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SUMMARY

This paper addresses the issues of motion/visual cueing fidelity requirements for vortex encounters during simulated transport visual approaches and landings. Four simulator configurations were utilized to provide objective performance measures during simulated vortex penetrations, and subjective comments from pilots were collected. The configurations used were as follows: fixed base with visual degradation (delay), fixed base with no visual degradation, moving base with visual degradation (delay), and moving base with no visual degradation.

The objective measures were chosen as a method of comparing performances during touchdown and as a method of comparing performances during the period immediately following the vortex encounter, based on the hypothesis that visual/motion effects may be more easily discriminated when pilot-vehicle stability margins are small.

The statistical comparisons of the objective measures and the subjective pilot opinions indicated that although both minimum visual delay and motion cueing are recommended for the vortex penetration task, the visual-scene delay characteristics were not as significant a fidelity factor as was the presence of motion cues. However, this indication was applicable to a restricted task and to transport aircraft.

Although they were statistically significant, the magnitudes of the effects of visual delay and motion cueing on the touchdown-related measures were considered to be of no practical consequence.

INTRODUCTION

Most current efforts directed toward improving the capacity of future high-density terminal areas are dependent on a solution of vortex-imposed separation requirements (ref. 1). Consequently, extensive research has begun on wake vortex characteristics and on the behavior of aircraft during vortex encounters. (See refs. 2, 3, and 4.) This concentration of activity and interest has also spawned the requirement for, and the capability of, providing real-time man-in-the-loop flight simulators for vortex studies.

As is the case in most efforts to develop a flight simulator to meet a stated requirement, the issues of the numerous trade-offs between simulation fidelity and the associated costs of available simulation devices have surfaced, as well as the interrelated issue of simulator validation. Hastings et al. (refs. 5 and 6) conducted a recent investigation of simulated wake vortex penetration at NASA Langley Research Center that successfully addressed the issue of simulator validation. This investigation resulted in closely correlated data from the Langley Vortex Research Facility, from actual flight tests, and from the Langley Visual/Motion Simulator. The flight simulator utilized in that study was configured with visual and motion cueing devices that, although commonly available as standard devices, have undergone several years of concentrated and documented improvement in both dynamic characteristics and drive techniques. (See refs. 7 to 11.)

This paper addresses the issues of motion/visual cueing fidelity requirements for vortex encounters during simulated visual approaches and landings of transport airplanes. Data are presented and compared for the following combinations of degraded cueing configurations: fixed base with visual degradation (delay), fixed base with no visual degradation, moving base with visual degradation (delay), and moving base with no visual degradation. The latter configuration was utilized previously by Hastings et al. Prior to the presentation of these comparisons, a brief description of the simulator characteristics and the experimental task, as well as some additional validation data, are presented.

SYMBOLS

$\bar{c}$	mean aerodynamic chord, m
g	gravitational constant, 9.81 m/sec^2
$\dot{h}$	sink rate, m/sec
h_{min}	minimum altitude achieved before sink-rate arrest, m
x	longitudinal position at touchdown as measured from glide-path intercept point, m
y	lateral position at touchdown as measured from runway centerline, m
ϕ_1	initial extrema roll upset angle, deg
ϕ_2	second extrema roll angle, deg
$\dot{\phi}_1$	initial extrema roll-rate upset, deg/sec
$\dot{\phi}_2$	second extrema roll rate, deg/sec

SIMULATOR CHARACTERISTICS

Airplane Mathematical-Model Characteristics

The mathematical model of a Boeing 737-100 airplane included a nonlinear data package for all flight regions; a nonlinear engine model; and nonlinear models of servos, actuators, and spoiler mixers. The simulation of the basic airframe was validated prior to its use in numerous studies.

For this investigation, the simulated aircraft was in the landing-approach configuration with the approximate flight characteristics presented in table I. The manual mode was used for flight control.

Additions to the aircraft force and moment equations caused by vortex flow fields were made based on a strip theory technique described in reference 12. Validation data demonstrating the successful application of this technique for imposing vortex-induced forces and moments on the basic penetrating aircraft dynamics are presented in references 5 and 6. Figure 1 presents additional validation data obtained during the present study by comparing piloted simulator data with flight data. The flight data from reference 13 show the time response of a piloted B-737-100 airplane as it encounters a clockwise vortex, shed by a B-747 in-ground effect at a separation distance of 1.8 n.mi. The pilot stabilized the B-737-100 airplane after complete penetration and initiated a go-round. In the simulated case, the separation distance was 1.75 n.mi., and the pilot maneuvered back to the runway and continued his approach to a successful landing. (The simulator data are representative of five similar approaches with the same encounter geometries.)

Computer Implementation

The mathematical model of the airplane, the inclusion of the vortex modifications to the airplane model, and the simulation hardware drives were implemented on the Langley Flight Simulation Computing Subsystem. This subsystem, consisting of a Control Data CYBER 175 computer and associated interface equipment, solved the programmed equations 32 times per second. The average time delay from input to output (1.5 times the sample period) was approximately 47 msec.

