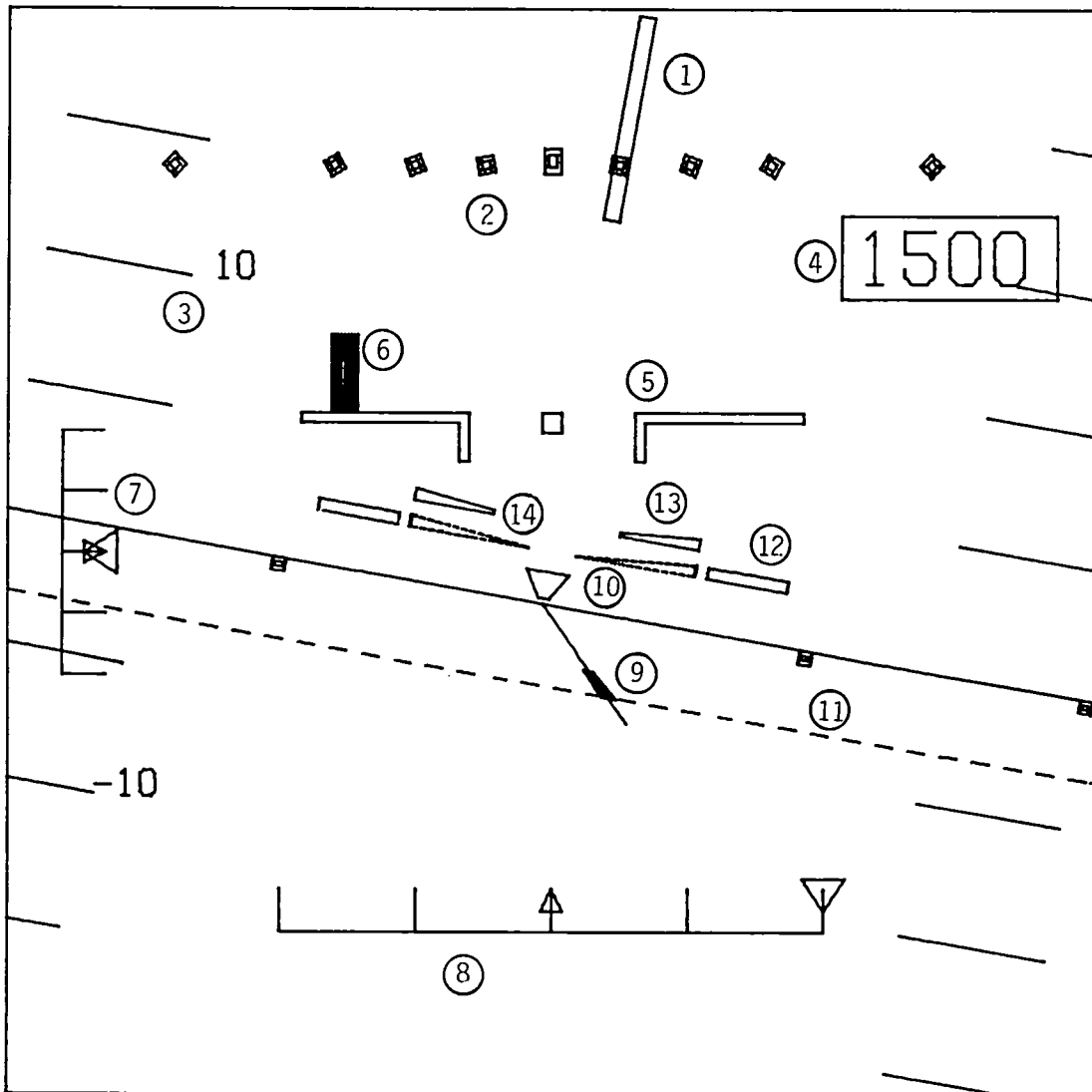
Figure 3.- Sketch of EADI.
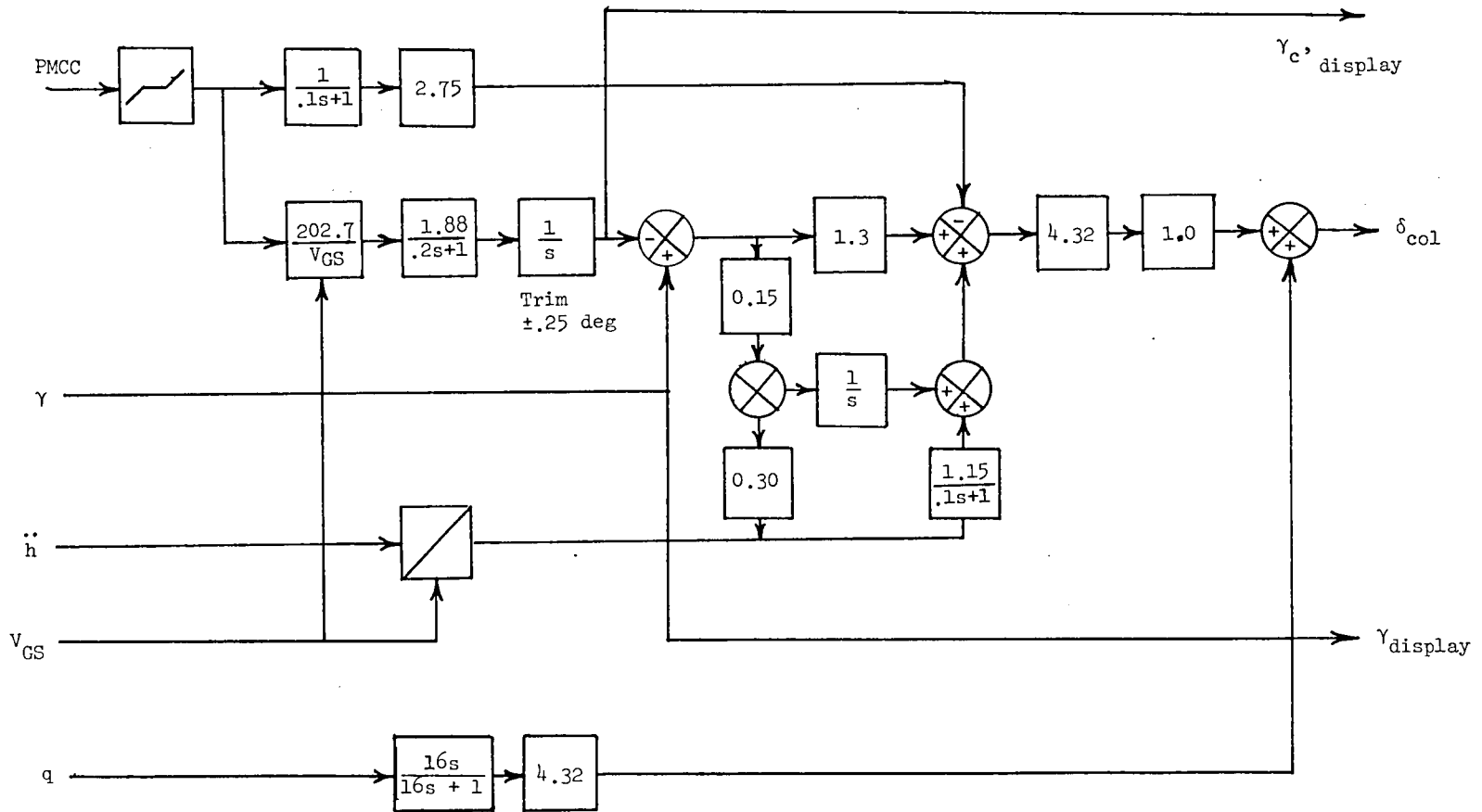
Figure 4.- Velocity-vector control mode for pitch axis (fig. 15 of ref. 4).
