AFRL-RH-WP-TR-2019-0032

VIBRATION EXPOSURE CHARACTERIZATION AND HEALTH RISK ASSESSMENT OF THE UH-60L BLACKHAWK

Suzanne D. Smith, PhD
Infoscitex, a DCS Corp

Mr. Steven G. Chervak
Jay E. Clasing, PhD
Army Public Health Center

May 2019
Interim Report

DISTRIBUTION STATEMENT A. Approved for public release.

AIR FORCE RESEARCH LABORATORY
711TH HUMAN PERFORMANCE WING
AIRMAN SYSTEMS DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

NOTICE AND SIGNATURE PAGE

AFRL-RH-WP-TR-2019-0032 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION.

HARVILLE.DONALD.L.1230636083 Digitally signed by HARVILLE.DONALD.L.1230636083 Date: 2019.08.07 08:45:29 -04'00'

DONALD L. HARVILLE
Work Unit Monitor
Applied Neuroscience Branch

OTTE.CLIFFORD.N.1102152383 Digitally signed by OTTE.CLIFFORD.N.1102152383 Date: 2019.08.13 12:34:56 -04'00'

CLIFFORD N. OTTE, DR-III
Chief, Applied Neuroscience Branch
Warfighter Interface Division

CARTER.LOUISE.ANN.1230249128 Digitally signed by CARTER.LOUISE.ANN.1230249128 Date: 2019.10.02 15:02:55 -04'00'

LOUISE A. CARTER, DR-IV, Ph.D.
Chief, Warfighter Interface Division
Airman Systems Directorate
711 Human Performance Wing
Air Force Research Laboratory

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
30 MAY 2019	Interim	1 May 2017 – 31 Dec 2018

4. TITLE AND SUBTITLE
VIBRATION EXPOSURE CHARACTERIZATION AND HEALTH RISK ASSESSMENT OF THE UH-60L BLACKHAWK

5a. CONTRACT NUMBER In-House
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER 62202F

6. AUTHOR(S)
Suzanne D. Smith*
Steven G. Chervak**
Jay E. Clasing**

5d. PROJECT NUMBER 5329
5e. TASK NUMBER 08
5f. WORK UNIT NUMBER H0GW (53290812)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
*Infoscitex, a DCS Corp
4027 Col Glenn Hwy, Suite 210
Dayton OH 45431

**Army Public Health Center (APHC)
8252 Blackhawk Rd.
Aberdeen Proving Ground MD 21010

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Secretary of the Army for Installation, Energy, and Environment
US Army Environmental Command
National Defense Center for Energy and Environment (NDCEE)
Pentagon 3D453
Washington, DC 20310

10. SPONSOR/MONITOR'S ACRONYM(S)
US ARMY IMCOM AEC

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-RH-WP-TR-2019-0032

12. DISTRIBUTION / AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A. Approved for public release

13. SUPPLEMENTARY NOTES
MSC/PA-2019-0265/88ABW-2019-3256, cleared 9 July 2019

14. ABSTRACT This study characterized and assessed aircrew vibration during operation of the UH-60L Blackhawk owned and operated by the Maryland Army National Guard. The study was part of a collaboration between the Army Public Health Center and the Air Force Research Laboratory, and was funded by the National Defence Center for Energy and Environment. The ISO 2631-1: 1997 was used as the guideline for the assessments. Triaxial accelerations were collected at the floor/seat base, seat pan, and seat back interfaces at the pilot station, two crew chief stations located mid cabin, and two passengers located in the rear of the aircraft. Data records were collected by aircraft task and the associated flight test conditions. All stations/locations showed a major spectral peak in all three directions between 17 and 17.5 Hz. These peaks were associated with the blade passage frequency of the Blackhawk helicopter. Based on the ISO 2631-1 guidelines, comfort reactions ranged from "a little uncomfortable" to even "very uncomfortable", particularly at the pilot station and left passenger location. Based on the seat pan point vibration total value (ISO 2631-1), the aircraft showed level flight exposures associated with the potential for health risk, and even likely health risks in less than 8 hours; the pilot being exposed to potential health risk in 1 to 3 hours of daily occupational exposure, and exposed to likely health risks in 3 to 7 hours at higher airspeeds. Both the pilot and left passenger exceeded the exposure limits presented in the MIL-STD-1472G. All occupants should be warned that they may be exposed to potential health risk in less than 8 hours of flight. In summary, the results of the assessments on the UH-60L further support the substantial influence of operational vibration on the discomfort and pain that has been associated with the operation of these aircraft, particularly given the magnitudes of the higher frequency exposures that still result in a potential health risk according to the standards and guidelines.

15. SUBJECT TERMS Human vibration, helicopters, health risk assessment, discomfort

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Donald L. Harville
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
Unclassified	Unclassified	Unclassified	SAR	56	

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

PREFACE

This report summarizes the vibration exposure assessment conducted on the UH-60L Blackhawk, owned and operated by the Maryland Army National Guard (MD ARNG) in accordance with the ISO 2631-1 (1997) Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration - Part 1: General requirements, ISO 2631-1 Amendment 1 (2010), and the MIL-STD-1472G Department of Defense Design Criteria Standard, Human Engineering (2012). The study is the first for the project entitled "Operational Vibration Assessment and Database Project 2: Expanded Flight Test Program. Project 2 was funded by the National Defense Center for Energy and Environment (NDCEE). Three additional platforms were targeted for the expanded test program; the CH-47F Chinook, MH-65D Dolphin, and UH-1N Huey helicopters. The test program included the development of a database quantifying operational vibration and active aircrew subjective perceptions, and integrated into the Air Force Collaborative Biomechanics Data Network (CBDN) managed by the 711 HPW/RH. The database will be made available to researchers, equipment designers, and standards developers for establishing effective near- and far-term pain and injury mitigation strategies. A Memorandum of Agreement (MOA) between the US APHC and the AFRL 711 HPW/RH was established that set forth the terms and conditions that the two organizations would use to conduct the project with funding from the NDCEE. The AFRL 711 HPW/RH prepared all required documentation including a Flight Test Plan, and conducted all required review boards including the Technical Review Board (TRB) and Safety Review Board (SRB), in accordance with Air Force Research Laboratory Instruction (AFRLI) 61-103, Scientific Research and Development, AFRL Research Test Management (2015).

ACKNOWLEDGEMENTS

The Army Public Health Center (APHC) and Air Force Research Laboratory (AFRL) thank the Maryland Army National Guard (MD ARNG) for their support of flight tests aboard the UH-60L Blackhawk.

The Army Public Health Center (APHC) and Air Force Research Laboratory (AFRL) thank the National Defense Center for Energy and Environment (NDCEE) for their financial support of this project.

1.0 SUMMARY

This study characterized and assessed aircrew vibration during operation of the UH-60L Blackhawk helicopter located at the Maryland Army National Guard (MD ARNG). The ISO 2631-1: 1997 and MIL-STD-1472G were used as the guideline for the comfort and health risk assessments. The study is part of a larger test program that includes additional aircraft platforms. The specific objectives of this study are:

1. Collect multi-axis acceleration data to characterize the vibration affecting the aircrew and interface equipment aboard the UH-60L Blackhawk helicopter.
2. Assess the comfort and health risk of the vibration exposures in accordance with existing human vibration standards.
3. Enter acceleration data into the 711 HPW/RH Collaborative Biomechanics Data Network (CBDN).

The study was a collaboration between the Army Public Health Center (APHC) and the Air Force Research Laboratory (AFRL), 711 Human Performance Wing (HPW), Airman Systems Directorate (RH), and was funded by the National Defense Center for Energy and Environment (NDCEE).

Four portable battery-powered data acquisition units (DAUs) were used to collect accelerations at the pilot station (right side), left and right side-facing crew chief stations located mid-cabin, and left and right rearward-facing passenger locations located in the aft cabin. Triaxial accelerometer packs were attached to the floor or base of each seat. Triaxial acceleration pads were placed on top of the seat pan and seat back cushions at the pilot and crew chief stations. Triaxial acceleration pads were placed on top of the seat pan at the two passenger locations. A helmet mount was attached to the top of the pilot helmet to collect triaxial translational accelerations. Data records were collected by aircraft task and the associated flight test conditions, including pre-departure checks, visual meteorological conditions (VMC), takeoff, hovering flight, VMC flight maneuvers, VMC approach, and terrain following flight. The onboard test conductor prompted triggering of the DAUs to collect for 20 second records once the aircraft was on a targeted condition. The acceleration spectra were estimated at each station/location and measurement site. The overall weighted accelerations were estimated in accordance with the ISO 2631. For assessing the ISO 2631-1 comfort reactions, the overall vibration total value (o*VTV)* was calculated as the vector sum of the weighted triaxial seat pan and seat back accelerations. For assessing the ISO 2631-1 health risks, the point vibration total value (*pVTV*) was calculated as the vector sum of the weighted triaxial seat pan accelerations.

For the UH-60L at all stations, measurement sites, and for most flight conditions, a major peak was observed between 17-17.5 Hz and was associated with the aircraft blade passage frequency (BPF). Additional peaks were also observed at multiples of the BPF. While not easily identified, vibration associated with the propeller rotation frequency (PRF) was estimated to be ~4-4.5 Hz, based on the BPF of the UH-60L. The most substantial peak observed at the respective BPF did not necessarily occur in the vertical direction.

Comfort reactions associated with the UH-60L exposures primarily ranged from being considered ‘a little uncomfortable’ to even ‘very uncomfortable’, particularly at the pilot station and left passenger location. The aircraft also showed level flight exposures associated with the

potential for health risk and even likely health risks in less than 8 hours. The results were quite dramatic at the pilot station and left passenger location. The pilot was being exposed to the potential for health risk in 1 to 3 hours of daily occupational flight at any operational airspeed, and exposed to likely health risks in 3 to 7 hours of flight at airspeeds above 80 KCAS (calibrated airspeed in knots). The left passenger was being exposed to the potential for health risk in 1 to 4 hours at any operational airspeed, and exposed to likely health risks in 4 to less than 8 hours at airspeeds above 80 KCAS. Both of these occupants exceeded the exposure limits presented in the MIL-STD-1472G. All occupants should be warned that they may be exposed to potential health risk in less than 8 hours.

Distribution A: Approved for public release.
88 ABW Cleared 9 July 2019; MSC/PA-2019-0265/88ABW-2019-3256

2.0 INTRODUCTION

Epidemiological surveys have consistently reported that ~85% of the rotary-wing aircrew surveyed has suffered back, leg, or neck pain associated with flying helicopters (Hamon, Healing, Contarino, & Ellenbecker, 2012). Poor posture, inadequate seats, and aircraft vibration have been targeted as contributing factors but their synergies and physiological mechanisms are unknown. The recent Business Case Analysis (BCA) conducted by R Cubed Consulting for the Office of the Under Secretary of Defense for Acquisition, Technology and Logistics (OUSD ATL), and Office of the Deputy Under Secretary of Defense Installations and Environment (DUSD I E) (Hamon et al., 2012) emphasized that musculoskeletal pain and discomfort in these aircrew have a significant negative impact on mission effectiveness and mission readiness with an average yearly avoidable cost of $239 M. The strong recommendation in the BCA for improved seating systems cannot be effectively addressed without clear guidelines on exposure effects, seat design, and validation testing. Appropriate science- and technology-based guidelines on exposure, seat design, and validation testing are non-existent, perpetuating the health issues.

The first step is to clearly characterize the actual human multi-axis vibration exposure aboard various rotary-wing/tilt-rotor aircraft to identify the frequency components, acceleration magnitudes, and direction of the vibration entering the occupant at the occupant/vehicle interfaces (typically the seating system). In addition, there are guidelines provided in human vibration exposure standards that can be applied to these data for assessing the health risk and discomfort associated with the exposures (ISO 2631-1: 1997; MIL-STD-1472G, 2012). Health risk and comfort assessments have been conducted on a limited number of platforms, the most recent including the HH-60M Medevac and UH-72 Lakota (Smith, Chervak, & Steinhauer, 2014) located at the Vermont Army National Guard (VT ARNG). The Army Public Health Center (APHC), National Guard Bureau (NGB), and the Air Force Research Laboratory, Airmen Systems Directorate (711 HPW/RH) conducted the study. The equipment and methodology established by AFRL for collecting and analyzing the actual multi-axis measurements at various occupant stations was used to characterize and compare the vibration during different flight conditions, and conduct the comfort and health risk assessments in accordance with the existing standards. An aircrew questionnaire developed by APHC and the 711 HPW/RH was distributed to aircrew members at the VT ARNG. The health risk assessments conducted so far have suggested that certain aircrew may be subjected to potential health risks in less than three hours for occupational exposures (Smith, 2005; Smith Gerdus, 2005; Smith, Jurcsisn, & Bowden, 2008; Smith, Chervak, & Steinhauer, 2014). The AFRL has also used these data to recreate the actual stressor environment in controlled laboratory testing for evaluating seat component influences, physiological responses, task performance, and task workload during simulated prolonged exposures.

This test program is an expansion of the previous studies conducted on rotary-wing/tilt-rotor aircraft and is being funded by the NDCEE. The APHC is the Responsible Test Organization (RTO) and the 711 HPW/RH is the Lead Development Test Organization (LDTO) for this program. Four to five aircraft platforms are targeted for the test program. The test program includes the development of a database quantifying operational vibration and active aircrew subjective perceptions, and integrated into the Air Force Collaborative Biomechanics Data

Network (CBDN) managed by the 711 HPW/RH. The database will be available to researchers, equipment designers, and standards developers for establishing effective near- and far-term pain and injury mitigation strategies.

The specific objectives of this study are:

1. Collect multi-axis acceleration data to characterize the vibration affecting the aircrew and interface equipment aboard the UH-60L Blackhawk helicopter.
2. Assess the comfort and health risk of the vibration exposures in accordance with existing human vibration standards.
3. Enter acceleration data into the 711 HPW/RH Collaborative Biomechanics Data Network (CBDN).

The primary metric being measured to characterize the vibration is the acceleration generated at the human/equipment interfaces in the three orthogonal axes. This may also include the measurement of triaxial accelerations at the helmet for selected aircrew. The accelerations collected at the interfaces will be frequency weighted for estimating the health risk and comfort reactions using guidelines provided in the standards. The survey/questionnaire metrics will include subjective ratings and responses on aircrew perception of the vibration, location of symptoms and discomfort, posture, and interface issues.

A Memorandum of Agreement (MOA) between the US APHC and the AFRL 711 HPW/RH was established that set forth the terms and conditions that the two organizations would use to conduct the project with funding from the NDCEE. The AFRL 711 HPW/RH prepared all required documentation including a Flight Test Plan, and conducted all required review boards including the Technical Review Board (TRB) and Safety Review Board (SRB), in accordance with the Air Force Research Laboratory Instruction 61-103 (2015).

This report focuses on the discomfort and health risk assessments conducted on the UH-60L Blackhawk. The aircrew survey results will be presented in a separate report. Subsequent reports will be forthcoming on additional platforms that were included as part of the larger project.

3.0 METHODS AND PROCEDURES

3.1 Aircraft and Measurement Locations

The UH-60L (tail number 01-26883) is owned and operated by the MD ARNG located at Weide Army Heliport, Aberdeen Proving Ground, MD. The measurement locations targeted included the pilot station located on the right side of the cockpit, the two crew chief stations located in the center of the aircraft behind the pilot/copilot, facing right and left, and two aircrew or passengers located in the rear of the aircraft facing rearward on the right and left sides. All measurement locations or stations were occupied by a pilot, co-pilot, crew chief, passenger, or test conductor.

3.2 Equipment, Instrumentation, and Measurement Sites

Four Remote Vibration Environment Recorders (REVERs), developed by the AFRL Airman Systems Directorate (711 HPW/RH), were used to collect multi-axis vibration data at the five aircrew stations or locations. Each REVER, illustrated in Figure 1, consists of the following:

1. A 16-channel data acquisition unit (DAU) (Large or Small)
2. Two battery packs (Large and Small) Methods info
3. Triaxial accelerometer pack
4. Two triaxial accelerometer seat pads
5. One six-axis helmet mount (Pilot REVER system)
6. One trigger device
7. Connection/extension cables as required
8. Laptop computer

Specifications for the REVER components, including dimensions and weights, are listed in Appendix A, Table A-1.

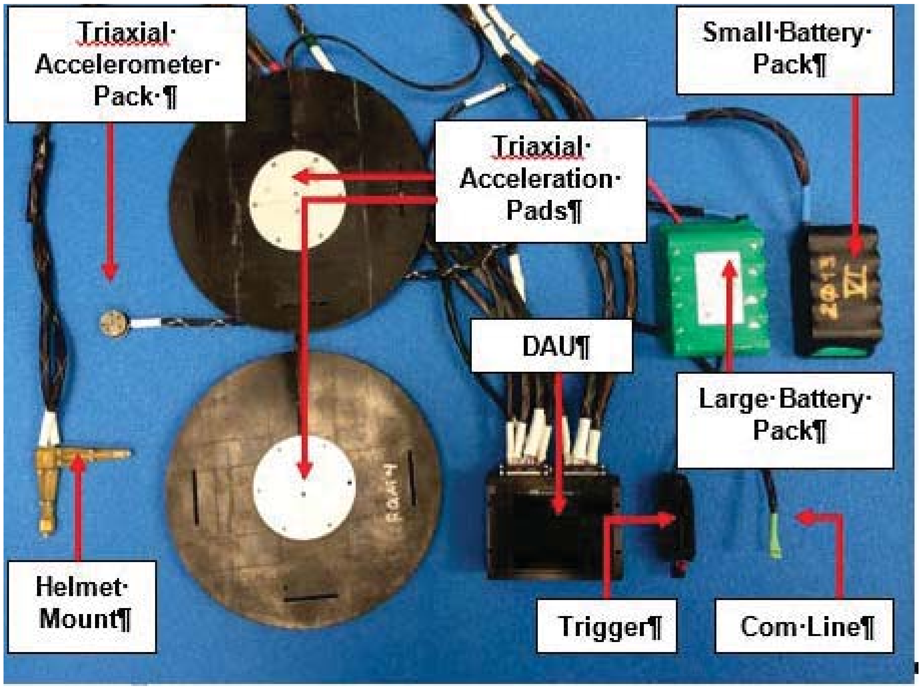


Figure 1. Remote Vibration Environment Recorder (REVER)

Table 1 lists the aircrew stations/locations and measurement sites targeted for data collection, including the type of instrumentation.

Table 1. UH-60L Measurement Sites and Type of Sensor

Station	Measurement Site	Instrumentation
Pilot Station (Right Side Cockpit)	Seat Base	Triaxial Accelerometer Pack
	Seat Pan	Triaxial Acceleration Pad
	Seat Back	Triaxial Acceleration Pad
	Helmet	Six-Axis Helmet Mount
Crew Chief Stations (Center Cabin, Right and Left Facing)	Floor beneath seat	Triaxial Accelerometer Pack
	Seat Pan	Triaxial Acceleration Pad
	Seat Back	Triaxial Acceleration Pad
Aircrew/Passenger Locations (Aft Cabin, Right and Left Sides, Rearward facing)	Floor beneath each seat	Triaxial Accelerometer Pack
	Seat Pan	Triaxial Acceleration Pad

At the pilot station, the small DAU and batteries were carried in pockets attached on the outside of a survival vest. Figure 2 illustrates the vest configuration.