Simulator Cockpit

The general-purpose cockpit of the Langley Visual/Motion Simulator (VMS) was configured as a transport cockpit. The primary instrumentation consisted of an attitude direction indicator (including active flight director bars and speed bug), a vertical-speed indicator, a horizontal-situation indicator, an altimeter, airspeed indicators (both indicated and true), angle-of-attack and angle-of-sideslip meters, and a turn-and-slip indicator. A stereo sound system was used to simulate engine noise.

The control forces on wheel, rudder pedals, and column were provided by a hydraulic system coupled with an analog computer. The system allows for the usual variable-feel characteristics of stiffness, damping, backlash, Coulomb friction, breakout forces, detents, and inertia. The stiffness (force gradient) was provided by the digital computer used to solve the aircraft mathematical model. Selection of the values of the parameters of the control loading system was included in the extensive validation process for the 737-100 flight simulation.

Visual Display

The VMS is provided with an "out-the-window" virtual-image system of the beam-splitter, reflective-mirror type. The system, located nominally 1.27 m from the pilot's eye, has a nominal field of view 48° wide and 36° high and uses a 525-line TV raster system. The display system provides a 46° by 26° instantaneous field of view. The system supplies a color picture of unity magnification with a resolution on the order of 9 minutes of arc.

The scene depicted in the virtual-image system was obtained from a television-camera transport system used in conjunction with a terrain model board. The model board, 7.32 m by 18.3 m, offers terrain and an airport complex at a 1500:1 scale, complete with taxi lights, visual approach slope indicators (VASI), runway end identifier lights (REILS), and so forth. Provision is made for day, dusk, and night scenes, including airplane landing lights during night landings. The maximum horizontal speed capability of the system is 444 knots, with a vertical-speed capability of ±30 000 ft/min.

The approximate second-order transfer-function parameters for the camera transport system are presented in reference 10 and show translational steady-state time lags of 15 msec or less and rotational lags of 22 msec or less. The average total visual delay, including computational throughput delay, was thus less than 70 msec.

An added visual delay of 126.5 msec, producing a total delay of about 200 msec, was imposed for the degraded visual fidelity factor. Thus, two levels of visual fidelity were examined, the VMS with its present capabilities and one with longer delay, intended to generally represent CGI (computer generated image) delay characteristics.

Motion System

The motion performance limits of the six-degree-of-freedom VMS are shown in figure 2. These limits are for single-degree-of-freedom operation. Conservatism must be exercised in the use of the position limits, because they change as the orientation of the synergistic base varies. References 7 and 14 to 16 document the characteristics of the system, which possesses steady-state time lags of less than 15 msec. Thus, the average total motion delay, including computational throughput, is less than 70 msec (ignoring the lead introduced by washout) and is quite compatible with the visual delays. The washout system used to present the motion-cue commands to the motion base is nonstandard (conventional washout systems are linear). It was conceived and developed at NASA Langley Research Center and is documented in references 8, 9, and 17. The nonlinear adaptive washout filters of this washout method are based on the optimization techniques of continuous steepest descent.

Motion was restricted to five degrees of freedom because of the objectionable hydraulic noise induced by the vertical motion of the synergistic base, and because only a small amount of vertical cue was available. The small amount of vertical-acceleration cue available was due to a combination of position limits of the motion base and the short-period frequency of the 737-100 airplane in the landing-approach configuration. The cue available for heave (vertical acceleration) under these conditions was less than 0.05g, which is the product of amplitude (0.4572 m) and the square of frequency (frequency was less than 1 rad/sec). Therefore, the heave axis was not used.

EXPERIMENTAL DESIGN

Five NASA research pilots participated in the full-factorial experiment. Each pilot repeated the task five times for each experimental condition.

The two factors of two levels each resulted in four experimental conditions. These conditions were, in terms of cue fidelity configurations, fixed base with visual degradation (delay), fixed base with no visual degradation, moving base with visual degradation (delay), and moving base with no visual degradation. A training period was conducted for each fidelity configuration to reduce learning effects.

Approach, Flare, and Touchdown Task

The simulated airplane was trimmed in a 3° descent at an airspeed of 125 knots on the glide slope and localizer at a range of 1.44 km from the runway threshold. The aim point on the runway was 305 m beyond the threshold. The pilot's task was to fly the approach through the vortex encounter, which always occurred at an altitude of 61 m. The vortex characteristics were identical for each run (122 m long, no ground effect, 1.75-n.mi. separation distance), and the vortex was aligned with the aircraft attitude at the time of the encounter to produce identical disturbances. The only variance introduced into this process was the random change of the sign of the disturbance to cause either an initial right-wing-down or left-wing-down upset. The pitch upset was always negative and required an immediate elevator input to avoid a crash. After stabilizing the aircraft, the pilot attempted to regain the runway centerline; then, while controlling speed, the pilot would complete the approach and then flare visually and touch down.

Time-history comparisons from a typical run for a fixed base condition with no visual degradation and from a typical run for a moving base condition with no visual degradation are presented in figure 3.