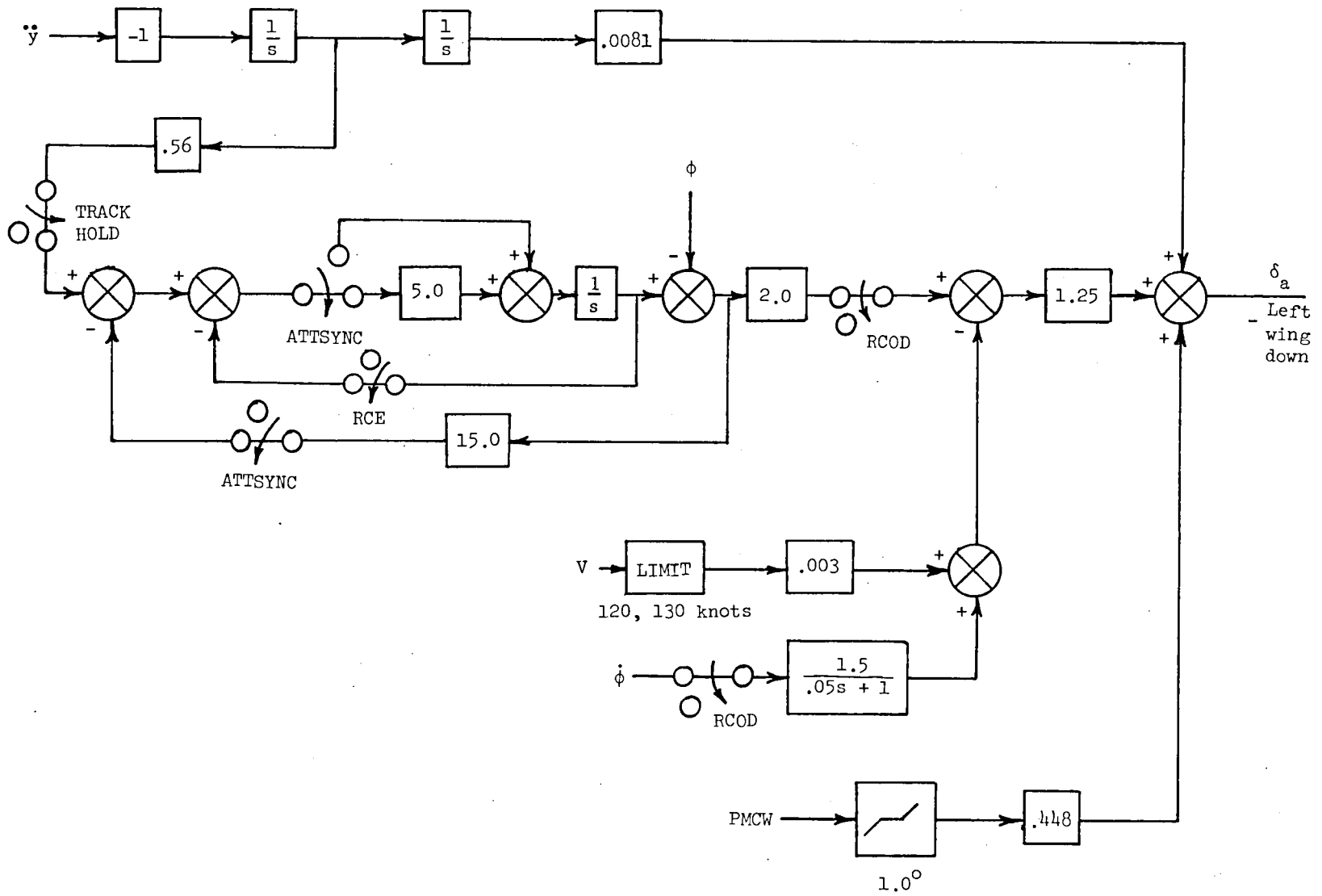
Figure 5.- Velocity-vector control mode for roll axis.
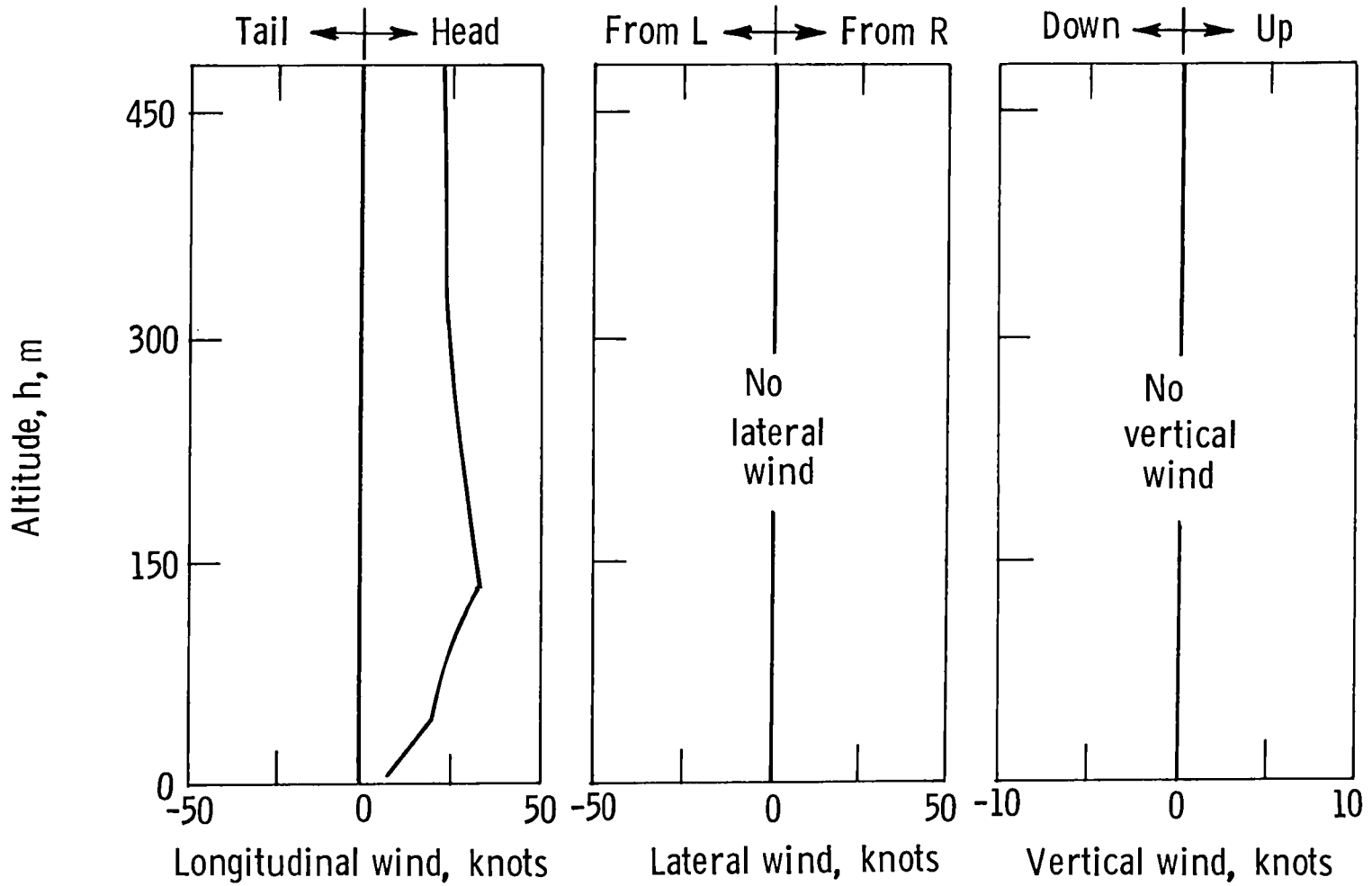
Figure 6.- Wind profile B2 (low severity).
