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William W.Y. Chung
Charles H. Perry, Jr.
Norman J. Bengford
Logicon Operations & Services
Moffett Field, CA

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INVESTIGATION OF EFFECTIVENESS OF THE DYNAMIC SEAT IN A BLACK HAWK FLIGHT SIMULATION

William W.Y. Chung*
Chuck Perry
Norm Bengford
Logicon Operations & Services
Moffett Field, California

Abstract

Low cost motion devices have been sought to provide motion cues in ground-based flight simulators to meet mission objectives. The ability to provide high frequency vibrations makes the dynamic seat attractive to helicopter training applications. Previous studies have found that dynamic seats enhance the realism of the cockpit and affect pilot workload. This investigation used a three degree-of-freedom dynamic seat, i.e., heave, surge, and sway, with limited travels in a research simulator configured as a UH-60 Black Hawk. The seat's effectiveness was studied using acceleration/deceleration, bob-up/bob-down, hover, pirouette, sidestep, and vertical landing maneuvers. Results from four different motion cueing levels, i.e., the dynamic seat, hexapod-like system, hexapod-like plus seat shaker, and large travel plus high frequency vibrations, found the dynamic seat has positive subjective effects in some of the maneuvers. However, no significant objective performance effects were found due to the dynamic seat.

Introduction

Low cost alternatives to traditional motion platforms have been sought to provide motion cues in ground-based flight simulators to meet mission objectives. One method that has been shown to be effective is the dynamic seat, which provides high-frequency/low-amplitude motions at the pilot station. Subjectively, high frequency vibration cues provide familiar cockpit oscillations due to structure, rotor dynamics, and airspeed for a helicopter flight simulation. Objectively, the limited onset cues may aid the pilot to develop similar control strategies in meeting mission requirements.

Previous studies[1,2] have shown that there are benefits in using limited-travel vibration devices in helicopter simulations, especially as a training device. White[1] found there was a significant difference in collective activity in a bob-up task using an idealized helicopter simulation with and without a g-seat. The g-seat had two independent actuators in heave degree-of-freedom (DOF) and was mounted on a three DOF motion platform, i.e., heave, pitch, and roll. The cockpit had a field-of-view (FOV) of 48 degrees in azimuth and 36 degrees in elevation. White also reports that pilots were more consistent in maintaining a linear relationship between collective activity and time to impact in a hurdle task with the g-seat. Pilot comments in this study gave preference to the use of the g-seat.

Greig[2] investigated the effectiveness of a multi-axis dynamic seat in the simulation of a Lynx helicopter on the Large Motion System (LMS) at UK's Defence Research Agency Advanced Flight Simulator (AFS). The dynamic seat had 5 independent hydraulic actuators to produce three DOF motion in heave, surge, and sway. The LMS has five DOF, i.e., heave, sway, roll, pitch, and yaw, and a FOV of +/- 63 degrees in azimuth and 24 degrees in elevation. The study found that subjective pilot ratings and comments favor the use of a dynamic seat in the five tasks evaluated, i.e., sidestep, quick hop, lateral jinking, spot turn, and NoE course.

The Joint Shipboard Helicopter Integration Process (JSHIP), a Navy program sponsored by the Office of the Secretary of Defense, was initiated to investigate the minimum ground-based simulation requirements to develop the launch and recovery operational envelope. Among many JSHIP investigation objectives, a multi-axis dynamic seat, Figure 1, that was similar to Greig's investigation was one of the simulation cueing devices evaluated. For this purpose, a UH-60 Black Hawk motion-based flight simulation experiment was developed at NASA Ames Research Center's Vertical Motion Simulator (VMS), Figure 2, using six ADS-33D[3] maneuvers. The JSHIP simulator cockpit has a FOV of 220 degrees in azimuth and 70 degrees in elevation.

Four different motion cueing levels were chosen to investigate the effects of the dynamic seat. The effectiveness of the dynamic seat was then determined by comparing pilots' workload, the perceived vehicle performance, and task performance in six selected maneuvers.

Experiment Description

Math Model

A high fidelity mathematical model of the UH-60A Black Hawk known as Gen Hel[4] was used in the investigation. The real-time simulation had a frame rate of 100 Hz. In hover and low speed, the Black Hawk was configured to have an augmented angular rate command system, and the

* Senior member.

collective controlled vertical acceleration. The angular rate frequency responses at hover generated by a handling qualities analysis program, CIFER®[5], are shown in Figure 3, and the heave control response is shown in Figure 4.

Motion Cueing

Four levels of motion cueing were developed to investigate the effects of the dynamic seat. They are:

I. The 3-DOF dynamic seat: Uses all three DOF of the dynamic seat, i.e., heave, sway, and surge. The dynamic seat provided high frequency heave and lateral vibrations, onset cues for heave, sway, and surge, and sustained sway and surge motion cues.
II. Hexapod-like travel: The VMS was driven by adaptive motion drive algorithms developed for a hexapod motion system[6,7] with six 60-inch stroke actuators.
III. Hexapod-like travel plus dynamic seat with only heave mode: The VMS was driven the same way as Level II. The dynamic seat was activated in heave DOF only as a seat shaker to provide the vertical vibration cues.
IV. Large motion travel plus 2-DOF dynamic seat: Full VMS travel was utilized to achieve the best possible motion fidelity. VMS was driven by the standard classical motion drive algorithms. The dynamic seat was activated in two DOF, i.e., heave and sway, to supplement the large motion travel with high frequency vibration cues. The dynamic seat commands, which provided sustained surge and sway components, were disabled.