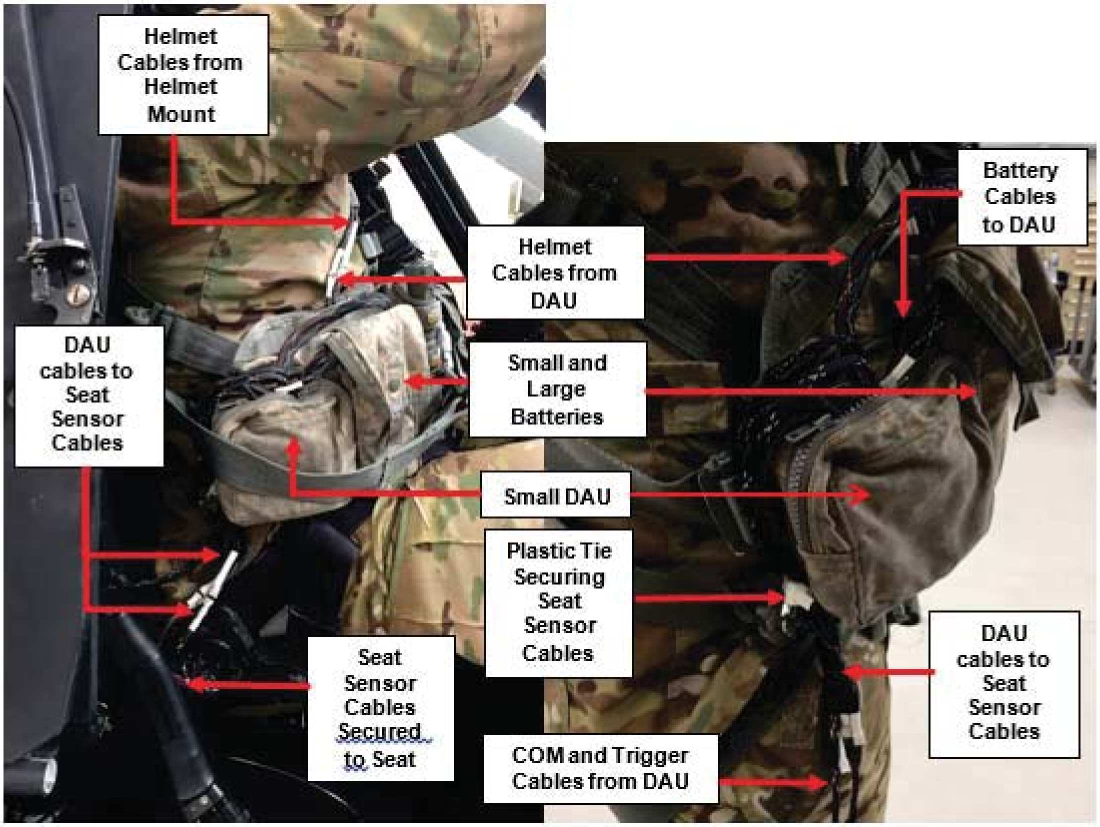


Figure 2. Pilot/Copilot Survival Vest Configuration

A helmet mount was attached onto the top of the pilot helmet using double-sided mounting tape. The helmet mount consisted of six miniature accelerometers strategically arranged to estimate helmet translations in the three orthogonal axes (fore-and-aft or X, lateral or Y, and vertical or Z) and, if desirable, helmet roll, pitch, and yaw. Figure 3 illustrates the helmet mount attached to the helmet. Figure 2 shows the routing and connection of the helmet cables to the respective DAU cables. The helmet mount was further secured with duct tape to prevent any snags.

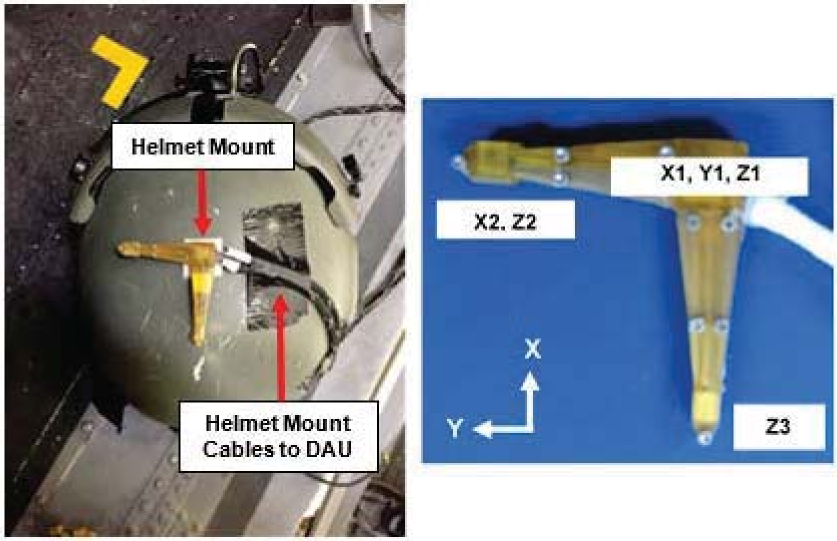


Figure 3. Helmet Mount

At each station or location, a triaxial accelerometer pack was used to measure the input acceleration either on a rigid seat component or on the floor beneath the seat (Fig. 1, Table 1; Appendix A, Table A-1) in the fore-and-aft (X), lateral (Y), and vertical (Z) axis, relative to the seat/occupant orientation. Each pack consisted of three orthogonally-arranged miniature accelerometers embedded in a Delrin® cylinder. Double-sided mounting tape was used to secure the pack to the appropriate site. Triaxial accelerometer pads were used to measure the vibration transmitted to the occupant via the seat pan and seat back (pilot, crew chief stations only) in accordance with the International Standards Organization, ISO-2631-1: 1997 Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration – Part I: General Requirements (ISO 2631-1: 1997). The pad consisted of a flat rubber disk with a triaxial accelerometer pack embedded in the center (Fig. 1; Appendix A, Table A-1). Double-sided adhesive tape and duct tape were used to secure the pads to the seat cushions or seat cloth. Figure 4 illustrates the location of the triaxial accelerometer pack and the seat acceleration pads at the pilot station. Note that the pack is attached to the bottom of the seat pan structure. Figure 5 illustrates the location of the floor accelerometer pack and acceleration pads at the two crew chief stations (illustrated for the right seat). Figure 6 illustrates the location of the floor accelerometer pack and seat acceleration pad at each of the aircrew or passenger locations in the rear of the aircraft. No seat back pads were installed at these locations. It is noted that, during actual flight, the seats located opposite those chosen were instrumented with the aircrew/passengers facing rearward.

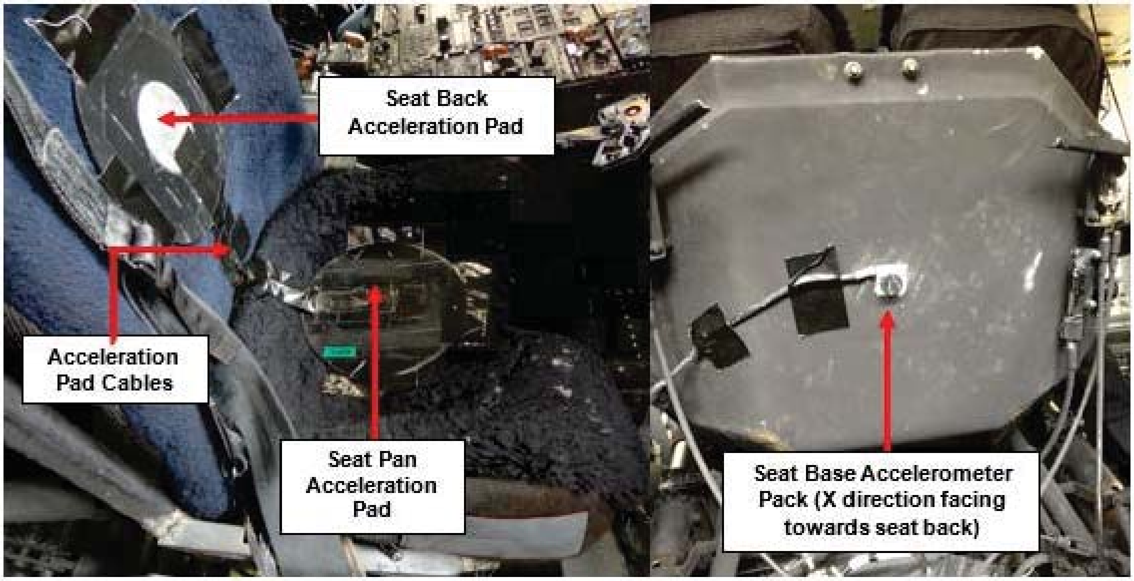


Figure 4. Accelerometer Pack and Acceleration Pads Attached to Pilot Seat

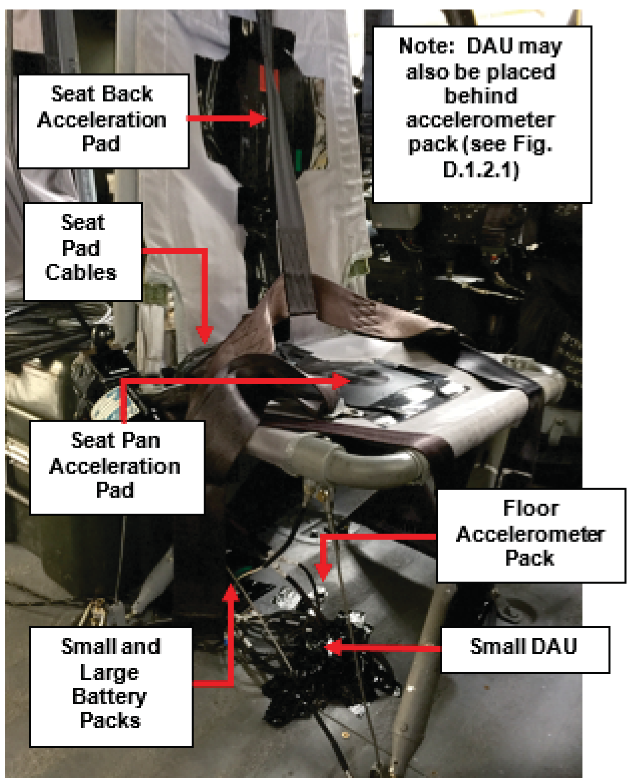


Figure 5. Right Crew Chief/Flight Engineer Station Instrument

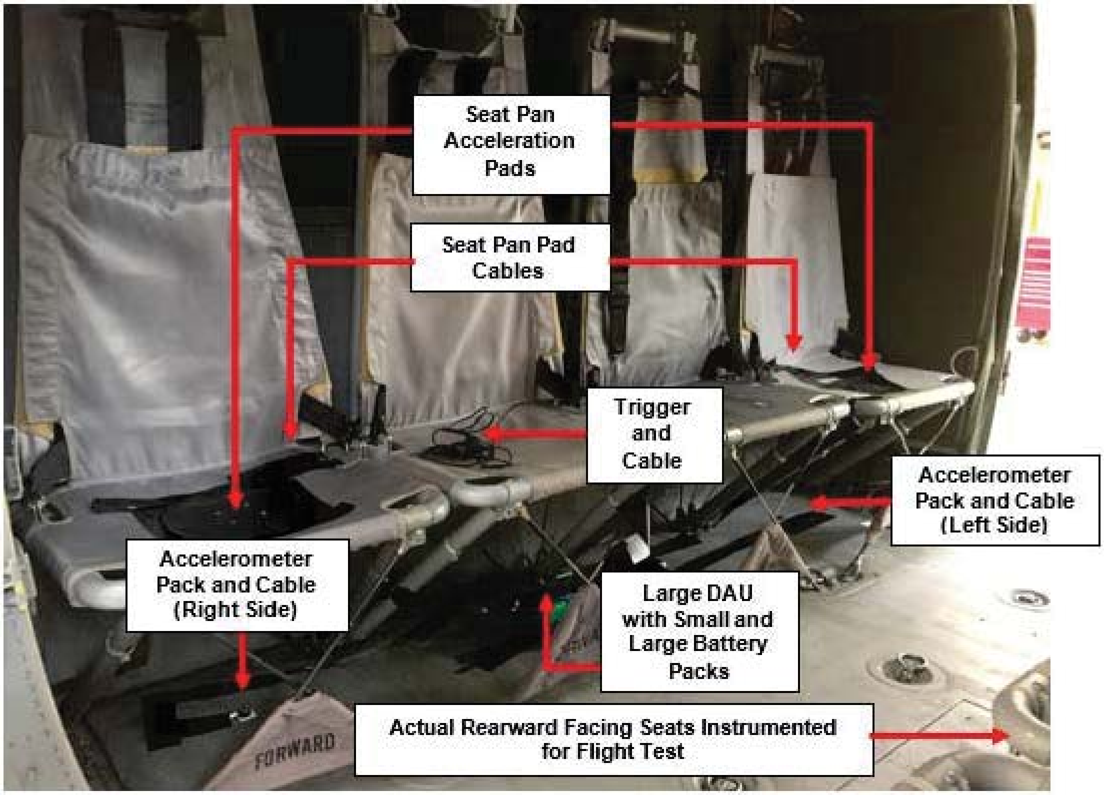


Figure 6. Aft Passenger Right and Left Seat Configurations. Note: actual instrumented seats during flight test faced rearward

When using the survival vest, the seat accelerometer cables were connected to the DAU cables at the lower back edge of the vest on the pilot's right side as illustrated in Figure 2. The cables were run beneath the lap belt to ensure no interference with the safety features of the aircraft or the occupant's task. The cables from the helmet were secured at the back of the helmet and run over the right shoulder to the DAU connection at the front of the vest as shown in Figure 2. All cable connections between the seat and helmet accelerometers and the DAU were made via break-away connectors. Each cable requires less than 21.8 N (4.9 pounds) of static weight to separate. The three-cable bundle shown in Figure 2 takes a peak force of 40 to 45 N (9 – 10 lbs) to separate when the occupant stands up (demonstrated in laboratory setting).

A triggering device (Fig. 1) was run from each DAU via cable to two designated individuals responsible for initiating data collection (see Section 3.3). Once triggered, the DAU would collect data for a pre-specified amount of time. Prior to flight, a laptop computer was used to conduct sensor balance, calibration checks, and arming of each DAU. The computer was used to assign a specific sensor associated with a measurement site and direction to a channel in the DAU. Once armed, the computer was disconnected from the DAU.

3.3 Data Collection, Processing, and Analysis

3.3.1 Data Collection.

Acceleration data were collected at aircrew/passenger stations/locations and measurement sites for the flight test conditions listed in Appendix A, Table A-2 Flight Test Records. The flight test conditions were organized relative to the specific flight tasks that were identified by the aircrew. For the UH-60L, the flight test tasks and conditions were similar to those previously defined by the VT ARNG for the HH-60M. Two individuals, one located at the crew chief station on the left side, the other seated at the right passenger seat located in the rear of the aircraft, were responsible for triggering data collection onto the four DAUs. The individual seated at the passenger location acted as the test conductor, who prompted data collection once the pilot or copilot indicated that the aircraft was on the flight test condition. Multiple data records were collected for several of the conditions. Data records were collected throughout the flight and not necessarily collected in the order presented in Table A-2. The designated test conductor insured that the data records were numbered consecutively in the order they were collected.

Once triggered, data were automatically collected for 20 seconds, filtered at 250 Hz, and digitized at 1024 samples per second. Upon return of the aircraft, the laptop was reconnected to each DAU and the time histories for each channel downloaded to the computer for processing.

All data were collected during one flight test. Appendix A, Table A-2 lists the number of records collected for each flight test condition.

3.3.2 Data Processing and Analysis.

A computer program developed by AFRL 711 HPW/RH was used to separate the 20-second records for each channel and assemble all channels for a particular record into a table of time histories. For each record, the time histories were processed using the MATLAB® Signal Processing Toolbox (The MathWorks, Inc., Natick, MA) to estimate the constant bandwidth spectral content. Using Welch's Method (Welch, 1967), each 20-second time history was divided into two-second sub-segments with a 50% overlap. A Hamming window was applied to each sub-segment and the resultant power spectral densities averaged over the 20-second period. The root-mean-square (rms) acceleration, a_{rms}, was calculated from the power spectral densities in 0.5 Hz intervals. The constant bandwidth rms acceleration spectra were used to locate the peak accelerations.

Each acceleration time history was also processed in one-third octave proportional frequency bands using a software program developed for MATLAB® (Couvreur, 1997). The accelerations were reported at the center frequency of each respective one-third octave band. These data were used to assess the exposures in accordance with current standards.

The overall unweighted acceleration level, a_{uw}, between 1 and 80 Hz was calculated for each station at the floor or seat base, seat pan, seat back, and helmet (pilot only):

$$a_{uw} \;=\; \left[\sum_i a_{rmsi}^2\right]^{1/2} \tag{1}$$

where a_{rmsi} is the rms acceleration associated with the *ith* frequency component (in 0.5 Hz increments for constant bandwidth analysis, and at the center frequency of the one-third octave band for proportional bandwidth analysis).

The assessment of discomfort (comfort reaction) and health risk followed the guidelines provided in ISO 2631-1 and the MIL-STD-1472G. The frequency weightings and multiplying factors listed in Table 2, based on human sensitivity to the location, frequency, and direction of vibration, were used to assess comfort reaction and health risk. Figure 7 illustrates the frequency weightings W_d, W_k, and W_c.

Table 2. ISO 2631 Frequency Weightings and Multiplying Factors (ISO 2631-1: 1997)

	HEALTH RISK Seat Pan		COMFORT REACTION Seat Pan		COMFORT REACTION Seat Back	
Direction	Frequency Weighting	Multiply Factor	Frequency Weighting	Multiply Factor	Frequency Weighting	Multiply Factor
X	W_d	$k = 1.4$	W_d	$k = 1.0$	W_c	$k = 0.8$
Y	W_d	$k = 1.4$	W_d	$k = 1.0$	W_d	$k = 0.5$
Z	W_k	$k = 1.0$	W_k	$k = 1.0$	W_d	$k = 0.4$

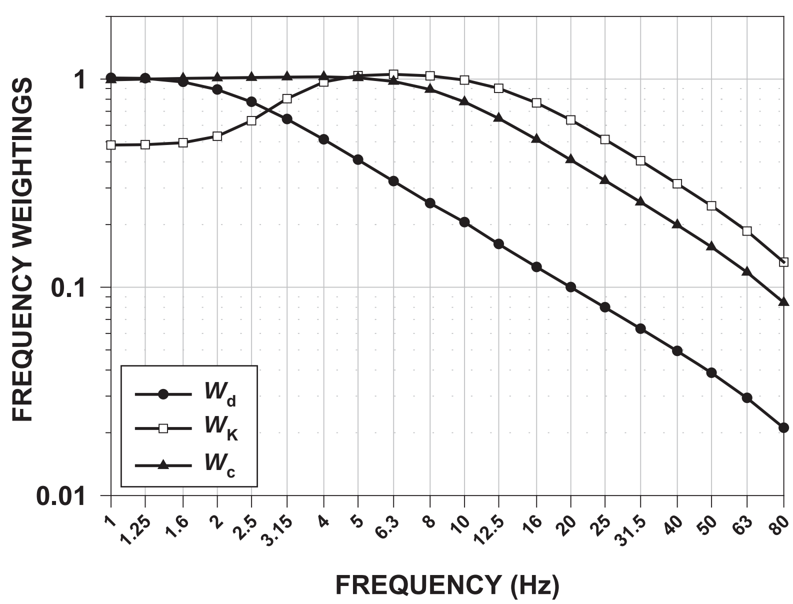


Figure 7. ISO 2631 Frequency Weightings W_d, W_k, and W_c (ISO 2631-1: 1997)

The overall weighted rms acceleration level, a_w, was calculated between 1 and 80 Hz in each axis (X, Y, and Z) relative to the coordinate system of the seated occupant using the one-third octave rms accelerations:

$$a_w \;=\; \left[k \sum W_{ij}^2 a_{rmsi}^2\right]^{1/2} \tag{2}$$

where *k* represents the multiplying factor associated with a particular direction (X, Y, Z), measurement site (seat pan, seat back), and type of assessment (comfort, health); and W_{ji} is the frequency weighting associated with a particular direction and measurement site *j*, for the *ith* one-third octave center frequency component. For assessing comfort reaction, the point vibration total value (*pVTV*) was calculated at both the seat pan and seat back as the vector sum of the weighted fore-and-aft, lateral, and vertical accelerations, respectively, after applying the appropriate multiplying factors for the measurement location (seat pan or seat back):

$$pVTV \;=\; \left[k_x^2 a_{wx}^2 \;+\; k_y^2 a_{wy}^2 \;+\; k_z^2 a_{wz}^2\right]^{1/2} \tag{3}$$

The overall vibration total value (*oVTV)* was calculated as the vector sum of the seat pan and seat back *pVTVs*. The *oVTVs* were compared to the weighted accelerations associated with the comfort reactions given in ISO 2631-1: 1997, Annex C. The comfort reactions include "Not Uncomfortable", "A Little Uncomfortable", "Fairly Uncomfortable", "Uncomfortable", "Very Uncomfortable", and "Extremely Uncomfortable".