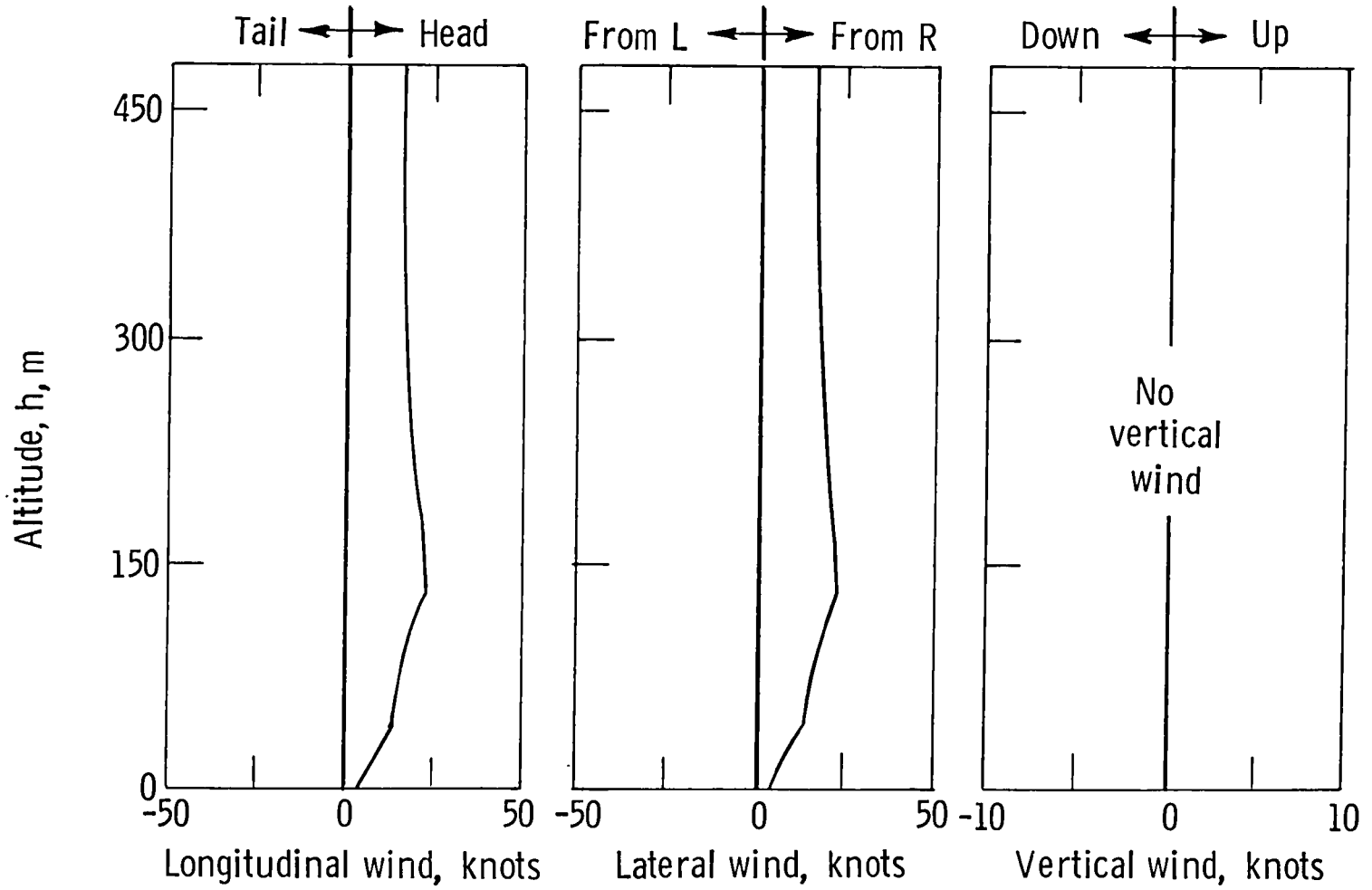
Figure 7.- Wind profile B3 (low severity).
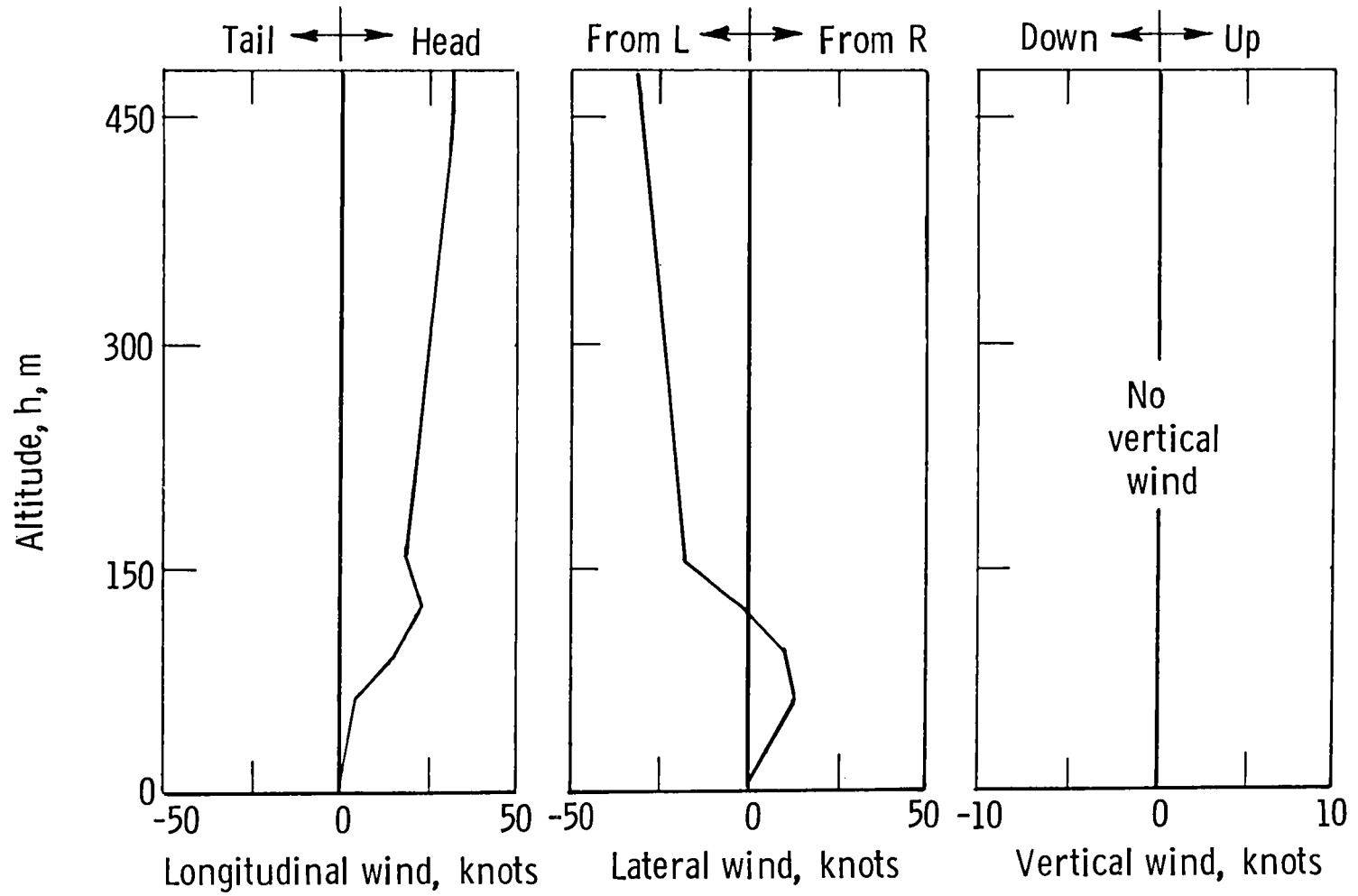
Figure 8.- Wind profile B6 (moderate severity).