Level I motion represents a low-cost option in providing motion cues. Level II represents a motion cueing fidelity that is common to the training community. With the addition of a seat shaker feature, any difference between Level II and III could be attributed directly to the effect of high frequency heave vibration. Level IV represents the best possible ground-based motion cueing fidelity by using the full translational travel envelope of the VMS.

Displacement, rate, and acceleration limits of the VMS and a hexapod-like system are shown in Table 1. The small-amplitude frequency responses of the VMS are plotted against the FAA Advisory Circular 120-63[8] motion specifications as shown in Figure 5. The motion fidelity according to Ref. 9 for all six DOF is shown in Figure 6. Another important motion fidelity factor, the lateral translational motion relative to simulator roll motion, to maintain the proper specific force direction, is low for the hexapod-like case (Level II and III), and is high for the large motion case (Level IV), according to Ref. 10.

Motion Cueing - Dynamic Seat

A multi-axis dynamic seat[11] provided by the Army Apache Training Command was integrated in one of the VMS's inter-changeable cabs. The dynamic seat has four independent actuators to provide three DOF of motion, i.e., heave, sway surge, and. The performance of each actuator is shown in Table 2. The small-amplitude frequency responses of the four actuators are shown in Figure 7.

The high frequency heave vibration cues were generated by the seat pan and driven directly according to four per rev of the UH-60 rotor rpm, i.e., at 17 Hz. According to pilot comments, one per rev high frequency lateral vibration cues were added to the back pad to mimic the UH-60 cockpit vibration characteristics during flight. The magnitude of heave vibrations was adjusted based on the Bob-Up/Bob-Down flight test data. The dynamic seat's gains and frequency content were adjusted to match the power-spectral density of the vertical acceleration sensor response taken from the flight test as shown in Figure 8. The onset cues in heave due to pilot control inputs and/or flight conditions have four components, which are translational lift, collective, normal acceleration, and airspeed. The translational lift provides the vibrations due to the change in inflow orientation between the forward and aft portions of the rotor disk in the speed range between 20 and 30 knots.

Sustained sway acceleration cues were developed by moving the back pad laterally as a function of pilot-station lateral accelerations. Onset lateral acceleration cues were generated by feeding roll angular acceleration and the high frequency component of lateral acceleration to drive the back pad in lateral motion.

Sustained deceleration was generated by moving the back pad forward and the seat pan downward synchronously. Sustained acceleration was developed by moving the back pad aft and the seat pan upward together. Onset longitudinal acceleration cues were generated by feeding pitch angular acceleration and the high frequency component of longitudinal acceleration to drive the back pad fore and aft.

Visual Cueing

The cockpit, as shown in Figure 9, with a wide field-of-view (FOV) display system, producing 220 degrees in azimuth and 70 degrees in elevation, was specially designed and developed for the JSHIP experiment. The primary image generation system is a five-channel E&S ESIG 4530 system operating at 60 Hz with a transport delay measured at 60 msec. The projection system used a projector-mirror design with five BARCO projectors.

A high resolution LHA visual model, LHA-5 USS Peleliu, was used for all test maneuvers. The model consists of 3000 textured polygons and employs 4 levels-of-detail. An E&S 3-Dimensional (3D) sea wave model provided additional wave dynamics relative to wave heights and period.

Aural Cueing

The simulator cab had a stereo sound system with six speakers and one sub-woofer around the pilot to provide high quality aural cues that included main rotor, tail rotor, engine, transmission, air, and landing gear as functions of collective control and flight conditions. Sound cues were evaluated by UH-60 pilots and were found to be representative of the UH-60 in test tasks evaluated.

Task Description

Six maneuvers modified from ADS-33D for shipboard operations were evaluated in the investigation. They were Acceleration/Deceleration, Bob-up/Bob-down, Hover, Pirouette, Sidestep, and Vertical Landing. Descriptions of maneuvers and performance criteria are presented in Ref. 12. Four experienced Army test pilots participated in this evaluation.

An additional test was done fixed-base with the dynamic seat on and off using a modified Bob-Up/Bob-Down maneuver to evaluate the effectiveness of the dynamic seat independent of platform motion. Instead making a Bob-Down maneuver immediately after a brief stabilization at the top, pilots were instructed to maintain stabilization for at least 10 seconds before initiating a Bob-Down. Three UH-60 pilots (two NASA and one Army) participated in this test.

Results

Subjective Evaluations

Handling Qualities Rating (HQR)[13] results for the six ADS-33D maneuvers are shown in Figure 10. Results from the 3-DOF dynamic seat, Level I, compare well with the large motion plus 2-DOF dynamic seat, Level IV, except Acceleration/Deceleration and Sidestep, where maneuvers in surge and sway DOF are more dominant. Heave vibration cues do improve the HQR for most of the maneuvers when comparing Level III motion with Level II motion.

HQR results for the fixed-base Bob-Up/Bob-Down task with the dynamic seat on and off are shown in Figure 11. A Motion Fidelity Scale[9] (MFS), as shown in Table 3, was used to subjectively determine consistency between perceived visual cues and motion cues. MFS results with the seat on and off are also shown in Figure 11.

Objective Performance Data

Objective performance data were analyzed for two test maneuvers, i.e., Bob-Up/Bob-Down, and Vertical Landing. Both maneuvers emphasized the vertical DOF, which was relevant to VMS large motion and the dynamic seat's primary motion cueing characteristic, i.e., heave.

In the Bob-Up/Bob-Down task, the simulated Black Hawk's altitude offset at the lower hover position was analyzed to investigate the pilot's altitude stabilization performance after the bob-down. Maximum descent speed was also analyzed to investigate the pilot's vertical speed control relative to the bob-down task. Both results are shown in Table 4.

In the Vertical Landing task, the pilot's landing spot offset in longitudinal and lateral directions were analyzed as well as the maximum descent speed. Results are shown in Table 5.