Objective Performance Measures

Analyses of variance were planned for the five encounter-related objective performance measures shown in figure 3, as well as on the measures of touchdown performance (longitudinal and lateral touchdown positions on the runway, and sink rate at touchdown). The encounter-related objective measures were chosen to be extrema that occurred during, or because of, the upset, based on the hypothesis that motion effects may be more easily discriminated when the pilot/vehicle stability margins are small. The measures used in figure 3 are as follows:

ϕ_1	initial extrema roll upset angle, deg
ϕ_2	second extrema roll angle, deg
$\dot{\phi}_1$	initial extrema roll-rate upset, deg/sec
$\dot{\phi}_2$	second extrema roll rate, deg/sec
h_{min}	minimum altitude achieved before sink-rate arrest, m

EXPERIMENTAL RESULTS

Table II is a summary of the analyses of variance for the eight performance measures. The discussion of these objective results is in two parts. The first part concerns the encounter-related measures, and the second part concerns the touchdown-related data. Subjective results are presented last.

Analysis of Objective Results

Encounter-Related Measures

The results are presented in figure 4 and table III for the encounter-related measures in terms of the visual by motion interaction, which contrasts the four cue fidelity configurations. The discussion of these results, however, follows the statistically significant sources of variance identified in table II.

Pilots.- The main effect of pilot variability was highly significant for all measures except $\dot{\phi}_1$. This measure reflects the severity of the initial roll-rate upset of the vortex encounter, and very little pilot reaction to that upset takes place before the maximum value is obtained. Therefore, it is not surprising that no pilot differences were detected with this measure. For the other measures, as in most tasks bordering on stability boundaries of pilot-vehicle systems, the pilot effect is large. (See ref. 14.)

Visual.- The effect of degraded visual fidelity, or additional visual delay, was detectable in ϕ_1, in the related measure $\dot{\phi}_2$, and in the altitude measure. The additional visual delay resulted in a somewhat larger initial bank angle due to delayed pilot reaction. Therefore, there was a larger roll rate to offset that bank angle. A lower altitude measure, caused by delayed pilot reaction, was also evident. Although these differences were detectable statistically, figure 4 indicates that degraded visual fidelity is probably not crucial to acceptable performance, especially if motion is present. Visual delays of the magnitude imposed in this study have a substantial effect, however, on fighter aircraft simulations. (See refs. 18 and 19.)

Pilot by visual interaction.- There were significant interactions between pilots and visual fidelity for ϕ_2 and h_{min}. No delay effect was apparent for four of the five pilots with the ϕ_2 measure. Visual delay was accompanied by a larger bank angle for the singular pilot. In the case of the altitude measure, for which the main effects (pilots and visual) were significant, the interaction was also significant and is interpreted to mean that the visual delay effect was more pronounced for three of the pilots. It was present to a lesser degree for the other two pilots.

Motion.- The motion effect was significant for all the encounter-related measures. Motion cueing produced smaller values for the lateral-axis measures than for the fixed-base performance, and the minimum-altitude measures were higher. These results imply that motion cues have an alerting function and supply lead information during the occurrence of a vortex encounter. The magnitudes of the differences between the fixed-base and moving-base performances shown in figure 4 are large enough, particularly with visual delays present, to suggest a need for motion cueing.

Pilot by motion interaction.- The interaction between pilots and motion was significant for all measures except $\dot{\phi}_2$. This indicates a more pronounced motion effect for some pilots. (Motion cueing affected all pilots in the same direction.) These pilot-dependent effects were not consistent across the measures, however, with the ranks of pilot sensitivities changing from measure to measure.

Visual by motion interaction.- The visual by motion interaction is presented graphically in figure 4 for all the encounter-related measures. However, the interaction was significant only for the initial maximum bank angle ϕ_1. For this measure, the presence of motion cues made the visual delay effect less noticeable. The visual delay effect was constant across motion conditions for the other measures for which it was significant.

General conclusions.- Although both minimum visual delay and motion cueing are recommended for this simulation task, the visual delay characteristics were not as significant a fidelity factor as was the presence or absence of motion cues.

Touchdown-Related Measures

The results from the analyses of the touchdown data (table II) are not incidental to the fidelity issues of vortex encounter simulation when the possibility of runway occupancy studies in a vortex environment is considered. In such studies, which most often deal with high-speed runway exits, the initial conditions on the runway are thought to be critical study parameters.

The sink-rate results for the fidelity configurations are presented in figure 5 and table IV.

Pilots.- Pilot differences were again highly significant for all measures. (See table II.)

Visual.- Visual delay effects were evident only in the sink-rate measure, with slightly higher touchdown rates (about 0.2 m/sec) associated with increased visual delay.

Motion.- The presence of motion cues was detectable statistically at slightly lower sink rates (about 0.2 m/sec) and slightly longer landings (about 100 m longer).

Pilot by motion interaction.- Two of the pilots made much longer landings with motion cues than with the fixed-base condition, and the motion effect was less pronounced (but still present) for the other pilots. These results are reflected in the significance of this interaction term for the longitudinal measure.

Pilot by visual by motion interaction.- The significance of this interaction, after further analysis, indicates that the visual delay effect on sink rate was more pronounced under fixed-base operation for three of the pilots. The effects were inconsistent for the other two pilots.

General conclusions.- Although the visual delay effects and the presence or absence of motion cues were statistically significant in some of the touchdown-related measures, the differences were not large enough to require practical consideration.