For assessing health risk, the highest weighted seat pan acceleration in any axis (fore-and-aft, lateral, or vertical) was used after applying the appropriate multiplying factors given in Table 3. The weighted data were compared to the ISO Health Guidance Caution Zones (HGCZs) (ISO 2631-1: 1997, Annex B). The ISO 2631-1: 1997 also states that the vector sum of the weighted accelerations at the seat pan (*pVTV*) after applying the appropriate multiplying factors for health risk can be used when vibration in two or more axes are similar. For weighted accelerations falling below the lower boundary of the ISO HGCZs for the expected duration, health risks are unlikely. For those levels falling between the two boundaries, caution is given with respect to health risk, or there is a potential for health risk. For those levels falling above the upper boundary, health risks are likely for repeated occupational exposures. The current MIL-STD-1472G uses the guidelines of the ISO 2631-1; for exposures of 3.5 hours and below, the lower boundary of the HGCZs follows the more conservative fourth power relationship described in the ISO Annex B. Figure 8 illustrates the ISO HGCZs and includes the lower boundary defined in the MIL-STD for exposures of 3.5 hours and below. The current MIL-STD-1472G states the following:

> *"For exposures lasting 8.0 hours or less, the seat pan frequency weighted triaxial RMS accelerations in any orthogonal direction for any occupied space shall not fall within the zone labeled "Health Risks are LIKELY". Preferably the weighted accelerations shall fall within the "Minimal Risk to Health" zone. For exposures lasting greater than 8.0 hours, the seat pan frequency weighted triaxial RMS accelerations shall not exceed 0.315 m/s^2. If the weighted accelerations fall within the "Caution Zone", a warning to occupants shall be provided indicating the potential health risk"*

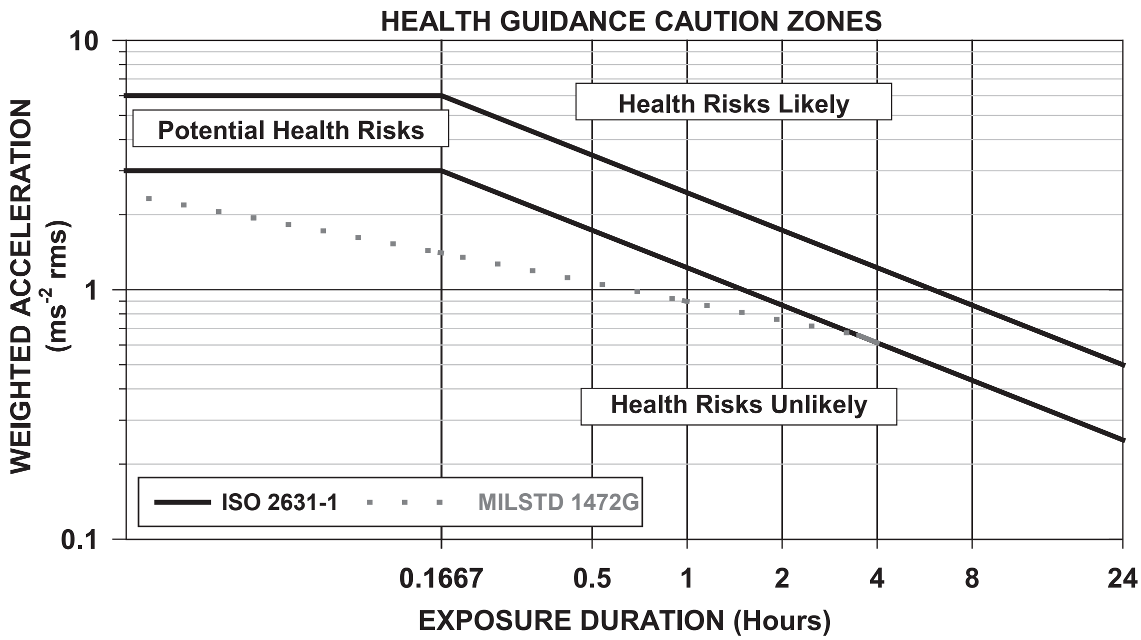


Figure 8. ISO 2631-1 Health Guidance Caution Zones (HGCZs). Plot includes more conservative lower boundary defined in MIL STD 1472G for exposures at 3.5 hours and below

A revision of the MIL-STD-1472 (version H) is in progress that may include modifications to the exposure criteria.

4.0 RESULTS

All Figures and Tables referred to in this section are located in Appendix A. In addition, the crew chief located on the right side may have been changing posture during the flight test in order to perform operational duties. As a result, several records were deleted that deviated dramatically from other records associated with the flight test condition, with the exception of the mean overall accelerations depicted in Figure A-6. The deletions included: Ground Idle (all records), Ground (Grd) Flight (Flt) 100% (all records), Take-Off (TO) Normal (record 7), Hover Stationary (Stat) In Ground Effect (IGE) (records 8, 9), Level Flight 80 (record 80), Level Flight 145 (record 60), Normal Approach (NA) Out of Ground Effect (OGE) Hover (record 87), Steep Approach (SA) IGE Hover (records 26, 27), and Nap-of-the-Earth (NOE) (all records).

4.1 Characteristics of the Multi-Axis Accelerations Aboard the UH-60L

4.1.1 UH-60L Acceleration Spectra.

It was expected that a peak in the acceleration spectra would occur in the vicinity of the main rotor speed of the aircraft. The frequency associated with the rotor speed is referred to as the propeller rotation frequency or PRF in this document. The highest peak typically occurs at the blade passage frequency or BPF, which is predicted as the number of blades multiplied by the PRF. Both the PRF and BPF may vary slightly depending on the flight maneuver and whether the aircraft is operated at 100% power. Additional peaks were also expected at multiples of the BPF. The direction of the highest acceleration associated with the BPF was unknown prior to the analysis of these data. The following summarizes the observations of the spectral content and the BPF accelerations for Hover IGE, Hover OGE, and Level Flight at the four airspeeds listed in Table A-2.

Figures A-1 through A-3 illustrate the acceleration spectra for the UH-60L at the floor or seat base, seat pan, seat back ((pilot and crew chief only) and helmet (pilot only)) for a selected data record collected during level flight at the pilot, left crew chief, and left aircrew or passenger station/locations, respectively. The figures also include the mean BPF accelerations for Hover IGE, Hover OGE, and Level Flight at the four airspeeds for all occupant stations/locations. As expected, the highest peaks tended to occur at what was presumed to be the BPF. The peak consistently occurred between 17 and 17.5 Hz. Based on these observations, it was estimated that the PRF for level flight was between 4 and 4.5 Hz, similar to the results observed for the HH-60M (13). Relatively small peaks below the BPF can be observed in the spectra at all stations/locations. Peaks were also observed at multiples of the BPF. It is not clear what contributed to peaks observed at other frequencies.

Table A-3 includes the statistical results using the one-way Repeated Measures Analysis of Variance (RM ANOVA) and the Bonferroni t-test to evaluate the effects of direction on the BPF acceleration (significant differences at $P<0.05$) for the Hover IGE, Hover OGE, and four level flight test conditions. The most notable differences at the pilot station occurred during level flight. The BPF peaks at the seat base, seat pan, and seat back were significantly higher in the lateral (Y) direction at 80 and 100 KCAS as compared to the fore-and-aft (X) and vertical (Z) directions. The lowest BPF peaks at the seat base occurred in the Z direction, while the lowest BPF peaks at the seat pan and seat back occurred in the X direction at 80 and 100 KCAS. The highest BPF peak became prevalent in the X direction at the seat base, and in the Z direction at the seat pan and seat back at 120 KCAS. The same results observed at 120 KCAS were observed at the seat base and seat pan at 145 KCAS, while the seat back showed the highest BPF peak in the Y direction at 145 KCAS. Both the pilot seat pan and seat back showed the lowest BPF peak in the X direction at 120 and 145 KCAS (Figure A-1). At the pilot station helmet, the highest peak associated with the BPF was observed in the Z direction (not statistically evaluated), with dampening of the vibration at higher frequencies. The helmet accelerations observed below 4 Hz are most likely due to pilot voluntary head motion. Given that it was not easy for the pilot to change his/her posture during flight, the mean BPF peaks illustrated in Figure A-1 show the relative dampening effects that occur between the rigid seat base and the pilot/seat interfaces. In general, both the Y and Z peaks were amplified at the seat pan, while the X peaks tended to be dampened at the seat pan, as compared to the seat base.

At the crew chief stations, the directional differences for level flight were not as dramatic as observed for the pilot (Figure A-2). Table A-3 includes the statistical comparison for the left crew chief station only. It is noted that the crew chief seat is oriented 90 degrees from the longitudinal (X) axis of the aircraft. The directions described below are all relative to the crew chief orientation, not the aircraft orientation. Statistically higher BPF peaks at the floor and seat pan occurred in the X direction at 80 and 100 KCAS, while variable results occurred at the seat back. The highest acceleration occurred in the Z direction at the seat pan and seat back at 120 and 145 KCAS. Figure A-2 shows that the directional effects tended to differ between the left and right side, but may have been due to changing posture by the crew chief located on the right side while performing operational duties.

At the passenger locations, more dramatic differences were observed in the BPF accelerations (Figure A-3). It is noted that the right passenger lateral (Y) seat pan sensor was not working properly. No statistical analysis was done at this passenger location. It is noted that the passengers faced rearward. Mixed results were observed at the left passenger floor (Table A-3). At the left passenger seat pan, dramatic effects were observed in the BPF peaks. The highest BPF peaks occurred in the X direction, while the lowest BPF peaks occurred in the Y direction at all four level flight airspeeds. Figure A-3 shows that these dramatic directional differences did not occur at the right passenger seat pan. Given the similarity in the floor accelerations at both passenger locations for the majority of illustrated conditions, it is speculated that passenger posture and anthropometry may have affected the results.

4.1.2 Overall Unweighted Accelerations.

It is cautioned that the summary provided below on the unweighted overall accelerations are observations and have not been statistically evaluated for significant effects of measurement site and direction.

Figures A-4 through A-7 illustrate the mean unweighted overall accelerations ± one standard deviation at the pilot, left crew chief, right crew chief, left passenger, and right passenger, respectively, for each flight test condition. Tables A-4 through A-8 list the unweighted overall seat pan accelerations for each level flight record at each of the four aircrew stations/locations.

In general, all stations/locations showed overall accelerations for level flight that were similar to or higher than the overall accelerations observed for the other flight test conditions. At the pilot station (Figure A-4), the overall unweighted acceleration levels tended to follow the trend observed for the BPF peak (Figure A-1); higher Y accelerations at 80 and 100 KCAS at all three measurement sites, higher X accelerations at 120 and 145 KCAS at the seat base, and higher Z accelerations at the seat pan and seat back at 120 KCAS. The seat pan did show higher Z accelerations at 145 KCAS, with the seat back also showing higher Z accelerations at 145 KCAS, in contrast to the BPF peaks.

At the left crew chief station (Figure A-5), the overall unweighted accelerations tended to be the highest in the Z direction at the seat base for all airspeeds, the highest in the X direction at the seat pan for 80 and 100 KCAS (Y direction relative to aircraft), and showed mixed results at the seat pan for the higher airspeeds, with mixed results at the seat back for all airspeeds. At the right crew chief station (Figure A-6), the overall unweighted accelerations include those data records that had been excluded in the BPF peaks and the data used for comfort and health risk assessment due to questionable crew member posture, resulting in relatively high mean accelerations and high standard deviations, particularly at the seat back.

At the left passenger location (Figure A-7), higher overall accelerations tended to occur in the Z direction at the floor, and in the X direction at the seat pan for all four airspeeds. The observations at the seat pan for the overall accelerations reflected the findings for the seat pan BPF accelerations (Figure A-3). At the right passenger location (Figure A-8), it is noted that the seat pan Y acceleration is not included due to a bad sensor.

4.2 Assessment of the UH-60L Aircrew Comfort and Health Risks

4.2.1 Overall Weighted Accelerations.

It is cautioned that the summary provided below on the weighted overall accelerations are observations and have not been statistically evaluated for significant effects of measurement site and direction.

Summary plots of the overall unweighted accelerations at the seat base, seat pan, and seat back, and the overall weighted accelerations at the seat pan and seat back are provided in Figure A-12 for comparison. The figure also includes plots of the *pVTV*s and *oVTV* for the comfort assessment, and the *pVTV*s for health assessment. The figure shows that the highest unweighted overall accelerations at the seat pan did not necessarily occur in the Z direction, while the highest weighted overall accelerations at the seat pan were notably in the Z direction. This difference was dramatic for most stations/locations even with the 1.4 multiplying factor applied to the horizontal directions in accordance with Table 2 for assessing health risk. Figure 7 also shows that the frequency weighting, W_d, for the horizontal directions reduce the contributing accelerations to a much greater extent than in the vertical direction (W_k). In contrast, the figures show that the highest unweighted overall accelerations at the seat back did not occur in the X direction, while the highest weighted overall accelerations did occur in the X direction. The multiply factors and frequency weightings also affected the contributions at the seat back (Table 2, Figure 7).

4.2.2 Aircrew Vibration Comfort Assessment (ISO 2631-1 Comfort Reactions).

The guidelines in ISO 2631-1 were used to assess the comfort reactions of the aircrew. At the pilot and two crew chief stations, the assessment was based on the *oVTV* calculated as the vector sum of the *pVTVs* estimated at the seat pan and seat back in accordance with Eq. (3) and using the frequency weightings and multiplying factors in Table 3. At the two passenger locations, comfort reactions were assessed using the seat pan *pVTV* calculated for health risk (including the 1.4 multiplying factor in the horizontal directions) since no data were collected at the seat back. The Comfort Reactions are independent of time.

Figures A-9 and A-10 plot the *oVTV*s for assessing comfort reaction for all flight test conditions at the pilot and two crew chief stations, respectively, and Figure A-11 plots the *pVTV*s for health risk for all flight test conditions at the two passenger locations. All figures include illustration of the ISO 2631-1 Comfort Reactions. Figure A-9 shows that the pilot *oVTV*s were primarily considered "uncomfortable" for Task 1052, which included level flight, with some exposures being considered "very uncomfortable". Figure A-10 shows that the comfort reactions at the two crew chief stations for Task 1052 were considered "a little uncomfortable" to "fairly uncomfortable". Figure A-11 shows that the comfort reactions for the right passenger were less severe than those of the left passenger. This was most likely due to the lack of Y-axis data in the *pVTV* calculation for the right passenger location. For the left passenger, the *pVTV*s for Task 1052 were associated primarily with a comfort reaction of "uncomfortable", with some exposures being considered "very uncomfortable", similar to the results for the pilot. Unlike the pilot seat pan accelerations, the highest level flight seat pan accelerations at the left passenger location tended to occur in the X direction (compare Figures A-1 and A-3 for the BPF peaks, and Figures A-4 and A-7 for the overall unweighted accelerations). Figure A-12 also shows that the weighted seat back accelerations made very little contribution to the comfort reaction at the pilot and left crew chief stations (compare the seat pan comfort *pVTV*s to the *oVTV*s). For the right crew chief station, Figure A-12 shows relatively large variations in the overall accelerations and *VTV*s that may be attributed to changing posture, even though certain records were eliminated from the calculations.

4.2.3 Aircrew Vibration Health Risk Assessment (ISO 2631-1).

The guidelines in the ISO 2631-1 were also used to assess health risk, using the level flight seat pan data. It was assumed that the aircrew would spend most of the daily mission in level flight. When assessing the potential for health risk, the lower boundary of the ISO Health Guidance Caution Zones (HGCZ) was used and not the more conservative MIL-STD-1472G boundary for exposures less than 3.5 hours (see Figure 8). The health risk assessment is dependent on the daily exposure duration. It was assumed that the range of accelerations collected at level flight were representative of the expected acceleration levels occurring for various missions. This is based on the assumption of no adverse weather (such as high wind) or evasive maneuvering (such as may occur when under live fire).

Tables A-4 through A-7 list the weighted overall seat pan accelerations and seat pan *pVTV*s for assessing health risk for each level flight record at each of the four aircrew stations/locations. The tables also list the minimum exposure duration for each listed record, in hours, for potential health risk (lower boundary of HGCZs) and likely health risks (upper boundary of HGCZs) (Figure 8 (ISO 2631-1 boundaries only)). These exposure durations were based on the highest overall seat pan acceleration in any direction, as well as the seat pan *pVTV* for health risk. The highest weighted acceleration at the seat pan always occurred in the vertical (Z) direction, regardless of the aircraft or station, as noted in the summary plots illustrated in Figure A-12 and Tables A-4 through A-8. Any exposure duration below the lower boundary would be associated with minimal health risk. Any exposure duration between the lower and upper boundaries would be associated with the potential for health risk, and any exposure at or above the upper boundary would be associated with a likely health risk. The durations were calculated based on the square root time dependency. The durations and associated acceleration levels are color-coded (orange for lower boundary and red for upper boundary) to easily identify which maneuvers and records would reach the two boundaries in less than 8 hours.

Figure A-13 illustrates the minimum exposure durations associated with the potential for health risk at all four stations at each airspeed based on the seat pan *pVTV*s. Figure A-14 illustrates the minimum exposure durations associated with likely health risks. The figures indicate that lower durations occurred at the higher airspeeds. These durations were associated with the tendency for higher seat pan *pVTV*s at higher airspeeds. In addition, the figure also indicates that the lowest durations were associated with the pilot station and left passenger location, and that, in general, the majority of exposures associated with level flight were restricted to durations of less than 8 hours to assure minimal health risk.

As mentioned previously, Tables A-4 through A-7 list the weighted seat pan overall Z accelerations and seat pan *pVTV*s (health risk). Those values highlighted in orange indicate that there is the potential for health risk in less than 8 hours. Those values highlighted in red indicate that health risks are likely in less than 8 hours. The following is a more detailed synopsis of the level flight exposure effects on health risk.

At the pilot station, Figure A-4 shows that the pilot was exposed to the potential for health risk in about 3 hours or less at all airspeeds, regardless of the assessment method (seat pan Z vs seat pan *pVTV*). For airspeeds of 100, 120, and 145 KCAS, pilot health risks were likely for occupational exposures lasting less than 8 hours, regardless of the assessment method.

Tables A5 and A-6 do show that both crew chiefs were exposed to the potential for health risk in less than 8 hours at higher airspeeds but neither station showed that health risks are likely in less than 8 hours of exposure.

Table A-6 shows that the left passenger, as with the pilot, was being exposed to the potential for health risk in less than 8 hours, and specifically in less than about 4 hours, at all four tested airspeeds, regardless of the assessment method. In addition, health risks are likely for exposures lasting 8 hours or less at 100, 120, and 145 KCAS for most records, regardless of the assessment method.

Table A-7 indicates that the right passenger, as with the pilot and left passenger, was being exposed to the potential for health risk in less than 8 hours, regardless of the assessment method. The durations tended to be higher than observed for the left passenger, even when only comparing the weighted seat pan Z acceleration. Only two exposures showed likely health risks in less than 8 hours at the right passenger location.

5.0 DISCUSSION AND CONCLUSIONS

This document provides a summary of the vibration exposure characterization and assessment conducted onboard the UH-60L Blackhawk helicopter. Included is a synopsis of the seat pan and seat back acceleration spectra generated by the aircraft. The characteristics of the spectra generated by the UH-60L were similar to that observed during other investigations conducted on rotary-wing and tilt-rotor aircraft, where the highest accelerations were associated with the propulsion system and occurred at relatively distinct frequencies (Smith, 2005; Smith, & Gerdus, 2005; Smith, Jurcsisn, & Bowden, 2008; Smith, Chervak, Steinhauer, 2014). The vibration associated with the propeller rotation frequency or PRF was typically quite low in magnitude and occurred below 10 Hz. The highest vibration tended to occur at the blade passage frequency or BPF in the vicinity of 17 to 17.5 Hz at all measurement sites, with additional peaks observed primarily as harmonics of the BPF. Peak magnitudes were observed in the fore-and-aft (X), lateral (Y), and vertical (Z) directions, depending on the flight test condition, station, and measurement site. These observations are similar to the trends observed in the HH-60M variant (Smith, Chervak, & Steinhauer, 2014)

As shown in Figure A-12, the higher frequencies associated with the UH-60L, as with other rotary-wing/tilt-rotor aircraft, can be highly weighted once the ISO 2631-1 frequency weightings and multiplying factors are applied for calculating the overall weighted accelerations, *pVTVs*, and *oVTVs*. This can dramatically reduce the contribution of the vibration to the comfort reaction and health risk assessments defined in the standards. Regardless, the aircraft did show that certain flight test conditions were associated with comfort reactions ranging from being considered 'a little uncomfortable' to even 'very uncomfortable', particularly at the pilot station and left passenger location, as illustrated in Figures A-9, A-10, and A-11. The aircraft also showed level flight exposures associated with the potential for health risk, and even likely health risks, in less than 8 hours, as illustrated in Figures A-13 and A-14. Figure 9 summarizes the mean minimum daily exposure durations ± one standard deviation among the three level flight airspeeds associated with the ISO 2631-1 potential for health risk and health risks likely (Health Guidance Caution Zones). The summary includes the pilot station, left crew chief station, and left passenger location. These stations and location included all level flight records measured during the study and represented the most consistent data collected during the flight test. As noted previously, the results were quite dramatic at the pilot station and left passenger location. Relative to one standard deviation, the pilot was being exposed to the potential for health risk in approximately 1 to 2 hours of flight with a mean duration of approximately 1.5 hours, and exposed to likely health risks in approximately 4 to 8 hours of flight with a mean duration of approximately 6.0 hours. The left passenger was being exposure to the potential for health risk in less than 1 to a little over 2 hours of flight with a mean duration of approximately 1.2 hours, and exposed to likely health risks in a little over 3 to approximately 9 hours of flight with a mean duration of approximately 6.1 hours. Shorter durations were associated with higher airspeeds. Both of these occupants exceeded the exposure limits presented in the MIL-STD-1472G. All occupants of the UH-60L should be warned that they may be exposed to potential health risk in less than 8 hours. It is emphasized that these guidelines are based on daily occupational exposures of the aircrew during their flying career.