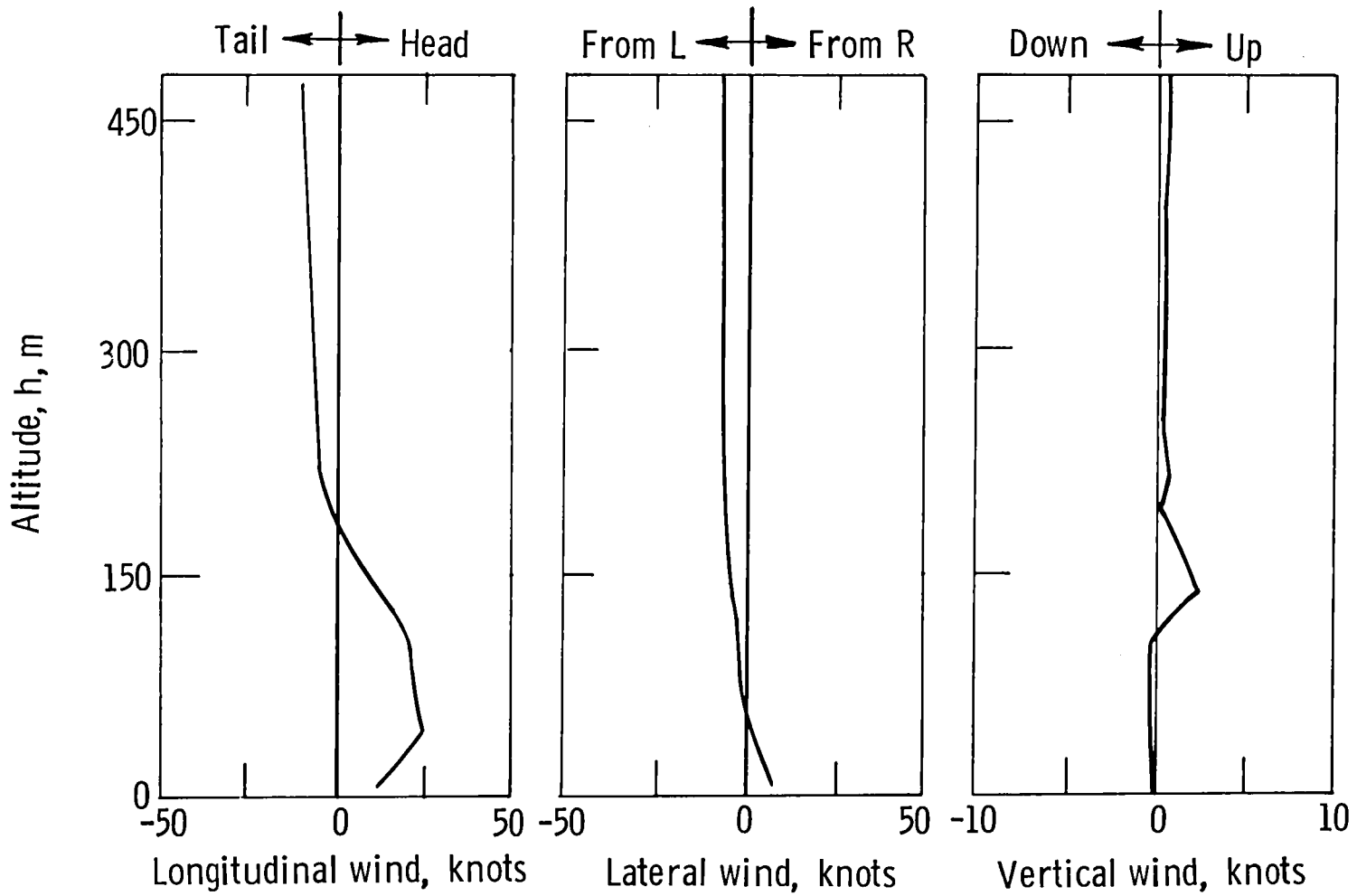
Figure 9.- Wind profile B7 (moderate severity).
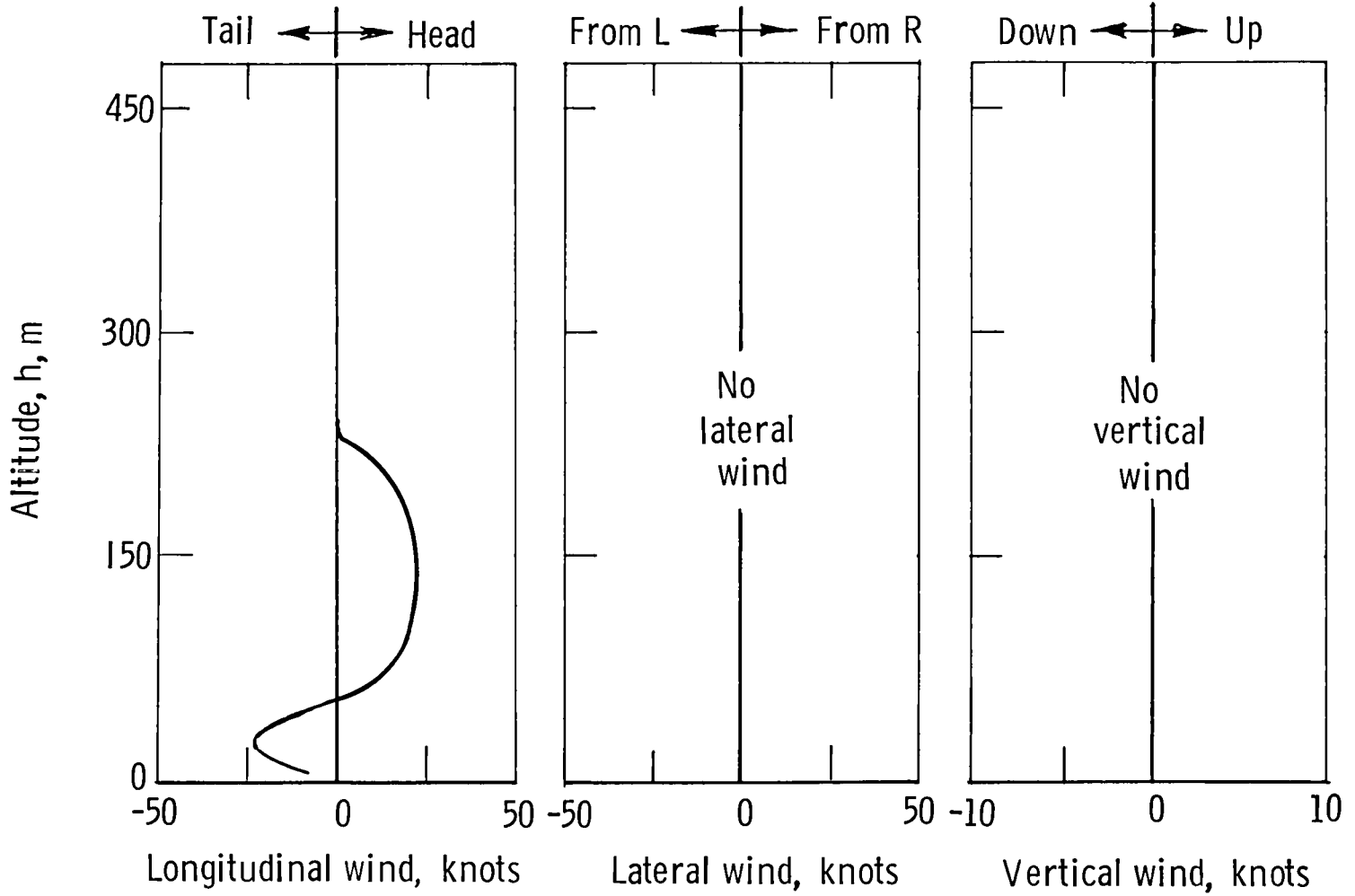
Figure 10.- Wind profile D3 (high severity).