In the fixed-base Bob-Up/Bob-Down test, the simulated Black Hawk's altitude offset at the lower hover position and the maximum descent speed with and without the use of the dynamic seat are shown in Table 6.

Power spectral density (PSD) of the collective and pilot's cut-off frequency were analyzed to characterize the pilot's inner-loop response that was related to work load and the task. The PSD directly reflects pilot control magnitude in the frequency domain. The cut-off frequency is defined as a measure of the pilot's control activity bandwidth. When the aircraft's bandwidth exceeds the task bandwidth, the pilot cut-off frequency approaches the pilot crossover frequency and gives a good approximation of the task bandwidth.[14] The purpose of using these measurements was to investigate the motion cueing effects in pilot control strategy and aggressiveness. Studies have shown that improved motion fidelity has led to increases in pilot's gain and crossover frequency.[15,16] Consequently, higher pilot gain leads to lower control PSD.

Average Root-Mean-Square (RMS) of the collective PSD and average pilot cut-off frequencies for four different levels of motion cueing conditions are shown in Table 4 for the Bob-Up/Bob-Down maneuver and in Table 5 for the Vertical Landing. Average RMS of the collective PSD, and pilot's cut-off frequency of the fixed-base Bob-Up/Bob-Down test are shown in Table 6.

Discussion

Subjective Data - HQR

As shown in Figure 10, according to the average HQRs, Level IV motion shows the best match with the flight test data among all six ADS-33 maneuvers. Level III also shows good results when compared with the flight test data. The differences between Level III and IV are minimal. Overall, pilots gave good marks to Level IV on motion cueing fidelity, citing that there was no negative cueing and that the realism was good.

Level I motion shows a good match in mean HQR with the flight test data in Hover and Vertical Landing tasks. In another vertical DOF task, Bob-Up/Bob-Down, the dynamic seat also fares well relative to the flight data with a mean HQR difference of 0.25 ($\Delta_{L\text{-}I/Flight}$=0.25). Level I has the worst mean HQR in Acceleration/Deceleration ($\Delta_{L\text{-}I/Flight}$ =0.85) and Sidestep ($\Delta_{L\text{-}I/Flight}$ =0.5) tasks, which may be attributed to the lack of motion travel in those two DOF. Level I also has the largest standard deviation in Pirouette ($\sigma_{L\text{-}I}$=1.29), Sidestep ($\sigma_{L\text{-}I}$=1.0), and Vertical Landing ($\sigma_{L\text{-}I}$=0.63). The widespread ratings suggest there is an inconsistency in pilots' determination in their workload and vehicle performance relative to the task. Some pilots commented that using the back pad to provide sustained sway cues was unnatural because only the upper body moved.

Level II motion shows a poor match in mean HQR relative to the flight test data ($\Delta_{L\text{-}II/Flight}$ >0.5) for Acceleration/Deceleration ($\Delta_{L\text{-}II/Flight}$ =0.65), Hover ($\Delta_{L\text{-}II/Flight}$ =0.75), and Sidestep ($\Delta_{L\text{-}II/Flight}$ =0.8). Level II has the largest standard deviation in Acceleration/Deceleration ($\sigma_{L\text{-}II}$=0.96), and Bob-Up/Bob-Down ($\sigma_{L\text{-}II}$=1.15).

Level III improves the mean HQR relative to flight test data in Acceleration/Deceleration ($\Delta_{L\text{-}III/L\text{-}II}$=0.25), Hover ($\Delta_{L\text{-}III/L\text{-}II}$ =0.75), Sidestep ($\Delta_{L\text{-}III/L\text{-}II}$ =0.68), and Vertical Landing ($\Delta_{L\text{-}III/L\text{-}II}$ =0.25) tasks. Level III matches very well with the flight test's mean HQR in Bob-Up/Bob-Down ($\Delta_{L\text{-}III/Flight}$ =0.17), Hover ($\Delta_{L\text{-}III/Flight}$ =0), Sidestep ($\Delta_{L\text{-}III/Flight}$ =0.12), and Vertical Landing ($\Delta_{L\text{-}III/Flight}$ =0.25). The results suggest that there is a benefit of having the high frequency heave vibration in a motion platform.

Level IV, the large motion travel and the 2 DOF dynamic seat, matches well with the mean HQR from the flight test in Acceleration/Deceleration ($\Delta_{L\text{-}IV/Flight}$ =0.2), Bob-Up/Bob-Down ($\Delta_{L\text{-}IV/Flight}$ =0), hover ($\Delta_{L\text{-}IV/Flight}$ =0.29), and Vertical Landing ($\Delta_{L\text{-}IV/Flight}$ =0.14).

Subjective Data – Fixed-Base

From Figure 11, with the dynamic seat on, the mean HQR of the Bob-Up/Bob-Down task improves by 0.5 relative to the seat-off condition. The standard deviation of the mean HQR with the seat on ($\sigma_{Seat\text{-}On}$=0.71) is also smaller than with the seat off ($\sigma_{Seat\text{-}On}$=1.325). Both results indicate an improvement in pilots' workload and their determination of the vehicle performance when the dynamic seat was on.

Motion Fidelity Scale results in Figure 11 show that pilots were less objectionable to the cueing differences between the flight response perceived from visual and the motion cues when the dynamic seat was on. All three pilots found the onset cues were helpful and recommended the use of the seat for the Bob-Up/Bob-Down task. Two of the pilots recommended the use of the vibration cues.