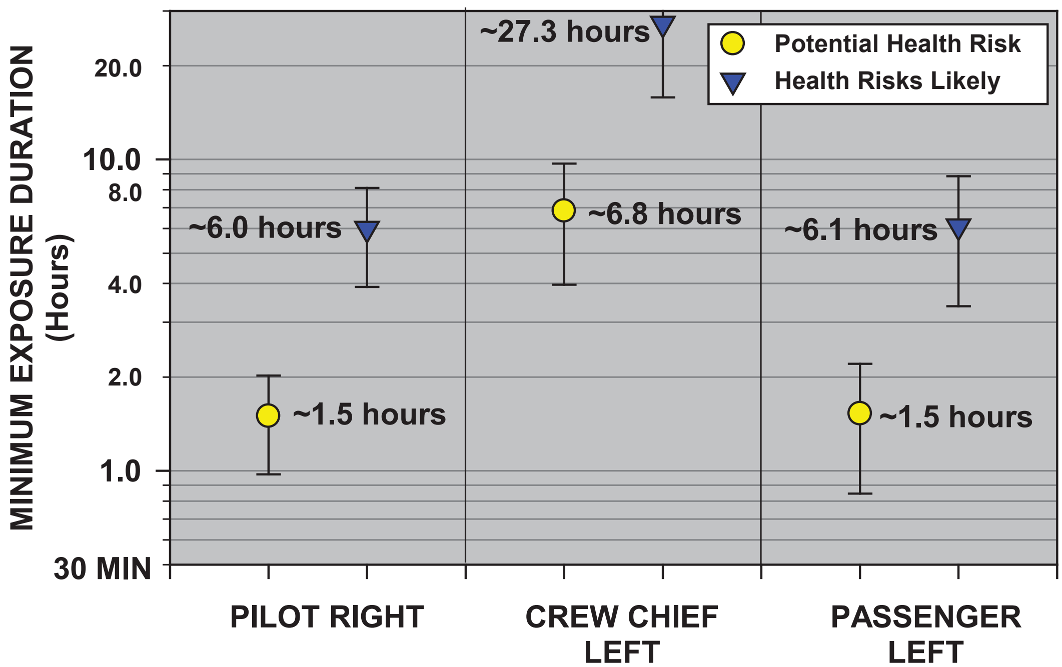


Figure 9. Mean Minimum UH-60L Daily Exposure Durations ± One Standard Deviation for Potential Health Risk and Health Risks Likely (ISO 2631-1)

Figure 10 compares the seat pan *pVTV*s from other aircraft that have been previously assessed for health risk in accordance with ISO 2631-1. The figure shows that the UH-60L showed relatively higher values when compared to other aircraft, particularly at the pilot station and left passenger location. This includes the HH-60M, a Blackhawk variant. The difference was particularly notable when comparing the pilot exposures. Both pilots were located on the right side of the cockpit and both had similar seating systems. The one difference was the configuration of the HH-60M with the Active Vibration Suppression System (AVSS), which primarily reduced the transmission of vertical vibration to the aircraft occupants. This had a dramatic effect on the minimum exposure duration for potential health risk; the HH-60M pilot reaching the minimum duration in 4 to greater than 8 hours, while the UH-60L pilot reached the minimum exposure in less than 4 hours (Figure 10). As mentioned above, the pilot was even exposed to the minimum duration for likely health risks in less than 8 hours at higher airspeeds.

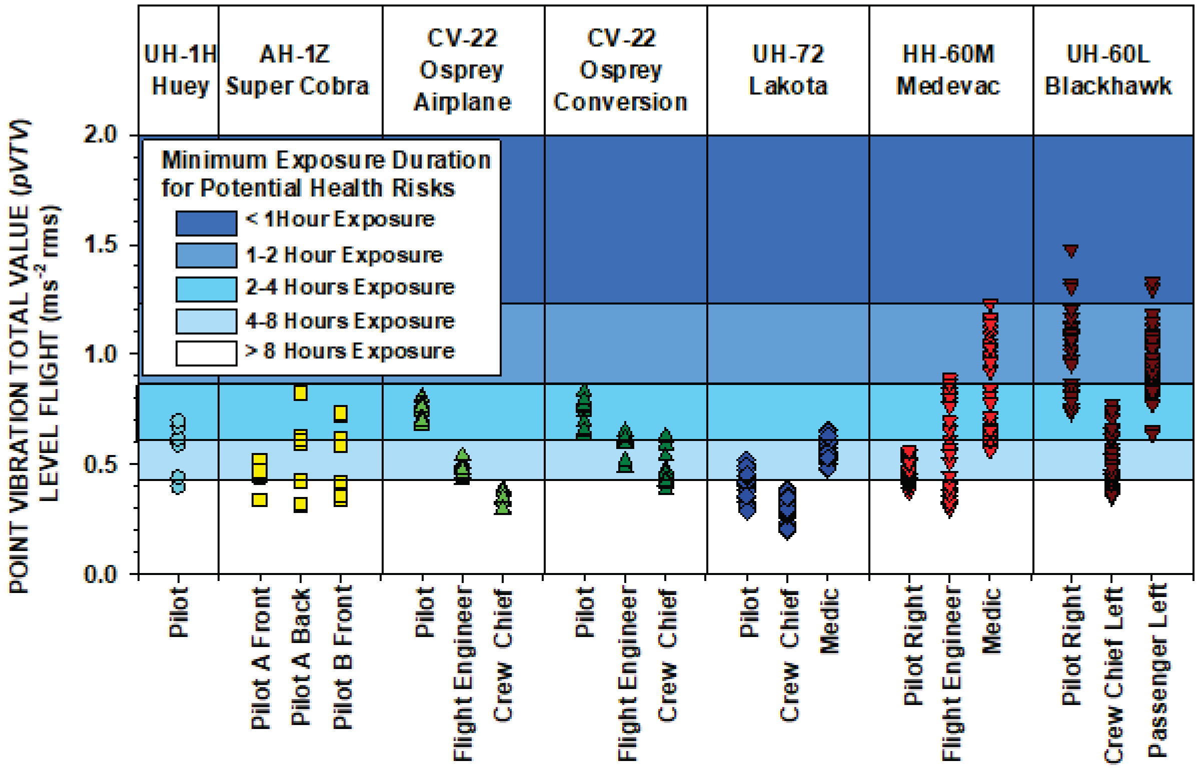


Figure 10. Comparison of Health Risk *pVTVs* Among Rotary-Wing/Tilt -Rotor Aircraft

The assessment guidelines provided in the standards are based on human physical and psychophysical (perceptional) responses to the frequency, magnitude, and direction of the vibration exposure. These response characteristics are expressed by the frequency weightings and multiplying factors that are applied during the assessment process. Humans are the most sensitive to vibration occurring below 10 Hz, particularly in the vertical (Z) direction. Vibration at these lower frequencies can produce relative motions between body regions (vertical motion) and cause postural instabilities (when combined with low frequency horizontal motion) that are readily perceived as being uncomfortable and even painful. Whole-body resonance has been identified during vertical vibration in the range of 4 and 8 Hz, where the large relative motions between the upper and lower torso transmit easily to the head. The comfort reactions defined in ISO 2631-1 (Appendix C) are based on passenger expectations in public transportation, where exposures are expected to occur at lower frequencies and shorter durations than in military operations. Caution should be taken in applying these reactions to military environments, where longer durations and higher frequency exposures could affect aircrew perception. Likewise, the ISO 2631-1 health risks of vibration have primarily been associated with the lumbar spine and connected nervous system. It is logical to conclude that higher magnitude lower frequency vibration could contribute to these symptoms due to the relative upper and lower torso motions and postural instability that can dynamically and repeatedly stress the spinal column. Vibration transmission to the upper torso and head dramatically decreases at frequencies beyond 10 Hz, unless there are substantial amplitudes or the upper torso/head is in direct contact with a vibrating surface. Humans primarily perceive higher frequency vibration at the interfaces where the body is in contact with the vibrating surface. The mechanisms by which higher frequency vibration generates spinal musculoskeletal stresses that contribute to discomfort and pain may be physiologically different than the mechanisms associated with low frequency vibration. This suggests there could be a substantial impact on the most appropriate criteria to apply for assessing discomfort and health risk in military air vehicles.

In summary, the results of the assessments on the UH-60L further support the substantial influence of operational vibration on the discomfort and pain that has been associated with the operation of these aircraft, particularly given the magnitudes of the higher frequency exposures that still result in a potential health risk according to the standards and guidelines. The higher frequency characteristics of the vibration do warrant investigation of the mechanisms by which the vibration can cause pain and injury, leading to the development of more robust discomfort and pain mitigation strategies.

6.0 RECOMMENDATIONS

1. Conduct periodic monitoring of the aircrew by occupational health specialists, particularly documenting reports of discomfort, pain, tingling, and numbness in the back, buttocks, and lower extremities. This could be accomplished using the aircrew surveys developed for this study or some modification. (The results of the survey conducted under this study will be documented in a subsequent report.)

2. Consider adding seat pan and seat back cushion support that may improve posture and also mitigate some of the higher frequency vibration entering the occupant at interfaces, particularly for aircrew occupying the back of the aircraft. Attention should be paid to the multi-axis characteristics of the exposures.

3. Consider the use of passive, semi-active, and active vibration mitigation technologies either added to the existing Blackhawk seat or via new seat design concepts. The data collected during this project on four different rotary-wing platforms, as well as the data from past studies on rotary-wing/tilt-rotor aircraft, should be leveraged in the development of appropriate equipment design criteria and testing strategies of equipment concepts for improving the safety and health of military aircrew.

7.0 REFERENCES

Air Force Research Laboratory, *Instruction 61-103*, *Scientific /Research and Development, AFRL Research Test Management*, AFRLI 61-103, 28 Oct 2015.

Couvreur, C., *FILTBANK - One-Third-Octave Band Frequency Analyzer* [computer program, MATLAB®], Faculte Polytechnique de Mons, Belgium, 1997.

Department of Defense, *Department of Defense Design Criteria Standard, Human Engineering*, MIL-STD-1472G, 11 Jan 2012.

Hamon, K., Healing, R., Contarino, R., Ellenbecker, D *Business Case Analysis: Improve Combat Readiness and Mission Effectiveness by Eliminating Avoidable Helicopter Seating Related Injuries*, R Cubed Consulting, Final Report, OUSD (AT L), DUSD (I E), 2012.

International Organization for Standardization, *Mechanical vibration and shock-Evaluation of human exposure to whole-body vibration-Part 1: General requirements*, ISO 2631-1: 1997. Geneva, Switzerland.

International Organization for Standardization, *Mechanical vibration and shock-Evaluation of human exposure to whole-body vibration-Part 1: General requirements-Amendment 1*, ISO 2631-1/Amd1:2010. Geneva, Switzerland.

Smith, S. D., *Super Cobra (AH-1Z) Human Vibration Evaluation*, AFRL-HE-WP-TR-2005-0114, Air Force Research Laboratory, Wright-Patterson AFB OH, August, 2005.

Smith S.D., Chervak, S., Steinhauer, B., *Vibration Characterization and Health Risk Assessment of the Vermont Army National Guard UH-72 Lakota and HH-60M Medevac*, AFRL-RH-WP-TR-2014-0053, Air Force Research Laboratory, Wright-Patterson AFB OH, 2014.

Smith, S. D. Gerdus, E., "Characterization and Assessment of Pilot Vibration Exposure Aboard the UH-1H Huey Helicopter", *Proceedings of the 4th American Conference on Human Vibration*, Hartford Connecticut (2005).

Smith S.D., Jurcsisn, J.G., Bowden, D. R., *CV-22 Human Vibration Evaluation*, AFRL-RH-WP-TR-2008-0095, Air Force Research Laboratory, Human Effectiveness Directorate, Wright-Patterson AFB OH, 2008.

Welch, P. D., "The Use of Fast Fourier Transform for the Estimation of Power spectra: A method Based on Time Averaging Over Short, Modified Periodograms," *IEEE Trans. Audio Electroacoust.*, **AU-15**, Jun 1967, pp. 70-73.

APPENDIX A: RESULTS – FIGURES AND TABLES

LIST OF FIGURES

LIST OF TABLES

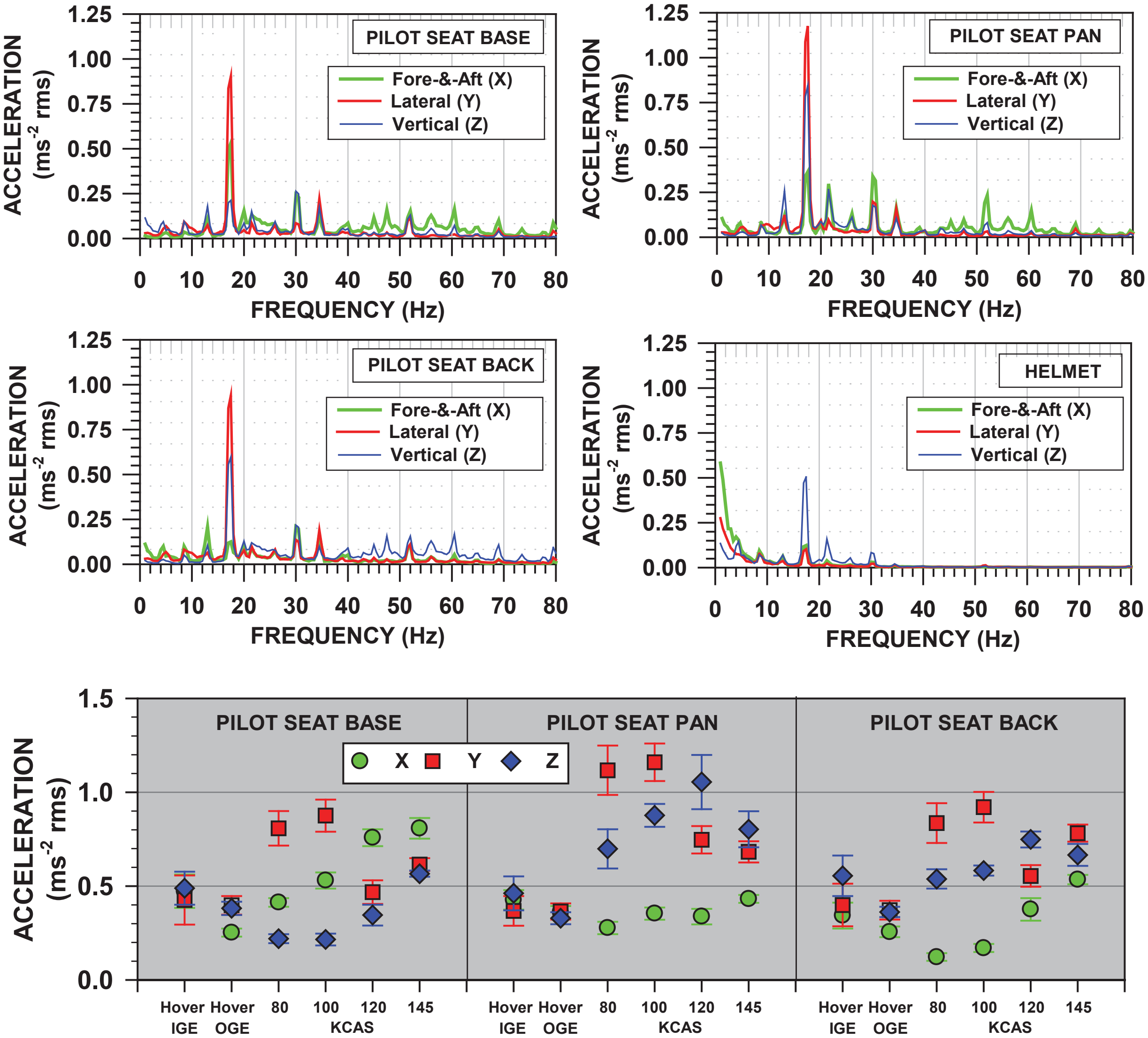


Figure A- 1. Sample Acceleration Spectra at Level Flight 100 KCAS at the Pilot Right Station (top). Mean BPF Acceleration ± One Standard Deviation at the Pilot Station (bottom).

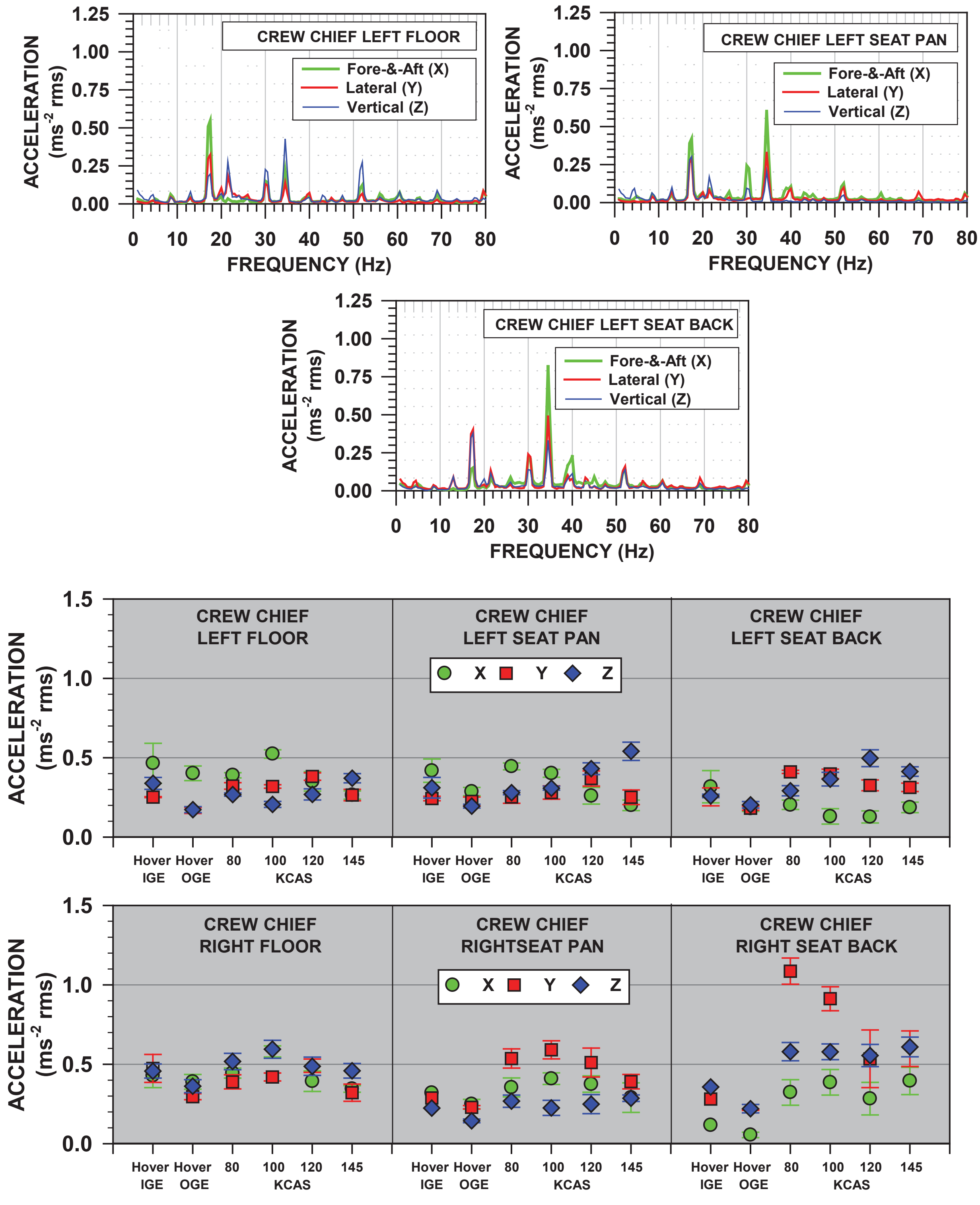


Figure A- 2. Sample Acceleration Spectra at Level Flight 100 KCAS at the Crew Chief Left Station (top). Mean BPF Acceleration ± One Standard Deviation at the Crew Chief Left and Right Stations (bottom).