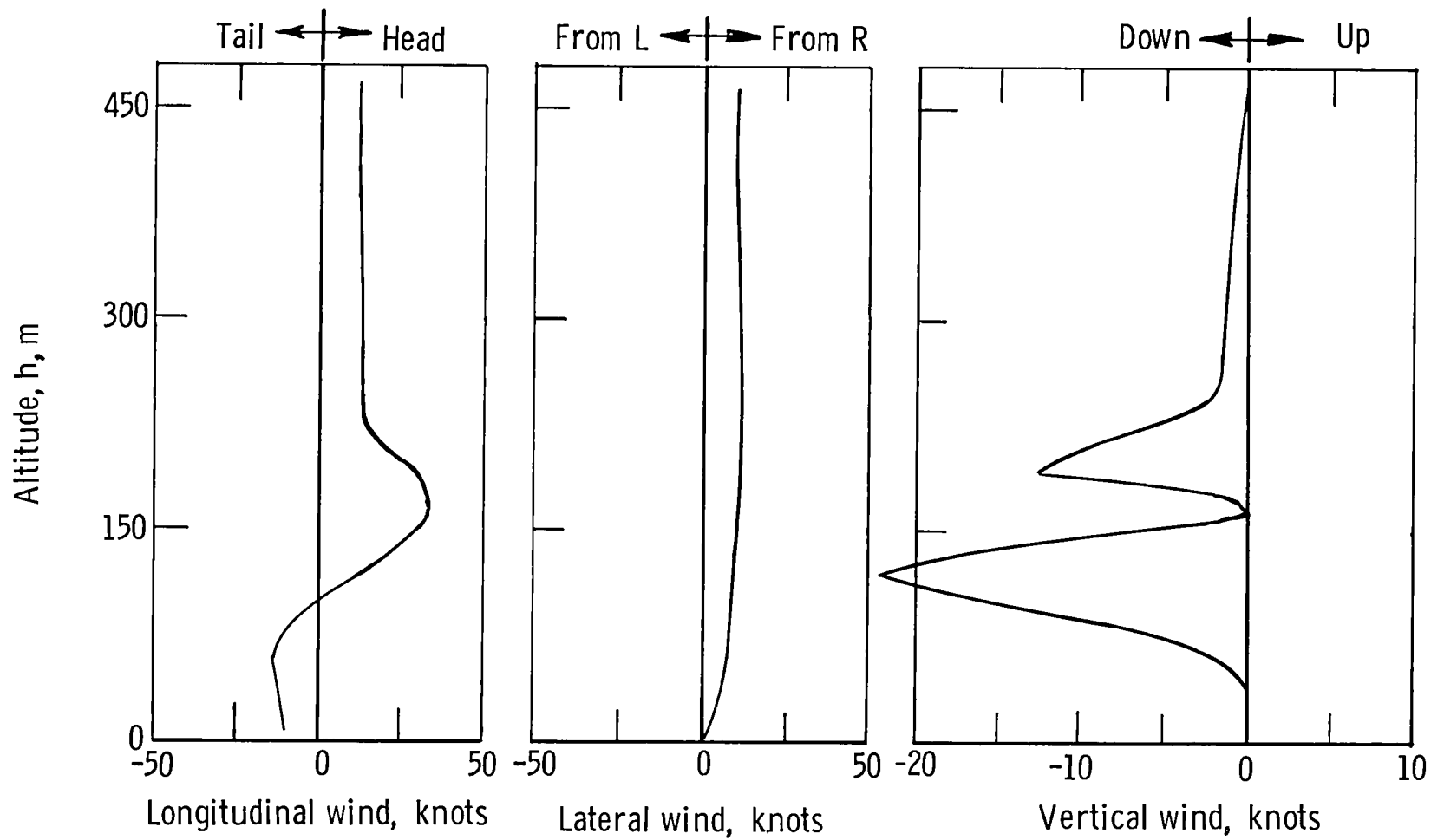
Figure 11.- Wind profile D10 (high severity). (Similar to profile at Eastern Airlines crash at John F. Kennedy International Airport.)
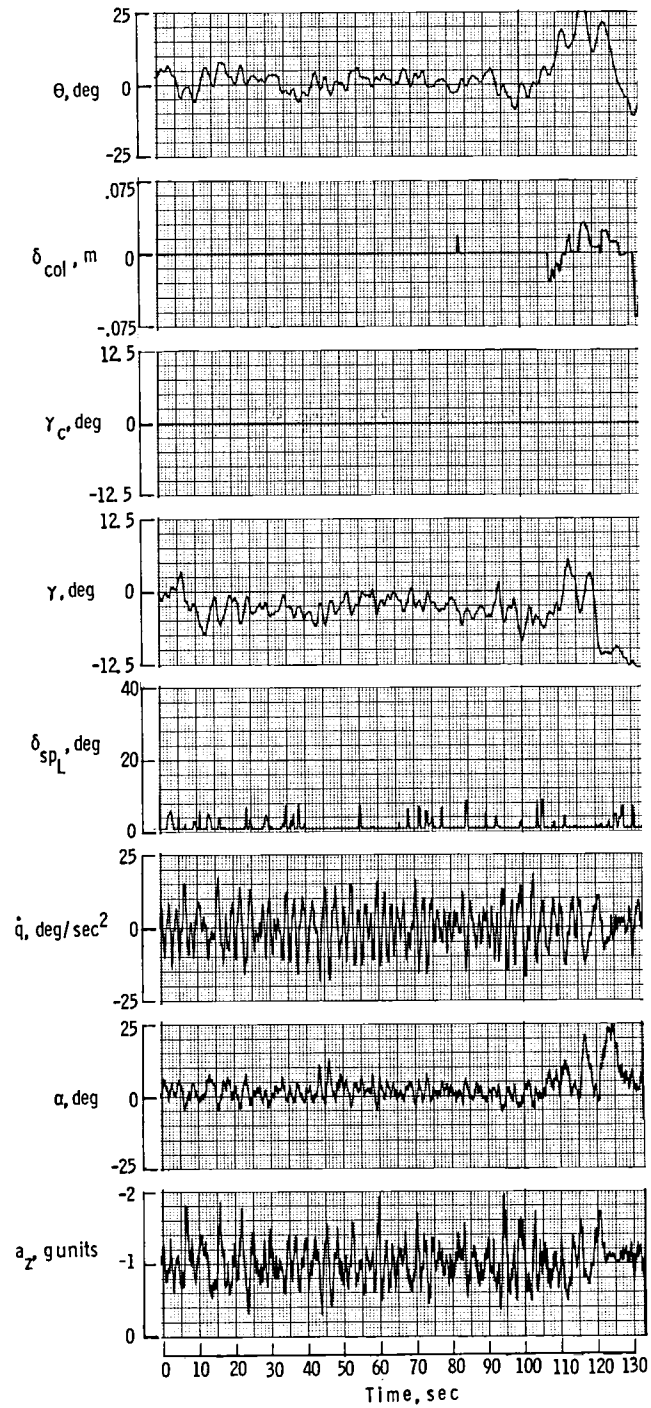
Figure 12.- Typical flight using VCWS in severe shear D10.
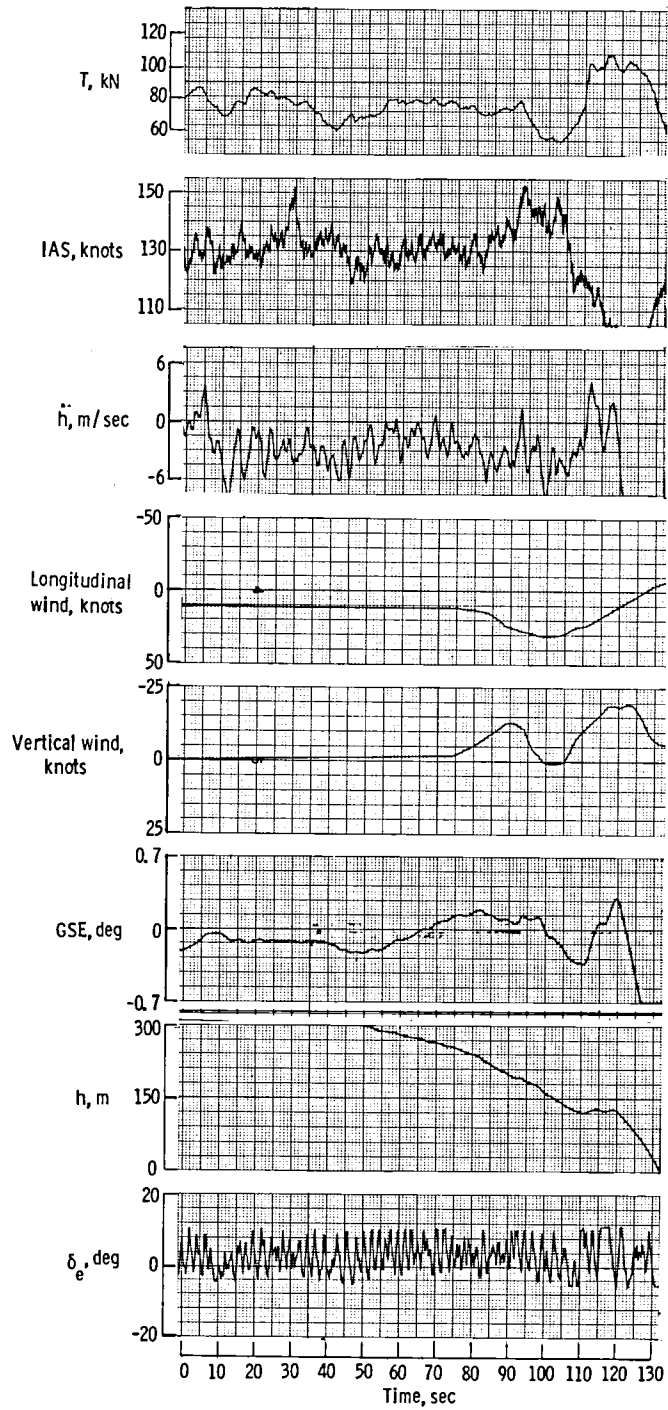
Figure 12.- Concluded.