Objective Data - Bob-Up/Bob-Down

From Table 4, the average altitude stabilization error at the lower hover position after a bob-down for all four motion cueing levels are very similar and are well within the satisfactory performance criterion, i.e., +/- 3 ft, for the task. Level IV motion has the smallest standard deviation ($\sigma_{L\text{-}IV}$=0.33 ft), but differences are relatively small.

There is little difference in average maximum descent speed among the four motion cueing levels. Level I motion and Level II motion, however, have larger standard deviations, i.e., 2.82 ft/sec and 3.17 ft/sec respectively, which indicates pilots were not as consistent in their vertical speed control. The mean standard deviations for the other two motion cueing conditions are 0.86 ft/sec for Level III and1.08 ft/sec for Level IV.

There is very little difference in average collective RMS and pilot cut-off frequency in this task. With platform motion on, i.e., Level II, III, and IV, the data show a trend with lower collective RMS and higher pilot cut-off frequency as the motion cueing fidelity increases from Level II to IV. This trend is consistent with the concept that pilot's gain and crossover frequency increases as the motion cueing fidelity improves. The increased pilot gain subsequently leads to lower control RMS. The 3-DOF dynamic seat, Level I, however, has the lowest collective RMS and a pilot cut-off frequency higher than the two hexapod motion cueing conditions which contradicts the trend. One possible explanation could be found in the pilot comments where all pilots explicitly indicated that they relied more on visual cues such as the superstructure to judge the translational rate when platform motion was absent.

Objective Data - Vertical Landing

From Table 5, landing spot offsets in longitudinal and lateral directions for all four motion-cueing levels are similar. No obvious trends could be found. Only Level IV motion had an average longitudinal offset that was within the satisfactory performance criterion, i.e., +/- 1 ft.

There is an obvious trend in the average maximum descent speed, where the maximum descent speed decreases as the motion fidelity increases from Level I through Level IV. This result is consistent with the finding from a PIO study[17] and shows pilots are more conscious of the descent speed as the motion fidelity improves.

The difference in average collective RMS and pilot cut-off frequency was relatively small among the four motion cueing levels. The large motion travel plus 2-DOF dynamic seat, Level IV, had the least average collective RMS and the pilot cut-off frequency suggests pilots might be easing off the collective due to pronounced vertical speed cues. The small standard deviations under the Level IV motion, i.e., 0.02 inch for collective RMS, 0.01 rad/sec in pilot cut-off frequency, and 0.77 ft/sec in the maximum descent speed, suggest pilots were more consistent in controlling the vertical speed in Level IV than in the other three levels.

Objective Data - Fixed-Base

From Table 6, the altitude error when stabilizing after the bob-down for the Bob-Up/Bob-Down task is improved when the dynamic seat is on, 1.12 ft vs. 1.52 ft when the dynamic seat is off. There is little difference in the other three objective measurements, which suggests the dynamic seat helps in improving realism of the Bob-Up/Bob-Down task and the task performance, but not pilots' perception of the vertical speed and their control activities.

Conclusions

There are benefits to use the dynamic seat in ground-based flight simulations. However, dynamic seat alone may not be adequate to meet certain mission requirements.

Addition of high frequency heave vibrations to the hexapod-like system has positive effects both subjectively and objectively.

Large motion travel with the 2-DOF dynamic seat has the closest representation of the flight.

References

1. White, A.D.: "G-Seat Heave Motion Cueing for Improved Handling in Helicopter Simulators," AIAA-89-3337-CP, 1989.

2. Greig, I.: "Evaluation of a Multi-Axis Dynamic Cueing Seat for Use in Helicopter Training Devices," Defence Research Agency, United Kingdom, I/ITSEC 1996, Orlando, Fl., November, 1996.

3. Aeronautical Design Standard, Handling Qualities Requirements for Military Rotorcraft, ADS-33D, July 1994.

4. Howlett, J.J.: UH-60A Black Hawk Engineering Simulation Program: Vol. I – Mathematical Model, NASA CR-166309, December 1981.

5. Tischler, M. B., Cauffman, M.G.: "Frequency-Response Method for Rotorcraft System Identification: Flight Applications to BO-105 Coupled Rotor/Fuselage Dynamics," *Journal of the American Helicopter Society*, Vol 37, No 3, pgs 3-17, July 1992.

6. Parrish, R.V., Dieudonne, J.E., Bowles, R.L., and Martin, Jr., D.J., "Coordinated Adaptive Washout for Motion Simulators," *Journal of Aircraft*, Vol. 12, No. 1, Jan., 1975, pp. 44-50.

7. Dieudonne, J.E.; Parrish, R.V.; and Bardusch, R.E.: "An Actuator Extension Transformation for a Motion Simulator and an Inverse Transformation Applying Newton-Raphson's Method", NASA TN D-7067, 1972.

8. AC-120-63, Helicopter Simulator Qualification, U.S. Department of Transportation, Federal Aviation Administration, October 1994.

9. Schroeder, J.A.: "Helicopter Flight Simulation Motion Platform Requirements," NASA/TP-1999-208766, July 1999.

10. Mikula, J.; Chung, W.W.; and Tran, D.: "Motion Fidelity Criteria for Roll-Lateral Translational Tasks," AIAA Modeling and Simulation Technologies Conference, Portland, Oregon, AIAA 99-4329, August, 1999.

11. Corlyon, P. and Humphrey, T.: "Force and Vibration Cueing with a Multi-Axis Dynamic Seat," I/ITSEC 1999, Orlando, Fl., November, 1999.

12. Roscoe, M.F.; Wilkinson, C.H.; and VanderVliet, G.M.: "The Use of ADS-33D Useable Cue Environment Techniques for Defining Minimum Visual Fidelity Requirements," AIAA Modeling and Simulation Technologies Conference, Montreal, Quebec, Canada, AIAA 2001-4063, August 2001.