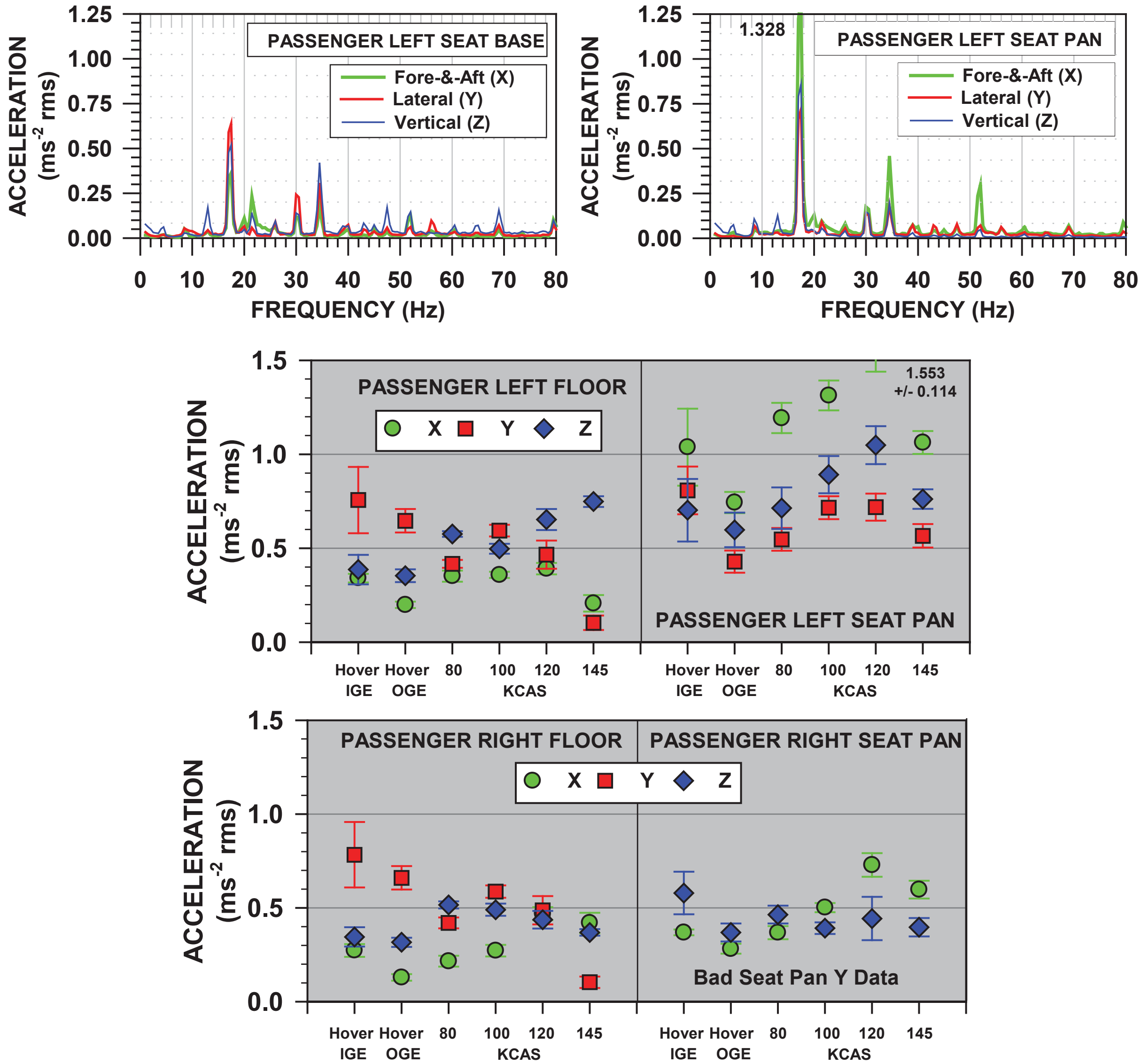


Figure A- 3. Sample Acceleration Spectra at Level Flight 120 KCAS at the Passenger Left Station (top). Mean BPF Acceleration ± One Standard Deviation at the Passenger Left and Right Stations (bottom).

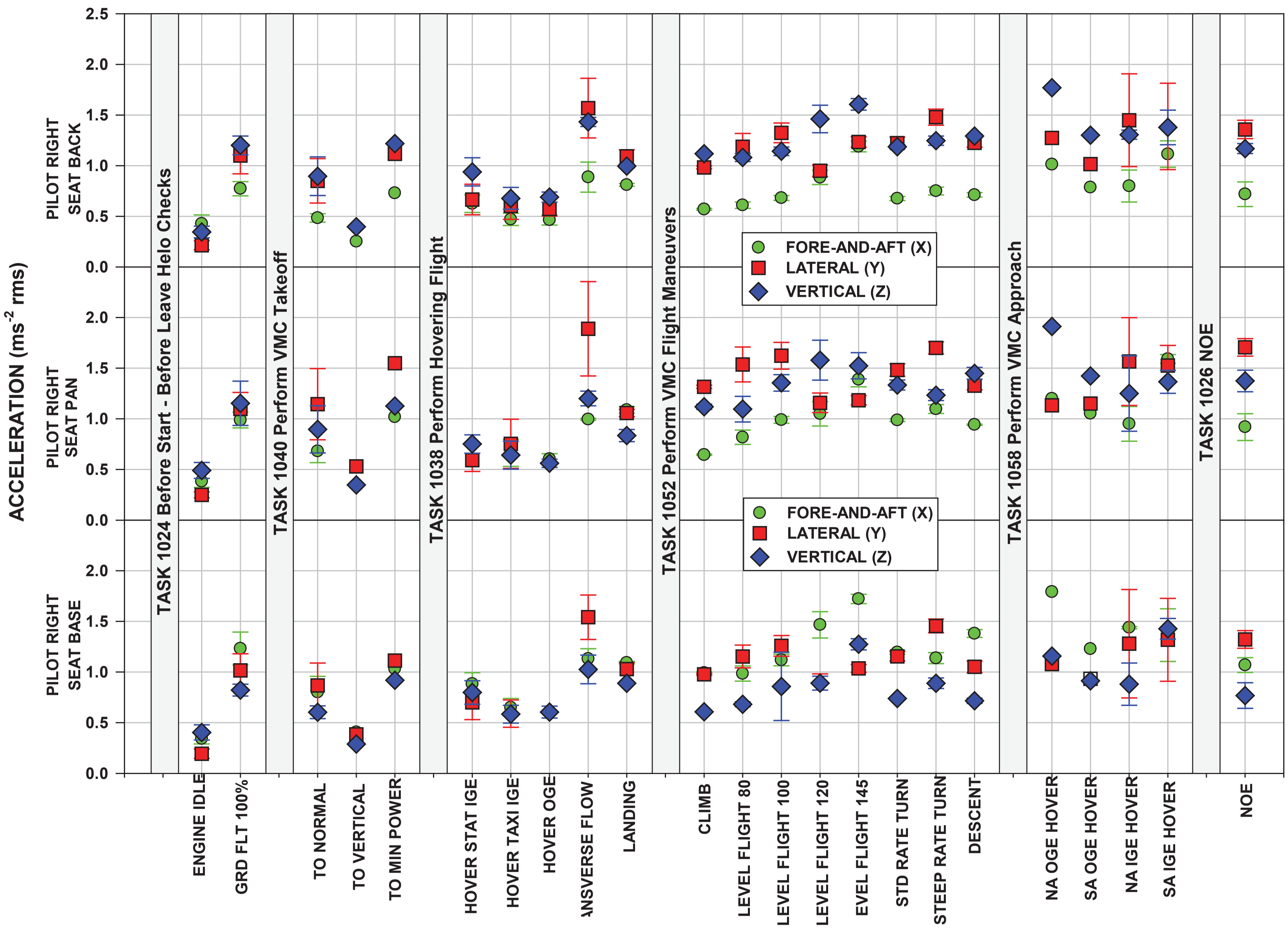


Figure A- 4. Pilot Mean Overall Unweighted Accelerations ± One Standard Deviation

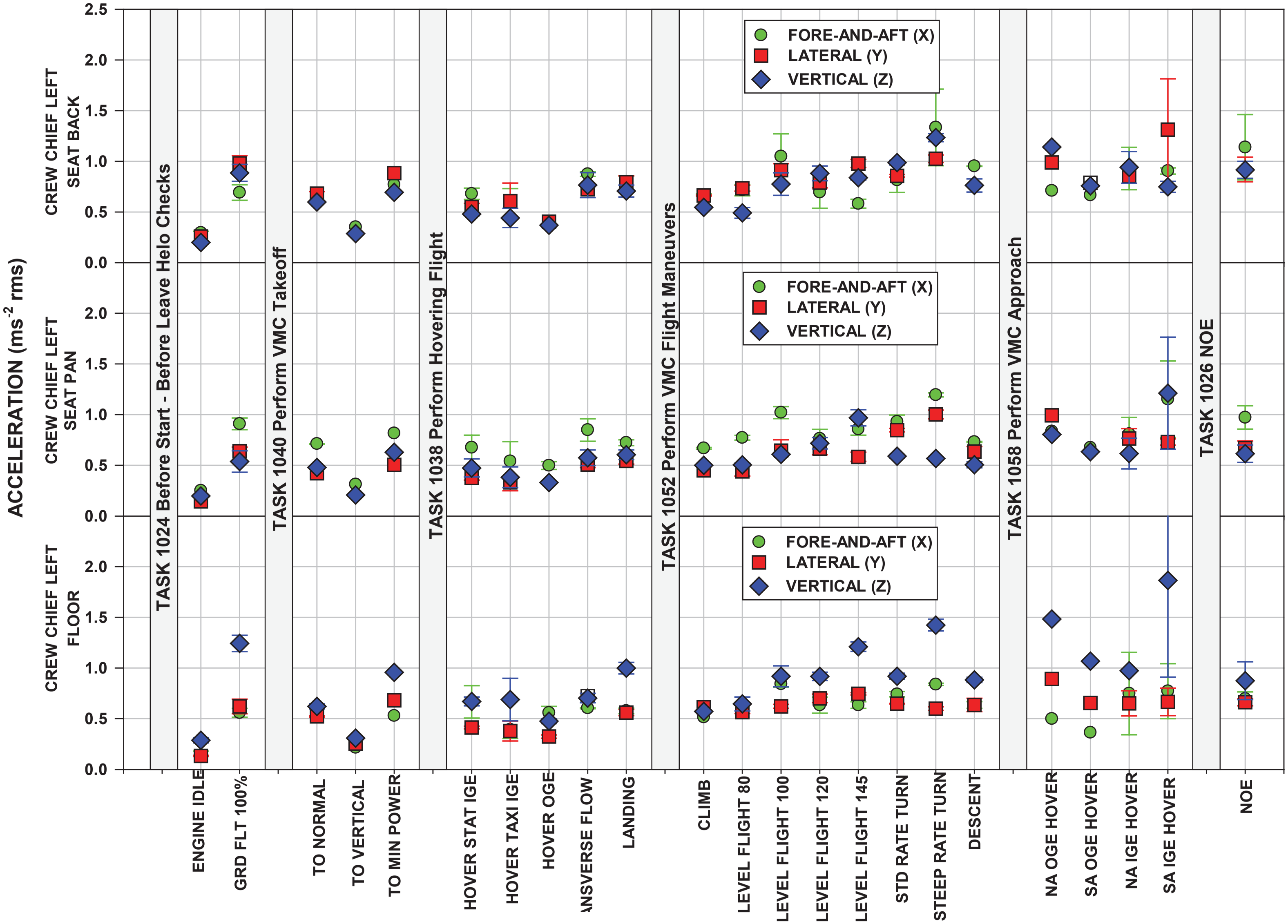


Figure A- 5. Left Crew Chief Mean Overall Unweighted Accelerations ± One Standard Deviation

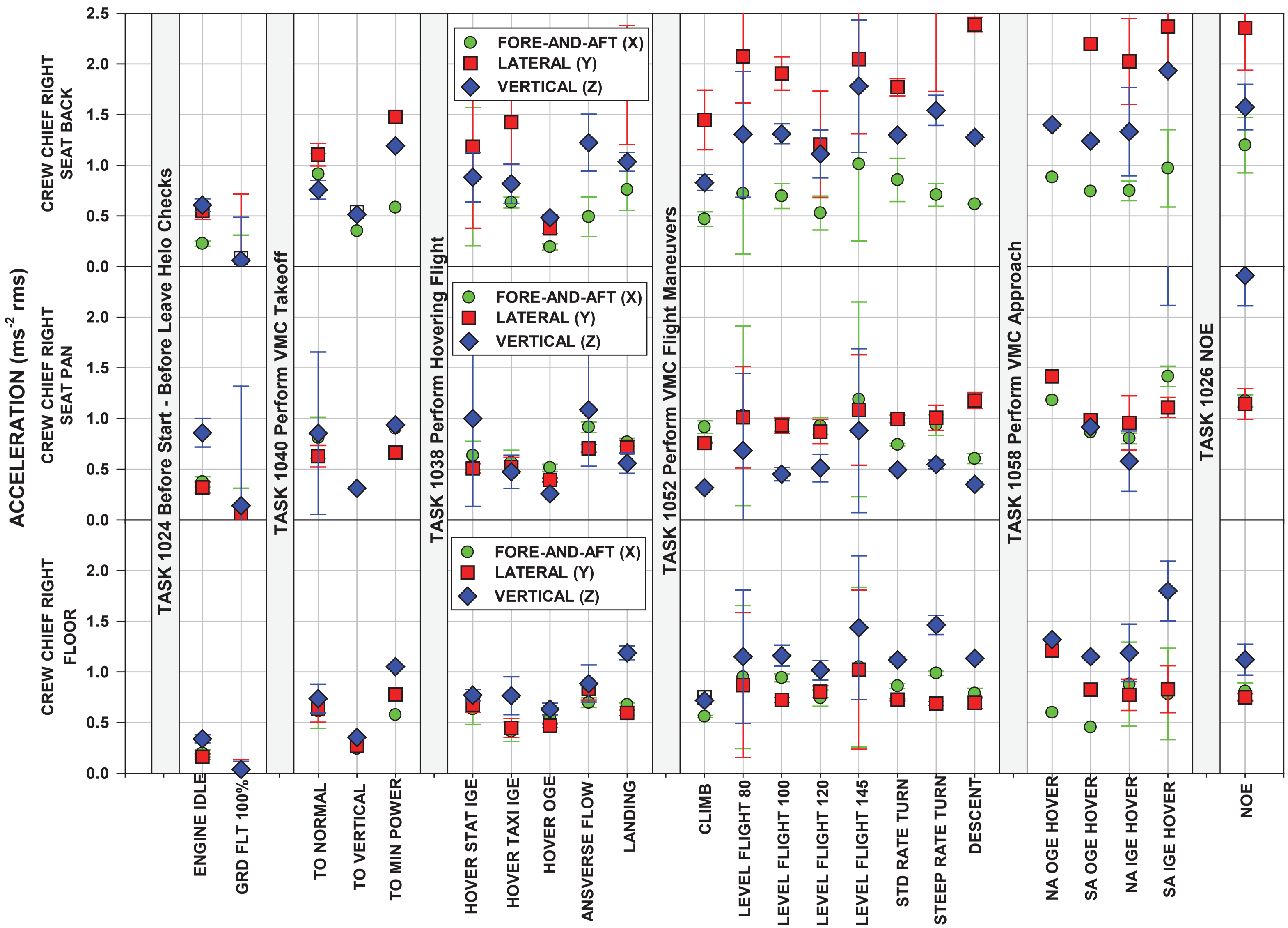


Figure A- 6. Right Crew Chief Mean Overall Unweighted Accelerations ± One Standard Deviation

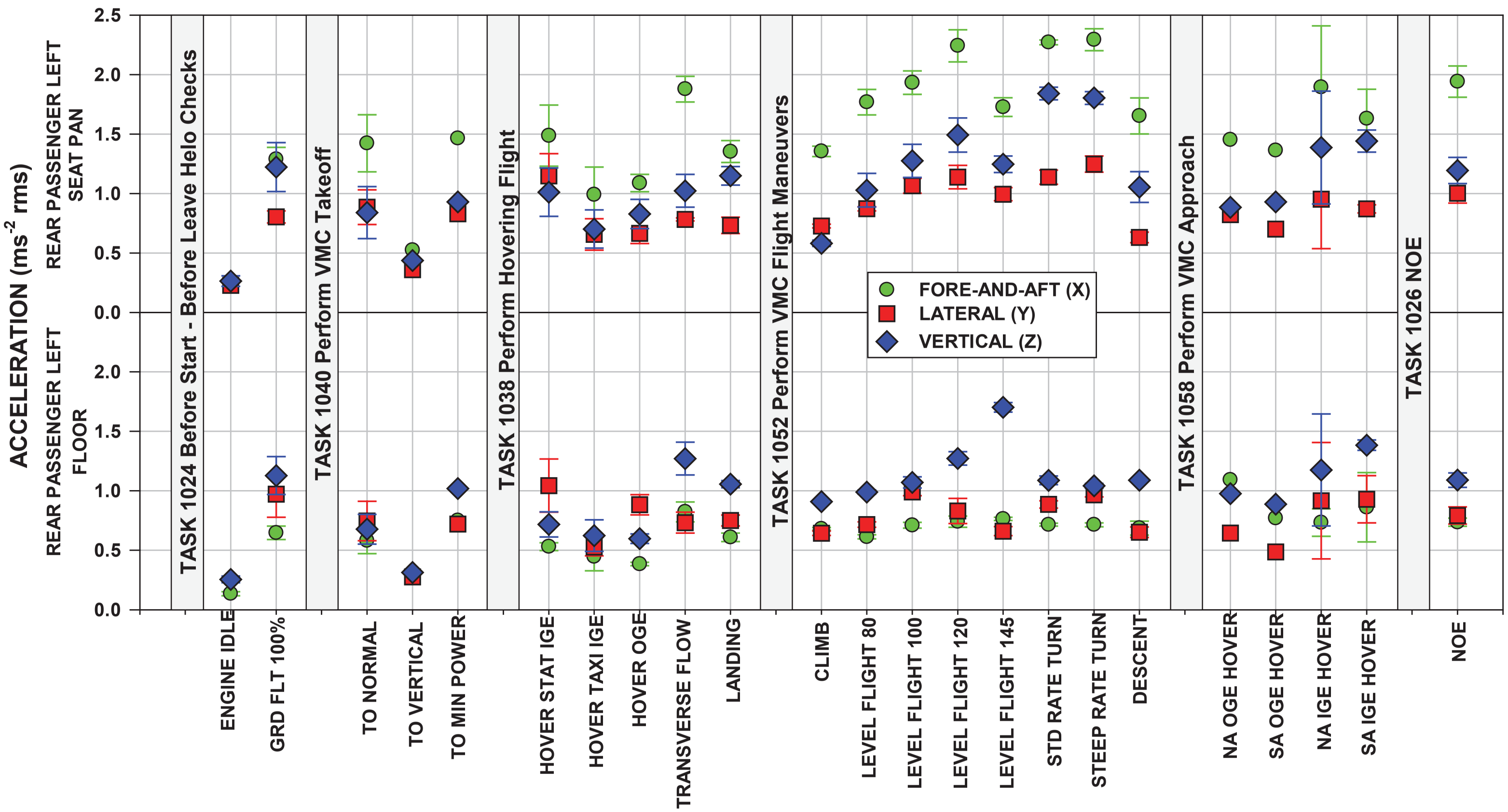


Figure A- 7. Left Passenger Mean Overall Unweighted Accelerations ± One Standard Deviation