Subjective Results

Unstructured pilot comments recorded during the experiment indicate that the degradation in the visual fidelity was barely discernible, and the contrast between fixed base and moving base was most pronounced. All the pilots felt that motion cues were not only desirable, but also probably necessary for reasonable vortex encounter simulations. In addition to the alerting functions (both occurrence and direction), motion provided information that allowed the pilot to damp the disturbance more rapidly after the initial upset had occurred.

CONCLUDING REMARKS

The satisfactory occurrence of agreement between objective measures and subjective options is evident in the results of this visual/motion cueing fidelity study. These results suggest that, in the simulation of vortex encounters by transport aircraft during visual approach and landing, although both minimum visual delay and motion cueing are recommended, the visual-scene delay characteristics are not as significant a fidelity factor as is the presence of motion cues. However, this indication is applicable to a restricted task and to transport aircraft. Visual delays are known to have pronounced effects on fighter aircraft simulations.

The results also suggest that although the visual delay effects and the presence or absence of motion cues were statistically significant in some of the touchdown-related measures, the differences were not large enough to require practical consideration.

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February 16, 1983

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TABLE I.- LINEAR APPROXIMATIONS OF THE FLIGHT CHARACTERISTICS OF THE B-737-100 AIRPLANE AT 125 KNOTS

Weight, N	400 341
Center of gravity	$0.31\bar{c}$
Flap deflection, deg	40
Landing gear	Down
Damping ratio for -	
Short period	0.562
Long period	0.089
Dutch roll	0.039
Period, sec, for -	
Short priod	6.30
Long period	44.3
Dutch roll	5.12
Spiral divergence	24.0
Roll subsidence	0.53

TABLE II.- SUMMARY OF ANALYSES OF VARIANCE

Factor (a)	Degrees of freedom	Significance[b] of performance measures							
		Encounter-related					Touchdown-related		
		ϕ_1	ϕ_2	$\dot{\phi}_1$	$\dot{\phi}_2$	h_{min}	x	y	$\dot{h}$
P	4	**	**	—	**	**	**	**	**
V	1	**	—	—	*	**	—	—	**
P × V	4	—	*	—	—	**	—	—	—
M	1	**	*	**	**	**	**	—	**
P × M	4	**	**	**	—	**	**	—	—
V × M	1	**	—	—	—	—	—	—	—
P × V × M	4	—	—	—	—	—	—	—	*
Repetitions	4	—	—	—	—	—	—	—	—
Error	76								

[a] Factors are as follows: P - pilot; V - visual; M - motion.

[b] Significance shown as follows:

— not significant at levels considered.

* significant at 5-percent level.

** significant at 1-percent level.

TABLE III.- MEANS AND STANDARD DEVIATIONS FOR ENCOUNTER-RELATED MEASURES ACROSS CUEING FIDELITY CONDITIONS

Performance measures	Fixed-base configuration				Moving-base configuration			
	No visual degradation		Visual degradation		No visual degradation		Visual degradation	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
ϕ_1, deg	34.04	4.56	37.32	3.14	29.44	5.65	30.34	6.34
ϕ_2, deg	20.86	5.03	21.76	7.20	18.52	7.30	19.36	6.73
$\dot{\phi}_1$, deg/sec	34.38	2.23	34.90	2.01	31.57	2.69	31.29	2.81
$\dot{\phi}_2$, deg/sec	39.71	4.18	41.78	6.99	37.07	5.44	38.33	5.10
h_{min}, m	24.56	4.69	22.03	5.52	29.91	4.33	29.02	5.78

TABLE IV.- MEANS AND STANDARD DEVIATIONS FOR SINK RATE AT TOUCHDOWN ACROSS CUEING FIDELITY CONDITIONS

Fixed-base configuration				Moving-base configuration			
No visual degradation		Visual degradation		No visual degradation		Visual degradation	
Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
1.08	0.53	1.34	0.63	0.92	0.55	1.06	0.55