13. Cooper, G. E., and Harper, R. P., Jr.: "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities," NASA TN D-5153, April 1969.

14. Blanken, C.L. and Pausder H.-J.: "Investigation of the Effects of Bandwidth and Time Delay on Helicopter Roll-Axis Handling Qualities," *Journal of the American Helicopter Society*, July 1994, Vol. 39 No. 3, p24-33.

15. Stapleford, R.L.; Peters, R.A.; and Alex, F.R.: "Experiments and a Model for Pilot Dynamics with Visual and Motion Inputs, " NASA CR-1325, 1969.

16. Jex, H.R.; Magdaleno, R.E.; and Junker, A.M.: "Roll Tracking Effects of G-Vector Tilt and Various Types of Motion Washout," NASA CP-2060, November 1978, pp. 463-502.

17. Schroeder, J.A.; and Chung, W.: "Simulator Platform Motion Effects on Pilot-Induced Oscillation Prediction," *Journal of Guidance, Control, and dynamics*, May-June 2000, Vol. 23, No. 3, p438-444.

Table 1. VMS and Hexapod-Like operational limits

Axis	Displacement		Velocity	Acceleration
	VMS	Hexapod-Like		
Roll	±18	±18	±40	±115
Pitch	±18	±18	±40	±115
Yaw	±24	±24	±40	±115
Longitudinal	±4	±4	±4	±10
Lateral	±20	±4	±8	±16
Vertical	±30	3.3 up/ 2.5 down	±16	±24
All numbers, units ft, deg, sec				

Table 2. System limits of the Dynamic Seat

	Seat-Pan (heave)	Back-Pad (sway)	Back-Pad (Surge)	Bucket (heave)
Displacement	± 0.59 inch	± 0.59 inch	± 0.59 inch	± 0.59 inch
Velocity	± 2.4 in/sec	± 2.4 in/sec	± 0.8 in/sec	± 2.4 in/sec
Acceleration	± 39.4 in/sec^2	± 39.4 in/sec^2	± 39.4 in/sec^2	± 39.4 in/sec^2

Table 3. Motion fidelity scale

	Description	Score
High Fidelity	Motion sensations are not noticeably different from those of visual flight	1
Medium Fidelity	Motion sensations are noticeably different from those of visual flight, but not objectionable	2
Low Fidelity	Motion sensations are noticeably different from those of visual flight and objectionable	3

Table 4. Objective data for Bob-Up/Bob-Down task

Bob-Up/Bob-Down		3-DOF dynamic seat (Level I)	Hexapod like only (Level II)	Hexapod like + seat shaker (Level III)	Large motion + 2-DOF dynamic seat (Level IV)
Altitude error (lower hover position),. ft	Average	1.45	1.36	1.1	1.41
	1 standard deviation	0.57	0.46	0.64	0.33
Maximum descent speed, ft/sec	Average	-10.83	-11.47	-11.87	-11.68
	1 standard deviation	2.82	3.17	0.86	1.08
Root-Mean-Square, Collective, inches	Average	0.372	0.445	0.435	0.415
	1 standard deviation	0.10	0.12	0.08	0.12
Pilot cut-off frequency, rad/sec	Average	1.34	1.28	1.26	1.37
	1 standard deviation	0.29	0.26	0.17	0.31

Table 5. Objective data for the Vertical Landing task

Vertical Landing		3-DOF dynamic seat (Level I)	Hexapod like only (Level II)	Hexapod like + seat shaker (Level III)	Large motion + 2-DOF dynamic seat (Level IV)
Landing spot offset, longitudinal, ft	Average	1.27	1.1	1.35	0.54
	1 standard deviation	1.19	1.04	0.54	0.34
Landing spot offset, lateral, ft	Average	1.05	1.18	1.19	1.29
	1 standard deviation	0.74	0.8	0.73	1.33
Maximum descent speed, ft/sec	Average	-4.77	-4.55	-3.72	-2.87
	1 standard deviation	2.43	2.33	1.58	0.77
Root-Mean-Square, Collective, inches	Average	0.7	0.75	0.62	0.63
	1 standard deviation	0.2	0.11	0.22	0.02
Pilot cut-off frequency, rad/sec	Average	0.93	0.925	0.91	0.83
	1 standard deviation	0.16	0.15	0.08	0.01

Table 6. Objective data for a Bob-Up/Bob-Down task in fixed-base

Bob-Up/Bob-Down (Fixed-Base)		Dynamic Seat On	Dynamic Seat Off
Altitude error (lower hover position), ft	Average	1.12	1.52
	1 standard deviation	0.47	0.32
Maximum descent speed, ft/sec	Average	-13.30	-13.69
	1 standard deviation	3.32	3.19
Root-Mean-Square, Collective, inches	Average	0.62	0.58
	1 standard deviation	0.2	0.23
Pilot cut-off frequency, rad/sec	Average	1.22	1.20
	1 standard deviation	0.18	0.19