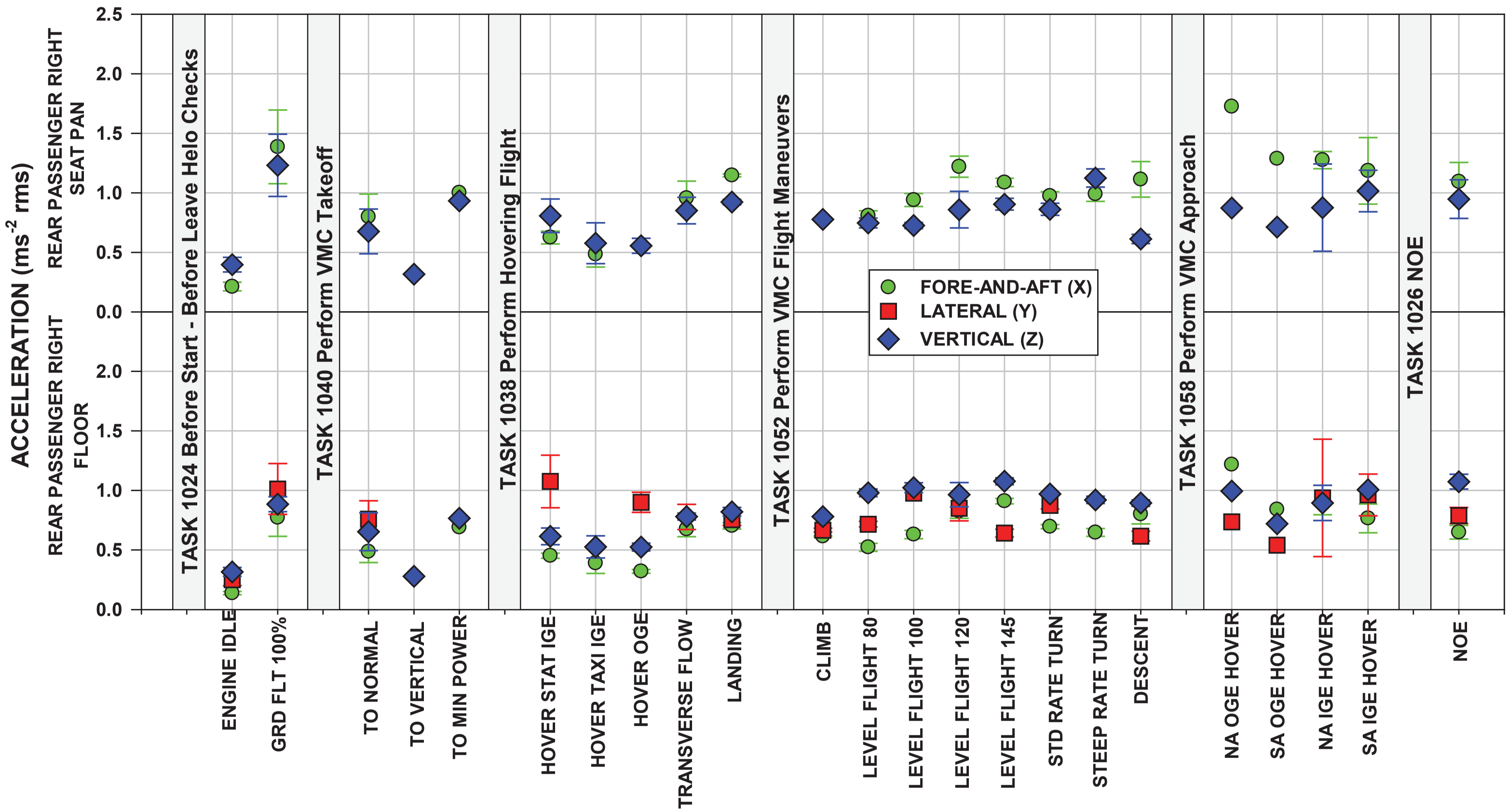


Figure A- 8. Right Passenger Mean Overall Unweighted Accelerations ± One Standard Deviation

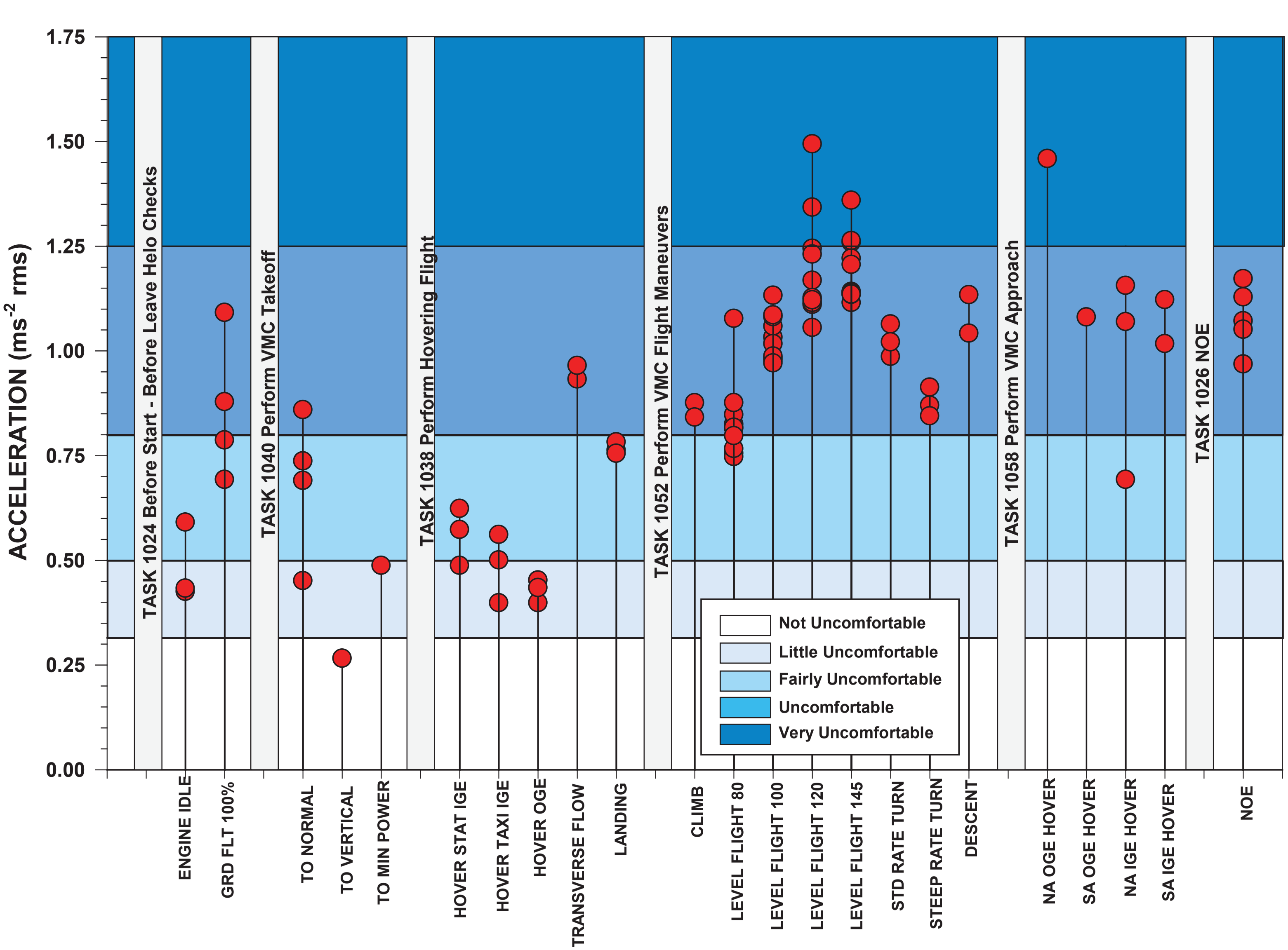


Figure A- 9. Pilot Right Side Overall Vibration Total Values (*oVTVs*)

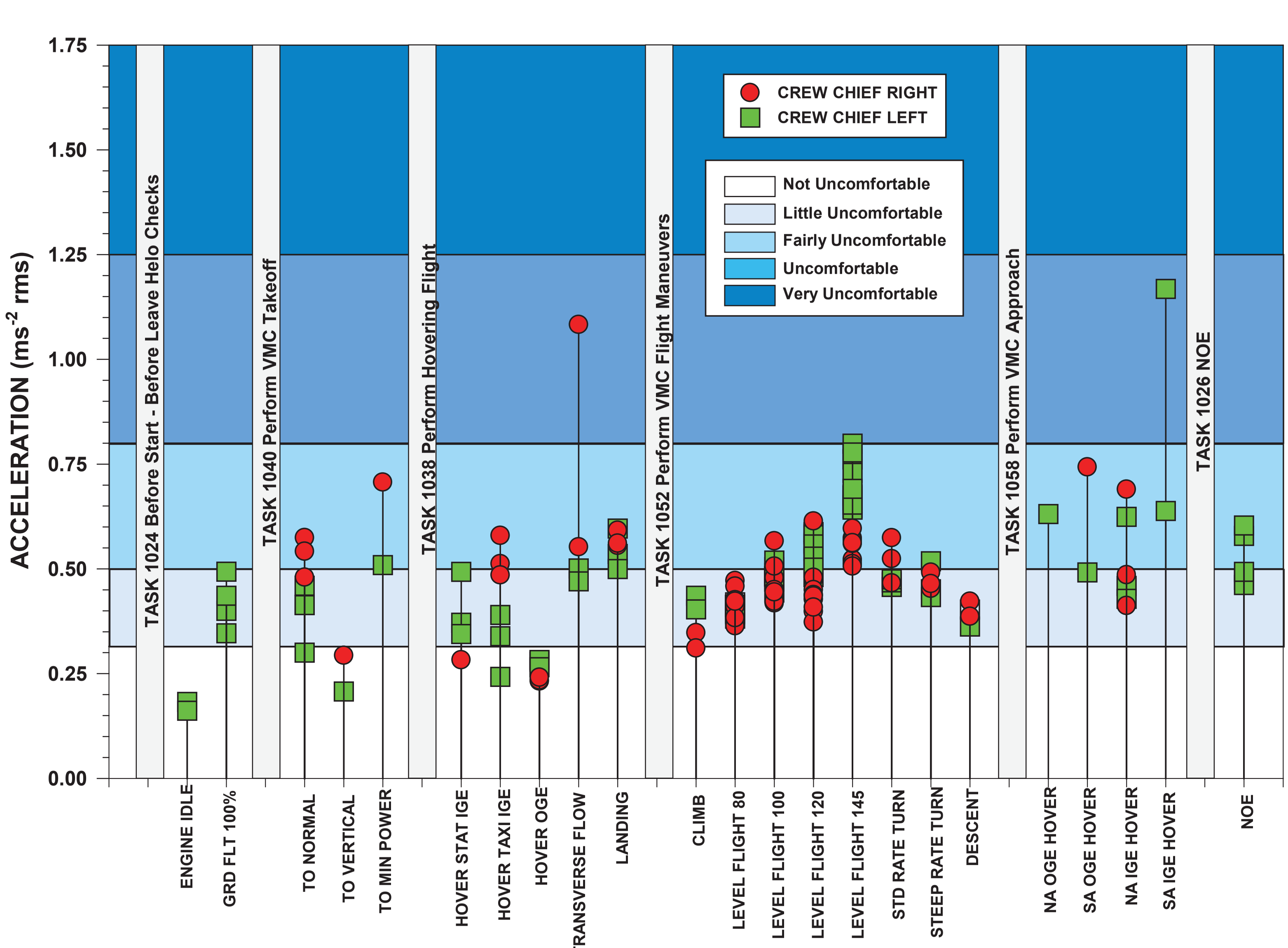


Figure A- 10. Crew Chief Left Side and Crew Chief Right Side Overall Vibration Total Values (*oVTVs*)

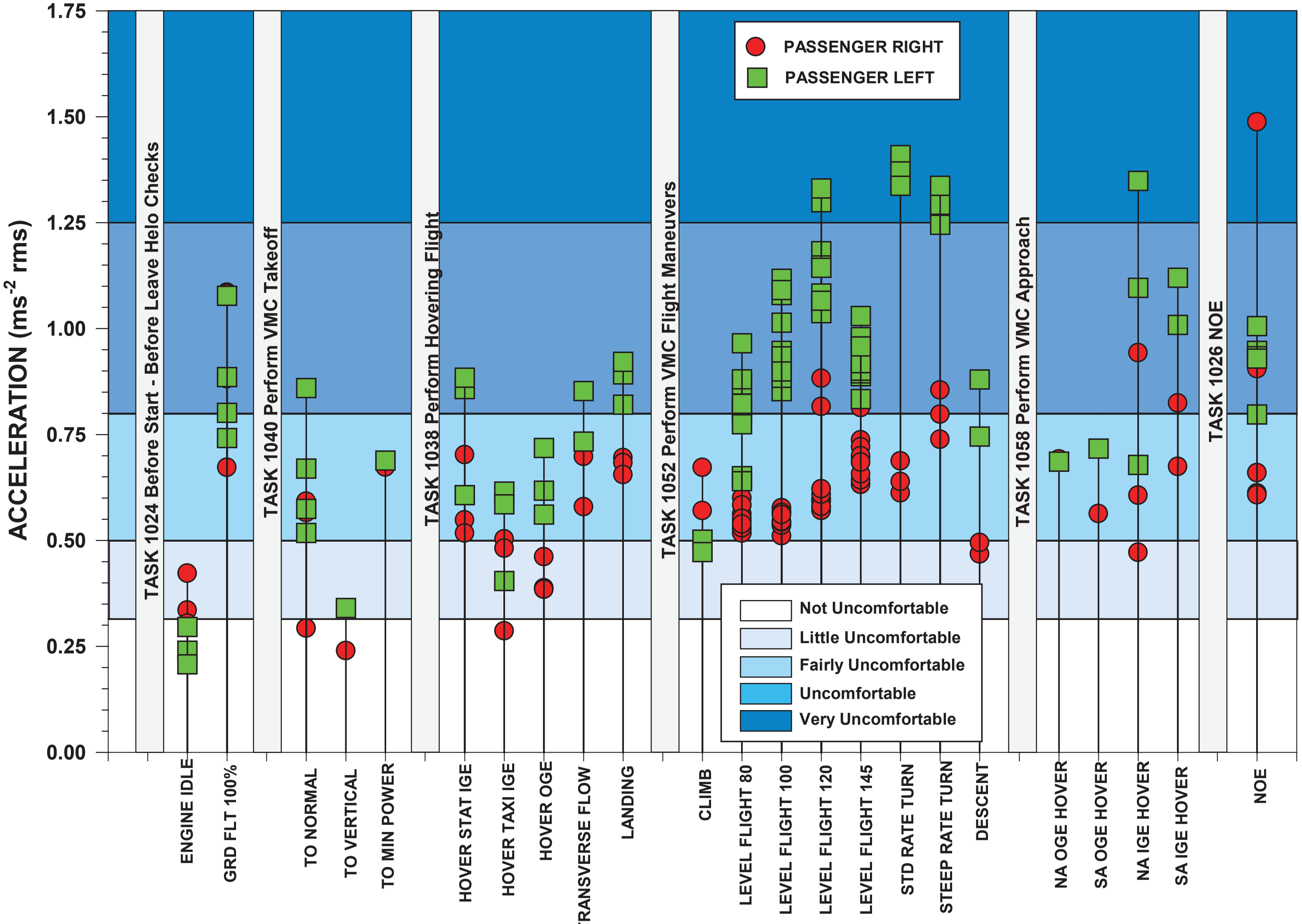


Figure A- 11. Passenger Left Side and Passenger Right Side Overall Vibration Total Values (*oVTVs*)

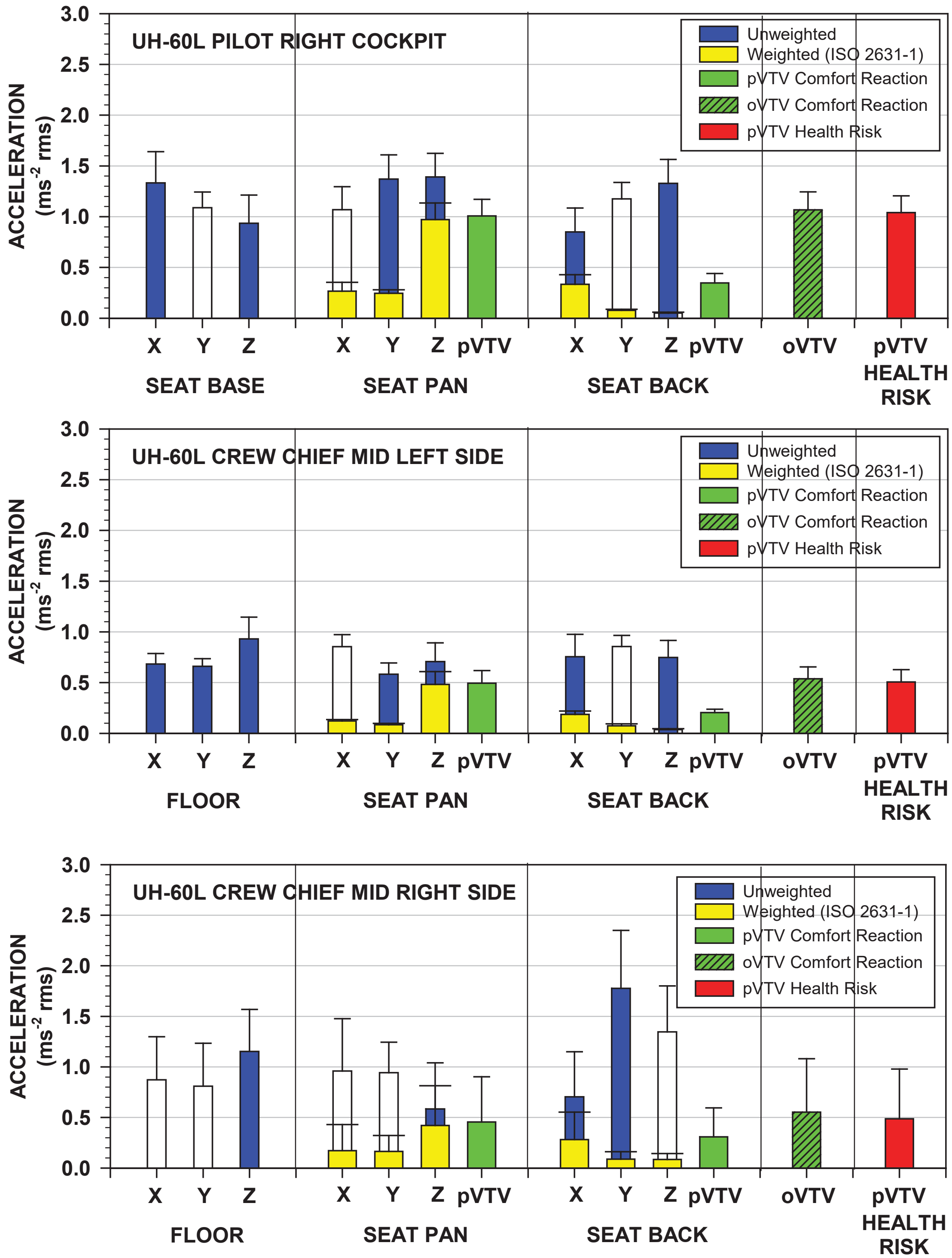
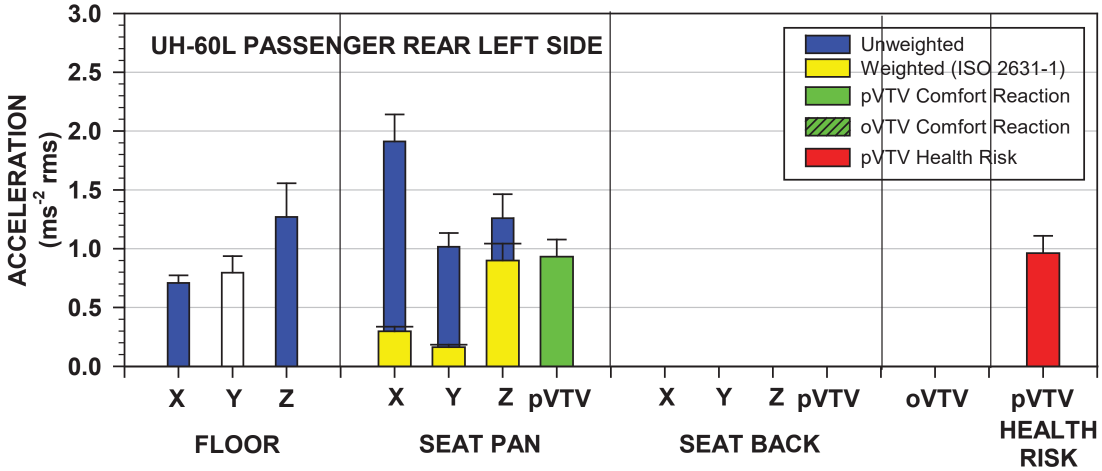