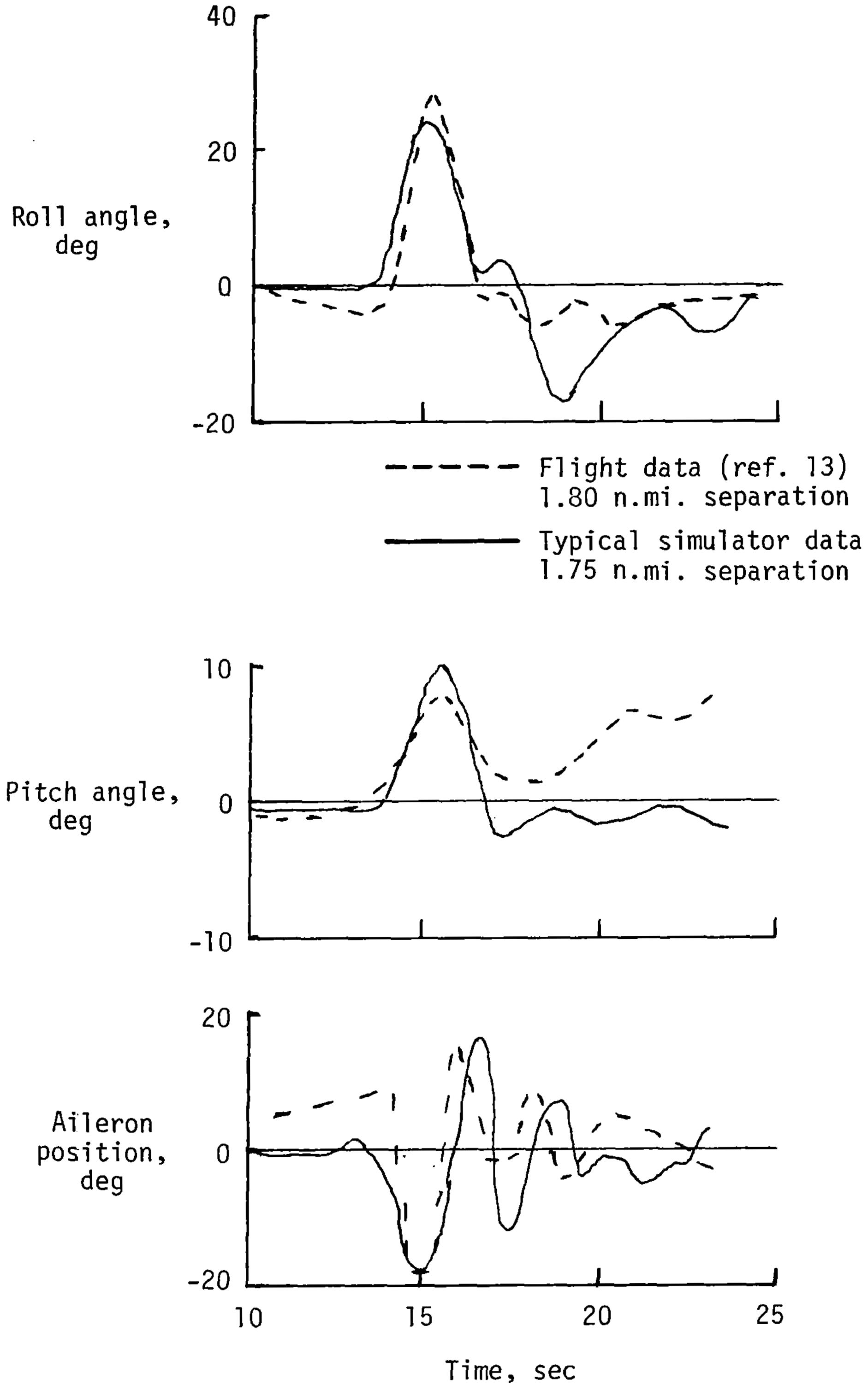
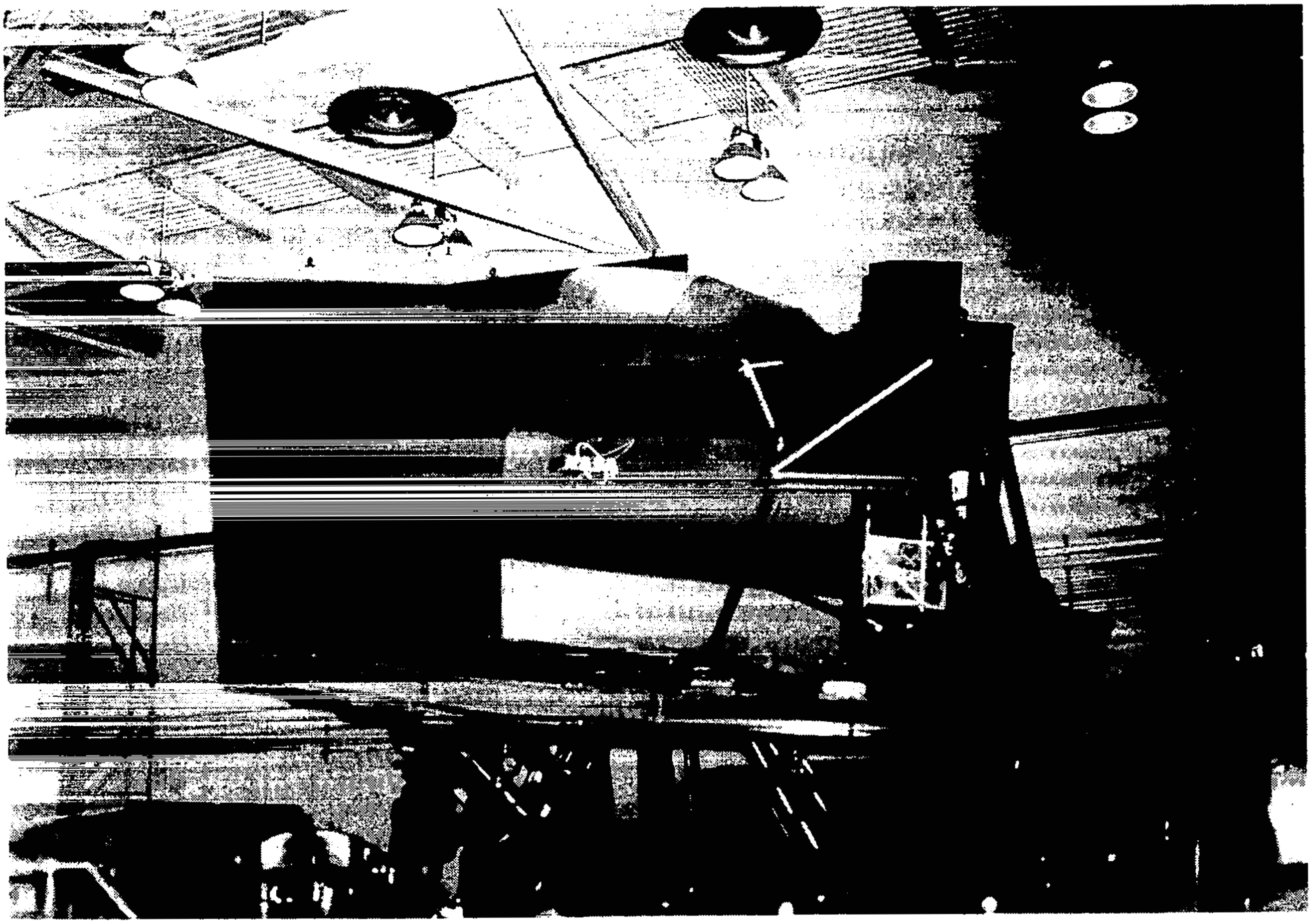