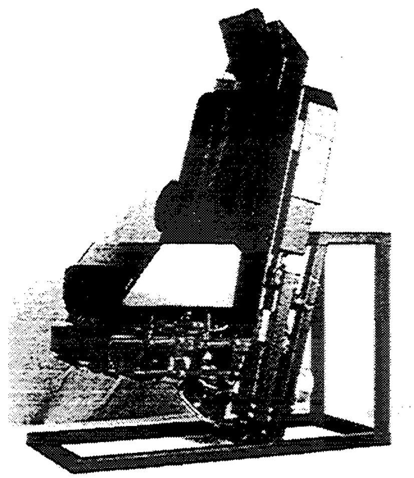

Figure 1. 3 degree-of-freedom (heave, surge, and sway) dynamic seat

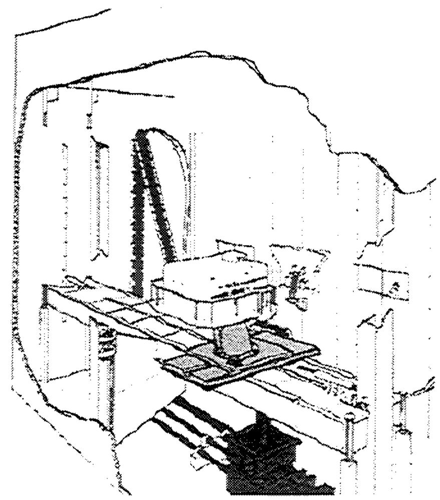

Figure 2. Vertical Motion Simulator (VMS)