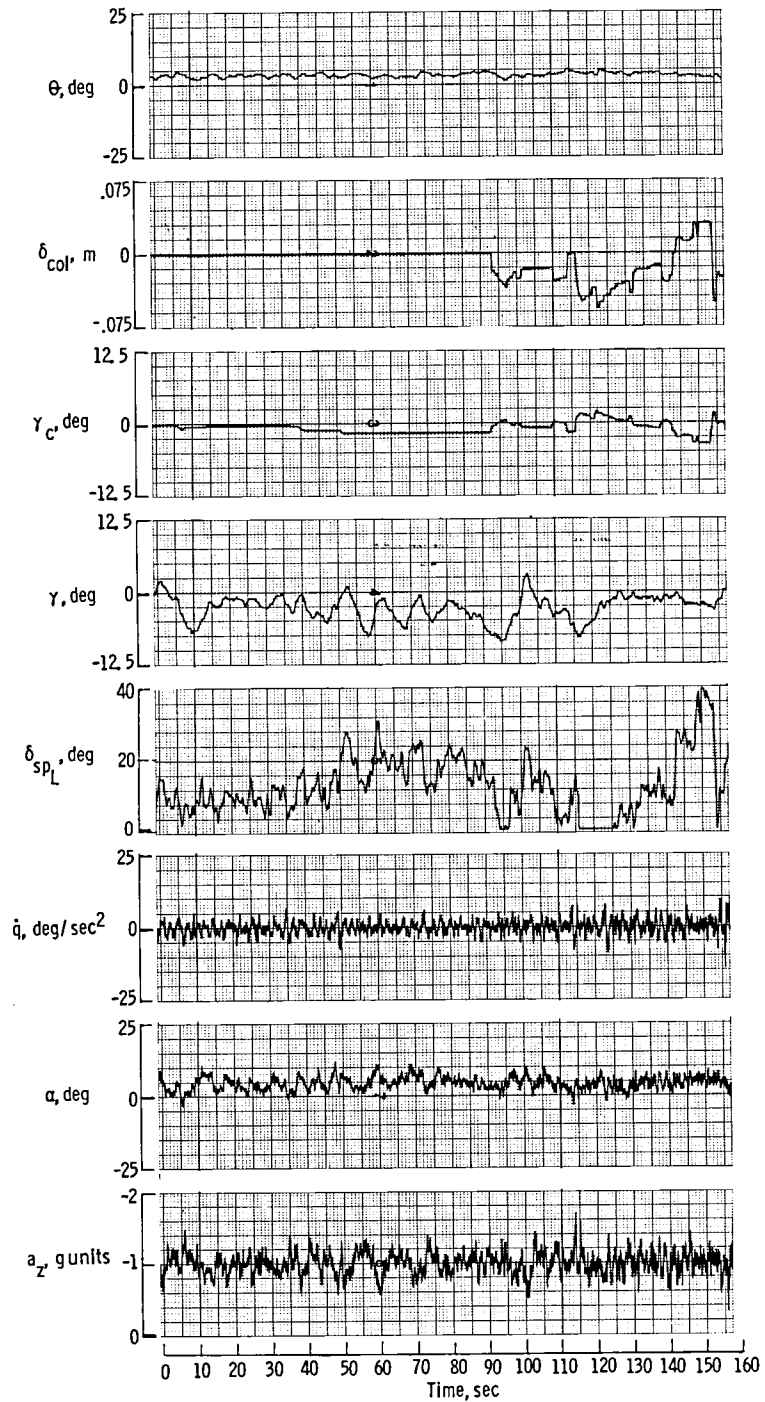
Figure 13.- Typical flight using decoupled controls in severe shear D10.
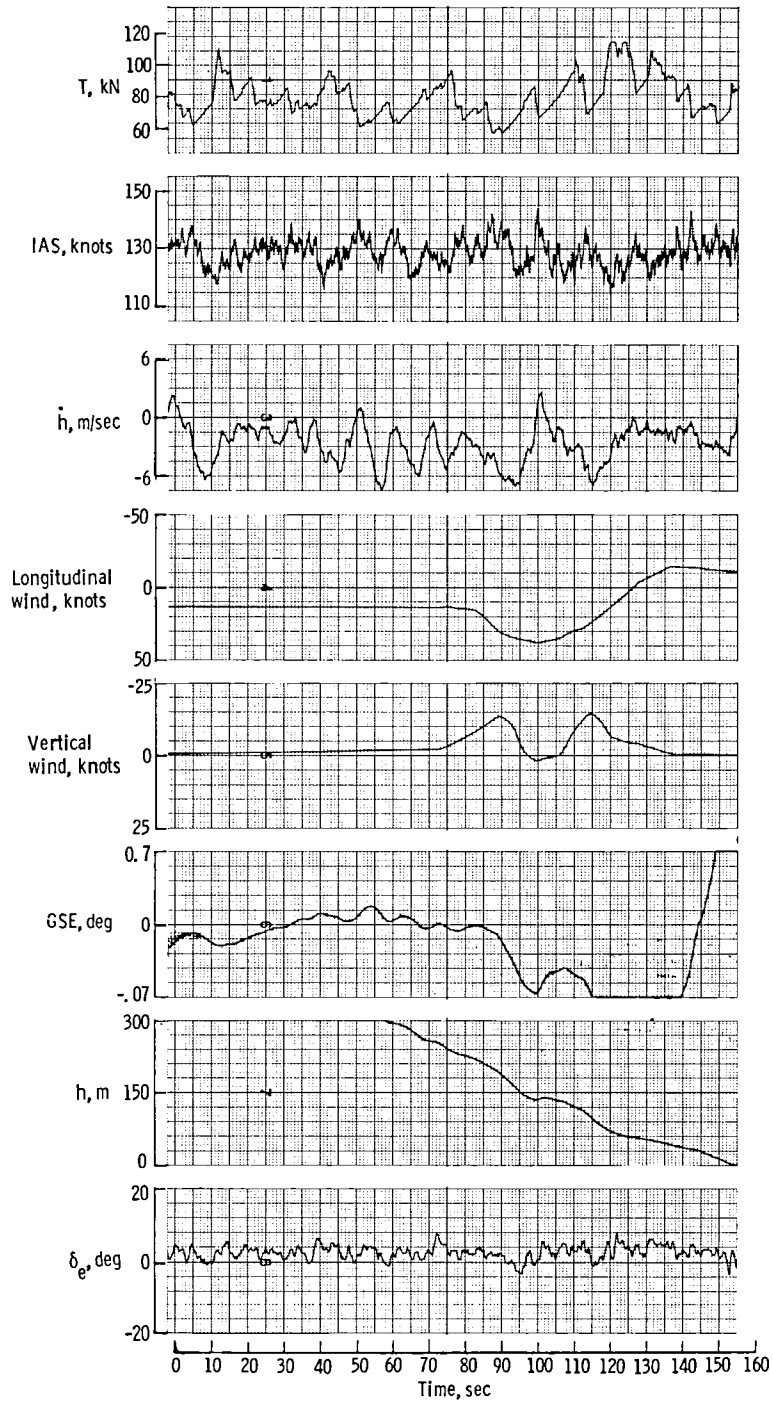
Figure 13.- Concluded.