Figure 1.- Encounter with clockwise vortex in-ground effect.



	Position	Velocity	Acceleration
Pitch	+30, -20°	±15 deg/sec	±50 deg/sec^2
Roll	±22°	±15 deg/sec	±50 deg/sec^2
Yaw	±32°	±15 deg/sec	±50 deg/sec^2
Vertical	+0.762, -0.991 m	±0.610 m/sec	±0.6g
Lateral	±1.219 m	±0.610 m/sec	±0.6g
Longitudinal	+1.245, -1.219 m	±0.610 m/sec	±0.6g

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Figure 2.- Motion performance limits of the Langley Visual Motion Simulator.

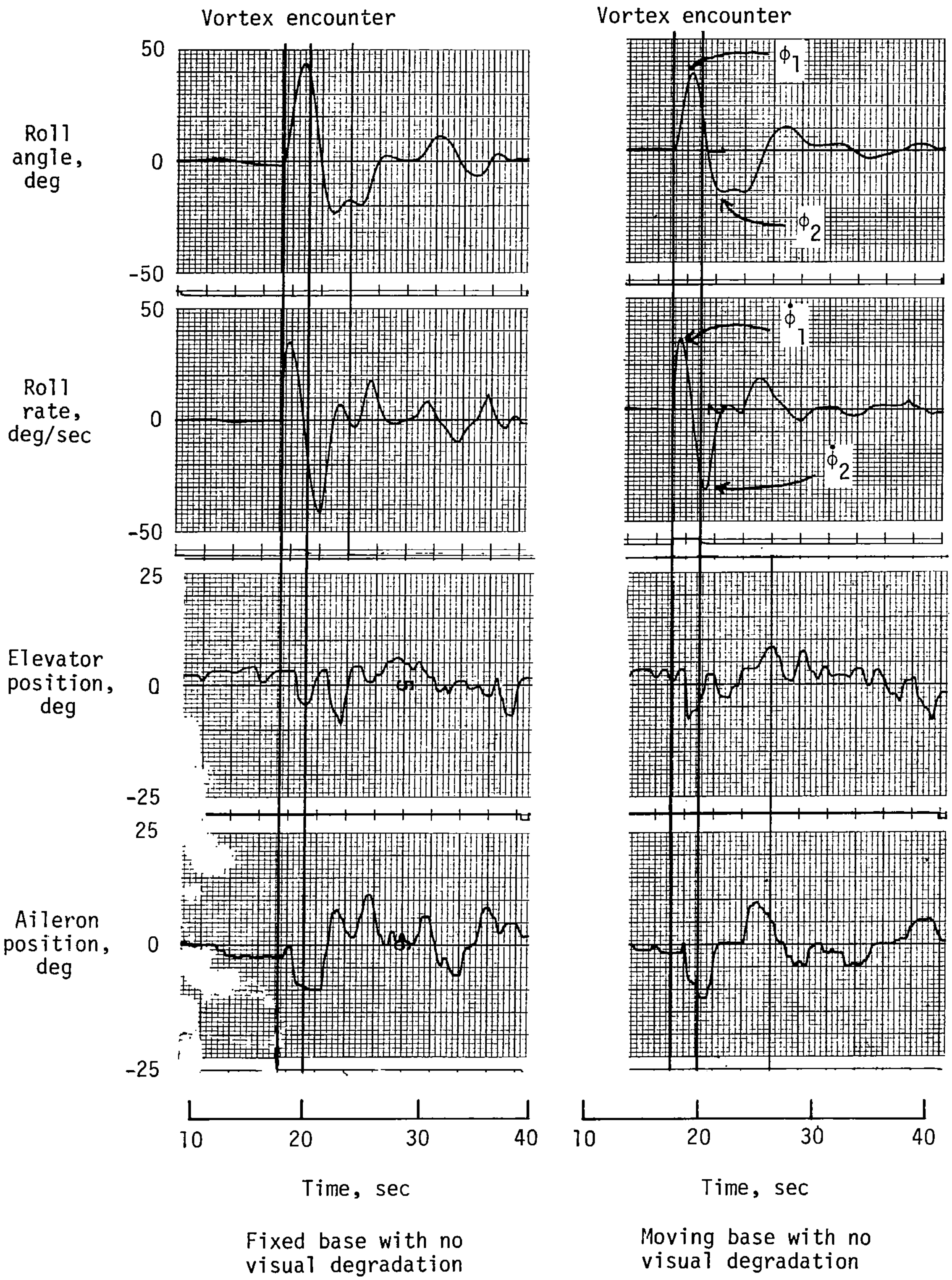
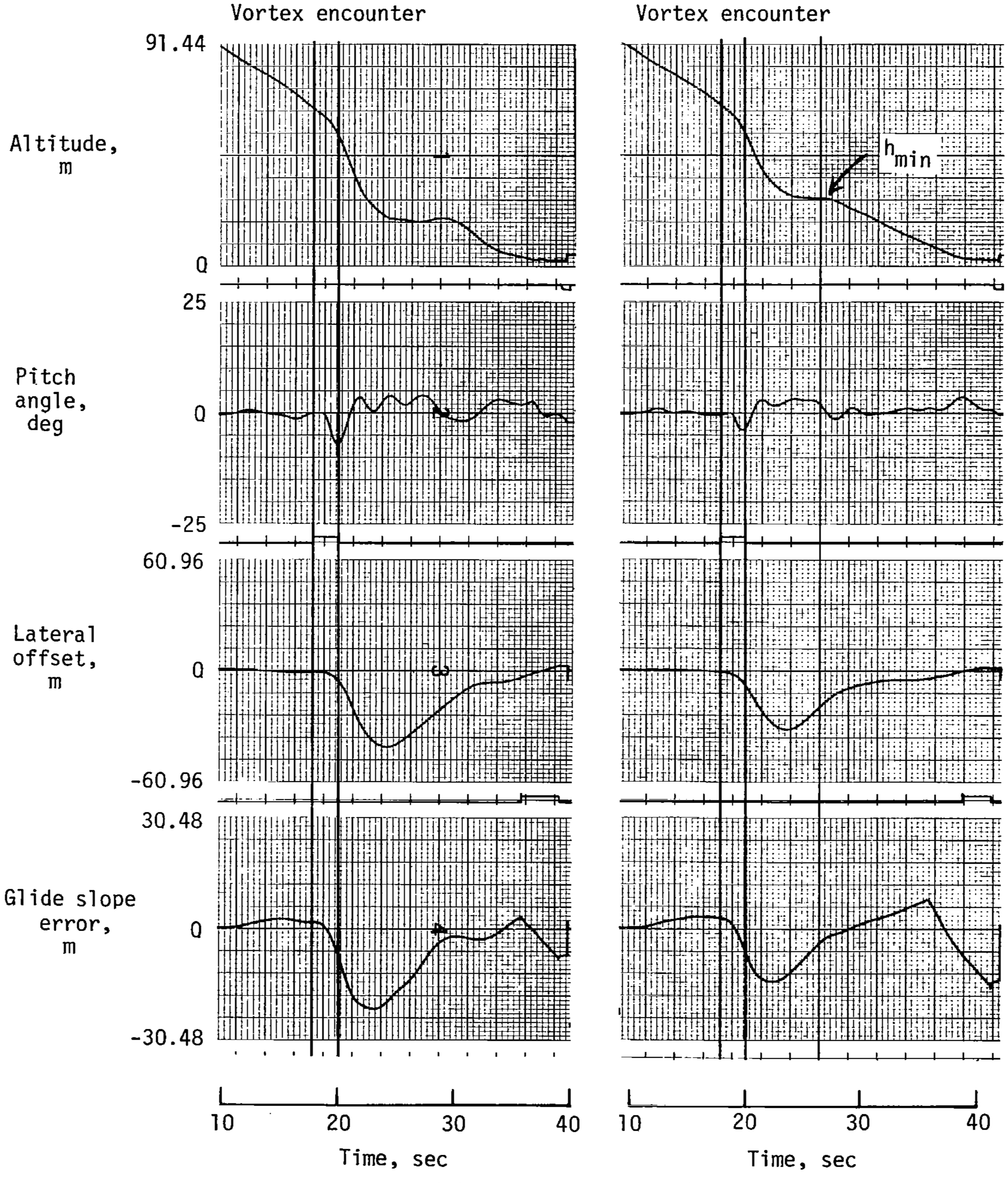


Figure 3.- Time histories of typical fixed-base and moving-base vortex encounters.



Fixed base with no visual degradation

Moving base with no visual degradation

Figure 3.- Concluded.