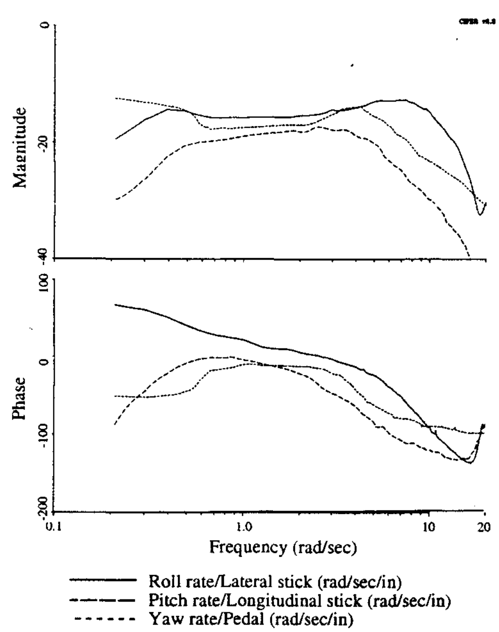

Figure 3. Angular rate response of the simulated UH-60 Black Hawk

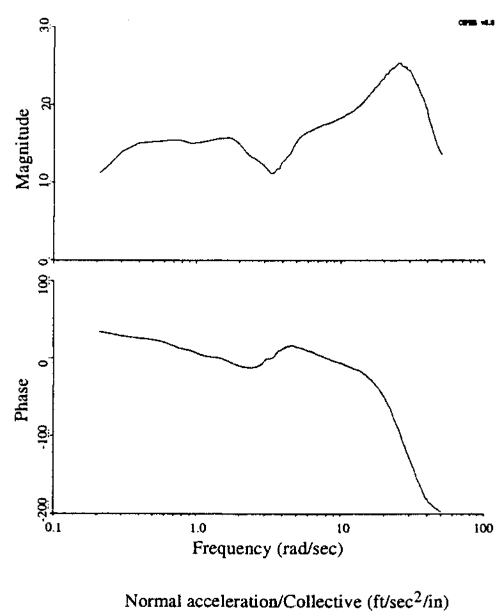

Figure 4. Simulated UH-60 Black Hawk collective response

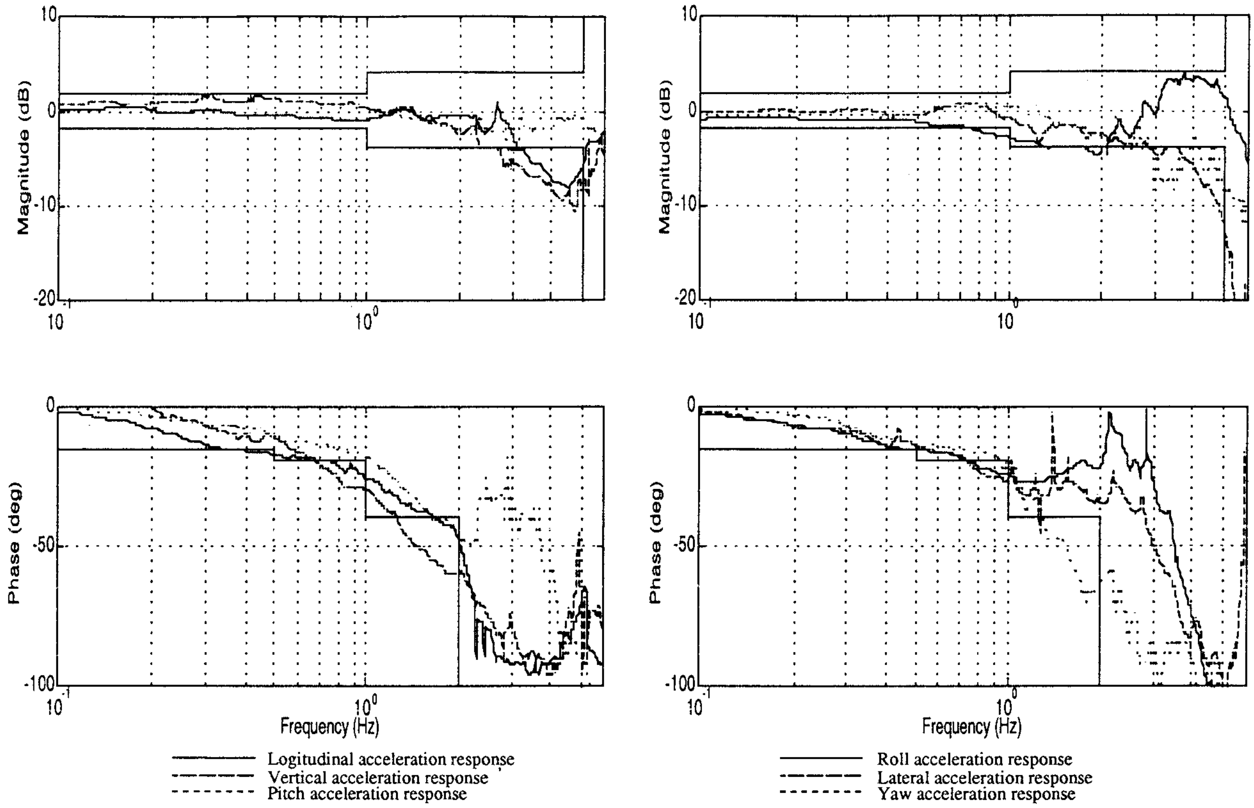

Figure 5. VMS frequency response vs. FAA AC 120-63 motion system specification

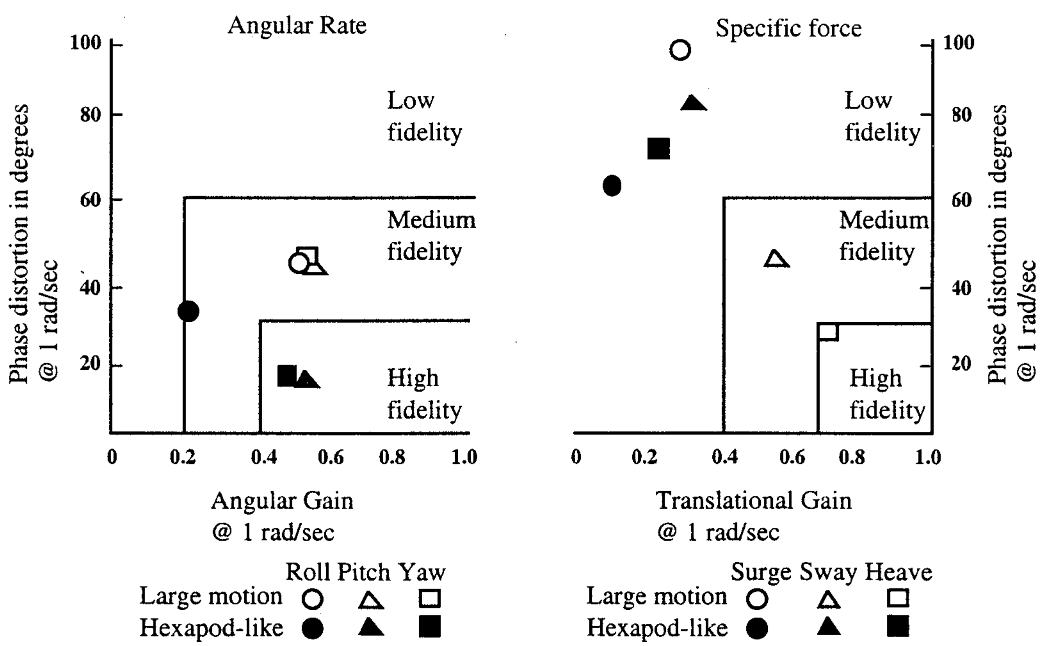

Figure 6. Motion cueing fidelity of the experiment

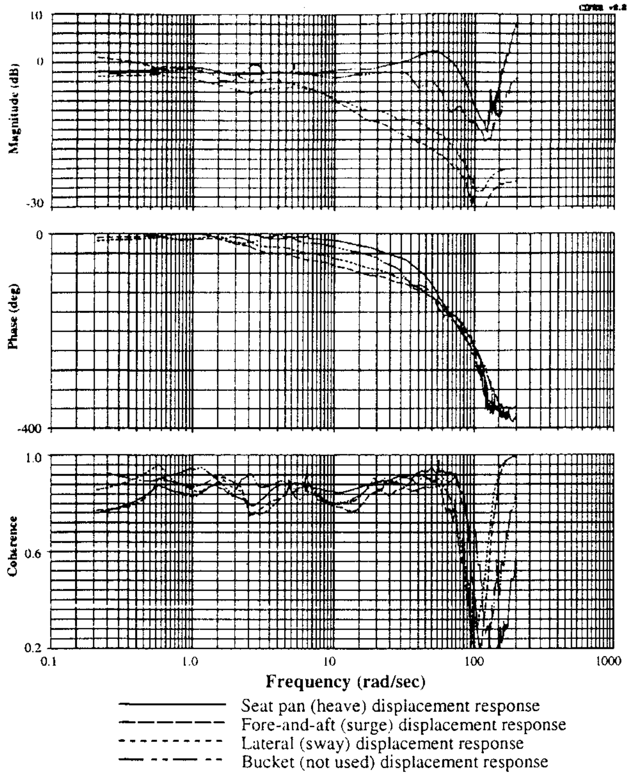

Figure 7. Dynamic seat actuator frequency response

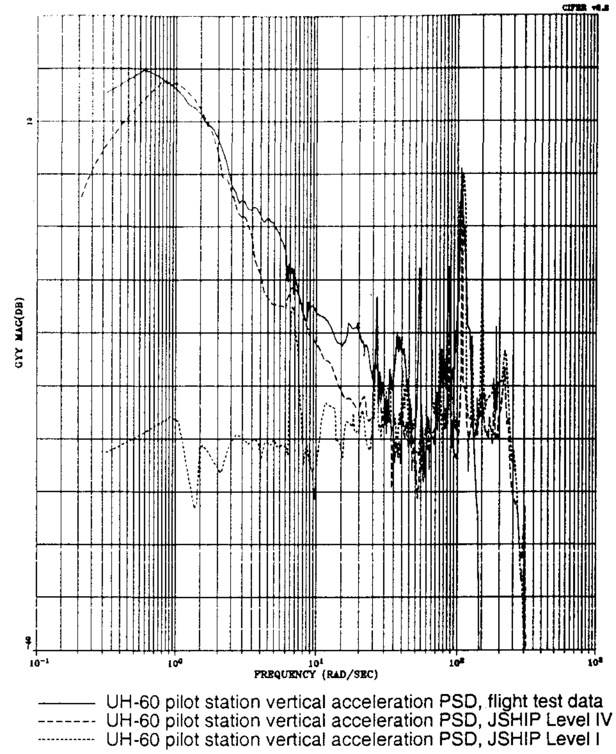

Figure 8. Auto-Spectrum of normal acceleration of flight test, large motion, and the dynamic seat $(ft/sec^2)^2$