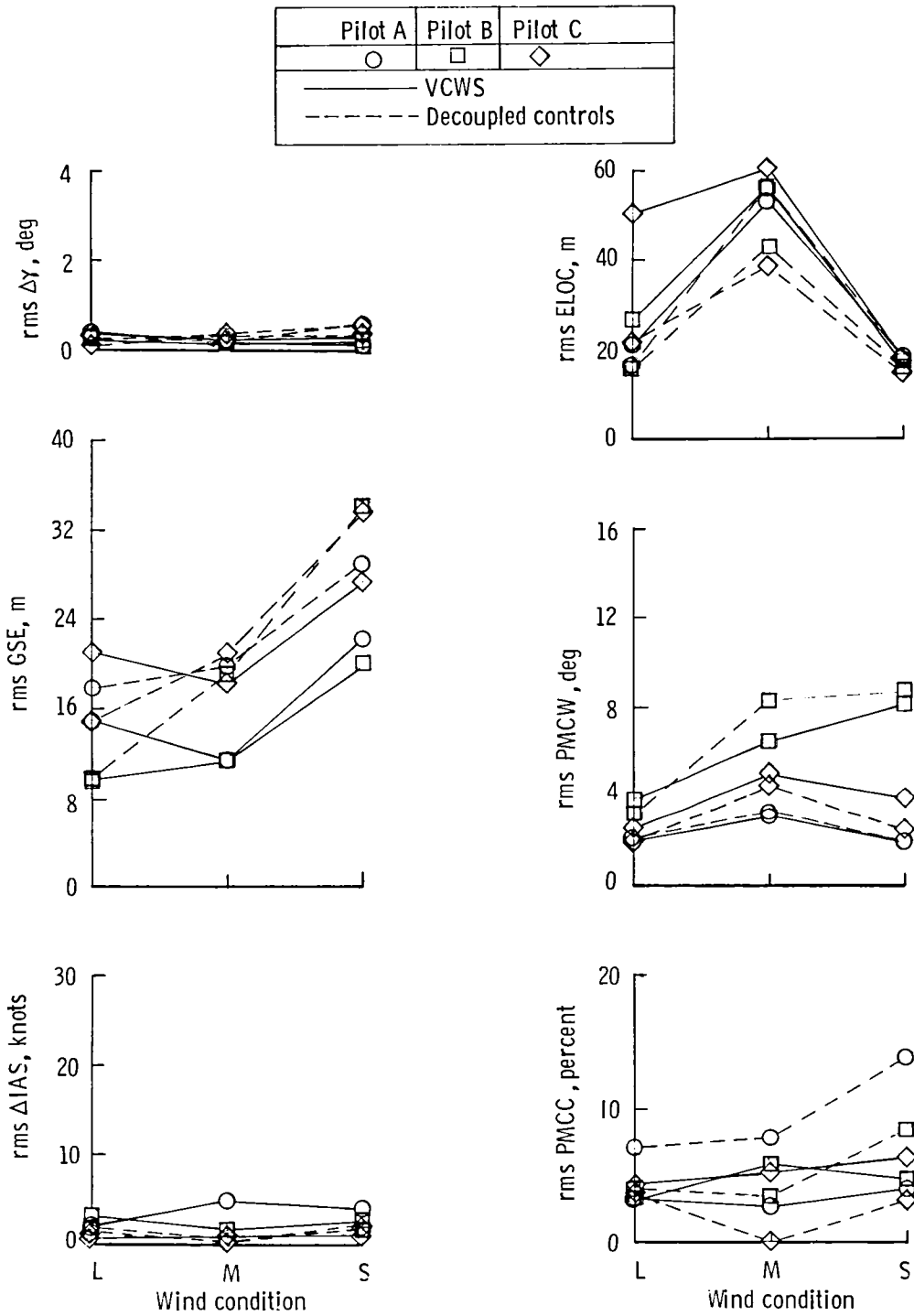
Figure 14.- Mean approach performance parameters (at altitudes between 457.2 m and 228.0 m).
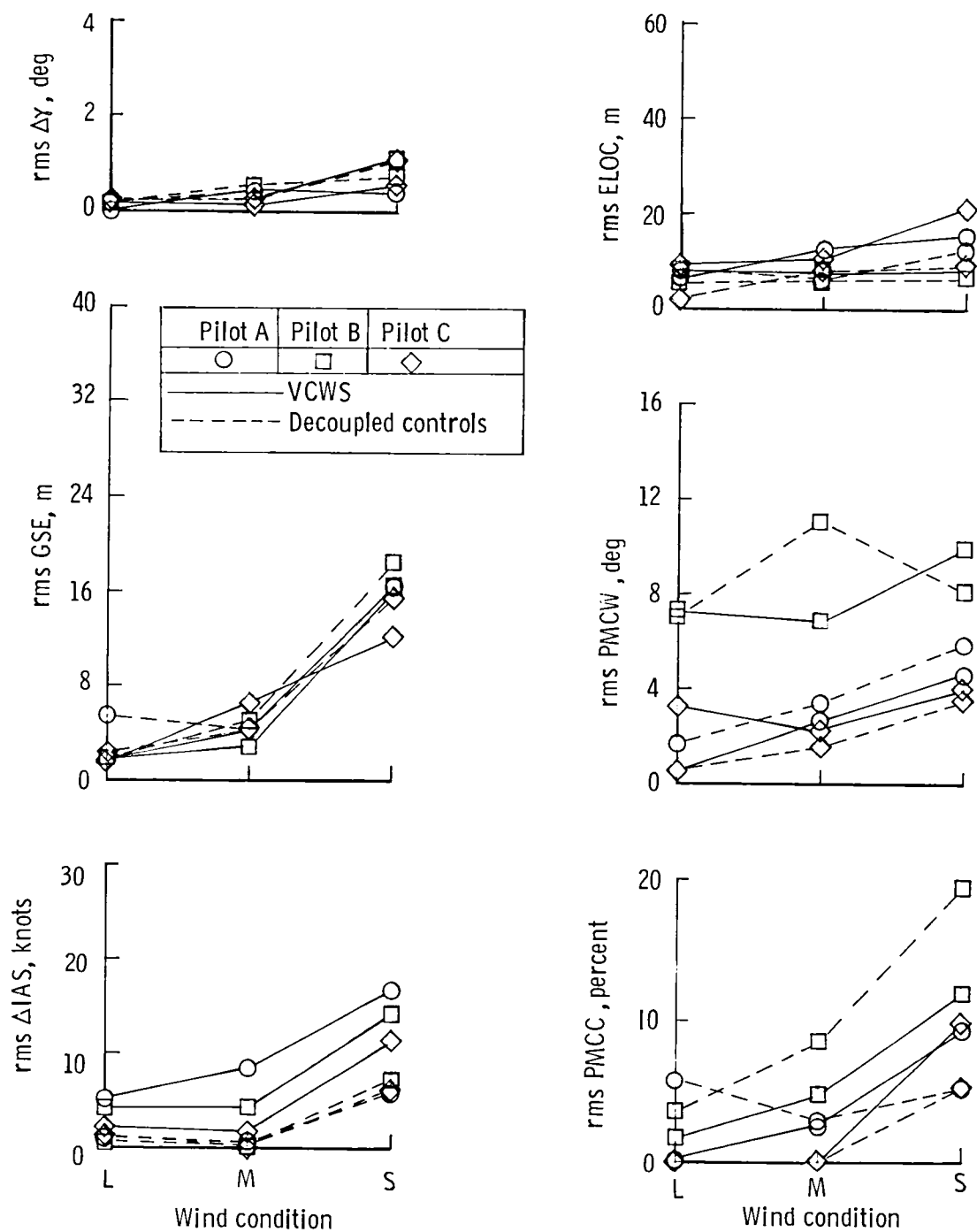
Figure 15.- Mean approach performance parameters (at altitudes between 76.1 m and 30.4 m).