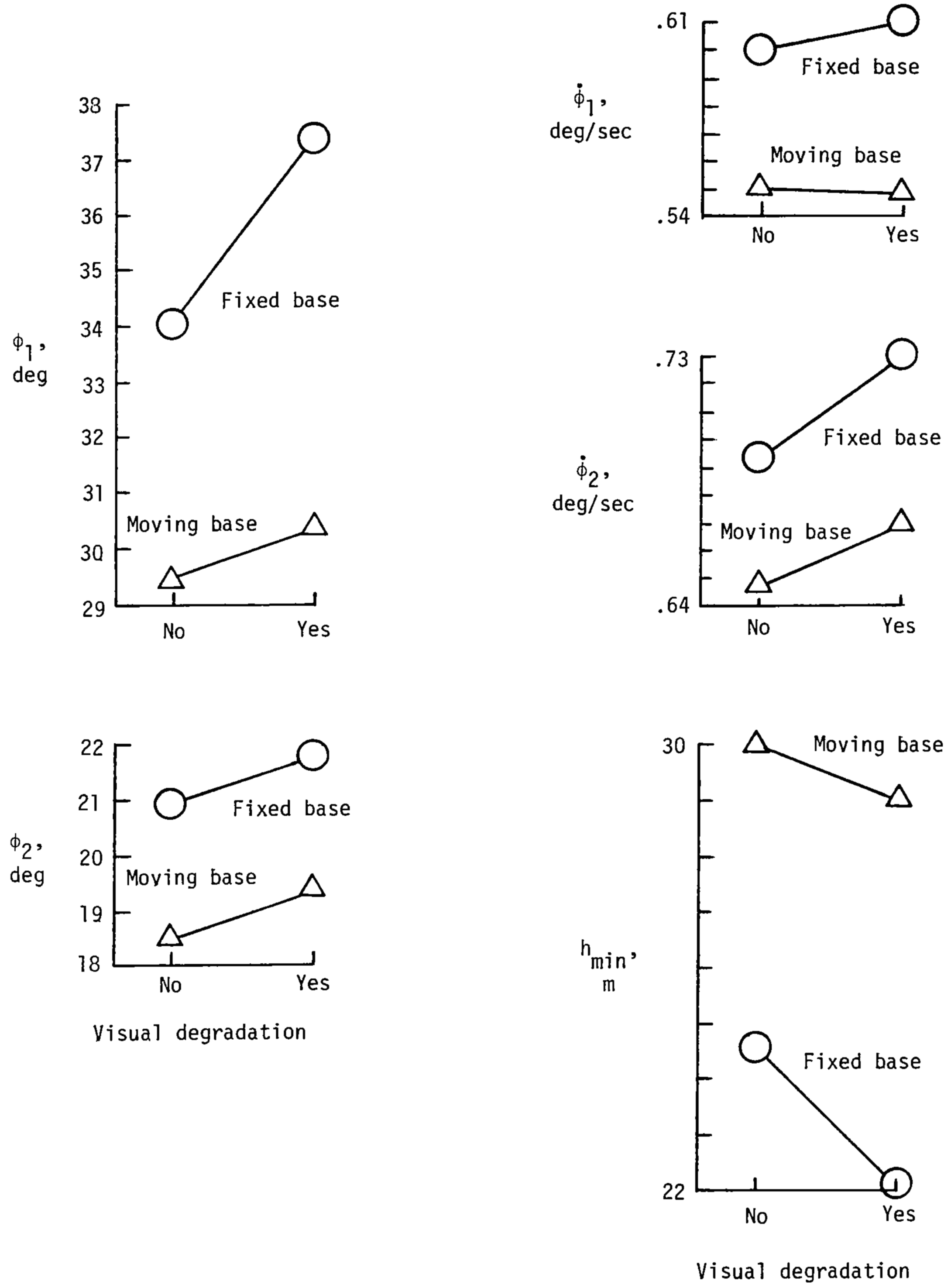


Figure 4.- Visual by motion interactions for encounter-related measures.

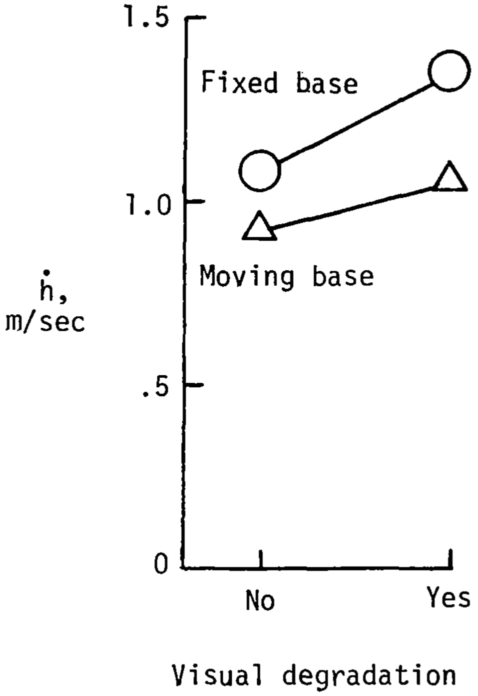


Figure 5.- Visual by motion interaction for sink rate at touchdown.

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16. Abstract

This paper addresses the issues of motion/visual cueing fidelity requirements for vortex encounters during simulated transport visual approaches and landings. Four simulator configurations were utilized to provide objective performance measures during simulated vortex penetrations, and subjective comments from pilots were collected. The configuratons used were as follows: fixed base with visual degradation (delay), fixed base with no visual degradation, moving base with visual degradation (delay), and moving base with no visual degradation. The statistical comparisons of the objective measures and the subjective pilot opinions indicated that although both minimum visual delay and motion cueing are recommended for the vortex penetration task, the visual-scene delay characteristics were not as significant a fidelity factor as was the presence of motion cues. However, this indication was applicable to a restricted task, and to transport aircraft. Although they were statistically significant, the effects of visual delay and motion cueing on the touchdown-related measures were considered to be of no practical consequence.

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