Figure 9. Field-of-view inside the cockpit

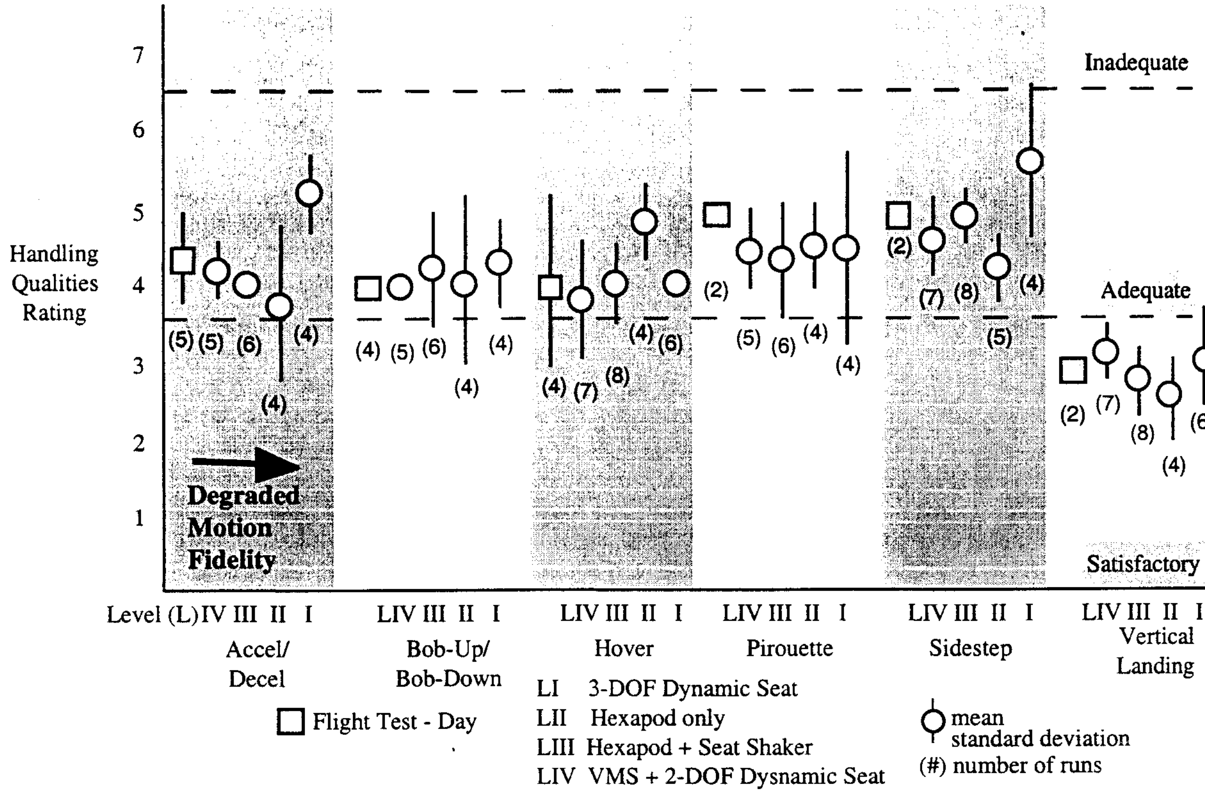

Figure 10. Handling Qualities Ratings of six ADS-33D maneuvers

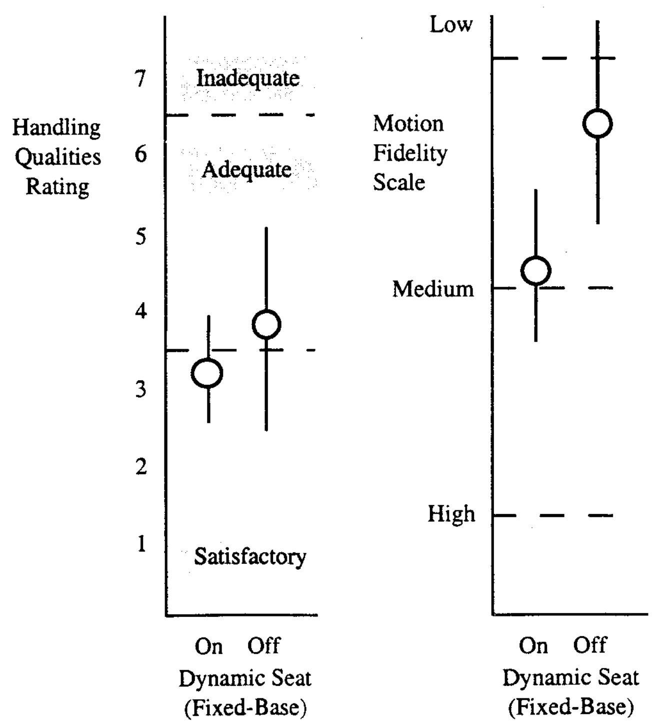

Figure 11. Handling Qualities Ratings and Motion Fidelity Scales of the fixed-base Bob-Up/Bob-Down task