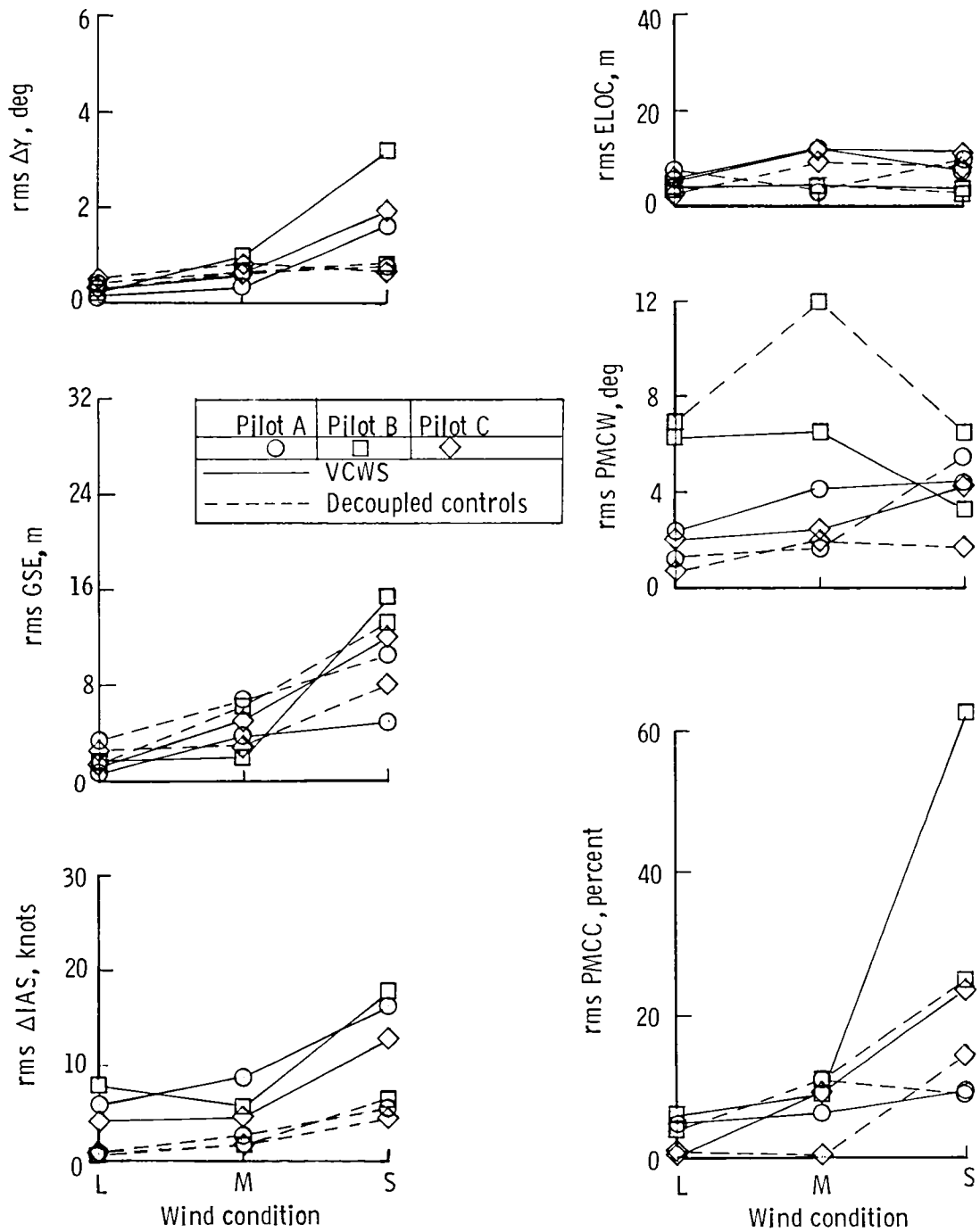
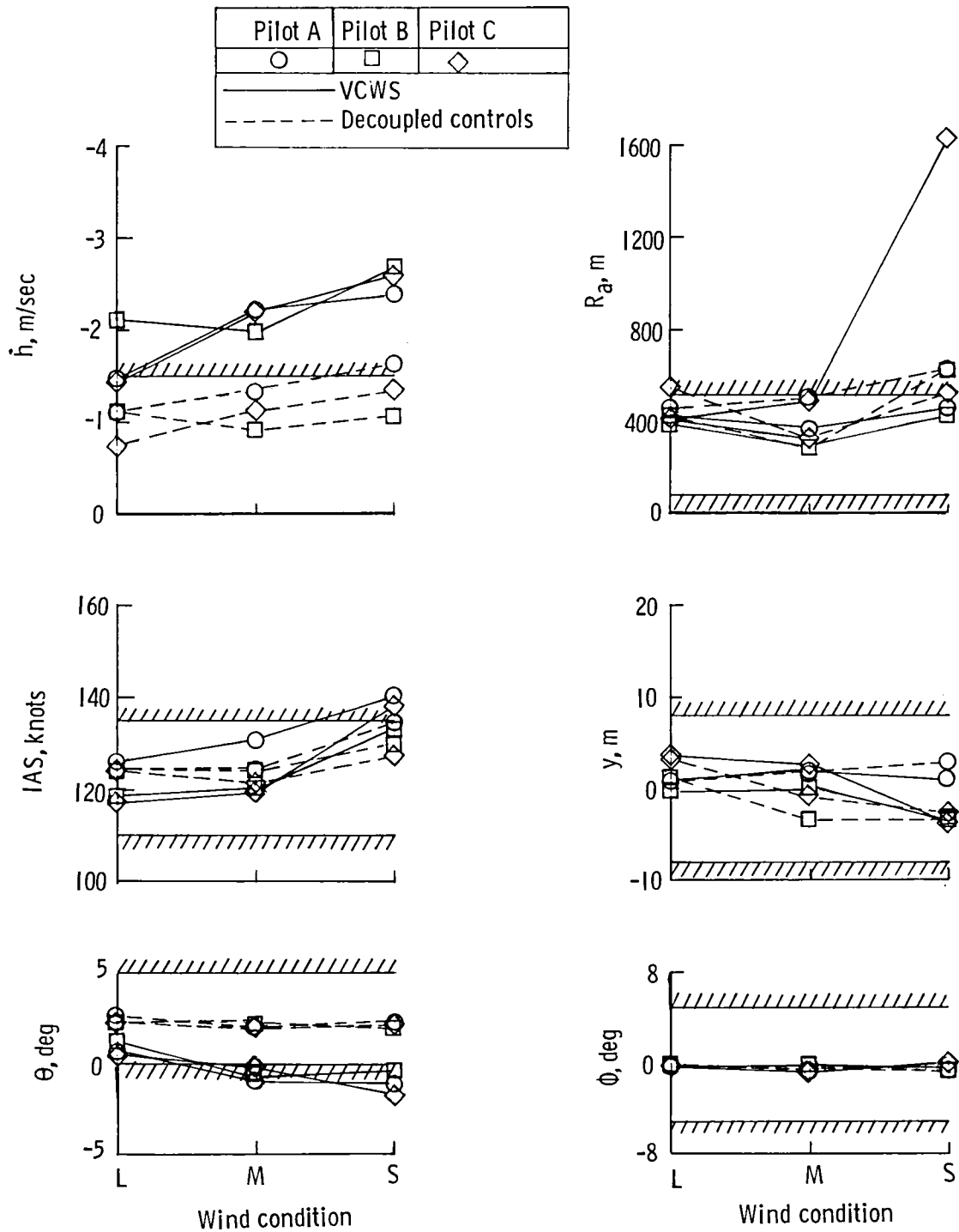Figure 16.- Mean approach performance parameters (at altitudes between 30.4 m and 15.1 m).

Figure 17.- Mean touchdown performance parameters. Limits denoted by hatched lines are defined in reference 6.

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15. Supplementary Notes

16. Abstract

This report presents a simulator comparison of the velocity-vector control wheel steering (VCWS) system that currently exists on the NASA Terminal Configured Vehicle (TCV) and a decoupled longitudinal control system. The piloting task was to use the electronic attitude-direction indicator (EADI) to capture and maintain a 3° glide slope in the presence of wind shear and to complete the landing using the perspective runway included on the EADI. The decoupled control system used constant prefilter and feedback gains to provide steady-state decoupling of flight-path angle, pitch angle, and forward velocity. The decoupled control system improved the pilots' ability to control airspeed and flight-path angle during the final stages of an approach made in severe wind shear. The system also improved their ability to complete safe landings. The pilots preferred the decoupled control system in severe winds and, on a pilot rating scale, rated the approach and landing task with the decoupled control system as much as 3 to 4 increments better than use of the VCWS system.

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