Figure A- 12. Mean Unweighted and Weighted Accelerations, pVTVs, and oVTVs ± One Standard Deviation



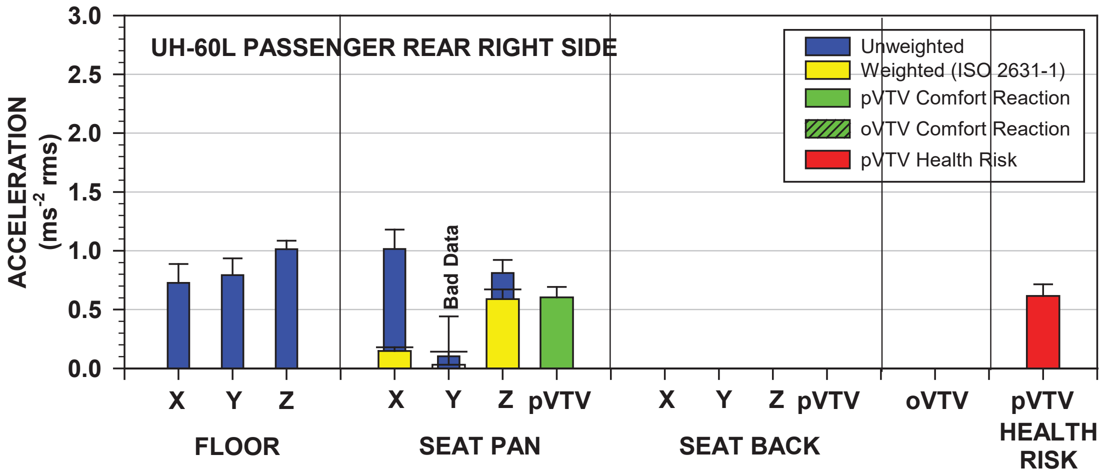


Figure A-12 (continued). Mean Unweighted and Weighted Accelerations, pVTVs, and oVTVs ± One Standard Deviation

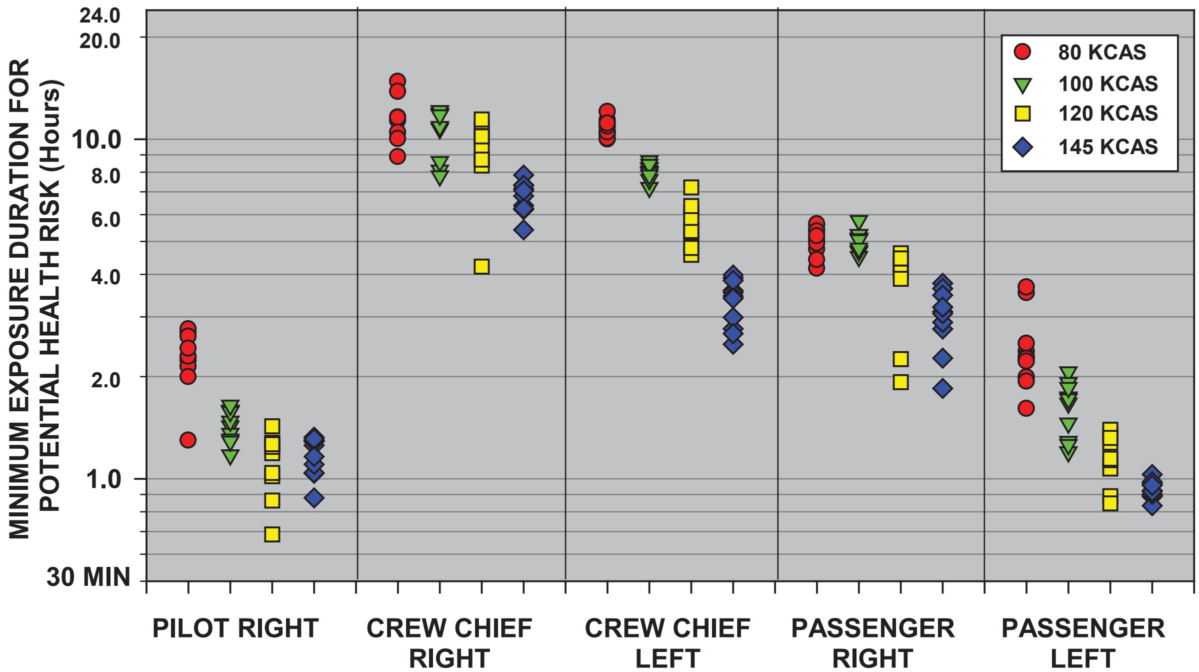


Figure A- 13. Minimum Exposure Duration for "Potential Health Risk" in a 24-Hour Period (ISO 2631-1)

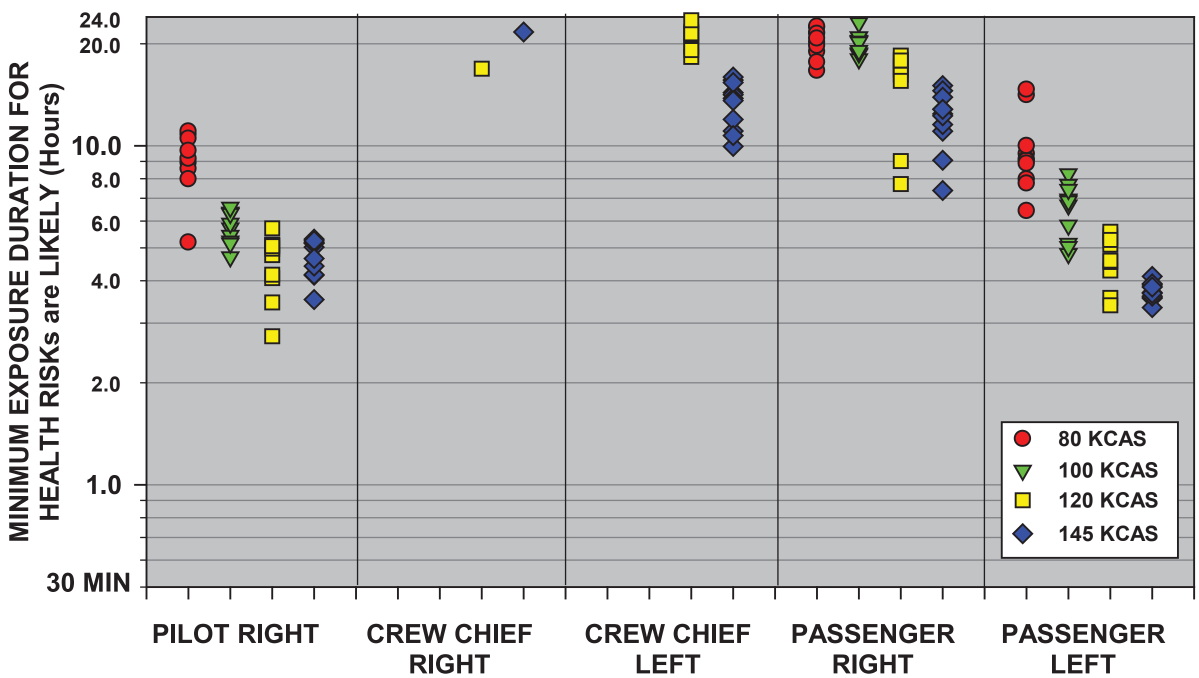


Figure A- 14. Minimum Exposure Duration for "Health Risks are Likely" in a 24-Hour Period (ISO 2631-1)

Table A- 1. REVER Component Details

Component	Dimensions (L/W/H cm)	Weight (Kg)	Item Identification
Large DAU	16.5/10.0/4.0	0.910 w/cables	EME S/N 98-11
Small DAUs	9.5/7.0/2.8	0.370 w/cables	EME S/N 04-22
			EME S/N 10-31
			EME S/N 10-41
Large Batteries	10.0/7.0/3.5	0.645	NA
Small Batteries	9.0/5.0/3.5	0.395	NA
Accelerometer Packs (Entran EGAX-25)	1.9 (diameter) 0.86 (thickness)	0.005 (0.060 w/ cable)	Pack M
			Pack N
			Pack O
			Pack X
			Pack Y
Accelerometer Pad (Entran EGAX-25) (Ride Quality Meter, RQM)	20.0 (diameter)	0.340 w/ cables	RQM 1 (Pack P)
			RQM 2 (Pack D)
			RQM 3 (Pack W)
			RQM 4 (Pack T)
			RQM 5 (Pack B)
			RQM 6 (Pack Q)
			RQM 7 (Pack J)
			RQM 8 (Pack G)
Triggers	7.6 (length) 2.2 (diameter)	0.030 w/cable	TRIG 1
			TRIG 2
			TRIG 3
			TRIG 4
Helmet Mounts (Entran EGA-125-10D)	6.5 (one arm)	0.050 w/cables	Helmet Mount
Extra Cable	183 (length)	0.100	
Total Estimated Weight w/ two batteries + cable and two acceleration pads		2.23 – 2.77	

Table A- 2. UH-60L Flight Tasks and Flight Test Condition Records

Task/Condition	# of Records
TASK 1024 Before Starting Through Before Leaving Helo Checks	
Engine Idle	3
Ground Flight 100%	4[1]
TASK 1040 Perform VMC Takeoff	
Takeoff Normal	4
Takeoff Vertical	1
Takeoff Minimum Power	1
TASK 1038 Perform Hovering Flight	
Hover Stationary IGE	3
Hover Taxi IGE	3
Hover OGE	3
Transverse Flow	2
Landing	3
TASK 1052 Perform VMC Flight Maneuvers	
Climb	2
Level Flight 80 KCAS	10
Level Flight 100 KCAS	10
Level Flight 120 KCAS	10
Level Flight 145 KCAS	11
Standard Rate Turn	3
Steep Rate Turn	3
Descent	2
TASK 1058 Perform VMC Approach	
Normal Approach to OGE Hover	1
Steep Approach to OGE Hover	1
Normal Approach to IGE Hover	3
Steep Approach to IGE Hover	2
TASK 2026 Perform Terrain Flight	
Nap-of-the-Earth (NOE)	5
[1]Both Crew Chief Stations included 5 records	

Table A- 3. Statistical Results for Directional Effects at the Pilot, Left Crew Chief, and Left Passenger Stations/Locations for Hover and Level Flight. Significant differences at P<0.05.

	Pilot			Crew Chief Left			Passenger Left	
	Seat Base	Seat Pan	Seat Back	Seat Base	Seat Pan	Seat Back	Seat Base	Seat Pan
HOVER IGE	X Y Z	X=Y=Z	Z>(Y=X)	X=Y=Z	Z=(X>Y)	X=Y=Z	Y>(Z=X)	X>(Y Z)
HOVER OGE	(Y=Z)>X	X Y Z	(Y Z)>X	X>(Y=Z)	X>(Y Z)	X Y Z	Y>Z>X	Z=(X>Y)
80 KCAS	Y>X>Z	Y>Z>X	Y>Z>X	X>Y>Z	X>(Y=Z)	Y>Z>X	Z>Y>X	X>Z>Y
100 KCAS	Y>X>Z	Y>Z>X	Y>Z>X	X>Y>Z	X>(Y=Z)	(Y Z)>X	Y>Z>X	X>Z>Y
120 KCAS	X>Y>Z	Z>Y>X	Z>Y>X	(X Y)>Z	Z>Y>X	Z>Y>X	Z>Y>X	X>Z>Y
145 KCAS	X>Y>Z	Z>Y>X	Y>Z>X	Z>(X=Y)	Z>Y>X	Z>Y>X	Z>X>Y	X>Z>Y

Table A- 4. Pilot Station Overall Unweighted and Weighted Seat Pan Accelerations, *pVTVs*, and Allowable Exposure Durations to Potential Health Risks (Lower HGCZ Boundary) and Health Risks Likely (Upper HGCZ Boundary)

FLIGHT #	AIRSPEED (KCAS)	RECORD #	PANX	PANY	PANZ	WT PANX	WT PANY	WT PANZ	pVTV	POTENTIAL HLTH RISKS WT PANZ	HLTH RISKS LIKELY WT PANZ	POTENTIAL HLTH RISKS PAN pVTV	HLTH RISKS LIKELY PAN pVTV
			ACCELERATION (ms^{-2} rms)							EXPOSURE DURATION (Hours)			
1	80	70	0.854	1.595	1.091	0.173	0.275	0.753	0.820	2.643	10.573	2.229	8.917
1	80	71	0.866	1.646	1.077	0.209	0.287	0.730	0.812	2.815	11.259	2.277	9.107
1	80	72	0.933	1.974	1.415	0.179	0.338	1.005	1.075	1.485	5.939	1.298	5.190
1	80	73	0.867	1.485	1.116	0.175	0.260	0.777	0.838	2.486	9.943	2.138	8.552
1	80	74	0.728	1.394	0.994	0.134	0.240	0.692	0.745	3.129	12.515	2.703	10.810
1	80	75	0.784	1.485	1.065	0.196	0.261	0.740	0.809	2.738	10.954	2.292	9.168
1	80	76	0.886	1.470	1.168	0.154	0.260	0.813	0.867	2.271	9.082	1.995	7.980
1	80	77	0.770	1.470	0.981	0.128	0.253	0.681	0.738	3.233	12.934	2.758	11.031
1	80	78	0.744	1.411	1.004	0.138	0.243	0.702	0.756	3.041	12.165	2.625	10.498
1	80	79	0.753	1.437	1.047	0.153	0.251	0.731	0.788	2.809	11.235	2.418	9.670
MEAN			0.818	1.537	1.096	0.164	0.267	0.762	0.825	2.665	10.660	2.273	9.092
STDEV			0.071	0.172	0.126	0.027	0.029	0.094	0.097	0.507	2.026	0.423	1.694
1	100	29	1.019	1.876	1.518	0.226	0.316	1.061	1.130	1.332	5.330	1.175	4.700
1	100	30	0.941	1.759	1.300	0.214	0.299	0.898	0.971	1.858	7.434	1.592	6.369
1	100	31	1.005	1.615	1.278	0.225	0.281	0.906	0.975	1.829	7.316	1.580	6.318
1	100	32	0.982	1.573	1.354	0.242	0.276	0.956	1.024	1.642	6.568	1.431	5.722
1	100	33	1.057	1.670	1.403	0.218	0.285	0.987	1.050	1.539	6.158	1.360	5.438
1	100	34	0.997	1.607	1.331	0.268	0.277	0.932	1.008	1.729	6.915	1.477	5.906
1	100	35	0.950	1.471	1.273	0.270	0.262	0.900	0.976	1.851	7.402	1.576	6.304
1	100	36	0.973	1.613	1.407	0.265	0.275	1.000	1.071	1.499	5.995	1.308	5.231
1	100	37	0.980	1.409	1.268	0.198	0.244	0.901	0.955	1.846	7.384	1.646	6.583
1	100	38	0.995	1.636	1.416	0.270	0.283	1.005	1.078	1.486	5.944	1.290	5.161
MEAN			0.990	1.623	1.355	0.240	0.280	0.955	1.024	1.661	6.645	1.443	5.773
STDEV			0.033	0.132	0.081	0.027	0.019	0.057	0.058	0.189	0.757	0.157	0.627
1	120	39	1.150	1.295	1.446	0.272	0.226	1.025	1.084	1.428	5.711	1.276	5.104
1	120	40	1.305	1.258	1.747	0.394	0.242	1.235	1.318	0.984	3.936	0.863	3.453
1	120	41	1.056	1.001	1.517	0.289	0.192	1.068	1.123	1.316	5.264	1.190	4.761
1	120	42	1.107	1.187	1.655	0.253	0.212	1.168	1.214	1.100	4.398	1.018	4.072
1	120	43	1.102	1.262	2.047	0.251	0.215	1.441	1.479	0.722	2.889	0.686	2.745
1	120	44	1.011	1.144	1.597	0.327	0.219	1.134	1.200	1.167	4.669	1.042	4.167
1	120	45	0.936	1.159	1.437	0.301	0.217	1.019	1.084	1.445	5.781	1.276	5.102
1	120	46	0.954	1.134	1.479	0.261	0.208	1.047	1.099	1.370	5.479	1.243	4.972
1	120	47	0.923	1.104	1.405	0.203	0.195	0.985	1.025	1.545	6.182	1.429	5.714
1	120	48	0.953	1.036	1.459	0.293	0.200	1.029	1.089	1.416	5.662	1.266	5.062
MEAN			1.050	1.158	1.579	0.284	0.213	1.115	1.171	1.249	4.997	1.129	4.515
STDEV			0.120	0.096	0.197	0.051	0.015	0.138	0.137	0.254	1.017	0.225	0.899
1	145	49	1.361	1.249	1.657	0.264	0.229	1.150	1.202	1.134	4.534	1.038	4.152
1	145	50	1.315	1.190	1.413	0.417	0.220	0.986	1.093	1.543	6.173	1.256	5.023
1	145	51	1.390	1.241	1.357	0.444	0.237	0.937	1.063	1.710	6.841	1.327	5.309
1	145	52	1.486	1.215	1.434	0.421	0.234	0.965	1.079	1.609	6.438	1.289	5.155
1	145	53	1.316	1.123	1.443	0.378	0.215	0.984	1.076	1.549	6.194	1.296	5.184
1	145	54	1.309	1.173	1.486	0.279	0.216	1.018	1.078	1.447	5.787	1.292	5.168
1	145	55	1.386	1.110	1.439	0.359	0.211	0.985	1.069	1.546	6.183	1.312	5.247
1	145	56	1.533	1.196	1.624	0.437	0.243	1.091	1.200	1.261	5.045	1.043	4.170
1	145	57	1.350	1.138	1.567	0.370	0.215	1.084	1.166	1.276	5.103	1.104	4.416
1	145	58	1.389	1.212	1.798	0.336	0.226	1.241	1.306	0.974	3.894	0.880	3.519
1	145	59	1.429	1.172	1.548	0.343	0.224	1.059	1.136	1.338	5.350	1.163	4.653
MEAN			1.388	1.183	1.524	0.368	0.224	1.046	1.133	1.399	5.595	1.182	4.727
STDEV			0.072	0.046	0.130	0.060	0.010	0.091	0.077	0.223	0.892	0.148	0.590

Table A- 5. Crew Chief Left Station Overall Unweighted and Weighted Seat Pan Accelerations, *pVTVs*, and Allowable Exposure Durations to Potential Health Risks (Lower HGCZ Boundary) and Health Risks Likely (Upper HGCZ Boundary)

FLIGHT #	AIRSPEED (KCAS)	RECORD #	PANX	PANY	PANZ	WT PANX	WT PANY	WT PANZ	pVTV	POTENTIAL HLTH RISKS WT PANZ	HLTH RISKS LIKELY WT PANZ	POTENTIAL HLTH RISKS PAN pVTV	HLTH RISKS LIKELY PAN pVTV
			ACCELERATION (ms^{-2} rms)							EXPOSURE DURATION (Hours)			
1	80	70	0.810	0.463	0.525	0.119	0.070	0.362	0.387	11.447	45.786	10.000	40.000
1	80	71	0.752	0.4598	0.518	0.120	0.073	0.353	0.380	12.010	48.042	10.366	41.464
1	80	72	0.790	0.4614	0.518	0.117	0.071	0.356	0.381	11.862	47.449	10.323	41.290
1	80	73	0.790	0.4913	0.525	0.117	0.076	0.360	0.386	11.548	46.194	10.052	40.207
1	80	74	0.758	0.3896	0.502	0.115	0.057	0.355	0.377	11.936	47.744	10.559	42.238
1	80	75	0.779	0.4006	0.509	0.125	0.062	0.352	0.378	12.120	48.480	10.481	41.926
1	80	76	0.798	0.5242	0.495	0.119	0.081	0.334	0.364	13.446	53.785	11.352	45.409
1	80	77	0.746	0.4004	0.469	0.111	0.057	0.330	0.353	13.749	54.996	12.038	48.151
1	80	78	0.742	0.4137	0.495	0.112	0.060	0.348	0.371	12.379	49.516	10.921	43.686
1	80	79	0.761	0.4042	0.492	0.119	0.060	0.342	0.367	12.817	51.268	11.125	44.499
	MEAN		0.773	0.441	0.505	0.117	0.067	0.349	0.374	12.331	49.326	10.722	42.887
	STDEV		0.024	0.046	0.018	0.004	0.009	0.011	0.011	0.775	3.101	0.639	2.555
1	100	29	1.001	0.5762	0.601	0.134	0.080	0.398	0.427	9.493	37.973	8.223	32.892
1	100	30	0.982	0.5785	0.592	0.139	0.074	0.403	0.433	9.231	36.925	8.012	32.046
1	100	31	1.034	0.6304	0.588	0.138	0.084	0.395	0.427	9.619	38.475	8.238	32.954
1	100	32	1.121	0.7141	0.641	0.137	0.099	0.424	0.456	8.344	33.375	7.201	28.804
1	100	33	1.109	0.8957	0.633	0.139	0.104	0.396	0.432	9.590	38.358	8.038	32.150
1	100	34	0.997	0.736	0.600	0.134	0.091	0.384	0.417	10.151	40.605	8.626	34.505
1	100	35	0.938	0.5878	0.626	0.140	0.084	0.413	0.444	8.790	35.159	7.602	30.408
1	100	36	0.974	0.5598	0.601	0.135	0.075	0.406	0.434	9.113	36.454	7.960	31.840
1	100	37	1.058	0.6025	0.593	0.131	0.081	0.393	0.422	9.722	38.887	8.427	33.708
1	100	38	0.993	0.5628	0.612	0.132	0.084	0.409	0.438	8.976	35.903	7.833	31.333
	MEAN		1.021	0.644	0.609	0.136	0.086	0.402	0.433	9.303	37.212	8.016	32.064
	STDEV		0.059	0.108	0.018	0.003	0.010	0.011	0.011	0.521	2.085	0.409	1.636
1	120	39	0.927	0.5966	0.726	0.131	0.083	0.502	0.526	5.948	23.790	5.432	21.727
1	120	40	0.919	0.7279	0.748	0.147	0.116	0.520	0.553	5.552	22.206	4.912	19.649
1	120	41	0.696	0.6858	0.797	0.102	0.102	0.555	0.573	4.879	19.514	4.570	18.281
1	120	42	0.783	0.784	0.727	0.103	0.112	0.509	0.531	5.792	23.168	5.316	21.264
1	120	43	0.786	0.6503	0.801	0.107	0.095	0.541	0.560	5.123	20.493	4.788	19.153
1	120	44	0.719	0.6994	0.719	0.125	0.110	0.502	0.529	5.957	23.828	5.366	21.465
1	120	45	0.688	0.6185	0.676	0.114	0.095	0.474	0.496	6.685	26.739	6.087	24.349
1	120	46	0.687	0.6434	0.693	0.103	0.095	0.486	0.506	6.353	25.413	5.868	23.471
1	120	47	0.731	0.5995	0.624	0.103	0.081	0.437	0.456	7.862	31.447	7.214	28.855
1	120	48	0.702	0.6392	0.668	0.105	0.094	0.465	0.486	6.946	27.785	6.359	25.434
	MEAN		0.764	0.664	0.718	0.114	0.098	0.499	0.521	6.110	24.438	5.591	22.365
	STDEV		0.091	0.060	0.055	0.015	0.012	0.035	0.036	0.889	3.556	0.806	3.223
1	145	49	0.815	0.623	0.933	0.108	0.089	0.632	0.647	3.761	15.045	3.586	14.342
1	145	50	0.842	0.640	0.939	0.116	0.092	0.634	0.651	3.732	14.927	3.538	14.153
1	145	51	0.922	0.655	1.048	0.134	0.098	0.717	0.737	2.915	11.658	2.765	11.061
1	145	52	0.968	0.597	1.111	0.135	0.085	0.760	0.776	2.600	10.399	2.490	9.959
1	145	53	0.810	0.575	0.887	0.124	0.084	0.601	0.620	4.147	16.589	3.905	15.619
1	145	54	0.872	0.592	0.934	0.112	0.079	0.645	0.659	3.608	14.431	3.452	13.808
1	145	55	0.887	0.593	1.007	0.126	0.087	0.692	0.708	3.136	12.544	2.989	11.956
1	145	56	0.900	0.572	1.077	0.143	0.090	0.729	0.748	2.823	11.290	2.679	10.715
1	145	57	0.767	0.540	0.890	0.115	0.081	0.597	0.613	4.209	16.835	3.987	15.946
1	145	58	0.813	0.531	0.887	0.111	0.079	0.610	0.625	4.031	16.125	3.840	15.360
1	145	59	0.833	0.508	0.946	0.117	0.076	0.650	0.664	3.555	14.219	3.398	13.592
	MEAN		0.857	0.584	0.969	0.122	0.085	0.661	0.677	3.501	14.006	3.330	13.319
	STDEV		0.059	0.045	0.080	0.012	0.007	0.055	0.056	0.555	2.222	0.521	2.084

Table A- 6. Crew Chief Right Station Overall Unweighted and Weighted Seat Pan Accelerations, *pVTVs*, and Allowable Exposure Durations to Potential Health Risks (Lower HGCZ Boundary) and Health Risks Likely (Upper HGCZ Boundary)

FLIGHT #	AIRSPEED (KCAS)	RECORD #	PANX	PANY	PANZ	WT PANX	WT PANY	WT PANZ	pVTV	POTENTIAL HLTH RISKS WT PANZ	HLTH RISKS LIKELY WT PANZ	POTENTIAL HLTH RISKS PAN pVTV	HLTH RISKS LIKELY PAN pVTV
			ACCELERATION (ms^{-2} rms)							EXPOSURE DURATION (Hours)			
1	80	70	0.871	0.950	0.353	0.121	0.146	0.256	0.319	22.906	91.624	14.759	59.036
1	80	71	0.826	0.925	0.440	0.123	0.147	0.309	0.364	15.710	62.840	11.346	45.384
1	80	72	0.676	0.884	0.455	0.094	0.131	0.326	0.364	14.114	56.457	11.346	45.384
1	80	73	0.660	0.900	0.444	0.098	0.138	0.317	0.360	14.908	59.633	11.606	46.425
1	80	74	0.652	0.737	0.415	0.093	0.111	0.296	0.330	17.120	68.481	13.808	55.230
1	80	75	0.663	0.778	0.533	0.116	0.128	0.374	0.411	10.753	43.010	8.867	35.468
1	80	76	0.787	0.981	0.421	0.113	0.155	0.305	0.360	16.167	64.668	11.574	46.296
1	80	77	0.832	0.779	0.477	0.112	0.121	0.341	0.379	12.915	51.660	10.459	41.837
1	80	78	0.778	0.786	0.474	0.110	0.134	0.346	0.387	12.559	50.235	10.021	40.082
1	80	79											
MEAN			0.750	0.858	0.446	0.109	0.135	0.319	0.364	15.239	60.956	11.532	46.127
STDEV			0.087	0.089	0.050	0.011	0.014	0.034	0.028	3.491	13.964	1.810	7.240
1	100	29	0.965	1.013	0.447	0.141	0.161	0.307	0.374	15.936	63.744	10.735	42.941
1	100	30	0.861	0.863	0.563	0.135	0.141	0.384	0.430	10.199	40.796	8.105	32.420
1	100	31	0.913	1.001	0.433	0.143	0.159	0.303	0.371	16.306	65.224	10.892	43.568
1	100	32	0.820	1.044	0.544	0.147	0.190	0.342	0.418	12.809	51.238	8.589	34.356
1	100	33	0.930	0.999	0.523	0.174	0.174	0.363	0.439	11.384	45.534	7.797	31.190
1	100	34	0.924	0.929	0.401	0.134	0.148	0.294	0.355	17.378	69.510	11.882	47.529
1	100	35	0.962	0.845	0.400	0.147	0.134	0.294	0.355	17.354	69.416	11.909	47.636
1	100	36	0.959	0.849	0.406	0.139	0.133	0.295	0.352	17.272	69.086	12.120	48.480
1	100	37	0.988	0.906	0.396	0.136	0.144	0.291	0.352	17.714	70.854	12.113	48.452
1	100	38	0.975	0.871	0.411	0.135	0.137	0.301	0.357	16.600	66.401	11.776	47.104
MEAN			0.930	0.932	0.452	0.143	0.152	0.317	0.380	15.295	61.180	10.592	42.368
STDEV			0.053	0.076	0.065	0.012	0.019	0.033	0.035	2.767	11.069	1.750	7.001
1	120	39	1.075	1.003	0.405	0.152	0.161	0.316	0.386	14.993	59.973	10.078	40.311
1	120	40	1.044	1.086	0.454	0.162	0.173	0.324	0.402	14.254	57.015	9.287	37.146
1	120	41	0.854	0.909	0.461	0.121	0.137	0.325	0.373	14.184	56.735	10.781	43.125
1	120	42	0.972	0.969	0.447	0.129	0.143	0.332	0.383	13.650	54.599	10.215	40.860
1	120	43	0.976	0.837	0.887	0.142	0.139	0.562	0.596	4.744	18.976	4.219	16.874
1	120	44	0.886	0.875	0.515	0.149	0.137	0.372	0.423	10.851	43.404	8.367	33.470
1	120	45	0.863	0.792	0.516	0.126	0.123	0.376	0.415	10.627	42.508	8.710	34.838
1	120	46	0.869	0.779	0.513	0.120	0.119	0.379	0.415	10.437	41.749	8.714	34.855
1	120	47	0.862	0.698	0.449	0.114	0.100	0.329	0.362	13.883	55.533	11.440	45.761
1	120	48	0.870	0.770	0.483	0.118	0.115	0.346	0.384	12.508	50.032	10.194	40.775
MEAN			0.927	0.872	0.513	0.133	0.135	0.366	0.414	12.013	48.052	9.200	36.802
STDEV			0.083	0.121	0.136	0.017	0.022	0.073	0.067	3.048	12.193	2.008	8.033
1	145	49	0.852	0.992	0.622	0.110	0.145	0.414	0.453	8.747	34.990	7.326	29.303
1	145	50	0.843	0.966	0.613	0.127	0.143	0.393	0.437	9.717	38.868	7.847	31.390
1	145	51	0.908	0.958	0.686	0.144	0.144	0.447	0.491	7.504	30.015	6.214	24.858
1	145	52	1.075	0.864	0.617	0.159	0.132	0.439	0.485	7.794	31.176	6.385	25.539
1	145	53	0.848	0.969	0.622	0.129	0.142	0.428	0.469	8.173	32.693	6.808	27.231
1	145	54	0.905	0.970	0.628	0.112	0.132	0.424	0.458	8.352	33.406	7.157	28.629
1	145	55	0.807	0.753	0.674	0.124	0.111	0.421	0.453	8.459	33.836	7.319	29.277
1	145	56	1.000	0.947	0.701	0.166	0.145	0.478	0.526	6.565	26.260	5.413	21.653
1	145	57	0.900	0.903	0.593	0.142	0.139	0.416	0.461	8.659	34.638	7.058	28.233
1	145	58	0.863	0.911	0.632	0.131	0.150	0.448	0.490	7.480	29.921	6.250	25.000
1	145	59											
MEAN			0.900	0.923	0.639	0.134	0.138	0.431	0.472	8.145	32.580	6.778	27.111
STDEV			0.081	0.071	0.035	0.018	0.011	0.023	0.026	0.864	3.455	0.713	2.851

Table A- 7. Passenger Left Station Overall Unweighted and Weighted Seat Pan Accelerations, *pVTVs*, and Allowable Exposure Durations to Potential Health Risks (Lower HGCZ Boundary) and Health Risks Likely (Upper HGCZ Boundary)

FLIGHT #	AIRSPEED (KCAS)	RECORD #	PANX	PANY	PANZ	WT PANX	WT PANY	WT PANZ	pVTV	POTENTIAL HLTH RISKS WT PANZ	HLTH RISKS LIKELY WT PANZ	POTENTIAL HLTH RISKS PAN pVTV	HLTH RISKS LIKELY PAN pVTV
			ACCELERATION (ms^{-2} rms)							EXPOSURE DURATION (Hours)			
1	80	70	1.639	0.866	0.816	0.253	0.117	0.589	0.652	4.319	17.277	3.529	14.114
1	80	71	1.604	0.866	0.802	0.247	0.122	0.578	0.640	4.496	17.984	3.663	14.653
1	80	72	1.862	0.853	1.124	0.288	0.131	0.808	0.868	2.296	9.183	1.991	7.964
1	80	73	1.872	0.867	1.143	0.291	0.134	0.820	0.880	2.230	8.921	1.935	7.741
1	80	74	1.734	0.891	1.012	0.271	0.140	0.735	0.796	2.777	11.106	2.367	9.469
1	80	75	1.778	0.909	1.034	0.279	0.147	0.747	0.811	2.686	10.744	2.281	9.122
1	80	76	1.959	0.870	1.269	0.301	0.126	0.909	0.966	1.817	7.266	1.609	6.435
1	80	77	1.738	0.848	1.044	0.270	0.128	0.758	0.815	2.611	10.445	2.260	9.042
1	80	78	1.754	0.863	1.049	0.275	0.140	0.763	0.823	2.578	10.312	2.216	8.865
1	80	79	1.733	0.883	0.980	0.270	0.137	0.713	0.774	2.953	11.812	2.501	10.005
MEAN			1.767	0.872	1.027	0.275	0.132	0.742	0.802	2.876	11.505	2.435	9.741
STDEV			0.107	0.018	0.141	0.016	0.009	0.100	0.099	0.869	3.476	0.662	2.648
1	100	29	2.084	1.179	1.427	0.329	0.190	1.010	1.079	1.470	5.882	1.288	5.153
1	100	30	1.806	1.015	1.103	0.281	0.171	0.786	0.853	2.426	9.702	2.064	8.256
1	100	31	1.933	1.042	1.200	0.299	0.168	0.863	0.928	2.016	8.066	1.740	6.961
1	100	32	1.919	0.970	1.237	0.299	0.151	0.886	0.948	1.909	7.636	1.671	6.683
1	100	33	2.039	1.051	1.327	0.317	0.167	0.949	1.014	1.666	6.662	1.458	5.832
1	100	34	1.898	1.041	1.212	0.294	0.171	0.871	0.935	1.979	7.918	1.717	6.868
1	100	35	1.803	1.021	1.140	0.284	0.170	0.820	0.884	2.232	8.930	1.920	7.681
1	100	36	1.836	1.077	1.158	0.283	0.179	0.834	0.899	2.156	8.624	1.857	7.427
1	100	37	2.027	1.139	1.489	0.317	0.186	1.056	1.118	1.346	5.386	1.201	4.803
1	100	38	1.978	1.117	1.450	0.310	0.182	1.030	1.091	1.414	5.656	1.260	5.041
MEAN			1.932	1.065	1.274	0.301	0.173	0.910	0.975	1.862	7.446	1.618	6.470
STDEV			0.099	0.063	0.139	0.016	0.011	0.095	0.094	0.371	1.485	0.300	1.201
1	120	39	2.116	1.249	1.569	0.334	0.197	1.117	1.183	1.202	4.806	1.072	4.288
1	120	40	2.404	1.150	1.716	0.389	0.192	1.224	1.298	1.002	4.007	0.890	3.560
1	120	41	2.288	0.989	1.498	0.366	0.159	1.078	1.149	1.292	5.166	1.136	4.542
1	120	42	2.520	1.063	1.744	0.403	0.167	1.257	1.331	0.949	3.795	0.847	3.387
1	120	43	2.287	1.115	1.498	0.363	0.175	1.070	1.144	1.310	5.239	1.147	4.589
1	120	44	2.138	1.006	1.373	0.326	0.168	0.994	1.059	1.518	6.071	1.337	5.346
1	120	45	2.127	1.113	1.374	0.335	0.175	0.981	1.051	1.560	6.240	1.358	5.433
1	120	46	2.188	1.199	1.413	0.344	0.182	1.011	1.083	1.469	5.875	1.279	5.115
1	120	47	2.125	1.249	1.349	0.334	0.190	0.963	1.037	1.618	6.474	1.396	5.583
1	120	48	2.223	1.249	1.380	0.351	0.194	0.987	1.066	1.539	6.154	1.321	5.282
MEAN			2.242	1.138	1.491	0.355	0.180	1.068	1.140	1.346	5.383	1.178	4.712
STDEV			0.135	0.098	0.144	0.026	0.013	0.104	0.104	0.236	0.946	0.195	0.780
1	145	49	1.628	1.062	1.177	0.250	0.172	0.834	0.888	2.154	8.618	1.903	7.612
1	145	50	1.628	1.058	1.202	0.248	0.173	0.842	0.895	2.116	8.465	1.874	7.497
1	145	51	1.711	0.992	1.236	0.263	0.164	0.870	0.924	1.982	7.927	1.759	7.035
1	145	52	1.784	0.918	1.123	0.258	0.152	0.778	0.834	2.476	9.905	2.157	8.626
1	145	53	1.657	0.933	1.211	0.255	0.161	0.849	0.901	2.082	8.330	1.849	7.398
1	145	54	1.678	0.906	1.239	0.258	0.150	0.869	0.919	1.988	7.951	1.778	7.110
1	145	55	1.750	0.986	1.303	0.269	0.164	0.920	0.973	1.771	7.086	1.586	6.344
1	145	56	1.824	1.038	1.375	0.281	0.177	0.975	1.030	1.578	6.310	1.414	5.656
1	145	57	1.683	1.004	1.276	0.258	0.167	0.909	0.960	1.815	7.258	1.629	6.514
1	145	58	1.832	0.998	1.300	0.284	0.164	0.924	0.980	1.758	7.032	1.562	6.246
1	145	59	1.821	1.040	1.263	0.278	0.170	0.901	0.958	1.848	7.393	1.634	6.536
MEAN			1.727	0.994	1.246	0.264	0.165	0.879	0.933	1.961	7.843	1.740	6.961
STDEV			0.079	0.055	0.069	0.012	0.008	0.054	0.054	0.245	0.981	0.204	0.817

LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

711 HPW	711 Human Performance Wing
AFRL	Air Force Research Laboratory
AFRLI	Air Force Research Laboratory Instruction
APHC	Army Public Health Center
ARNG	Army National Guard
BCA	Business Case Analysis
BPF	Blade Passage Frequency
CBDN	Collaborative Biomechanics Data Network
DAU	Data Acquisition Unit
DUSD T&E	Office of the Deputy Under Secretary of Defense Installations and Environment
Flt	Flight
Grd	Ground
HGCZs	Health Guidance Caution Zones (ISO 2631-1, Annex B)
IGE	In Ground Effect
ISO	International Organization for Standardization
KCAS	Knots Calculated Airspeed
LTO	Lead Development Test Organization
MIL-STD	Military Standard
MOA	Memorandum of Agreement
NA	Normal Approach
NDCEE	National Defense Center for Energy and Environment
NGB	National Guard Bureau
NOE	Nap-of-the-Earth
OGE	Out of Ground Effect
OUSD ATL	Under Secretary of Defense for Acquisition, Technology and Logistics
PRF	Propeller Rotation Frequency
REVER	Remote Vibration Environment Recorder
RM ANOVA	Repeated Measures Analysis of Variance
SA	Steep Approach
SRB	Safety Review Board
Stat	Stationary

TO	Take-Off
TRB	Technical Review Board
VMC	Visual Meteorological Conditions
rms	Root-Mean-Square
a_{rms}	Root-Mean-Square Acceleration
a_{uw}	Overall Unweighted Acceleration Level
a_w	Overall Weighted Acceleration Level
k	Multiplying Factor (ISO 2631-1)
oVTV	Overall Vibration Total Value
pVTV	Point Vibration Total Value
W	Frequency Weighting (ISO 2631-1)